



microID[®] 13.56 MHz RFID System Design Guide

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Table of Contents

| | <u>PAGE</u> |
|--|-------------|
| PASSIVE RFID BASICS | |
| Introduction..... | 1 |
| Definitions..... | 1 |
| System Handshake | 3 |
| Backscatter Modulation | 3 |
| Data Encoding..... | 4 |
| Data Modulation for 125 kHz Devices (MCRF2XX) | 6 |
| Anti-collision | 7 |
| MCRF355/360 DATA SHEET | |
| Features | 9 |
| Application | 9 |
| Package Type | 9 |
| Description | 10 |
| 1.0 Electrical Characteristics..... | 11 |
| 2.0 Functional Description..... | 15 |
| 3.0 Resonant Circuit..... | 17 |
| 4.0 Device Programming..... | 18 |
| MCRF355/360 Guide Product Identification System..... | 27 |
| MICROCHIP DEVELOPMENT KIT SAMPLE FORMAT FOR THE MCRF355/360 DEVICES | |
| | 29 |
| FACTORY PROGRAMMING SUPPORT (SQTPSM) | |
| Introduction..... | 31 |
| File Specification | 31 |
| MCRF450/451/452/455 DATA SHEET | |
| Features | 33 |
| Applications..... | 33 |
| Package Types..... | 34 |
| 1.0 Description | 35 |
| 2.0 Electrical Characteristics..... | 37 |
| 3.0 Block Diagram | 44 |
| 4.0 Analog Front-End | 46 |
| 5.0 Detection and Encoding | 47 |
| 6.0 Read/Write Anti-Collision Logic..... | 48 |
| 7.0 Memory Section | 64 |
| 8.0 Device Testing..... | 67 |
| 9.0 Examples..... | 68 |
| 10.0 Failed Die Identification..... | 72 |
| 11.0 Wafer Delivery Documentation..... | 72 |
| 12.0 Notice on Die and Wafer Handling | 72 |
| 13.0 References..... | 72 |
| 14.0 Packaging Information..... | 73 |
| MCRF450/451/452/455 Product Identification System | 79 |

Table of Contents

| | <u>PAGE</u> |
|---|-------------|
| CRC ALGORITHM FOR MCRF45X READ/WRITE DEVICE | |
| Introduction..... | 81 |
| Computation Algorithm..... | 82 |
| Example with Source Code for CRC Calculation | 84 |
| MCRF355/360 APPLICATION NOTE: MODE OF OPERATION AND EXTERNAL RESONANT CIRCUIT | |
| Introduction..... | 87 |
| Mode of Operation..... | 87 |
| Anti-collision Features | 89 |
| External Circuit Configuration..... | 90 |
| Programming of Device..... | 92 |
| ANTENNA CIRCUIT DESIGN FOR RFID APPLICATIONS | |
| Introduction..... | 93 |
| Review of a Basic Theory for RFID antenna Design..... | 93 |
| Induced Voltage in an Antenna Coil..... | 95 |
| Wire Types and Ohmic Losses | 98 |
| Inductance of Various Antenna Coils | 101 |
| Configuration of Antenna Circuits..... | 111 |
| Consideration on Quality Factor Q and Bandwidth of Tuning Circuit..... | 113 |
| Resonant Circuits | 114 |
| Tuning Method | 117 |
| Read Range of RFID Devices | 118 |
| References | 139 |
| MCRF355/360 READER REFERENCE DESIGN | |
| 1.0 Introduction..... | 141 |
| 2.0 Reader Circuits..... | 141 |
| 3.0 Optimization for Long-Range Applications | 143 |
| 4.0 Reader Schematic..... | 145 |
| 5.0 Reader Bill of Materials | 146 |
| 6.0 Reader Source Code for the PICmicro® MCU | 148 |
| 13.56 MHZ READER REFERENCE DESIGN FOR THE MCRF450/451/452/455 READ/WRITE DEVICES AND MCRF355/360 READ-ONLY DEVICES | |
| 1.0 Introduction..... | 163 |
| 2.0 Interrogator Circuits..... | 165 |
| INTERFACE CONTROL DOCUMENT FOR THE 13.56 MHZ MCRF450/451/452/455 ANTI-COLLISION INTERROGATOR | |
| Scope | 177 |
| Referenced Documents..... | 189 |
| External Interfaces | 177 |



Table of Contents

| | <u>PAGE</u> |
|--|-------------|
| PICMICRO® MICROCONTROLLER FIRMWARE FLOW CHART | 191 |
| RECOMMENDED ASSEMBLY FLOWS | |
| 1.0 Wafer on Frame Assembly Flow | 205 |
| 2.0 Wafer Assembly Flow..... | 206 |
| WORLDWIDE SALES AND SERVICE | 208 |

NOTES:

Passive RFID Basics

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INTRODUCTION

Radio Frequency Identification (RFID) systems use radio frequency to identify, locate and track people, assets and animals. Passive RFID systems are composed of three components – a reader (interrogator), passive tag and host computer. The tag is composed of an antenna coil and a silicon chip that includes basic modulation circuitry and nonvolatile memory. The tag is energized by a time-varying electromagnetic radio frequency (RF) wave that is transmitted by the reader. This RF signal is called a *carrier signal*. When the RF field passes through an antenna coil, there is an AC voltage generated across the coil. This voltage is rectified to result in DC voltage for the device operation. The device becomes functional when the DC voltage reaches a certain level. The information stored in the device is transferred to the reader by reflecting, or loading, the reader's carrier. This is often called backscattering. By detecting the backscattering signal, the information stored in the device can be fully identified.

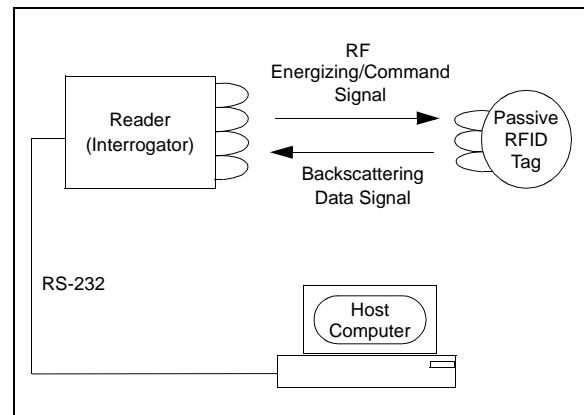
Because of its simplicity for use, the passive RFID system has been used for many years in various RF remote sensing applications, specifically in access control and animal tracking applications.

In recent years, there have been dramatic increases in application demands. In most cases, each application uses a unique packaging form factor, communication protocol, frequency, etc. Because the passive tag is remotely powered by the reader's RF signal, it deals with very small power ($\sim \mu\text{w}$). Thus, the read range (communication distance between reader and tag) is typically limited within a proximity distance. The read range varies with design parameters, such as frequency, RF power level, reader's receiving sensitivity, size of antenna, data rate, communication protocol, current consumptions of the silicon device, etc.

Low frequency bands (125 kHz to 400 kHz) were traditionally used in RFID applications. This was because of the availability of silicon devices. Typical carrier frequency (reader's transmitting frequency) in today's applications range from 125 kHz to 2.4 GHz.

In recent years, the applications with high frequency (4 to 20 MHz) and microwave (2.45 GHz) bands have risen with the advent of new silicon devices. Each frequency band has advantages and disadvantages. The 4 to 20 MHz frequency bands offer the advantages of both low (125 kHz) frequency and microwave (2.4 GHz) bands. Therefore, this frequency band becomes the most dominant frequency band in passive RFID applications.

FIGURE 1: SIMPLE CONFIGURATION OF RFID SYSTEMS



DEFINITIONS

Reader, Interrogator

RFID readers are used to activate passive tags with RF energy and to extract information from the tag.

For this function, the reader includes RF transmission, receiving and data decoding sections. In addition, the reader often includes a serial communication (RS-232, USB, etc.) capability to communicate with a host computer. Depending on the complexity and purpose of applications, the reader's price range can vary from ten dollars to a few thousand dollars worth of components and packaging.

The RF transmission section includes an RF carrier generator, antenna and a tuning circuit. The antenna and its tuning circuit must be properly designed and tuned for the best performance. See Application Note "Antenna Circuit Design for RFID Applications" (DS00710) for the antenna circuit design.

Data decoding for the received signal is accomplished using a microcontroller. The firmware algorithm in the microcontroller is written in such a way to transmit the RF signal, decode the incoming data and communicate with the host computer.

Typically, the reader is a read-only device, while the reader for a read and write device is often called interrogator. Unlike the reader for a read-only device, the interrogator uses command pulses to communicate with a tag for reading and writing data.

Tag

Tags consist of a silicon device and antenna circuit.

The purpose of the antenna circuit is to induce an energizing signal and to send a modulated RF signal. The read range of a tag largely depends upon the antenna circuit and size.

The antenna circuit is made of a LC resonant circuit or E-field dipole antenna, depending on the carrier frequency. The LC resonant circuit is used for frequencies of less than 100 MHz. In this frequency band, the communication between the reader and tag takes place with magnetic coupling between the two antennas through the magnetic field. An antenna utilizing inductive coupling is often called a magnetic dipole antenna.

The antenna circuits must be designed in such a way to maximize the magnetic coupling between them. This can be achieved with the following parameters:

- a) LC circuit must be tuned to the carrier frequency of the reader.
- b) Maximize Q of the tuned circuit.
- c) Maximize antenna size within physical limit of application requirement.

See Application Note “*Antenna Circuit Design for RFID Applications*” (DS00710) for more details.

Read-Only Device, Read/Write Device:

For the read-only device, the information that is in the memory cannot be changed by an RF command once it has been written.

Read-only devices are programmed as follows:

- a) In the factory as a part of manufacturing process
- b) Contactlessly programmed one time after the manufacturing (MCRF200 and MCRF250) or
- c) Can be programmed and also reprogrammed in Contact mode (MCRF355 and MCRF360)

A device with memory cells that can be reprogrammed by RF commands is called a read/write device. The information in the memory can be reprogrammed by Interrogator command (MCRF450).

Read/Write Range

Read/write range is the communication distance between the reader (interrogator) and tag. Specifically, the read range is the maximum distance to read data out from the tag and the write range is the maximum distance to write data from interrogator to the tag.

The read/write range is related to:

- (1) Electromagnetic coupling of the reader (interrogator) and tag antennas
- (2) RF Output power level of reader (interrogator)
- (3) Carrier frequency bands
- (4) Power consumption of the device

The electromagnetic coupling of the reader and tag antennas increases using a similar size of antenna with high Q in both sides. The read range is improved by increasing the carrier frequency. This is due to the gain in the radiation efficiency of the antenna as the frequency increases. However, the disadvantage of high frequency (900 MHz to 2.4 GHz) application is shallow skin depth and narrower antenna beam width. These cause less penetration and more directional problems, respectively. Low frequency application, on the other hand, has an advantage in the penetration and directional, but a disadvantage in the antenna performance.

Read range increases by reducing the current consumption in the silicon device. This is because the LC antenna circuit couples less energy from the reader at further distances. A lower power device can make use of less energy for the operation.

Modulation Protocol

The passive RFID tag uses backscattering of the carrier frequency for sending data from the tag to the reader. The amplitude of backscattering signal is modulated with modulation data of the tag device. The modulation data can be encoded in the form of ASK (NRZ or Manchester), FSK or PSK. Therefore, the modulation signal from the tag is Amplitude-Amplitude, Amplitude-FSK and Amplitude-PSK. See the *microID® 125 kHz Design Guide* (DS51115) for Amplitude, Amplitude-FSK and Amplitude-PSK reader reference designs.

Carrier

The carrier is the transmitted radio signal of the reader (interrogator). This RF carrier provides energy to the tag device, and is used to detect modulation data from the tag using a backscattering. In read/write devices, the carrier is also used to deliver the interrogator's commands and data to the tag.

Typical passive RFID carrier frequencies are:

- a) 125 kHz
- b) 13.56 MHz
- c) 900 MHz to 2.45 GHz.

The frequency bands must be selected carefully for applications because each one has its own advantages and disadvantages. Table 1 shows the characteristic of each frequency bands.

TABLE 1:

| Frequency Bands | Antenna Components | Read Range (typical) | Penetration (skin depth) | Orientation (Directionality) | Usability in metal or humid environment | Applications (typical) |
|------------------------------------|---------------------------------------|----------------------|--------------------------|------------------------------|---|-------------------------------|
| Low Frequency (120 to 400) kHz | Coil (> 100 turns) and capacitor | Proximity | Best | Least | Possible | Proximity |
| Medium Frequency (4 MHz to 24 MHz) | Coil (< 10 turns) and capacitor | Medium | Good | Not much | Possible | Low cost and high volume |
| High Frequency (>900 MHz) | E-field dipole (a piece of conductor) | Long (> 1 m) | Poor | Very high | Difficult | Line of sight with long range |

SYSTEM HANDSHAKE

Typical handshake of a tag and reader (interrogator) is as follows:

A. Read-Only Tag

(Example: MCRF200, MCRF355)

1. The reader continuously transmits an RF signal while always watching for modulated backscattering signal.
2. Once the tag has received sufficient energy to operate correctly, it begins clocking its data to a modulation transistor, which is connected across the antenna circuit.
3. The tag's modulation transistor shorts the antenna circuit, sequentially corresponding to the data which is being clocked out of the memory array.
4. Shorting and releasing the antenna circuit according to the modulation data causes amplitude fluctuation of antenna voltage across the antenna circuit.
5. The reader detects the amplitude variation of the tag and uses a peak-detector to extract the modulation data.

B. Read and Write Tag

(Example: MCRF45X devices with FRR and Reader Talks First mode)

1. The interrogator sends a command to initiate communication with tags in the field. The RF carrier is also used for energizing the device.
2. Once the tag has received sufficient energy and command, it responds back with its ID for acknowledgment.
3. The interrogator now knows which tag is in the field. The interrogator sends a command to the identified tag for instructions: processing (read or write) or Sleep.

4. If the tag receives processing and reading commands, it transmits a specified block data and waits for the next command.
5. If the tag receives processing and writing commands along with block data, it writes the block data into the specified memory block, and transmits the written block data for verification.
6. After the processing, the interrogator sends an End command to send the tag into the Sleep ("silent") mode.
7. If the device receives an End command after processing, it sends an acknowledgement (8-bit preamble) and stays in Sleep mode. During the Sleep mode, the device remains in non-modulating (detuned) condition as long as it remains in the power-up.
8. The interrogator is now looking for the next tag for processing, establishes a handshake and repeats the processing.
9. See Figure 4-1 in the MCRF45X Data Sheet (DS40232) for more details.

BACKSCATTER MODULATION

This terminology refers to the communication method used by a passive RFID tag to send data to the reader using the reader's own carrier signal. The incoming RF carrier signal to the tag is loaded and unloaded, causing amplitude modulation of the carrier, corresponding to the tag data bits.

The RF voltage induced in the tag's antenna is amplitude-modulated by the modulation signal (data) of the tag device. This amplitude-modulation can be achieved by using a modulation transistor across the LC resonant circuit or partially across the resonant circuit.

Changes in the voltage amplitude of the tag's antenna can affect the voltage of the reader antenna. By monitoring the changes in the reader antenna voltage (due to the tag's modulation data), the data in the tag can be reconstructed.

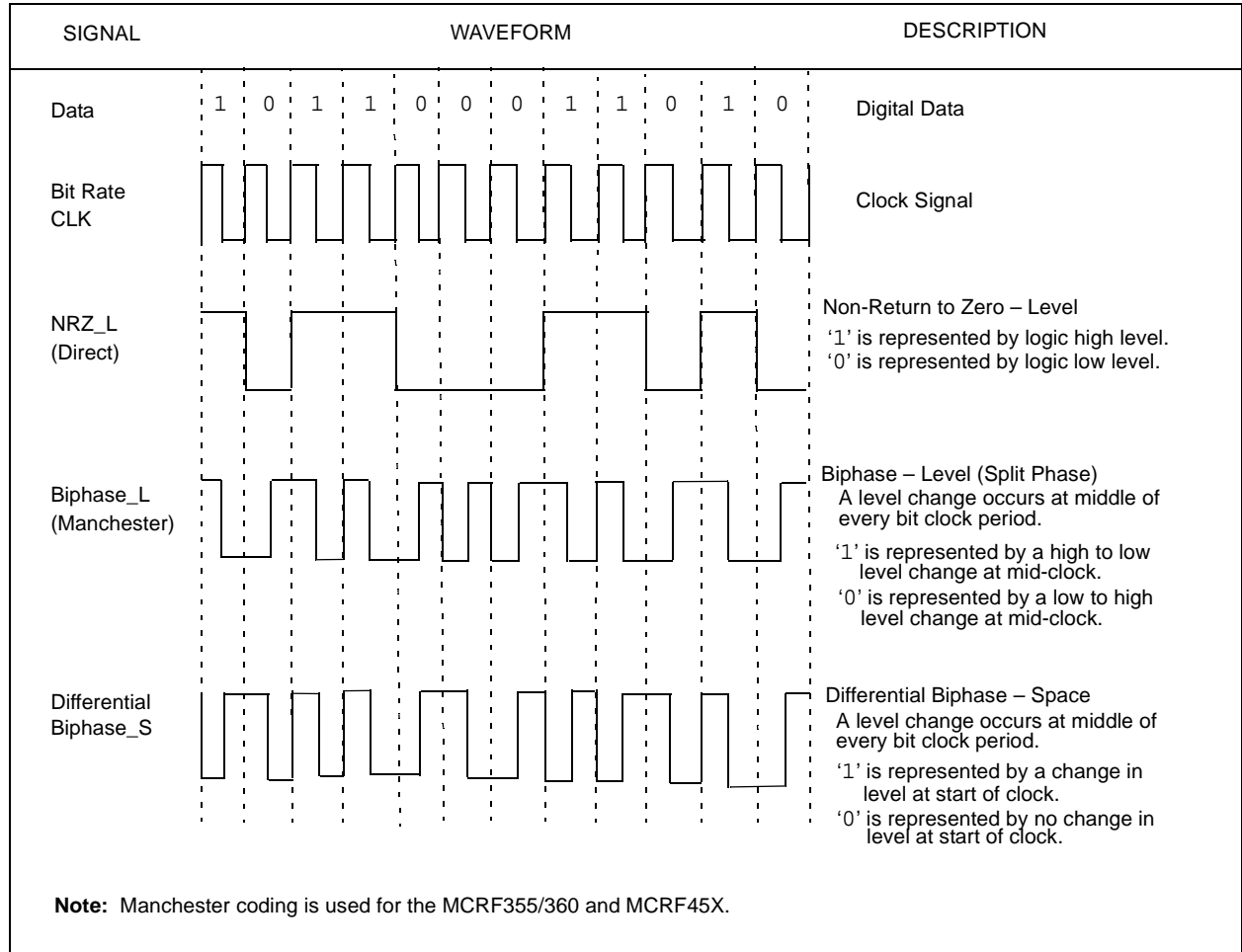
The RF voltage link between the reader and tag antennas are often compared to weakly coupled transformer coils; as the secondary winding (tag coil) is momentarily shunted, the primary winding (reader coil) experiences a momentary voltage change. Opening and shunting the secondary (tag coil) in sequence with the tag data is seen as amplitude modulation at the primary (reader coil).

DATA ENCODING

Data encoding refers to processing or altering the data bit stream in between the time it is retrieved from the RFID chip's data array and its transmission back to the reader. The various encoding algorithms affect error recovery, cost of implementation, bandwidth, synchronization capability and other aspects of the system design. Entire textbooks are written on the subject, but there are several popular methods used in RFID tagging today:

1. **NRZ (Non-Return to Zero) Direct.** In this method no data encoding is done at all; the 1's and 0's are clocked from the data array directly to the output transistor. A low in the peak-detected modulation is a '0' and a high is a '1'.
2. **Differential Biphase.** Several different forms of differential biphase are used, but in general the bit stream being clocked out of the data array is modified so that a transition always occurs on every clock edge, and 1's and 0's are distinguished by the transitions within the middle of the clock period. This method is used to embed clocking information to help synchronize the reader to the bit stream. Because it always has a transition at a clock edge, it inherently provides some error correction capability. Any clock edge that does not contain a transition in the data stream is in error and can be used to reconstruct the data.
3. **Biphase_L (Manchester).** This is a variation of biphase encoding in which there is not always a transition at the clock edge, but it does always have a transition in the middle of the clock cycle, so it can be used to extract a clock signal in asynchronous designs. **The MCRF355/360 and MCRF45X devices use this encoding method.**

FIGURE 2: SAMPLE DATA CODING WAVEFORMS



DATA MODULATION FOR 125 KHZ DEVICES (MCRF2XX)

Although all the data is transferred to the host by amplitude-modulating the carrier (backscatter modulation), the actual modulation of 1's and 0's is accomplished with three additional modulation methods:

1. **Direct.** In direct modulation, the amplitude modulation of the backscatter approach is the only modulation used. A high in the envelope is a '1' and a low is a '0'. Direct modulation can provide a high data rate but low noise immunity.
2. **FSK (Frequency Shift Keying).** This form of modulation uses two different frequencies for data transfer; the most common FSK mode is $F_c/8/10$. In other words, a '0' is transmitted as an amplitude-modulated clock cycle with period corresponding to the carrier frequency divided by 8, and a '1' is transmitted as an amplitude-modulated clock cycle period corresponding to the carrier frequency divided by 10. The amplitude modulation of the carrier thus switches from $F_c/8$ to $F_c/10$ corresponding to

0's and 1's in the bit stream, and the reader has only to count cycles between the peak-detected clock edges to decode the data. FSK allows for a simple reader design, provides very strong noise immunity, but suffers from a lower data rate than some other forms of data modulation. In Figure 3, FSK data modulation is used with NRZ encoding.

3. **PSK (Phase Shift Keying).** This method of data modulation is similar to FSK, except that only one frequency is used, and the shift between 1's and 0's is accomplished by shifting the phase of the backscatter clock by 180 degrees. Two common types of PSK are:
 - Change phase at any '0', or
 - Change phase at any data change (0 to 1 or 1 to 0).

PSK provides fairly good noise immunity, a moderately simple reader design, and a faster data rate than FSK. Typical applications utilize a backscatter clock of $F_c/2$, as shown in Figure 4.

FIGURE 3: FSK MODULATED SIGNAL, $F_c/8 = 0$, $F_c/10 = 1$

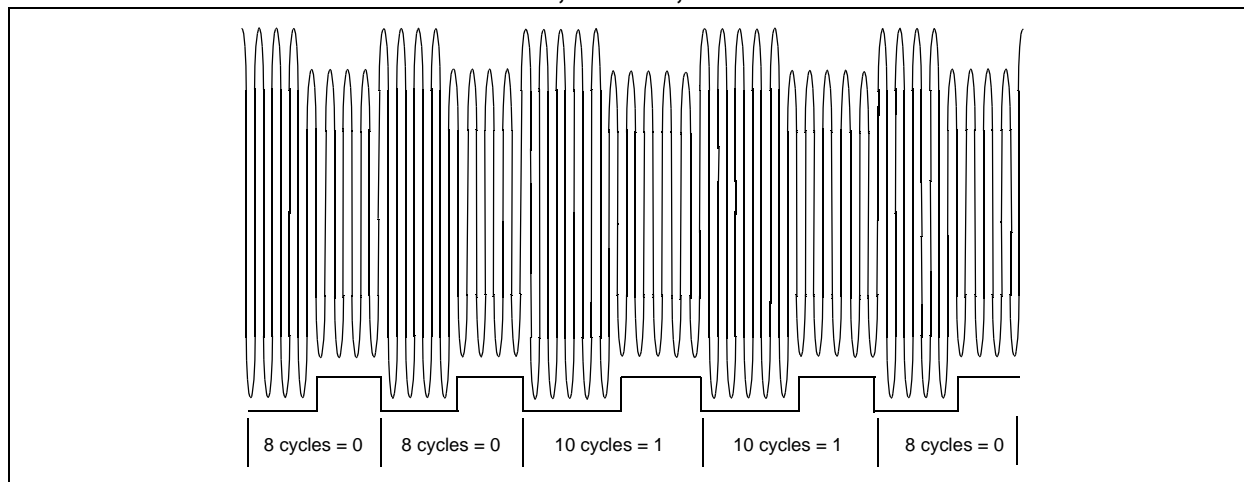
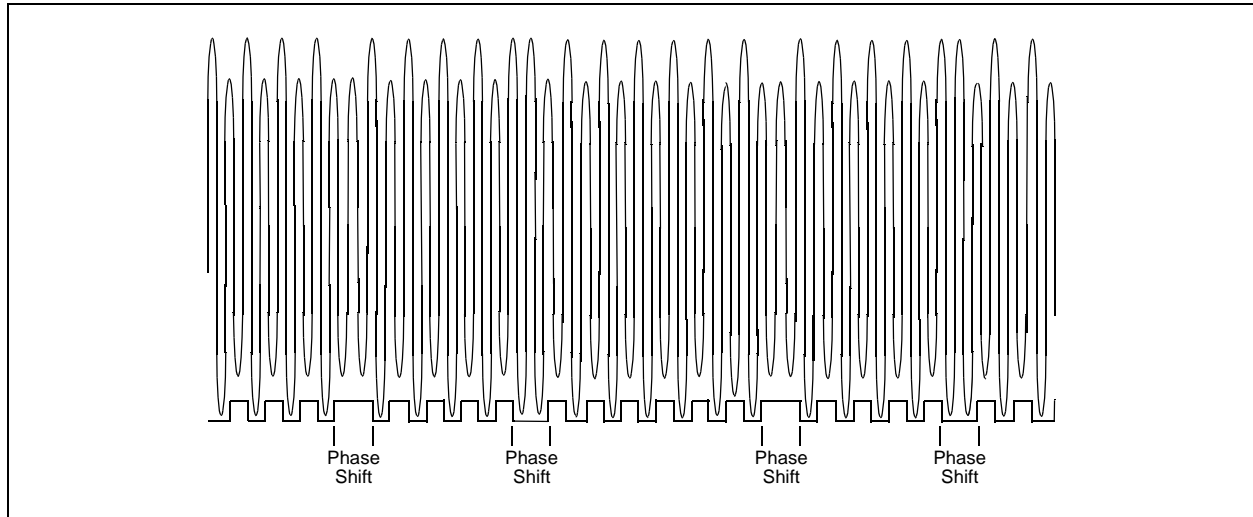


FIGURE 4: PSK MODULATED SIGNAL



ANTI-COLLISION

In many existing applications, a single-read RFID tag is sufficient and even necessary: animal tagging and access control are examples. However, in a growing number of new applications, the simultaneous reading of several tags in the same RF field is absolutely critical: library books, airline baggage, garment and retail applications are a few examples.

In order to read multiple tags simultaneously, both the tag and reader must be designed to detect the condition that more than one tag is active. Otherwise, the tags will all backscatter the carrier at the same time and the amplitude-modulated waveforms shown in Figure 3 and Figure 4 would be garbled. This is referred to as a *collision*. No data would be transferred to the reader. The tag/reader interface is similar to a serial bus, even though the “bus” travels through the air. In a wired serial bus application, arbitration is necessary to prevent bus contention. The RFID interface also requires arbitration so that only one tag transmits data over the “bus” at one time.

A number of different methods are in use and in development today for preventing collisions; most are patented or patent pending. Yet, all are related to making sure that only one tag “talks” (backscatters) at any one time. See the MCRF250 (DS21267), MCRF355/360 (DS21287) and MCRF45X (DS40232) data sheets for various anti-collision algorithms.

AN680

REVISION HISTORY

Revision A

Initial release

Revision D (03/04)

Corrections and general updates throughout document.

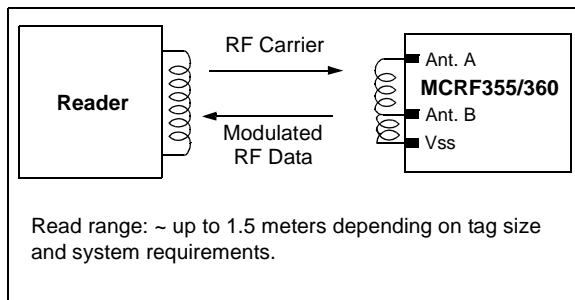
13.56 MHz Passive RFID Device with Anti-Collision Feature

Features:

- Carrier frequency: 13.56 MHz
- Data modulation frequency: 70 kHz
- Manchester coding protocol
- 154 bits of user memory
- On-board 100 ms SLEEP timer
- Built-in anti-collision algorithm for reading up to multiple tags in the same RF field
- "Cloaking" feature to minimize the detuning effects of adjacent tags
- Internal 100 pF resonant capacitor (MCRF360)
- Read only device in RF field
- Long read range
- Rewritable with contact programmer or factory-programmed options
- Very low power CMOS design
- Die, wafer, bumped wafer, COB, PDIP or SOIC package options

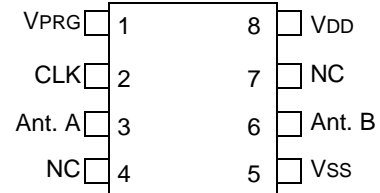
Application:

- Book store and library book ID
- Airline baggage tracking
- Toys and gaming tools
- Access control/asset tracking
- Applications for reading multiple tags and long read range



Package Type

PDIP/SOIC

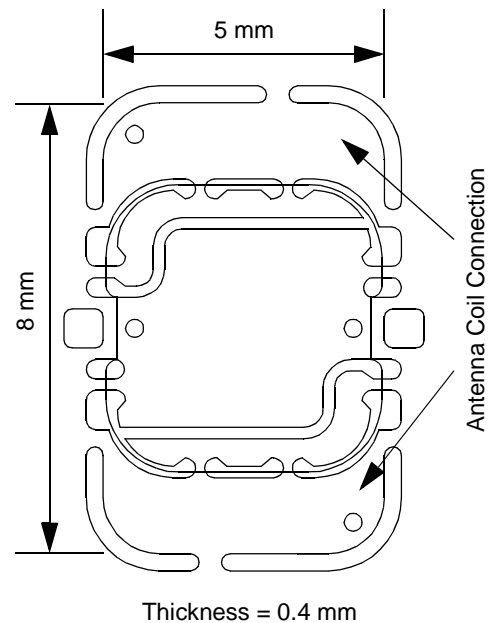


Note: Pins 1, 2, 5 and 8 are for device testing and contact programming.

Pins 3, 5 and 6 are for external antenna connection.

NC = Not connected

MCRF355 COB



MCRF355/360

Description:

The MCRF355 and MCRF360 are Microchip's 13.56 MHz microID[®] family of RFID tagging devices. They are uniquely designed read-only passive Radio Frequency Identification (RFID) devices with an advanced anti-collision feature. They are programmable with a contact programmer. The device is powered remotely by rectifying RF magnetic fields that are transmitted from the reader.

The device has a total of six pads (see Figure 1-1). Three (ant. A, B, VSS) are used to connect the external resonant circuit elements. The additional three pads (VPRG, CLK, VDD) are used for programming and testing of the device.

The device needs an external resonant circuit between antenna A, B, and VSS pads. The resonant frequency of the circuit is determined by the circuit elements between the antenna A and VSS pads. The resonant circuit must be tuned to the carrier frequency of the reader for maximum performance. The circuit element between the antenna B and VSS pads is used for data modulation. See Application Note AN707 for further operational details.

The MCRF360 includes a 100 pF internal resonant capacitor (100 pF). By utilizing this internal resonant capacitor, the device needs external coils only for the resonant circuit. Examples of the resonant circuit configuration for both the MCRF355 and MCRF360 are shown in Section 3.0.

When a tag (device with the external LC resonant circuit) is brought to the reader's RF field, it induces an RF voltage across the LC resonant circuit. The device rectifies the RF voltage and develops a DC voltage. The device becomes functional as soon as VDD reaches the operating voltage level.

The device includes a modulation transistor that is located between antenna B and VSS pads. The transistor has high turn-off (a few M Ω) and low turn-on (3 Ω) resistance. The turn-on resistance is called modulation resistance (RM). When the transistor turns off, the resonant circuit is tuned to the carrier frequency of the reader. This condition is called uncloaking. When the modulation transistor turns on, its low turn-on resistance shorts the external circuit element between the antenna B and VSS. As a result, the resonant circuit no longer resonates at the carrier frequency. This is called cloaking.

The induced voltage amplitude (on the resonant circuit) changes with the modulation data: higher amplitude during uncloaking (tuned), and lower amplitude during cloaking (detuned). This is called "amplitude modulation" signal. The receiver channel in the reader detects this amplitude modulation signal and reconstructs the modulation data.

The occurrence of the cloaking and uncloaking of the device is controlled by the modulation signal that turns the modulation transistor on and off, resulting in communication from the device to the reader.

The data stream consists of 154 bits of Manchester-encoded data at a 70 kHz rate. The Manchester code waveform is shown in Figure 2-2. After completion of the data transmission, the device goes into SLEEP mode for about 100 ms. The device repeats the transmitting and SLEEP cycles as long as it is energized. During the SLEEP time the device remains in an uncloaked state.

SLEEP time is determined by a built-in low-current timer. There is a wide variation of the SLEEP time between each device. This wide variation of SLEEP time results in a randomness of the time slot. Each device wakes up and transmits its data in a different time slot with respect to each other. Based on this scenario, the reader is able to read many tags that are in the same RF field.

The device has a total of 154 bits of reprogrammable memory. All bits are reprogrammable by a contact programmer. A contact programmer (part number PG103003) is available from Microchip Technology Inc. Factory programming prior to shipment, known as Serialized Quick Turn ProgrammingSM (SQTPSM), is also available. The device is available in die, wafer, bumped wafer, wafer-on-frame, PDIP, SOIC and COB modules.

| |
|---|
| Note: Information provided herein is preliminary and subject to change without notice. |
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1.0 ELECTRICAL CHARACTERISTICS

TABLE 1-1: ABSOLUTE RATINGS

| Parameters | Symbol | Min | Max | Units | Conditions |
|----------------------|--------------------|-----|-----|-------|---------------------------|
| Coil Current | I _{PP_AC} | — | 40 | mA | Peak-to-Peak coil current |
| Assembly temperature | T _{ASM} | — | 265 | °C | < 10 sec |
| Storage temperature | T _{STORE} | -65 | 150 | °C | — |

TABLE 1-2: DC CHARACTERISTICS

| All parameters apply across the specified operating ranges, unless otherwise noted. | | Commercial (C): T _{AMB} = -20°C to 70°C | | | | |
|---|---------------------|--|-----|------------------------|-------|--|
| Parameters | Symbol | Min | Typ | Max | Units | Conditions |
| Reading voltage | V _{DDR} | 2.4 | — | — | V | VDD voltage for reading |
| Hysteresis voltage | V _{HYST} | — | TBD | — | TBD | — |
| Operating current | I _{DDR} | — | 7 | 10 | μA | VDD = 2.4V during reading at 25°C |
| Testing voltage | V _{DDT} | — | 4 | — | V | — |
| Programming voltage: | | | | | | |
| High level input voltage | V _{IH} | 0.7 * V _{DDT} | — | — | V | External DC voltage for programming and testing |
| Low level input voltage | V _{IL} | — | — | 0.3 * V _{DDT} | V | |
| High voltage | V _{HH} | — | 20 | — | V | |
| Current leakage during SLEEP time | I _{DD_OFF} | — | 10 | — | nA | (Note 1) |
| Modulation resistance | R _M | — | 3 | 4 | Ω | DC resistance between Drain and Source gates of the modulation transistor (when it is turned on) |
| Pull-Down resistor | R _{PDW} | 5 | 8 | — | kΩ | CLK and VPRG internal pull-down resistor |

Note 1: This parameter is not tested in production.

MCRF355/360

TABLE 1-3: AC CHARACTERISTICS

| All parameters apply across the specified operating ranges, unless otherwise noted. | | Commercial (C): T _{AMB} = -20°C to 70°C | | | | |
|---|----------------------|--|-------|-----|-----------------|--|
| Parameters | Symbol | Min | Typ | Max | Units | Conditions |
| Carrier frequency | FC | | 13.56 | | MHz | Reader's transmitting frequency |
| Modulation frequency | FM | 58 | 70 | 82 | kHz | Manchester coding, at V _{DD} = 2.6 VDC - 5 VDC |
| Coil voltage during reading | V _{PP_AC} | 4 | — | — | V _{PP} | Peak-to-Peak AC voltage across the coil during reading |
| Coil clamp voltage | V _{CLMP_AC} | — | 32 | — | V _{PP} | Peak-to-Peak coil clamp voltage |
| Test mode clock frequency | F _{CLK} | | 115 | 500 | kHz | 25°C |
| SLEEP time | T _{OFF} | 50 | 100 | 200 | ms | Off time for anti-collision feature, at 25°C and V _{DD} = 2.5 VDC |
| Internal resonant capacitor (MCRF360) | C _{RES} | 85 | 100 | 115 | pF | Internal resonant capacitor between Antenna A and V _{SS} , at 13.56 MHz |
| Write/Erase pulse width | T _{WC} | — | 2 | 10 | ms | Time to program bit, at 25°C |
| Clock high time | T _{HIGH} | — | 4.4 | — | μs | 25°C for testing and programming |
| Clock low time | T _{LOW} | — | 4.4 | — | μs | 25°C for testing and programming |
| STOP condition pulse width | T _{PW:STO} | — | 1000 | — | ns | 25°C for testing and programming |
| STOP condition setup time | T _{SU:STO} | — | 200 | — | ns | 25°C for testing and programming |
| Setup time for high voltage | T _{SU:HH} | — | 800 | — | ns | 25°C for testing and programming |
| High voltage delay time | T _{DL:HH} | — | 800 | — | ns | Delay time before the next clock, at 25°C for testing and programming |
| Data input setup time | T _{SU:DAT} | — | 450 | — | ns | 25°C for testing and programming |
| Data input hold time | T _{HD:DAT} | — | 1.2 | — | μs | 25°C for testing and programming |
| Output valid from clock | T _{AA} | — | 200 | — | ns | 25°C for testing and programming |
| Data retention | — | 200 | | — | Years | For T < 120°C |

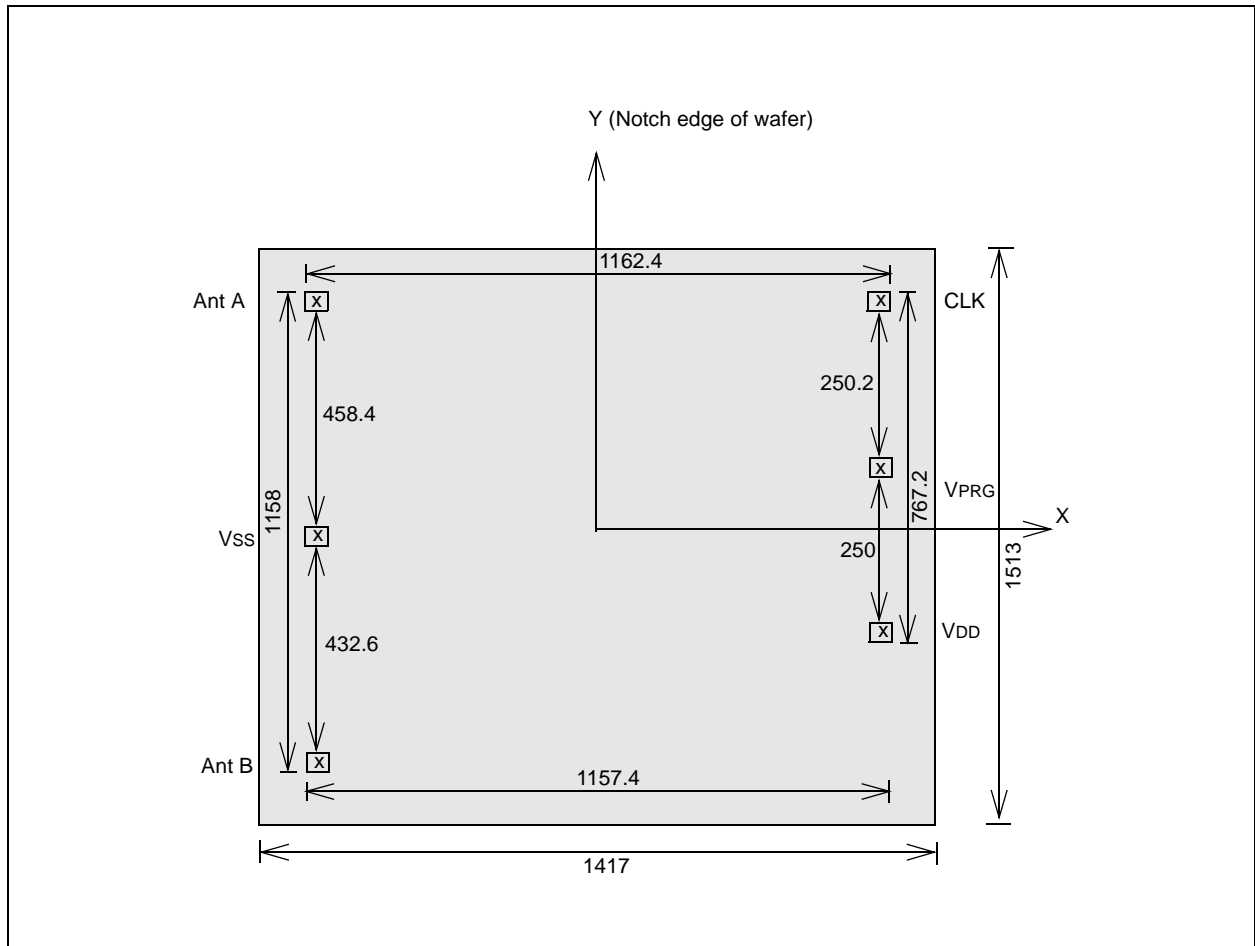
TABLE 1-4: PAD COORDINATES (MICRONS)

| Pad Name | Lower Left X | Lower Left Y | Upper Right X | Upper Right Y | Passivation Openings | | Pad Center X | Pad Center Y |
|----------|--------------|--------------|---------------|---------------|----------------------|------------|--------------|--------------|
| | | | | | Pad Width | Pad Height | | |
| Ant. A | -610.0 | 489.2 | -521.0 | 578.2 | 89 | 89 | -565.5 | 533.7 |
| Ant. B | -605.0 | -579.8 | -516.0 | -490.8 | 89 | 89 | -560.5 | -535.3 |
| VSS | -605.0 | -58.2 | -516.0 | 30.8 | 89 | 89 | -560.5 | -13.7 |
| VDD | 463.4 | -181.4 | 552.4 | -92.4 | 89 | 89 | 507.9 | -136.9 |
| CLK | 463.4 | 496.8 | 552.4 | 585.8 | 89 | 89 | 507.9 | 541.3 |
| VPRG | 463.4 | 157.6 | 552.4 | 246.6 | 89 | 89 | 507.9 | 202.1 |

Note 1: All coordinates are referenced from the center of the die. The minimum distance between pads (edge to edge) is 10 mil.

2: Die Size = 1.417 mm x 1.513 mm = 1417 μm x 1513 μm = 55.79 mil x 59.57 mil

FIGURE 1-1: DIE LAYOUT



Die size before saw:

1417 μm x 1513 μm
55.79 mil x 59.57 mil

Die size after saw:

1353.8 μm x 1450.34 μm
53.3 x 57.1 mil

Bond pad size:

89 μm x 89 μm
3.5 mil x 3.5 mil

MCRF355/360

TABLE 1-5: PAD FUNCTION TABLE

| Name | Function |
|--------|---|
| Ant. A | Connected to external resonant circuit, (Note 1) |
| Ant. B | Connected to external resonant circuit, (Note 1) |
| Vss | Connected to external resonant circuit, (Note 1) Device ground during Test mode |
| VDD | DC voltage supply for programming and Test mode |
| CLK | Main clock pulse for programming and Test mode |
| VPRG | Input/Output for programming and Test mode |

Note 1: See Figure 3-1 for the connection with external resonant circuit.

TABLE 1-6: DIE MECHANICAL DIMENSIONS

| Specifications | Min. | Typ. | Max. | Unit | Comments |
|--|-------|---------------|-------|-------|--|
| Wafer Diameter | — | 8 | — | inch | |
| Die separation line width | — | 80 | — | μm | |
| Dice per wafer | — | 12,000 | — | die | |
| Batch size | — | 24 | — | wafer | |
| Bond pad opening | — | 3.5 x 3.5 | — | mil | (Note 1, Note 2) |
| | — | 89 x 89 | — | μm | |
| Die backgrind thickness | 7.5 | 8 | 8.5 | mil | Sawed 8" wafer on frame (option = WF) (Note 3) |
| | 190.5 | 203.2 | 215.9 | μm | |
| | 10 | 11 | 12 | mil | <ul style="list-style-type: none"> • Bumped, sawed 8" wafer on frame (option = WFB) • Unsawed wafer (option = W) • Unsawed 8" bumped wafer (option = WB), (Note 3) |
| | 254 | 279.4 | 304.8 | μm | |
| Die passivation thickness (multilayer) | — | 1.3 | — | μm | (Note 4) |
| Die Size: | | | | | |
| Die size X*Y before saw (step size) | — | 55.79 x 59.57 | — | mil | — |
| Die size X*Y after saw | — | 53.3 x 57.1 | — | mil | — |

- Note 1:** The bond pad size is that of the passivation opening. The metal overlaps the bond pad passivation by at least 0.1 mil.
Note 2: Metal Pad Composition is 98.5% Aluminum with 1% Si and 0.5% Cu.
Note 3: As the die thickness decreases, susceptibility to cracking increases. It is recommended that the die be as thick as the application will allow.
Note 4: The Die Passivation thickness (1.3 μm) can vary by device depending on the mask set used.
 - Layer 1: Oxide (undoped oxide)
 - Layer 2: PSG (doped oxide)
 - Layer 3: Oxynitride (top layer)
Note 5: The conversion rate is 25.4 μm/mil.

Note: Extreme care is urged in the handling and assembly of die products since they are susceptible to mechanical and electrostatic damage.

2.0 FUNCTIONAL DESCRIPTION

The device contains three major sections: (1) Analog Front-End, (2) Controller Logic and (3) Memory. Figure 2-1 shows the block diagram of the device.

2.1 Analog Front-End Section

This section includes power supply, Power-on Reset, and data modulation circuits.

2.1.1 POWER SUPPLY

The power supply circuit generates DC voltage (VDD) by rectifying induced RF coil voltage. The power supply circuit includes high-voltage clamping diodes to prevent excessive voltage development across the antenna coil.

2.1.2 POWER-ON-RESET (POR)

This circuit generates a Power-on Reset when the tag first enters the reader field. The RESET releases when sufficient power has developed on the VDD regulator to allow for correct operation.

2.1.3 DATA MODULATION

The data modulation circuit consists of a modulation transistor and an external LC resonant circuit. The external circuit must be tuned to the carrier frequency of the reader (i.e., 13.56 MHz) for maximum performance.

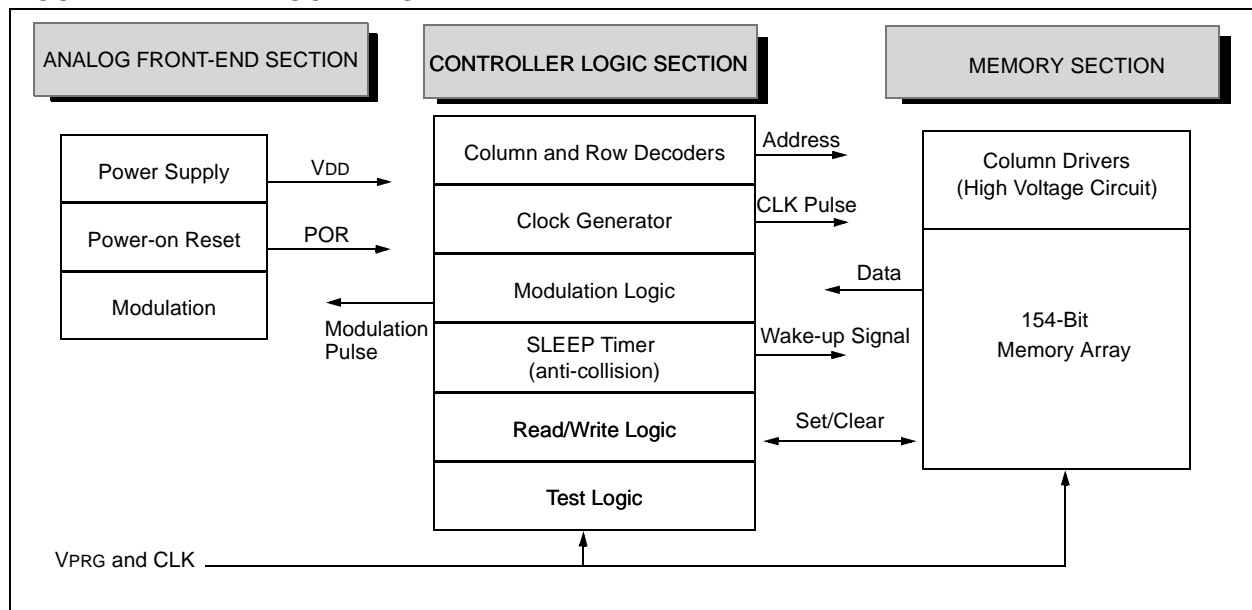
The modulation transistor is placed between antenna B and Vss pads and has small turn-on resistance (RM). This small turn-on resistance shorts the external circuit between the antenna B and Vss pads as it turns on.

The transistor turns on during the “Hi” period of the modulation data and turns off during the “Lo” period.

When the transistor is turned off, the resonant circuit resonates at the carrier frequency. Therefore, the external circuit develops maximum voltage across it. This condition is called uncloaking (tuned). When the transistor is turned on, its low turn-on resistance shorts the external circuit, and therefore the circuit no longer resonates at the carrier frequency. The voltage across the external circuit is minimized. This condition is called cloaking (detuned).

The device transmits data by cloaking and uncloaking based on the on/off condition of the modulation transistor. Therefore, with the 70 kHz - Manchester format, the data bit “0” will be sent by cloaking (detuned) and uncloaking (tuned) the device for 7 μs each. Similarly, the data bit “1” will be sent by uncloaking (tuned) and cloaking (detuned) the device for 7 μs each. See Figure 2-2 for the Manchester waveform.

FIGURE 2-1: BLOCK DIAGRAM



MCRF355/360

2.2 Controller Logic Section

2.2.1 CLOCK PULSE GENERATOR

This circuit generates a clock pulse (CLK). The clock pulse is generated by an on-board time-base oscillator. The clock pulse is used for baud rate timing, data modulation rate, etc.

2.2.2 MODULATION LOGIC

This logic acts upon the serial data (154 bits) being read from the memory array. The data is then encoded into Manchester format. The encoded data is then fed to the modulation transistor in the Analog Front-End section. The Manchester code waveform is shown in Figure 2-2.

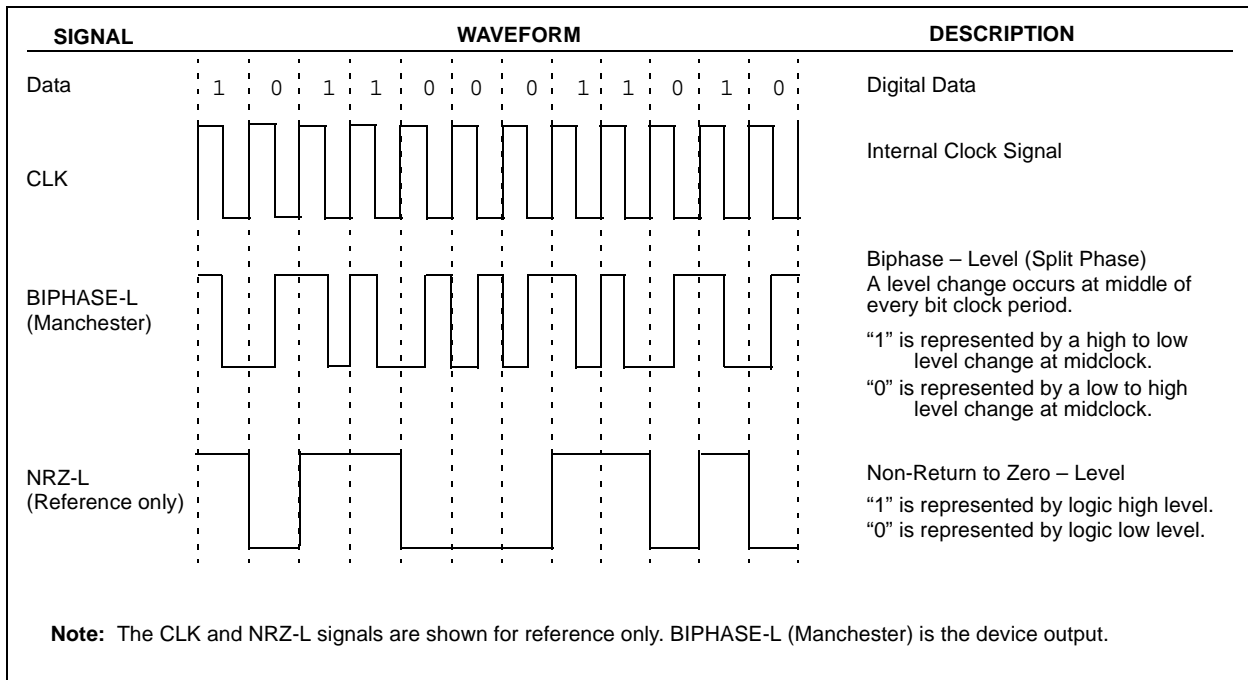
2.2.3 SLEEP TIMER

This circuit generates a SLEEP time (100 ms \pm 50%) for the anti-collision feature. During this SLEEP time (TOFF), the modulation transistor remains in a turned-on condition (cloaked) which detunes the LC resonant circuit.

2.2.4 READ/WRITE LOGIC

This logic controls the reading and programming of the memory array.

FIGURE 2-2: CODE WAVEFORMS



3.0 RESONANT CIRCUIT

The MCRF355 requires external coils and capacitor in order to resonate at the carrier frequency of the reader. About one-fourth of the turns of the coil should be connected between antenna B and Vss; remaining turns should be connected between antenna A and B pads. The MCRF360 includes a 100 pF internal resonant capacitor. Therefore, the device needs only external coils for the resonant circuit. For example, the device needs 1.377 μH of inductance for the carrier frequency = 13.56 MHz.

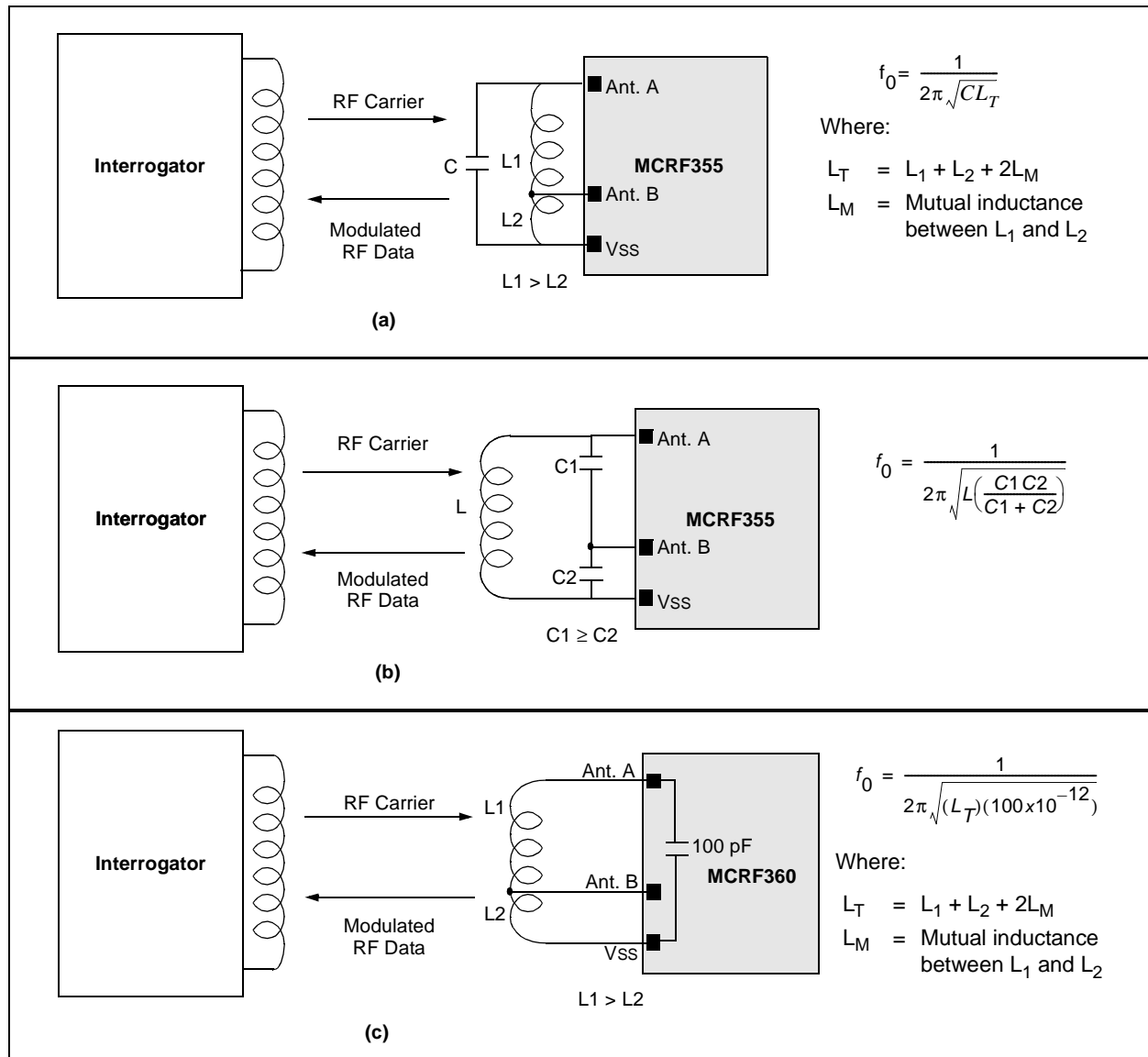
Figures 3-1 (a) and (b) show possible configurations of the external circuits for the MCRF355. In Figure 3-1 (a), two external antenna coils (L1 and L2) in series and a

capacitor that is connected across the two inductors form a parallel resonant circuit to pick up incoming RF signals and also to send modulated signals to the reader. The first coil (L1) is connected between antenna A and B pads. The second coil (L2) is connected between antenna B and Vss pads. The capacitor is connected between antenna A and Vss pads.

Figure 3-1(b) shows the resonant circuit formed by two capacitors (C1 and C2) and one inductor.

Figure 3-1(c) shows a configuration of an external circuit for the MCRF360. By utilizing the 100 pF internal resonant capacitor, only L1 and L2 are needed for the external circuit.

FIGURE 3-1: CONFIGURATION OF EXTERNAL RESONANT CIRCUITS



MCRF355/360

4.0 DEVICE PROGRAMMING

MCRF355/360 is a reprogrammable device in Contact mode. The device has 154 bits of reprogrammable memory. It can be programmed in the following procedure. (A programmer, part number PG103003, is also available from Microchip).

4.1 Programming Logic

Programming logic is enabled by applying power to the device and clocking the device via the CLK pad while loading the mode code via the VPRG pad (See Examples 4-1 through 4-2 for test definitions). Both the CLK and the VPRG pads have internal pull-down resistors.

4.2 Pin Configuration

Connect antenna A, B and VSS pads to ground.

4.3 Pin Timing

1. Apply VDDT voltage to VDD. Leave VSS, CLK and VPRG at ground.
2. Load mode code into the VPRG pad. The VPRG is sampled at CLK low to high edge.

3. The above mode function (3.2.2) will be executed when the last bit of code is entered.
4. Power the device off ($V_{DD} = V_{SS}$) to exit Programming mode.
5. An alternative method to exit the Programming mode is to bring CLK logic "High" before VPRG to VHH (high voltage).
6. Any Programming mode can be entered after exiting the current function.

4.4 Programming Mode

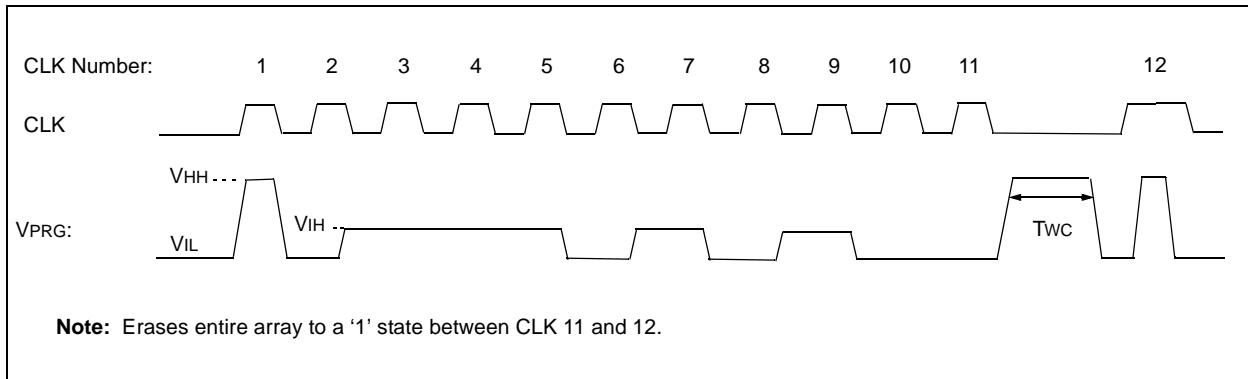
1. Erase EE Code: 0111010100
2. Program EE Code: 0111010010
3. Read EE Code: 0111010110

Note: '0' means logic "Low" (VIL) and '1' means logic "High" (VIH).

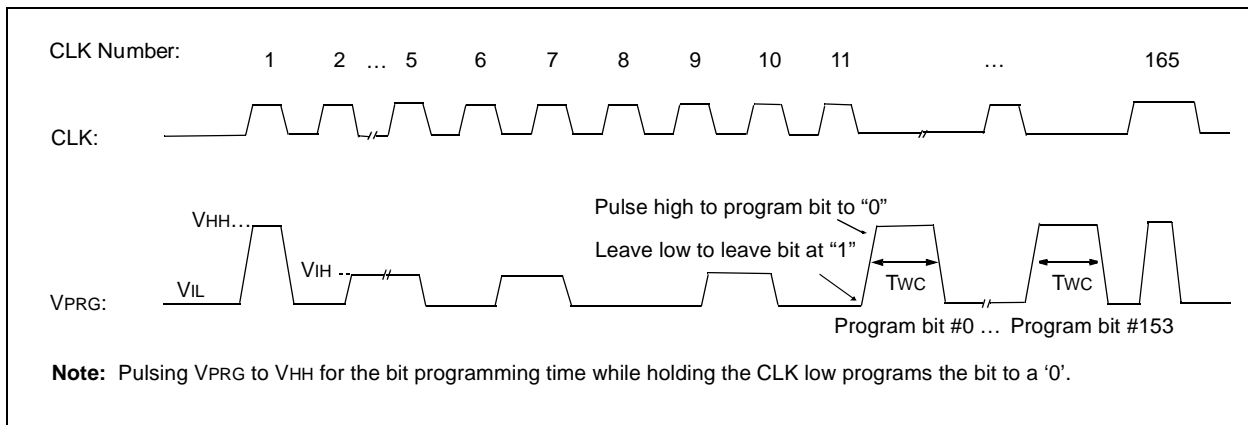
4.5 Signal Timing

Examples 4-1 through 4-2 show the timing sequence for programming and reading of the device.

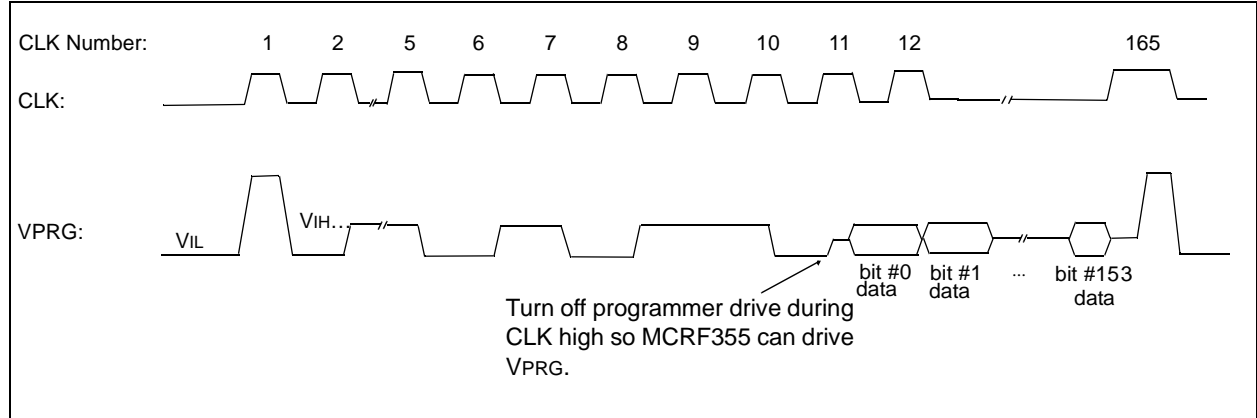
EXAMPLE 4-1: PROGRAMMING MODE 1: ERASE EE



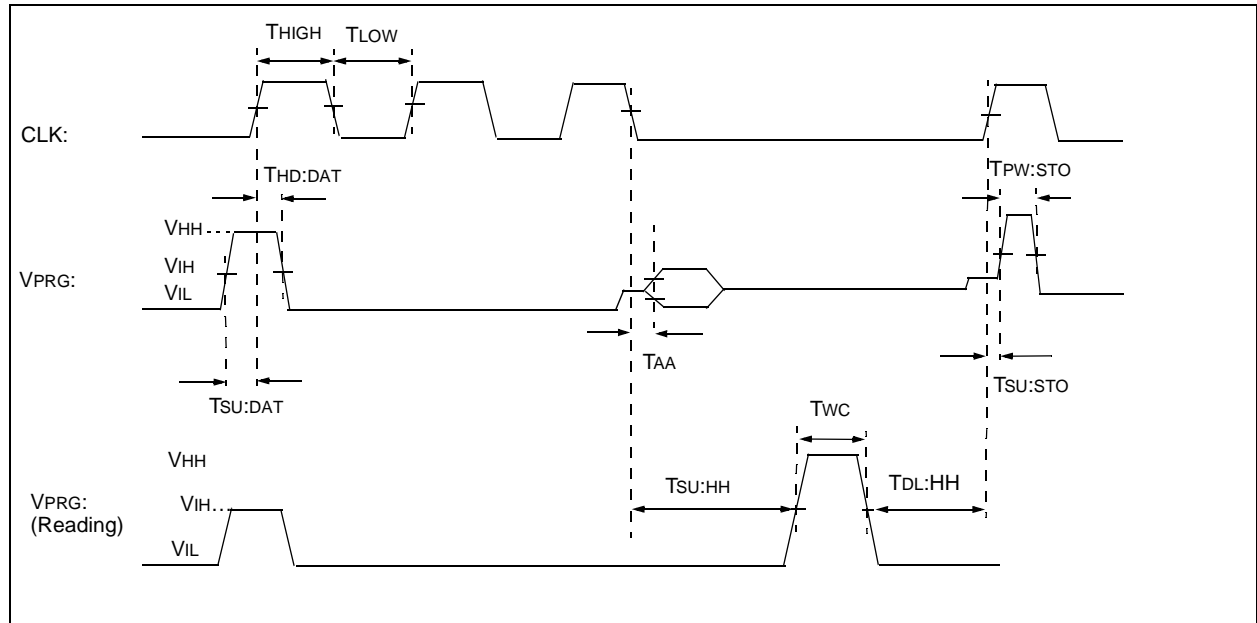
EXAMPLE 4-2: PROGRAMMING MODE 2: PROGRAM EE



EXAMPLE 4-1: PROGRAMMING MODE 3: READ EE



EXAMPLE 4-2: TIMING DATA



5.0 FAILED DIE IDENTIFICATION

Every die on the wafer is electrically tested according to the data sheet specifications and visually inspected to detect any mechanical damage, such as mechanical cracks and scratches.

Any failed die in the test or visual inspection is identified by black colored ink. Therefore, any die covered with black ink should not be used.

The ink dot specification:

- Ink dot size: 254 μm in circular diameter
- Position: central third of die
- Color: black

6.0 WAFER DELIVERY DOCUMENTATION

The wafer is shipped with the following information:

- Microchip Technology Inc. MP Code
- Lot Number
- Total number of wafers in the container
- Total number of good dice in the container
- Average die per wafer (DPW)
- Scribe number of wafers with number of good dice

7.0 NOTICE ON DIE AND WAFER HANDLING

The device is very susceptible to Electro-Static Discharge (ESD), which can cause a critical damage to the device. Special attention is needed during the handling process.

Any ultraviolet (UV) light can erase the memory cell contents of an unpackaged device. Fluorescent lights and sunlight can also erase the memory cell, although it takes more time than UV lamps. Therefore, keep any unpackaged device out of UV light and also avoid direct exposure of strong fluorescent lights and shining sunlight.

Certain IC manufacturing, COB and tag assembly operations may use UV light. Operations such as backgrind de-tape, certain cleaning procedures, epoxy or glue cure should be done without exposing the die surface to UV light.

Using X-ray for die inspection will not harm the die, nor erase memory cell contents.

8.0 REFERENCES

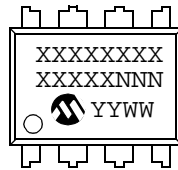
It is recommended that the reader reference the following documents.

1. "Antenna Circuit Design for RFID Applications", AN710, DS00710.
2. "RFID Tag and COB Development Guide with Microchip's RFID Devices", AN830, DS00830.
3. "MCRF355/360 Application Note: Mode of Operation and External Resonance Circuit", AN707, DS00707.
4. "Microchip Development Kit Sample Format for the MCRF355/360 Devices", TB031, DS91031.
5. "MCRF355/360 Reader Reference Design", DS21311.

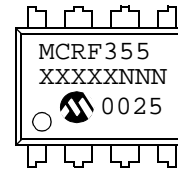
PACKAGING INFORMATION

8.1 Package Marking Information

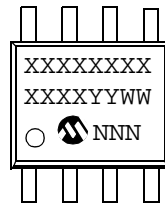
8-Lead PDIP (300 mil)



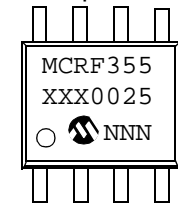
Example:



8-Lead SOIC (150 mil)



Example:

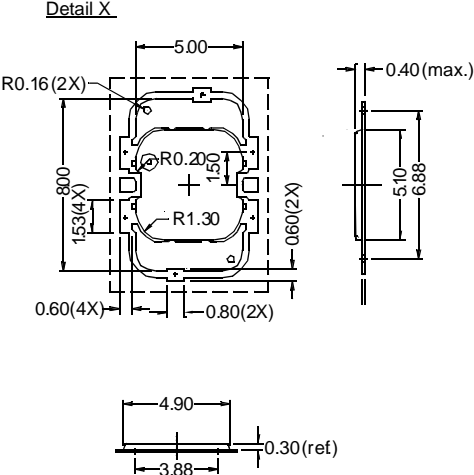
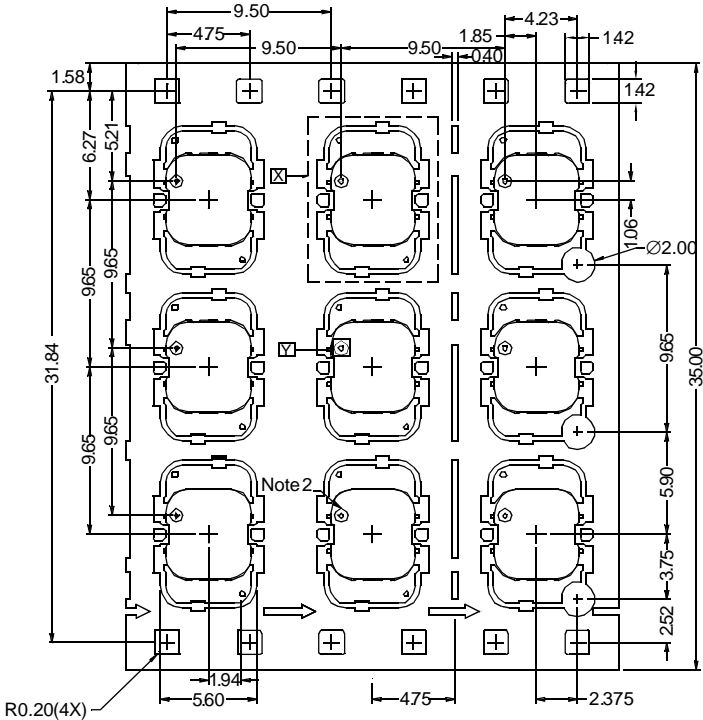


| | | |
|----------------|--|--|
| Legend: | XX...X | Customer specific information* |
| | Y | Year code (last digit of calendar year) |
| | YY | Year code (last 2 digits of calendar year) |
| | WW | Week code (week of January 1 is week '01') |
| | NNN | Alphanumeric traceability code |
| Note: | In the event the full Microchip part number cannot be marked on one line, it will be carried over to the next line thus limiting the number of available characters for customer specific information. | |

* Standard device marking consists of Microchip part number, year code, week code, and traceability code.

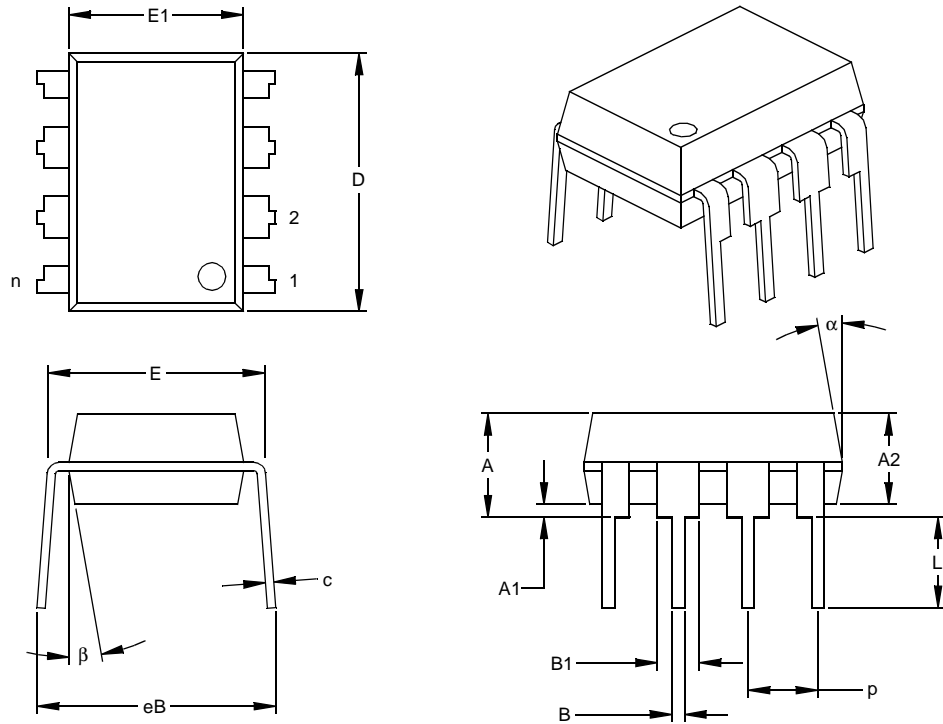
MCRF355/360

MCRF355 COB



Note:
1. Reject hole by device testing
2. Top gate mark (Option)
3. Total package thickness excludes punching burr

8-Lead Plastic Dual In-line (P) – 300 mil (PDIP)



| UNITS | | INCHES* | | | MILLIMETERS | | |
|----------------------------|------|---------|------|------|-------------|------|-------|
| DIMENSION LIMITS | | MIN | NOM | MAX | MIN | NOM | MAX |
| Number of Pins | n | | 8 | | | 8 | |
| Pitch | p | | .100 | | | 2.54 | |
| Top to Seating Plane | A | .140 | .155 | .170 | 3.56 | 3.94 | 4.32 |
| Molded Package Thickness | A2 | .115 | .130 | .145 | 2.92 | 3.30 | 3.68 |
| Base to Seating Plane | A1 | .015 | | | 0.38 | | |
| Shoulder to Shoulder Width | E | .300 | .313 | .325 | 7.62 | 7.94 | 8.26 |
| Molded Package Width | E1 | .240 | .250 | .260 | 6.10 | 6.35 | 6.60 |
| Overall Length | D | .360 | .373 | .385 | 9.14 | 9.46 | 9.78 |
| Tip to Seating Plane | L | .125 | .130 | .135 | 3.18 | 3.30 | 3.43 |
| Lead Thickness | c | .008 | .012 | .015 | 0.20 | 0.29 | 0.38 |
| Upper Lead Width | B1 | .045 | .058 | .070 | 1.14 | 1.46 | 1.78 |
| Lower Lead Width | B | .014 | .018 | .022 | 0.36 | 0.46 | 0.56 |
| Overall Row Spacing | § eB | .310 | .370 | .430 | 7.87 | 9.40 | 10.92 |
| Mold Draft Angle Top | α | 5 | 10 | 15 | 5 | 10 | 15 |
| Mold Draft Angle Bottom | β | 5 | 10 | 15 | 5 | 10 | 15 |

* Controlling Parameter

§ Significant Characteristic

Notes:

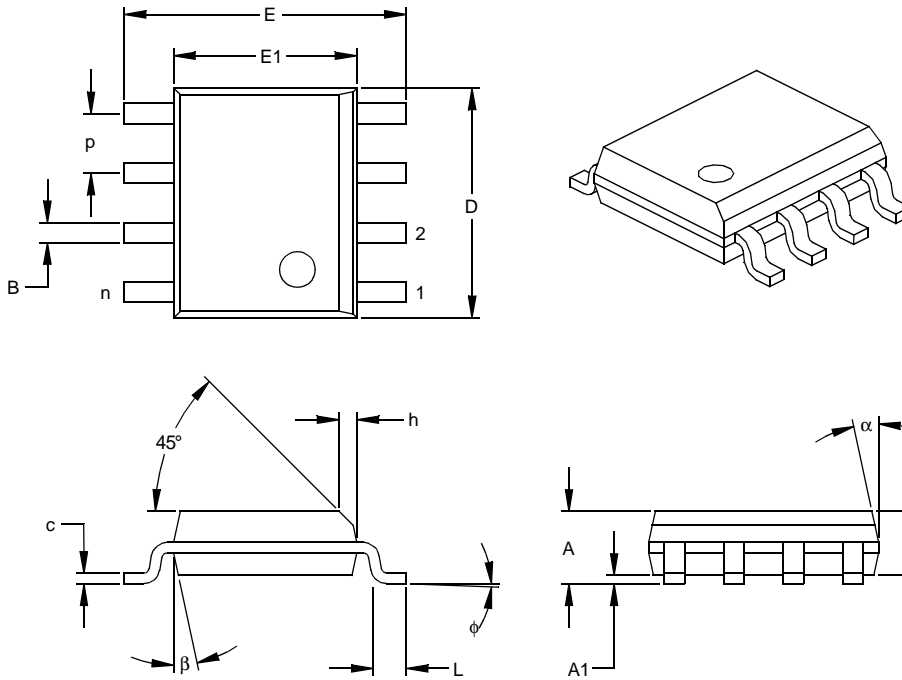
Dimensions D and E1 do not include mold flash or protrusions. Mold flash or protrusions shall not exceed .010" (0.254mm) per side.

JEDEC Equivalent: MS-001

Drawing No. C04-018

MCRF355/360

8-Lead Plastic Small Outline (SN) – Narrow, 150 mil (SOIC)



| UNITS | | INCHES* | | | MILLIMETERS | | |
|--------------------------|----|---------|------|------|-------------|------|------|
| DIMENSION LIMITS | | MIN | NOM | MAX | MIN | NOM | MAX |
| Number of Pins | n | | 8 | | | 8 | |
| Pitch | p | | .050 | | | 1.27 | |
| Overall Height | A | .053 | .061 | .069 | 1.35 | 1.55 | 1.75 |
| Molded Package Thickness | A2 | .052 | .056 | .061 | 1.32 | 1.42 | 1.55 |
| Standoff § | A1 | .004 | .007 | .010 | .10 | .18 | .25 |
| Overall Width | E | .228 | .237 | .244 | 5.79 | 6.02 | 6.20 |
| Molded Package Width | E1 | .146 | .154 | .157 | 3.71 | 3.91 | 3.99 |
| Overall Length | D | .189 | .193 | .197 | 4.80 | 4.90 | 5.00 |
| Chamfer Distance | h | .010 | .015 | .020 | .25 | .38 | .51 |
| Foot Length | L | .019 | .025 | .030 | .48 | .62 | .76 |
| Foot Angle | φ | 0 | 4 | 8 | 0 | 4 | 8 |
| Lead Thickness | c | .008 | .009 | .010 | .20 | .23 | .25 |
| Lead Width | B | .013 | .017 | .020 | .33 | .42 | .51 |
| Mold Draft Angle Top | α | 0 | 12 | 15 | 0 | 12 | 15 |
| Mold Draft Angle Bottom | β | 0 | 12 | 15 | 0 | 12 | 15 |

* Controlling Parameter

§ Significant Characteristic

Notes:

Dimensions D and E1 do not include mold flash or protrusions. Mold flash or protrusions shall not exceed .010" (0.254mm) per side.

JEDEC Equivalent: MS-012

Drawing No. C04-057

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www.microchip.com

The file transfer site is available by using an FTP service to connect to:

<ftp://ftp.microchip.com>

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1-480-792-7302 for the rest of the world.

MCRF355/360

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Device: MCRF355/360 Literature Number: DS21287F

Questions:

1. What are the best features of this document?

2. How does this document meet your hardware and software development needs?

3. Do you find the organization of this document easy to follow? If not, why?

4. What additions to the document do you think would enhance the structure and subject?

5. What deletions from the document could be made without affecting the overall usefulness?

6. Is there any incorrect or misleading information (what and where)?

7. How would you improve this document?

PRODUCT IDENTIFICATION SYSTEM

To order or obtain information, e.g., on pricing or delivery, refer to the factory or the listed sales office.

| <u>PART NO.</u> | <u>X</u> | <u>/XXX</u> |
|--------------------|--|-------------|
| Device | Temperature Range | Package |
| Device: | MCRF355 = 13.56 MHz Anti-Collision device. | |
| | MCRF355/6C = MCRF355 Cross Technology World II COB module with dual 68 pF capacitors | |
| | MCRF355/7M = MCRF355 IST I0A2 COB module with dual 68 pF capacitors | |
| | MCRF355/7M: = MCRF355 COB module with dual 68 pF capacitors. | |
| | MCRF360 = 13.56 MHz Anti-Collision device with 100 pF on-chip resonance capacitor. | |
| Temperature Range: | = -20°C to +70°C | |
| Package: | W = Wafer (11 mil backgrind) | |
| | WB = Bumped wafer (8 mil backgrind) | |
| | WF = Sawed wafer on frame (8 mil backgrind) | |
| | WFB = Bumped, sawed wafer on frame (8 mil backgrind) | |
| | P = Plastic PDIP (300 mil Body) 8-lead | |
| | S = Dice in waffle pack (8 mil) | |
| | SB = Bumped die in waffle pack (8 mil) | |
| | SN = Plastic SOIC (150 mil Body) 8-lead | |

Examples:

- a) MCRF355/W: = 11-mil wafer.
- b) MCRF355/WF: = 8-mil wafer on frame.
- c) MCRF355/P: = PDIP package.

- a) MCRF360/WFB: = Bumped 8-mil wafer on frame
- b) MCRF360/SB: = Bumped 8-mil die.
- c) MCRF360/SN: = SOIC package.

Sales and Support

Data Sheets

Products supported by a preliminary Data Sheet may have an errata sheet describing minor operational differences and recommended workarounds. To determine if an errata sheet exists for a particular device, please contact one of the following:

1. Your local Microchip sales office
2. The Microchip Corporate Literature Center U.S. FAX: (480) 792-7277
3. The Microchip Worldwide Site (www.microchip.com)

Please specify which device, revision of silicon and Data Sheet (include Literature #) you are using.

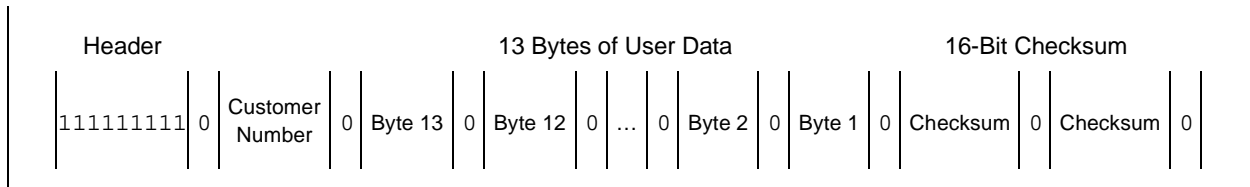
New Customer Notification System

Register on our web site (www.microchip.com/cn) to receive the most current information on our products.

MCRF355/360

NOTES:

Microchip Development Kit Sample Format for the MCRF355/360 Devices



- 9 -bit header
- 8 -bit customer number
- 104 bits (13 x 8) of user data
- 17 bits of zeros between each byte, header, and checksum
- 16 bits of checksum

Total: 154 bits

Notes:

- Users can program all 154 bits of the MCRF355/360. The array can be programmed in any custom format and with any combination of bits.
- The format presented here is used for Microchip microID[®] Development Systems (DV103003 and DV103006) and can be ordered as production material with a unique customer number.
- See TB032 for information on ordering custom programmed production material.
- The Microchip Development System (DV103003) uses nine 1's (111111111) as header.
- The preprogrammed tag samples in the development kit have hex 11(= 0001 0001) as the customer number.
- For the development system, users can program the customer number (1 byte) plus the 13 bytes of user data or they can deselect the "Microchip Format" option in the microID[®] rFLAB[™] and program all 154 bits in any format.
- When users program the samples using the microID rFLAB, the rFLAB calculates the checksum (2 bytes) automatically by adding up all 14 bytes (customer number + 13 bytes of user data), and put into the checksum field in the device memory. See Example 1 for details.
- When the programmed tag is energized by the reader field, the tag outputs all 154 bits of data.
- When the demo reader detects data from the tag, it reports the 14 bytes of the data (customer number plus 13 bytes of user data) to the host computer if the header and checksum are correct. The reader does not send the header and checksum to the host computer.
- The "microID rFLAB" or a simple terminal program such as "terminal.exe" can be used to read the reader's output (28 hex digits) on the host computer.
- When the demo reader is used in the Terminal mode ("terminal.exe), the tag's data appear after the first two dummy ASCII characters (GG). See Example 2 for details.

EXAMPLE 1: CHECKSUM

Checksum (XXXXXXXX XXXXXXXX) = Byte 1 + Byte 2 ++ Byte 13 + Customer Number (1 byte)

EXAMPLE 2: READER'S OUTPUT IN TERMINAL MODE ("TERMINAL.EXE")

The demo reader outputs GG+28 hex digits (i.e., GG 12345678901234567890ABCDEF GF).

The first two ASCII characters (GG) are dummy characters.

The tag's data are the next 28 hex digits (112 bits) after the first two ASCII characters (GG).

TB031

NOTES:

MCRF355/360 Factory Programming Support (SQTPSM)

INTRODUCTION

The MCRF355 and MCRF360 are 13.56 MHz RF tags which can be contact programmed. The contact programming of the device can be performed by the user or factory-programmed by Microchip Technology Inc. upon customer request. All 154 bits of data may be programmed in any format or pattern defined by the customer.

For factory programming, ID codes and series numbers must be supplied by the customer. The customer may supply the ID codes and series numbers on floppy disk, data CD or via email. The codes must conform to the Serialized Quick Turn ProgrammingSM (SQTPSM) format below:

FILE SPECIFICATION

SQTP codes supplied to Microchip must comply with the following format:

The ID code file is a plain ASCII text file from floppy disk, CD or email (no file headers).

If code files are compressed, they should be in zipped (.zip) files, not self-extracting (.exe) files.

The code files are used in alphabetical order of their file names (including letters and numbers).

Used (i.e., programmed) code files are discarded by Microchip after use.

Each line of the code file must contain one ID code for one IC.

The code is in hexadecimal format.

The code line is exactly 154 bits (39 hex characters, where the last 2 bits of the last character are don't cares).

Each line must end with a carriage return.

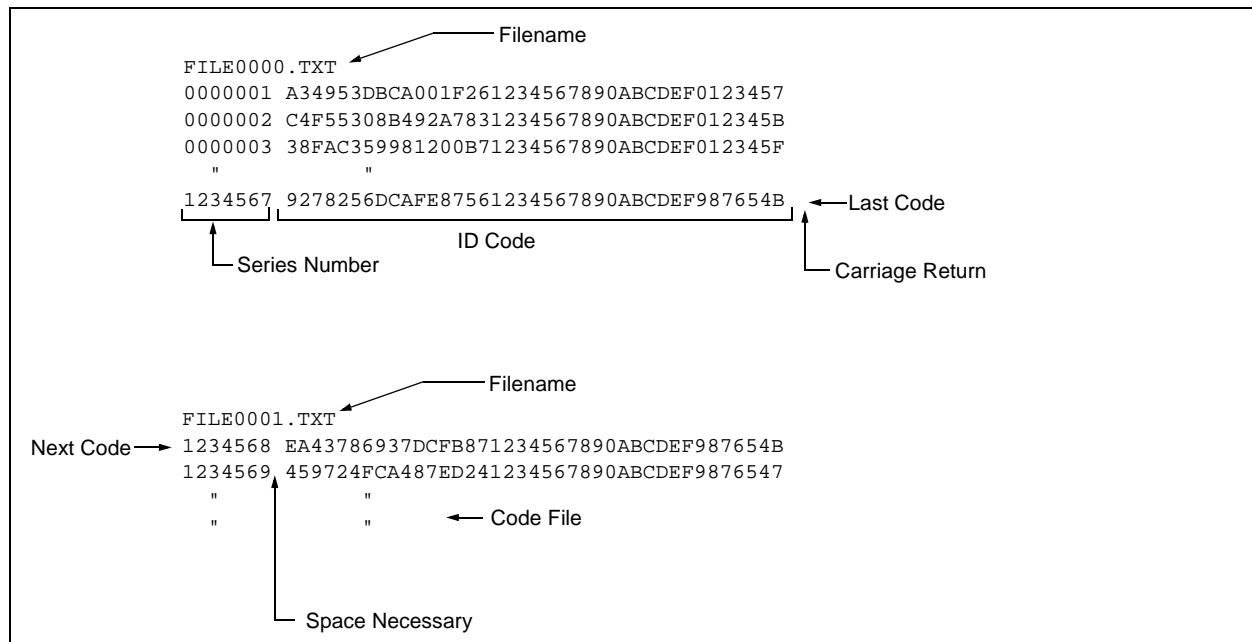
Each hexadecimal ID code must be preceded by a decimal series number of five, six or seven digits.

Series number and ID code must be separated by a space.

The series number must be unique and ascending to avoid double programming.

The series numbers of consecutive files must also increment serially for proper linking.

FIGURE 1: EXAMPLE OF TWO SEQUENTIAL CODE FILES



Serialized Quick Turn Programming (SQTP) is a service mark of Microchip Technology Inc.

TB032

NOTES:



MICROCHIP MCRF450/451/452/455

13.56 MHz Read/Write Passive RFID Device

Features:

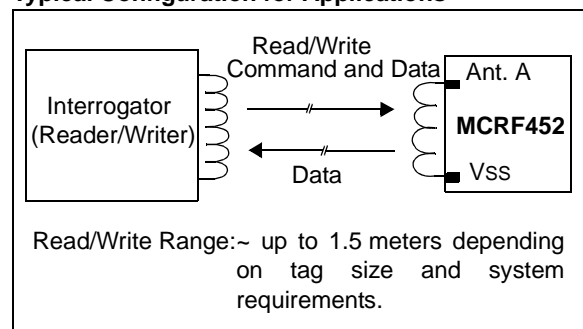
- Contactless read and write with anti-collision algorithm
- 1024 bits (32 blocks) of total memory
- 928 bits (29 blocks) of user programmable memory
- Unique 32-bit tag ID (factory programmed)
- 32 bits for data and 16 bits for CRC per block
- Block write protection
- 70 Kbit/s read data rate (Manchester format)
- Special bit (Fast Read) for fast identification and anti-counterfeit applications (EAS)
- 1-of-16 PPM encoding for writing data
- Interrogator-Talks-First (ITF) or Tag-Talks-First (TTF) operation
- Long range for reading and writing
- High-speed anti-collision algorithm for reading and writing
- Fast and Normal modes for write data speed
- Anti-tearing feature for secure write transactions
- Asynchronous operation for low power consumption and flexible choice of carrier frequency bands
- Internal resonance capacitors (MCRF451/452/ 455)
- Two pad connections for external antenna circuit (MCRF452)
- Three pad connections for external antenna circuit (MCRF450, 451, 455)
- Very low power CMOS design
- Die in waffle pack, wafer, wafer on frame, bumped wafer, COB, PDIP or SOIC package options

Applications:

- **Item Level Tagging:** To read and write multiple items in long read range environment.
- **Anti-Counterfeit:** The device has a unique feature to distinguish between paid, unpaid or returned merchandise.
- **Inventory Management:** Tag's data can be read or updated (written) in multiple tags and long range environment. Its memory (32 blocks, 1 Kbit, each block = 32 bits) is well organized for the inventory management applications.
- **Product Identifications**
- Airline Baggage Tracking
- Book Store and Library Book ID
- **Low Cost Animal Ear Tags:** The device's long range reading performance combined with 1 Kbit of memory is suitable for animal tagging applications. Tag cost can be cheaper and read range is much longer than existing 125 kHz conventional animal ear tags.
- **Toys and Gaming Tools:** Device's anti-collision feature for reading and writing allows to make intelligent interactive toys and gaming tools.
- **Access Control and Time Attendance Cards:** Device's long range performance allows to make long range access control, parking lot entry, and time attendance cards.

Inexpensive finished tags and readers are available from Microchip's worldwide OEM partners. Please contact Microchip Technology Inc. near you or visit <http://www.microchip.com> for further product information and inquiries for your applications.

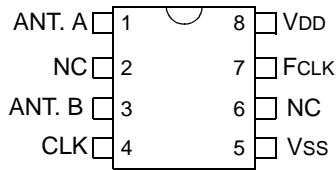
Typical Configuration for Applications



MCRF450/451/452/455

Package Types

PDIP ("P")

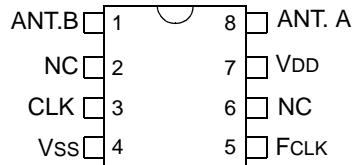


Note: Pins 4, 7 and 8 are for device test purposes only
NC = Not Connected

MCRF450/451/455: Antenna connections = pins 1, 3 and 5

MCRF452: Antenna connections = pins 1 and 5

ROTATED SOIC ("X/SN")

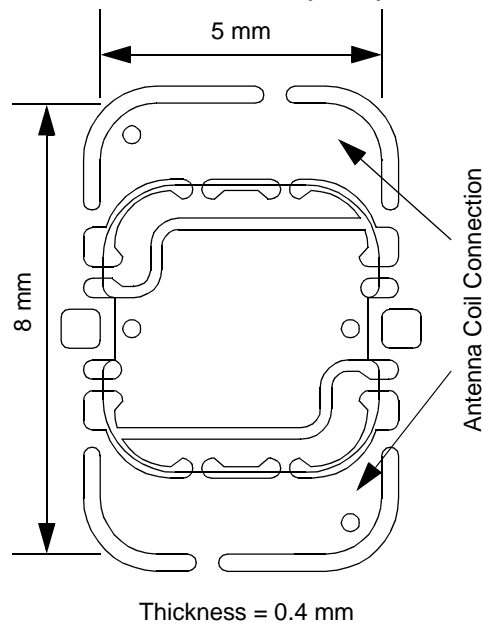


Note: Pins 3, 5 and 7 are for device test purposes only
NC = Not Connected

MCRF450/451/455: Antenna connections = pins 1, 4 and 8

MCRF452: Antenna connections = pins 4 and 8

MCRF450 COB ("7M")



1.0 DESCRIPTION OF DEVICE FEATURES

The MCRF450/451/452/455 is a contactless read/write passive RFID device that is optimized for 13.56 MHz RF carrier signal. The device needs an external LC resonant circuit to communicate wirelessly with the Interrogator. The device is powered remotely by rectifying an RF signal that is transmitted from the Interrogator and transmits or updates its contents from memory-based on commands from the Interrogator.

The device is engineered to be used effectively for item level tagging applications, such as retail and inventory management, where a large volume of tags are read and written in the same Interrogator field.

The device contains 32 blocks (B0-B31) of EEPROM memory. Each block consists of 32 bits. The first three blocks (B0-B2) are allocated for device operation, while the remaining 29 blocks (B3-B31: 928 bits) are for user data. Block 1 contains unique 32 bits of Tag ID. The Tag ID is preprogrammed at the factory and write protected.

All blocks, except for the Tag ID (Block 1), are contactlessly writable block-wise by Interrogator commands. All data blocks, with the exception of bits 30 and 31 in Block 0, are write-protectable.

The device can be configured as either Tag-Talks-First (TTF) or Interrogator-Talks-First (ITF). In TTF mode, the device transmits its fast response data (160 bits max., see Example 9-1) as soon as it is energized, then waits for the next command. In ITF mode, the device requires an Interrogator command before it sends any data. The control bits for TTF and ITF modes are bits 30 and 31 in Block 0.

All downlink commands from the Interrogator are encoded using 1-of-16 Pulse Position Modulation (PPM) and specially timed gap pulses. This encoded information amplitude modulates the Interrogator's RF carrier signal.

At the other end, the MCRF450/451/452/455 device demodulates the received RF signal and then sends data (from memory) at 70 Kbit/s back to the Interrogator in Manchester format.

The communication between Interrogator and device takes place asynchronously. Therefore, to enhance the detection accuracy of the device, the Interrogator sends a time reference signal (time calibration pulse) to the device, followed by the command and programming data. The time reference signal is used to calibrate timing of the internal decoder of the device.

There are device options for the internal resonant capacitor between antenna A and Vss: (a) no internal resonant capacitor for the MCRF450, (b) 100 pF for the MCRF451, (c) two 50 pF in series (25 pF in total) for the MCRF452 and (d) 50 pF for the MCRF455. The internal resonant capacitors for each device are shown in Figures 2-2 through 2-5.

The MCRF450 needs an external LC resonant circuit connected between antenna A, antenna B and Vss pads. See Figure 2-2 for the external circuit configuration. The MCRF452 needs a single external antenna coil only between antenna A and Vss pads, as shown in Figure 2-4.

This external circuit, along with the internal resonant capacitor, must be tuned to the carrier frequency of the Interrogator for maximum performance.

When a tag (device with the external LC resonant circuit) is brought to the Interrogator's RF field, it develops an RF voltage across the external circuit. The device rectifies the RF voltage and develops a DC voltage (VDD). The device becomes functional as soon as VDD reaches the operating voltage level.

The device then sends data stored in memory to the Interrogator by turning on/off the internal modulation transistor. This internal modulation transistor is located between antenna B and Vss. The modulation transistor has a very small turn-on resistance between Drain (antenna B) and Source (Vss) terminals during its turn-on time.

When the modulation transistor turns on, the resonant circuit component between antenna B and Vss, which is in parallel with the modulation transistor, is shorted due to the low turn-on resistance. This results in a change in the LC value of the circuit. As a result, the circuit no longer resonates at the carrier frequency of the Interrogator. Therefore, the voltage across the circuit is minimized. This condition is called "cloaking".

When the modulation transistor turns off, the circuit resonates at the carrier frequency of the Interrogator and develops maximum voltage. This condition is called "uncloaking". Therefore, the data is sent to the Interrogator by turning on (cloaking) and off (uncloaking) the modulation transistor.

The voltage amplitude of the carrier signal across the LC resonant circuit changes depending on the amplitude of modulation data. This is called an amplitude modulation signal. The receiver channel in the Interrogator detects this amplitude modulation signal and reconstructs the modulation data for decoding.

The device includes a unique anti-collision algorithm to be read or written effectively in multiple tag environments. To minimize data collision, the algorithm utilizes time division multiplexing of the device response. Each device can communicate with the Interrogator in a different time slot. The devices in the Interrogator's RF field remain in a nonmodulating condition if they are not in the given time slot. This enables the Interrogator to communicate with the multiple devices one at a time without data collision. The details of the algorithm are described in **Section 6.0 "Read/Write Anti-Collision Logic"**.

MCRF450/451/452/455

To enhance data integrity for writing, the device includes an anti-tearing feature. This anti-tearing feature provides verification of data integrity for incomplete write cycles due to failed communication between the Interrogator and the device during the write sequences.

1.1 Device's Communication with Interrogator

The device can be operated in either Fast Read Request (FRR) or Fast Read Bypass (FRB) mode, depending on the status of bit 31 (FR: bit) of Block 0. If the FR bit is set, the device is operated in FRR mode, and FRB mode, if the FR bit is cleared. The FR bit is always reprogrammable and not write-protectable. The FRR mode is a default setting. The communication between the Interrogator and tag starts with a FRR or FRB command.

In FRR mode, the device sends a response only when it receives the FRR command, not the FRB command.

Conversely, the device in FRB mode sends a response when it receives the FRB command only, not the FRR command.

If the device is set to FRR mode and also set to TTF mode (TF bit = set), the device can send the FRR response as soon as it is energized.

One of the main purposes of using the two different modes (FRR and FRB) is to use the device effectively in the item level supply-chain application, where a rapid identification and an effective anti-collision read/write process is needed (i.e., to identify whether it is a paid or unpaid item, or whether it passed one particular point of interest or not). This can be done by either checking the status of the FR bit or by checking the response of the tag to the command. For this reason, the FR bit is also called an Electronic Article Surveillance (EAS) bit.

1.1.1 OPERATION OF TAG IN FRR MODE

If the device is in the FRR mode (FR bit = set), the communication between the Interrogator and the device can start in two ways, depending on the status of TF (Bit 30 of Block 0). If the TF bit is cleared, it is called ITF mode. In this case, the tag waits for the Interrogator's FRR command and sends the FRR response data when it sees the FRR command. If the TF bit is set, the device is in a TTF mode. In this case, the tag sends the FRR response as soon as it is energized, even without the FRR command. The tag has a short listening window (1 ms) immediately after the FRR response. The Interrogator sends its next command during this listening window.

The FRR response includes the 32 bits of tag ID and FRF (Blocks 3 -5). See Tables 7-3, 7-4 and 7-6 for data. The Interrogator identifies which tags are in the field by receiving their FRR responses.

Based upon the FRR response, the Interrogator will send Matching Code 1 (MC1) or Matching Code 2 (MC2) during the tag's listening window. The Interrogator sends the MC1 to put the tag into Sleep mode. Tags in Sleep mode never respond to any command. Removal of the Interrogator's RF energy from the device is the only way to wake-up the device.

If the tag needs further read/write processing, the Interrogator sends the MC2, followed by a Read or Write command. After the completion of reading or writing of block data, the Interrogator sends an End command to put the tag into Sleep mode.

The reading and writing of the FRR devices takes place in the Anti-collision mode. For instance, if there are multiple tags in the field, the Interrogator selects one tag at a time by controlling the tag's time slot for the FRR response. The Interrogator repeats this sequence until all tags in its field are processed:

- send FRR command
- receive FRR response
- send Matching Code 1 or 2 at tag's listing window
- send Read Block command/or send Write Block command and data
- verify read/write response
- send End command
- verify the End command response
- look for other tag's FRR responses

1.1.2 OPERATION OF TAG IN FRB MODE

The communication with the device in the FRB mode is initiated by the FRB command only. If the device sees the Interrogator's FRB command, it sends its 32-bit tag ID and waits for the MC2. This is followed by a Read or Write command. Once the device is read or written, the Interrogator sends an End command. Unlike the FRR mode, the reading and writing of the tag are processed in a non Anti-collision mode.

See **Section 6.0 "Read/Write Anti-Collision Logic"**, for the read and write anti-collision algorithm. See Example 9-1 for command sequences and device responses.

2.0 ELECTRICAL CHARACTERISTICS

TABLE 2-1: ABSOLUTE RATINGS

| Parameters | Symbol | Min | Max | Units | Conditions |
|--|--------------------|-----|------|-------|---------------------------|
| Coil current into coil pad | I _{PP_AC} | — | 40 | mA | Peak-to-Peak coil current |
| Maximum power dissipation | PMPD | — | 0.5 | W | — |
| Ambient temperature with power applied | T _{AMB} | -40 | +125 | °C | — |
| Assembly temperature | T _{ASM} | — | 300 | °C | < 10 sec. |
| Storage temperature | T _{STORE} | -65 | 150 | °C | — |

Note: Stresses above those listed under “Maximum ratings” may cause permanent damage to the device. This is a stress rating only and functional operation of the device at those or any other conditions above those indicated in the operational listings of this specification is not implied. Exposure to maximum rating conditions for extended periods may affect device reliability.

TABLE 2-2: OPERATING DC CHARACTERISTICS

| Standard Operating Conditions (unless otherwise stated) Operating Temperature = -20°C to +70°C | | | | | | |
|---|---------------------|-----|-----|-----|-----------------|---|
| Parameters | Symbol | Min | Typ | Max | Units | Conditions |
| Reading voltage | V _{DDR} | 2.8 | — | — | V | V _{DD} voltage for reading at 25°C |
| Operating current in Normal mode | I _{OPER_N} | — | 20 | — | μA | V _{DD} = 2.8V during reading at 25°C |
| Operating current in Fast mode | I _{OPER_F} | — | 45 | — | μA | V _{DD} = 2.8V during reading at 25°C |
| Writing current | I _{WRITE} | — | 130 | — | μA | At 25°C, V _{DD} = 2.8V |
| Writing voltage | V _{WRITE} | 2.8 | — | — | V _{DC} | At 25 °C |
| Modulation resistance | R _M | — | 3.0 | 5.0 | Ω | DC turn-on resistance between Drain and Source terminals of the modulation transistor at V _{DD} = 2.8V |
| Data retention | — | 200 | — | — | Years | For T < 120°C |
| Endurance | — | 1.0 | — | — | Million Cycles | At 25°C |

MCRF450/451/452/455

TABLE 2-3: OPERATING AC CHARACTERISTICS

| Standard Operating Conditions (unless otherwise stated) Operating Temperature = -20°C to +70°C. | | | | | | |
|--|--------------|-------|-------|-------|---------|--|
| Parameters | Symbol | Min | Typ | Max | Units | Conditions |
| Carrier frequency | FC | 2.0 | 13.56 | 35 | MHz | |
| Device data rate | FM | 58 | 70 | 82 | kHz | Manchester coding, both Normal and Fast modes, 70 kHz $\pm 17\%$ (Note 1) |
| Pulse width of 1-of-16 PPM for Normal mode | PWPPM_N | 145 | 175 | 205 | μ s | See Figure 6-2 and Table 6-7, 175 μ s $\pm 17\%$ |
| Pulse width of 1-of-16 PPM for Fast mode | PWPPM_F | 8.3 | 10 | 11.7 | μ s | See Figure 6-2 and Table 6-7 |
| Symbol duration of 1-of-16 PPM for Normal mode | SWPPM_N | 2.32 | 2.8 | 3.28 | ms | See Figure 6-9 |
| Symbol duration of 1-of-16 PPM for Fast mode | SWPPM_F | 133 | 160 | 187 | μ s | |
| Modulation index of gap pulse | MODINDEX_GAP | 20 | 60 | 100 | % | See Figure 6-2 |
| Gap width of Interrogator command and data except Fast mode data | GAPWIDTH_N | 20 | 100 | 150 | μ s | See Figure 6-2 and Table 6-7 |
| Gap width of Fast mode data | GAPWIDTH_F | 6.0 | 7.0 | 8.0 | μ s | See Figure 6-2 and Table 6-7 |
| Coil voltage during reading | VPP_AC | 4.0 | — | — | VPP | Peak-to-Peak voltage across the coil during reading |
| Detuning voltage | VDETUNE | 3.0 | 4.0 | — | VDC | VDD voltage at which the input voltage limiting circuit becomes active |
| EEPROM (Memory) Writing Time | TWRITE | — | 5.0 | — | ms | Write time for a 32-bit block |
| Command Decode Time | TDECODE | 0.97 | 1.225 | 1.48 | ms | Time delay between end of command symbol and start of the device response |
| Time slot | TSLOT | 2.1 | 2.5 | 2.93 | ms | |
| Listening Window | TLW | 0.82 | 1.0 | 1.17 | ms | |
| Command Duration of Fast Read command (FRR and FRB) | T_CMD_FRR | 1.305 | 1.575 | 1.845 | ms | 175 μ s/pulse position x 9 pulse positions = 1.575 ms |
| Internal Resonant Capacitor | CRES_100 | 85.5 | 95 | 104.5 | pF | Between Ant. A and VSS pads at 13.56 MHz and at 25°C (MCRF451) See Figure 2-3 |
| | CRES_2_50 | 27 | 30 | 33 | pF | Between Ant. A and VSS pads at 13.56 MHz and at 25°C (MCRF452) See Figure 2-4 |
| | CRES_50 | 45 | 50 | 55 | pF | Between Ant. A and VSS pads at 13.56 MHz and at 25°C (MCRF455) See Figure 2-5 |
| Parasitic Input Capacitance of MCRF450 | CPARA_IN | — | 3.5 | — | pF | Between antenna pad A and VSS, at 13.56 MHz with modulation transistor off (no external coils). Not tested in production |

Note 1: Tested in production at VDD = 2.8 VDC and 5.0 VDC.

MCRF450/451/452/455

TABLE 2-4: PAD COORDINATES (MICRONS)

| Pad Name | Lower | | Upper | | Passivation Openings | | Pad Center X | Pad Center Y |
|------------|---------|---------|---------|---------|----------------------|------------|--------------|--------------|
| | Left X | Left Y | Right X | Right Y | Pad Width | Pad Height | | |
| Ant. Pad A | -853.50 | -992.10 | -764.50 | -903.10 | 89.00 | 89.00 | -809.00 | -947.60 |
| Ant. Pad B | 759.50 | -993.70 | 848.50 | -904.70 | 89.00 | 89.00 | 804.00 | -949.20 |
| VSS | 769.10 | 977.90 | 858.10 | 1066.90 | 89.00 | 89.00 | 813.60 | 1022.40 |
| VDD | -839.50 | 45.50 | -750.50 | 134.50 | 89.00 | 89.00 | -795.00 | 90.00 |
| CLK | 721.10 | 77.80 | 810.10 | 166.80 | 89.00 | 89.00 | 765.60 | 122.30 |
| FCLK | -821.50 | 910.70 | -732.50 | 999.70 | 89.00 | 89.00 | -777.00 | 955.20 |

Note 1: All coordinates are referenced from the center of the die.

TABLE 2-5: DIE MECHANICAL DIMENSIONS

| Specifications | Min | Typ | Max | Unit | Comments |
|--|-------|----------------------|-------|-----------|--|
| Bond pad opening | — | 3.5 x 3.5 89 x 89 | — | mil μm | Note 1, Note 2 |
| Die backgrind thickness | 7.5 | 8 | 8.5 | mil | Sawed 8" wafer on frame (option = WF) (Note 3) |
| | 190.5 | 203.2 | 215.9 | μm | |
| | 10 | 11 | 12 | mil | <ul style="list-style-type: none"> • Bumped, sawed 8" wafer on frame (option = WFB) • Unsawed wafer (option = W) • Unsawed 8" bumped wafer (option = WB), (Note 3) |
| 254 | 279.4 | 304.8 | μm | | |
| Die passivation thickness (multilayer) | — | 1.3 | — | μm | Note 4 |
| Die Size: | | | | | |
| Die size X*Y before saw (step size) | — | 1904 x 2340.8 | — | μm | — |
| Die size X*Y after saw | — | 1840.5 x 2277.3 | — | μm | — |

Note 1: The bond pad size is that of the passivation opening. The metal overlaps the bond pad passivation by at least 0.1 mil.

2: Metal Pad Composition is 98.5% Aluminum with 1% Si and 0.5% Cu.

3: As the die thickness decreases, susceptibility to cracking increases. It is recommended that the die be as thick as the application will allow.

4: The Die Passivation Thickness (1.3 μm) can vary by device depending on the mask set used. The passivation is formed by:

- Layer 1: Oxide (undoped oxide)
- Layer 2: PSG (doped oxide)
- Layer 3: Oxynitride (top layer)

5: The conversion rate is 25.4 μm/mil.

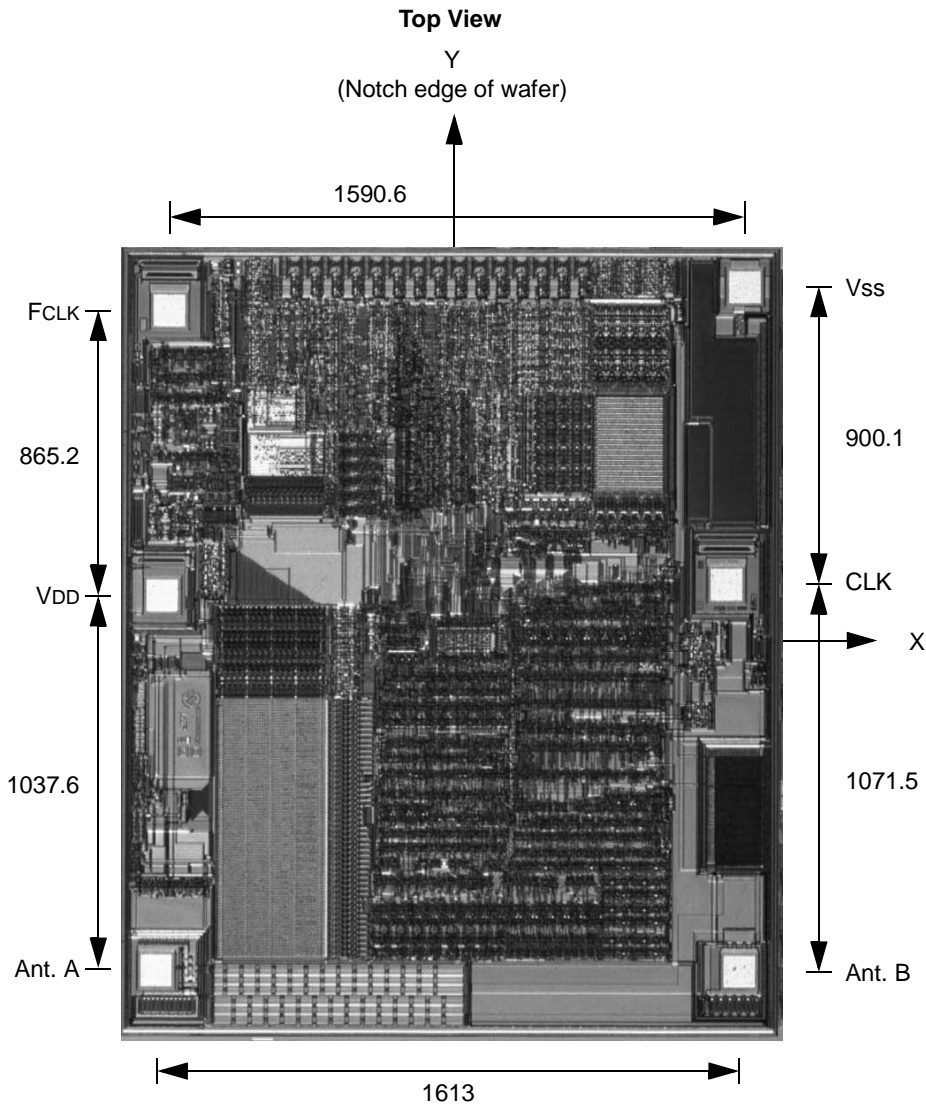
Notice: Extreme care is urged in the handling and assembly of die products since they are susceptible to mechanical and electrostatic damage.

TABLE 2-6: WAFER MECHANICAL SPECIFICATIONS

| Specifications | Min | Typ | Max | Unit | Comments |
|---------------------------|-----|-------|-----|-------|----------|
| Wafer Diameter | — | 8 | — | inch | |
| Die separation line width | — | 80 | — | μm | |
| Dice per wafer | — | 6,600 | — | die | |
| Batch size | — | 24 | — | wafer | |

MCRF450/451/452/455

FIGURE 2-1: MCRF450/451/452/455 DIE LAYOUT



Note: Coordinate units are in μm .
See Table 2-5 for die mechanical dimensions.

Die size before saw:

1904.0 μm x 2340.8 μm
1.904 mm x 2.3408 mm
74.96 mil x 92.16 mil

Die size after saw:

1840.5 μm x 2277.3 μm
1.8405 mm x 2.2773 mm
72.46 mil x 89.66 mil

Bond pad size:

89 μm x 89 μm
0.089 mm x 0.089 mm
3.5 mil x 3.5 mil

Bumped die:

Bumped Pad: Four corner pads (FCLK, VSS, Antenna B, Antenna A)

Bumping Material: 99.6% Gold

Bump Height: 25 μm \pm 3 μm

Bump Size: 103 μm x 103 μm (Covered all passivation opening of bond pad)

Other area except the four bumped pads: Covered by Polyamide

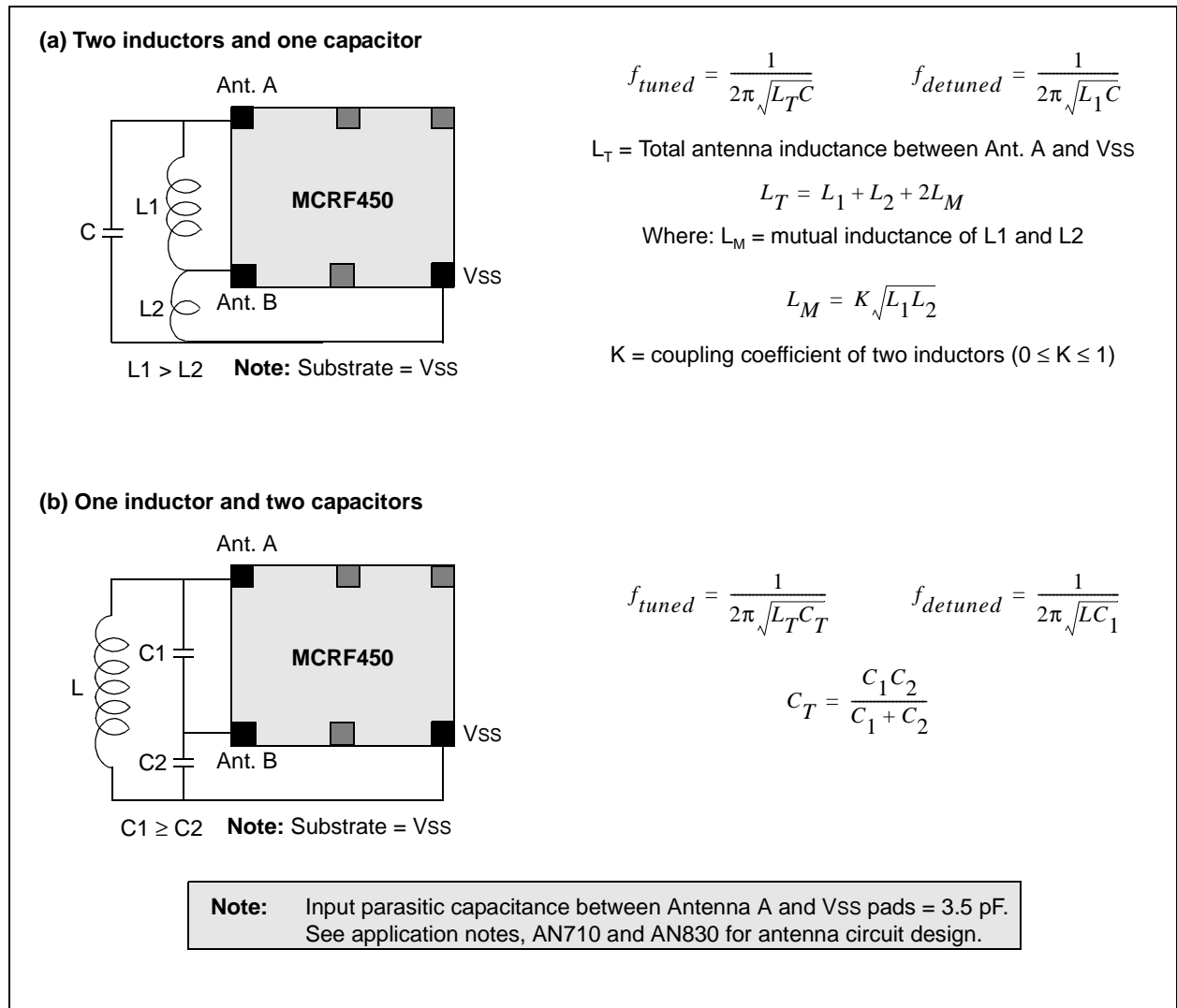
Thickness of Polyamide: 3 μm

TABLE 2-7: PAD FUNCTION TABLE

| Name | Function |
|------------|---|
| Ant. Pad A | Connected to antenna coil L1. |
| Ant. Pad B | Connected to antenna coils L1 and L2 for MCRF450/451/455, NC for MCRF452. |
| VSS | Connected to antenna coil L2. Device ground during Test mode. (VSS = substrate) |
| FCLK | For device test only. Leave floating or connect to VSS in applications. |
| CLK | For device test only. Leave floating or connect to VSS in applications. |
| VDD | For device test only. Leave floating in applications. |

Note: NC = Not Connected.

FIGURE 2-2: EXTERNAL CIRCUIT CONFIGURATION FOR MCRF450



MCRF450/451/452/455

FIGURE 2-3: EXTERNAL CIRCUIT CONFIGURATION FOR MCRF451

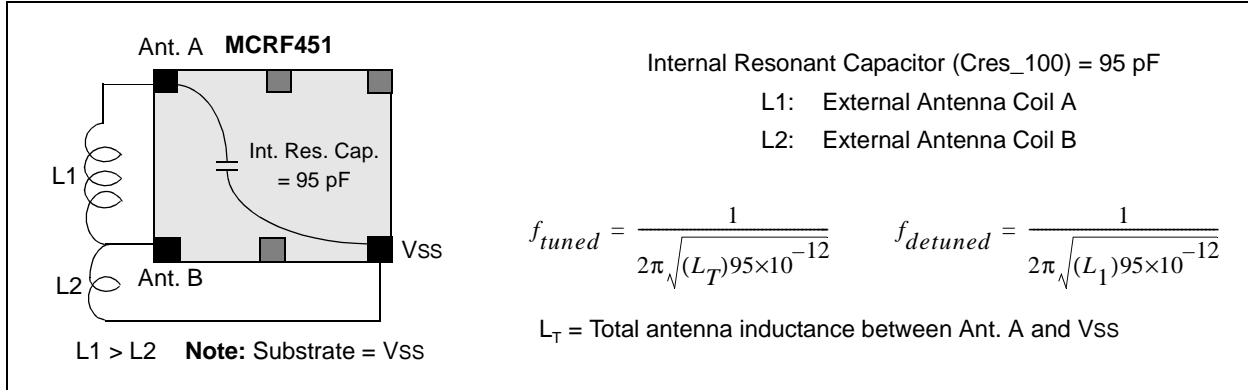


FIGURE 2-4: EXTERNAL CIRCUIT CONFIGURATION FOR MCRF452

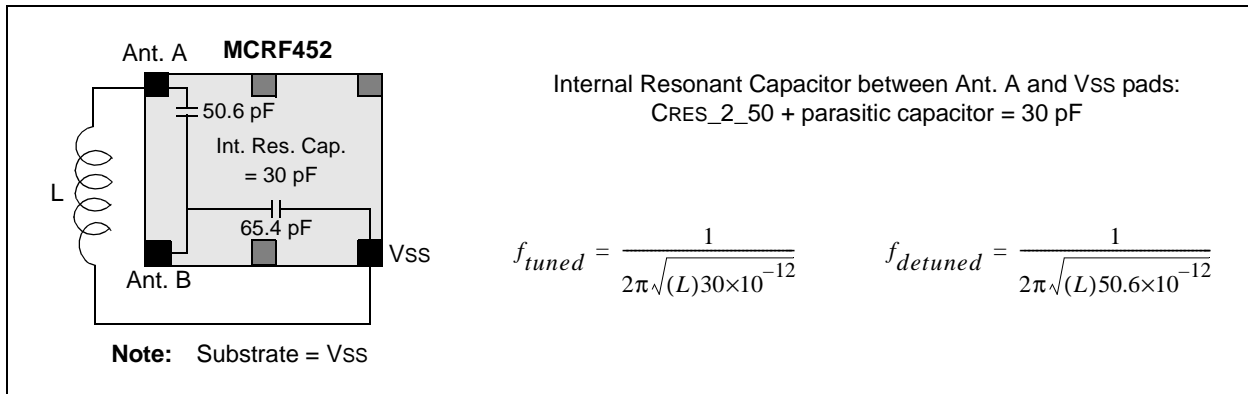
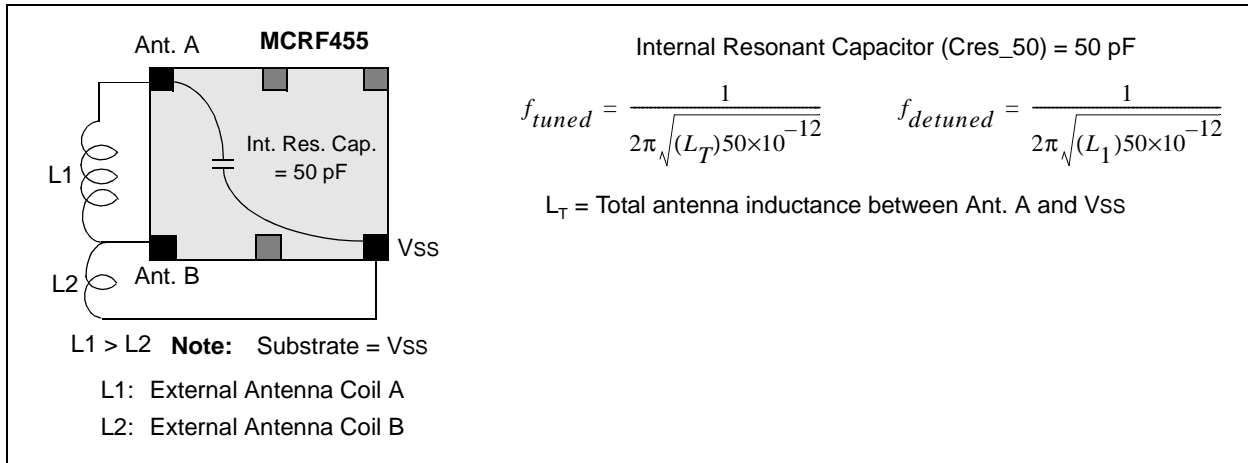


FIGURE 2-5: EXTERNAL CIRCUIT CONFIGURATION FOR MCRF455



Note: See application notes AN710 and AN830 for antenna circuit design of Figure 2-2 through Figure 2-5.

TABLE 2-8: INTERNAL RESONANT CAPACITANCE AND ANTENNA INDUCTANCE REQUIREMENTS

| Device Name | Resonant Capacitance (Antenna A to Vss) | External Inductance Requirement between Antenna A and Vss for 13.56 MHz tag | Connection to External Antenna Circuit | Reference |
|-------------|---|---|--|---|
| MCRF451 | 95 pF \pm 10% | 1.45 μ H \pm 10% | Antenna A, B, and Vss pads | This device requires three connections to an external circuit. Good for direct die attachment onto antenna. |
| MCRF452 | 30 pF \pm 10% | 4.591 μ H \pm 10% | Antenna A and Vss pads | This device requires only two antenna connections. Good for both direct die attachment and COB. |
| MCRF455 | 50 pF \pm 10% | 2.76 μ H \pm 10% | Antenna A, B, and Vss pads | This device requires three connections to an external circuit. Good for direct die attachment onto antenna. |

Note: The internal capacitance value for bumped die is about 1 pF higher than the unbumped die's capacitor.

MCRF450/451/452/455

3.0 BLOCK DIAGRAM

The device contains four major sections. They are: Analog Front-End, Detection/Encoding, Read/Write Anti-collision Logic and Memory sections. Figure 3-1 shows the block diagram of the device.

FIGURE 3-1: BLOCK DIAGRAM

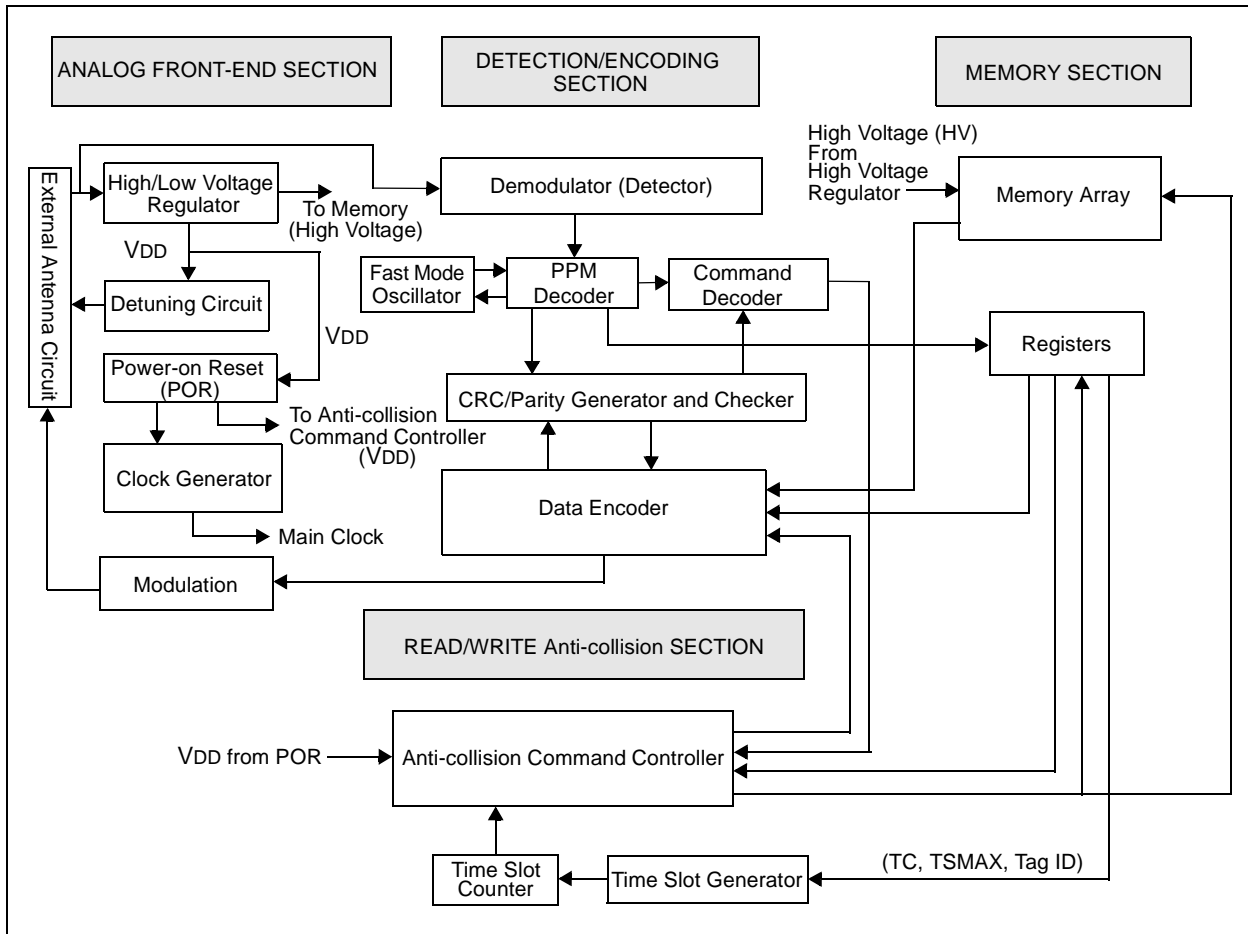
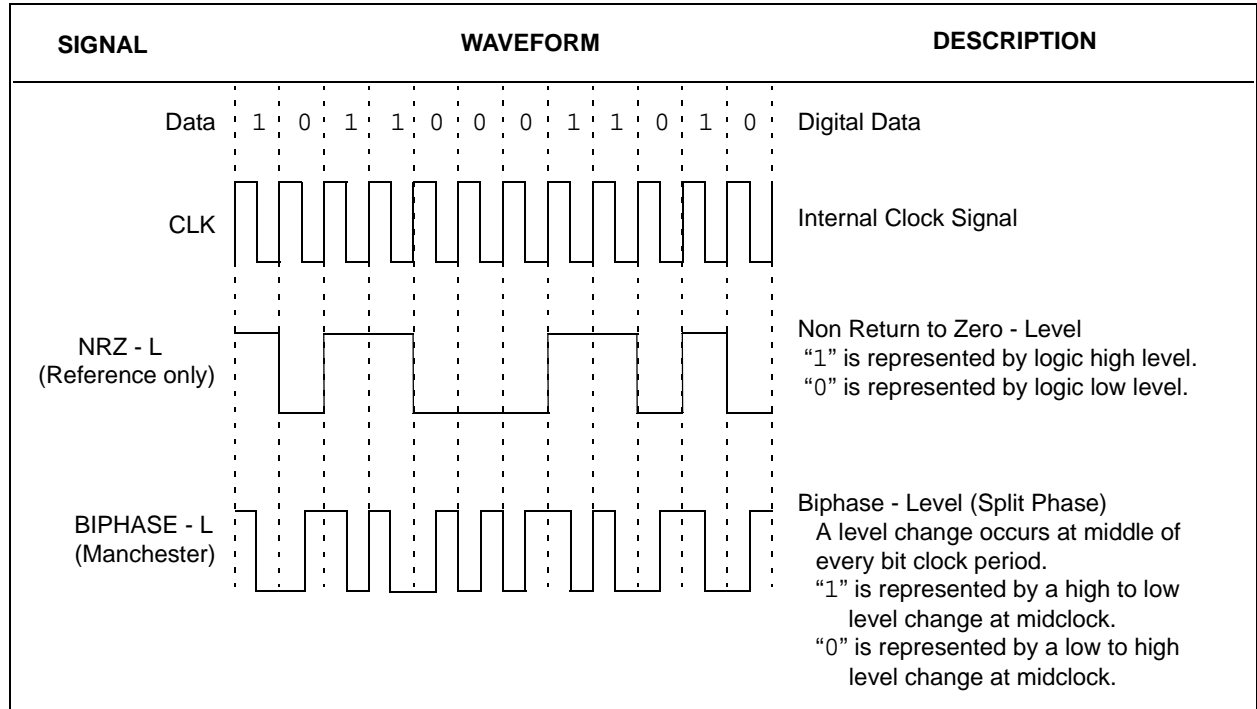


FIGURE 3-2: DATA WAVEFORM OF DEVICE



MCRF450/451/452/455

4.0 ANALOG FRONT-END

This section includes high and low voltage regulators, Power-on Reset, 70 kHz clock generator and modulation circuits.

4.1 High and Low Voltage Regulator

The high voltage circuit generates the programming voltage for the memory section. The low voltage circuit generates DC voltage (V_{DD}) to operate the device.

4.2 Power-On Reset (POR)

This circuit generates a Power-on Reset (POR) voltage. The POR releases when sufficient power has been developed by the voltage regulator to allow for correct operation.

4.3 Clock Generator

This circuit generates a clock (CLK). The main clock is generated by an on-board 70 kHz time base oscillator. This clock is used for all timing in the device, except for the Fast mode PPM decoding.

4.4 Data Modulation

The data modulation circuit consists of a modulation transistor and a LC resonant circuit. The resonant circuit must be tuned to the carrier frequency of the Interrogator (i.e., 13.56 MHz) for maximum performance.

The modulation transistor is placed between antenna B and VSS pads. It is designed to result in the turn-on resistance of less than five ohms (R_M). This small turn-on resistance shorts the resonant circuit component between antenna B and VSS pads as it turns on. This results in a change of the resonant frequency of the resonant circuit. Consequently, the resonant circuit becomes detuned with respect to the carrier frequency of the Interrogator. The voltage across the resonant circuit is minimized during this time. This condition is called "cloaking".

The transistor, however, releases the resonant circuit as it turns off. Therefore, the resonant circuit tunes to the carrier frequency of the Interrogator again and develops maximum voltage. This condition is called "uncloaking".

The device transmits data by cloaking and uncloaking, based on the on/off condition of the modulation transistor. Using the 70 kHz Manchester format, the data bit '0' will be sent by cloaking and uncloaking the device for 7 μ s each. Similarly, the data bit '1' will be sent by uncloaking and cloaking the device for 7 μ s each. See Figure 6-1 for the Manchester waveform.

4.5 Detuning Circuit

The purpose of this circuit is to prevent excessive RF voltage across the resonant circuit.

This circuit monitors V_{DD} and detunes the resonant circuit if the RF coil voltage exceeds the threshold limit (V_{DETUNE}), which is above the operating voltage of the device.

5.0 DETECTION AND ENCODING

This section encodes data with the Manchester format and also detects commands from the Interrogator.

5.1 Demodulator (Detector)

This circuit demodulates the Interrogator commands and sends them to the PPM decoder.

5.2 Fast Mode Oscillator

This oscillator generates a clock frequency that is used for decoding Fast mode commands.

5.3 PPM Signal Decoder

This section decodes the PPM signals and sends the results to the command decoder and CRC/parity checker.

5.4 Command Decoder

This section decodes the Interrogator commands and sends the results to the Anti-collision/command controller.

5.5 CRC/Parity Generator and Checker

This section generates Cyclic Redundancy Code (CRC) and parity bits for transmitting and receiving data. The device utilizes a 16-bit CRC for error detection. Its polynomial and initial values are:

CRC Polynomial: $X^{16}+X^{12}+X^5+X^0$

Initial Value: \$FFFF

This polynomial is also known as CRC CCITT (Consultative Committee for International Telegraph and Telephone). The Interrogator also uses the same CRC for data processing. The device uses the CRC in the following ways:

1. **CRC for blocks (except Blocks 0 and 2):** The Interrogator will send a Write command with CRC. When the device receives this command, it checks the CRC prior to any processing. If it is a correct CRC, the device programs the block data and also stores the CRC in the EEPROM. As soon as the data is written into memory, both the programmed data and Stored CRC (SCRC) are sent back to the Interrogator as verification. The device also sends the programmed data and SCRC when there is a response to the Read command.

If the CRC is incorrect, the device ignores the incoming message (does not respond to the Interrogator) and waits for the next command with a correct CRC.

2. **CRC for Blocks 0 and 2:** When reading Block 0 or 2, a Calculated CRC (CCRC) is sent. This is because both the TF and FR bits in Block 0 are non write-protectable, while the rest of the bits in the block are write-protectable. This means the SCRC in the block no longer represents the CRC of the block data, if only the TF or the FR bit is reprogrammed. This is also true for Block 2, which is a write protection block. The write-protected bit cannot be reprogrammed once it has been written. Therefore, the SCRC in Blocks 0 and 2 are not used. Instead, the device calculates the current CRC of the block and sends it to the Interrogator.

3. **CRC for FRR response:** For the Fast Read (FR) response (this is the device response to an FRR command), the CCRC of the tag ID and FRF (Blocks 3-5) data is sent. The data length of the FRF is determined by DF bits (see Table 7-6).

5.6 Data Encoder

This section multiplexes serial data, encodes it into Manchester format and sends it to the modulation circuit. See Figure 3-2 for the Manchester waveform.

6.0 READ/WRITE ANTI-COLLISION LOGIC

This section includes the anti-collision algorithm of the device and consists of the Anti-collision/command controller, the time slot generator and the time slot counter.

6.1 Description of Algorithm

The read/write anti-collision algorithm is based on time division multiplexing of tag responses. Each device is allowed to communicate with the Interrogator in its time slot only. When not in its assigned time slot, the device remains in a nonmodulating condition. This enables the Interrogator to communicate with other devices in the same Interrogator field with fewer chances of data collision.

Figure 6-1 shows the anti-collision algorithm flowchart, which consists of four control loops. They are: Detection, Processing, Sleeping and Reactivation loops. All devices in the Interrogator's RF field are controlled by five different commands and internal control flags.

The Interrogator commands are:

1. **Fast Read Request (FRR):** If the TF bit (bit 30 or Block 0) is cleared, the device responds only to the FRR command. The FRR command consists of five specially timed gap pulses (refer to Figures 6-3 to 6-7). The position of the five gap pulses in the given time span (1.575 ms) determines the parameters of the command. The command has three parameters: TC_{MAX}, TS_{MAX} and Data transmission speed. The details of these parameters will be discussed in the following sections. If the device receives the FRR command, it sends the FR response and then listens for 1 ms (TLW) for a matching code from the Interrogator.
2. **Fast Read Bypass (FRB):** This command is used in the Reactivation loop and is only applicable to a device with the FR bit (bit 31 in Block 0) cleared. The device responds with 64 bits of data, which includes Block 1 data (32-bit Tag ID), and then listens for 1 ms (TLW) for a matching code from the Interrogator. The command structure is the same as the FRR command: five specially timed gap pulses (1.575 ms). The command parameter (Figure 6-8) determines the data rate (normal speed or fast speed) of subsequent Interrogator commands.
3. **Matching Code 1 (MC1):** This command consists of time calibration pulses (TCP) followed by 1-of-16 PPM signals. It is used when the device does not need any further processing. This MC1 command causes a device, which is in the detection loop, to enter the sleeping loop.

4. **Matching Code 2 (MC2):** The command structure is the same as MC1: TCP followed by 1-of-16 PPM signals. The command is used when the device needs further processing (read/write). The device enters the processing loop if it receives this command in the detection loop.

The MC1 and MC2 matching code command consists of 12 bits or 3 symbols. The first 8 bits, or the first two symbols, are selected from the 32-bit Tag ID. The next 4 bits, or the 3rd symbol, determine the matching code type (3 bits) and a parity bit (see **Section 6.2.3.6 "Calculation Of Matching Code"**). The command lasts for about 11.2 ms, including the TCP.

5. **End Process (EP):** This command consists of the time reference pulses followed by 1-of-16 PPM signals. The EP command causes a device to exit the processing loop and enter the sleeping loop.

6.1.1 DETECTION LOOP

If the FR bit (bit 31 of Block 0) is set, the device can enter this loop in two ways, depending on the condition of the TF bit (bit 30 of Block 0). They are:

1. When the TF bit is cleared, the device enters this loop and waits for a FRR command. This is called the "Interrogator-Talks-First" (ITF) mode.
2. When the TF bit is set, the device enters this loop by transmitting the FR response without waiting for an FRR command. This is called the "Tag-Talks-First" (TTF) mode.

For case 1 above, the parameters of the FRR are:

- Maximum number of time slots (TS_{MAX} = 1, 16, or 64),
- Maximum transmission counter (TC_{MAX} = 1, 2, or 4),
- Data transmission speed (Normal or Fast mode).

The purpose of the TS_{MAX} and TC_{MAX} parameters is to acknowledge the device in the detection loop as fast as possible. TS_{MAX} represents the maximum number of time slots between the end of the FRR command and the beginning of the FR response. One time slot (TSLOT) represents 2.5 ms. For example, TS_{MAX} = 64 represents a maximum time delay of 160 ms before sending the FR response. See **Section 6.3 "Time Slot Generator"** for the calculation of actual time delay. TC_{MAX} represents the maximum number of FR responses a device can send after an FRR command. For example, TC_{MAX} = 4 means the device can send its FR response four times (after the FRR command) for acknowledgment (matching code).

The TSMAX and TCMAX values are determined by the Interrogator's decision on how many tags are in the field. The Interrogator may assign TSMAX = 1 and TCMAX = 1, assuming there is only one tag in the field. The efficiency of the detection will increase in multiple tag environments by assigning a higher number to both the TSMAX and TCMAX. If the device receives the FRR, it clears the Position 1 flag, waits for its time slot, replies with the FR response and then listens for 1 ms. The FR response consists of a maximum of 160 Manchester data bits (default: 96 bits), which includes the 32-bit Tag ID and the FRF data (Blocks 3-5) (see Table 6-3 and Example 9-1).

To acknowledge the FR response, the Interrogator can start to send a matching code (MC) during the device's 1 ms listening window (TLW). The MC is encoded with 1-of-16 PPM signal (see Figure 6-9). The MC1 is given to the device if the device does not need any further processing. If the device receives the MC1, it enters the sleeping loop and stays in the loop in a nonmodulating condition. The MC2 command is given to the device if further processing (read/write) is required. If the device receives the MC2 command, it enters the processing loop.

If the device misses the MC within the listening window, it sends the FR response again after its time slot when two conditions are met: (1) Position 1 flag is cleared and, (2) TCMAX has not elapsed. The device checks the condition (elapsed or not elapsed) of TCMAX using an internal transmission counter (TC). The TC consists of 3 bits. If the Position 1 flag is cleared, the device increments the TC by 1 each time it does not receive a MC during its listening window. See Figure 6-1 for a flow chart showing the conditional incrementing of the transmission counter. Table 6-1 shows an example of detecting the elapsed TCMAX using a rolling modulo-8 transmission counter.

For the TTF case, the device repeats its FR response (as long as it is energized) according to the TCMAX and TSMAX parameters, as specified in Table 7-5. Even though the device is operating in the TTF mode, it will respond to its correct MC during its listening window. If TCMAX = 1, 2 or 4, it will also respond to FRR commands, just as in the ITF case (see **Section 6.1.1.1 "Matching Code Queuing"**).

6.1.1.1 Matching Code Queuing

Once the device receives the FRR command, it sends the FR response and waits for a matching code (MC) during its listening window. If the device does not receive its correct MC code before its TCMAX has elapsed (see Table 6-1), it goes back to the beginning of the detection loop (position 1 in the loop) and waits for either a new FRR command or for the MC1 or MC2 matching code. This is called "matching code queuing". In this queuing, the device stays in the detection loop waiting for an Interrogator command (FRR or MC). This

queuing takes place within the detection loop and is controlled by the conditions of "Set Position 1 Flag" and TCMAX.

This queuing allows the Interrogator to communicate with a device outside its listening window. The result is enhanced and accelerated processing of individual devices in a multiple tag environment.

TABLE 6-1: CONDITIONS FOR TCMAX = ELAPSED FOR ITF MODE

| Rolling Modulo -8 TC | | | TCMAX = 1 | TCMAX = 2 | TCMAX = 4 |
|----------------------|---|---|-----------|-----------|-----------|
| 0 | 0 | 1 | elapsed | — | — |
| 0 | 1 | 0 | elapsed | elapsed | — |
| 0 | 1 | 1 | elapsed | — | — |
| 1 | 0 | 0 | elapsed | elapsed | elapsed |
| 1 | 0 | 1 | elapsed | — | — |
| 1 | 1 | 0 | elapsed | elapsed | — |
| 1 | 1 | 1 | elapsed | — | elapsed |
| 0 | 0 | 0 | elapsed | elapsed | — |

6.1.2 PROCESSING LOOP

The reading and writing processes take place in this loop. Devices in this loop are waiting for commands for processing. In order to read from, or write to, the device, its "Processing Flag" (PF) must be set. Any device entering this loop with its PF cleared is called a "follow-along" tag. This follow-along tag in the loop is not processed for reading or writing.

If the device with the PF flag set receives the EP command, it exits this loop and enters the sleeping loop. However, the same EP command sends the follow-along tag back to the detection loop.

If the device receives the FRR or FRB command in this loop, it sees the command as invalid, resets itself and goes back to the initial power-up state.

6.1.3 SLEEPING LOOP

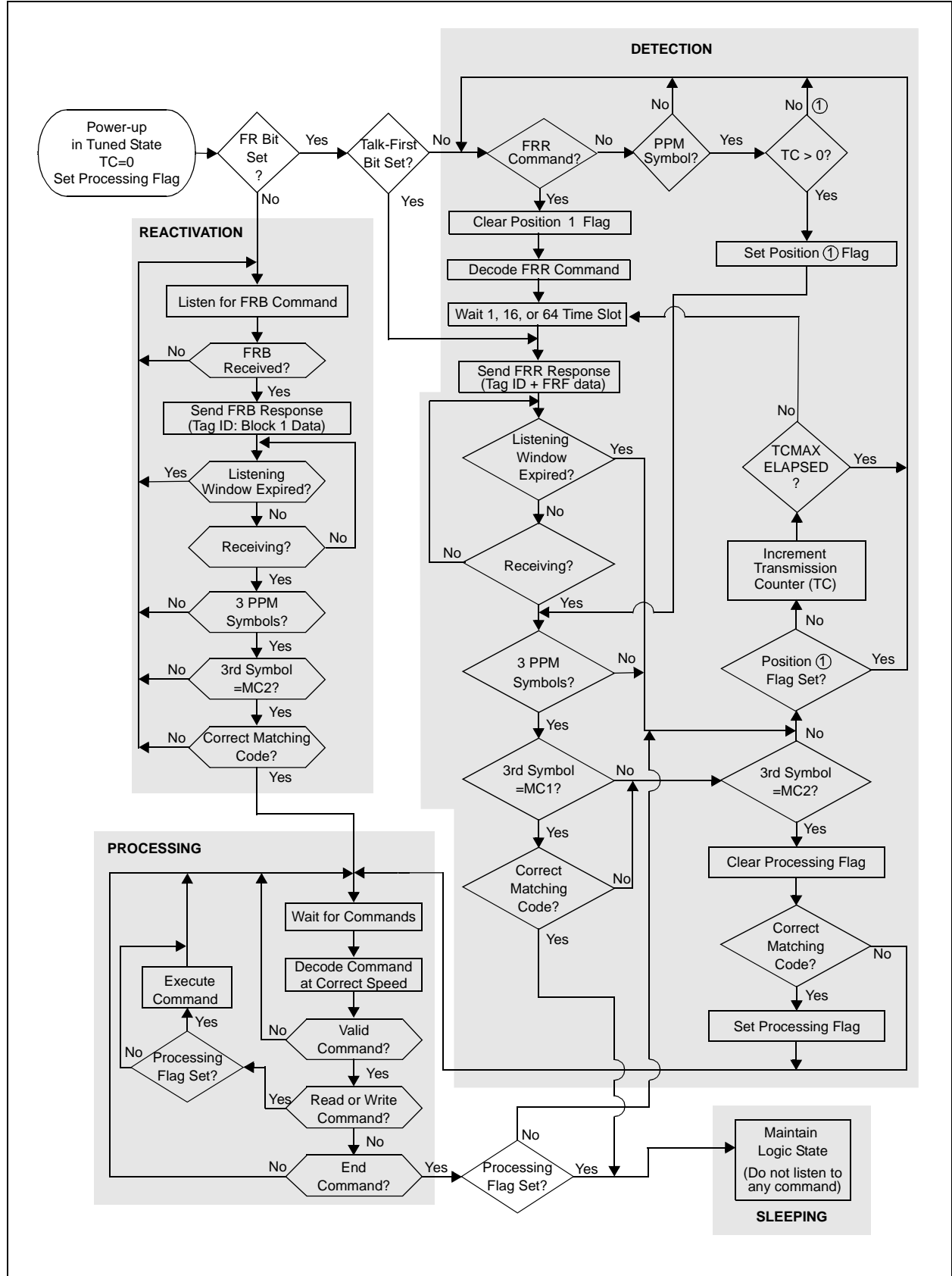
The sleeping loop is used to keep all processed devices in a "silent" condition. The devices stay in this loop in a nonmodulating condition as long as they remain in the field.

MCRF450/451/452/455

6.1.4 REACTIVATION LOOP

The reactivation loop is used to process a device with its FR bit cleared. A device in this loop waits for the FRB command. If a device receives the FRB command, it transmits the contents of Block 1 (Tag ID) to its memory and waits for a MC2 in its listening window. If the device receives the MC2, it leaves this loop and enters the processing loop. This reactivation loop has no anti-collision capability. It is designed for reactivation of single devices. This loop can be effectively used in retail store applications to process returning items from customers.

FIGURE 6-1: ANTI-COLLISION FLOWCHART



MCRF450/451/452/455

6.2 Anti-Collision Command Controller

This section discusses the anti-collision algorithm and describes the communications between the Interrogator and device.

6.2.1 STRUCTURE OF READ/WRITE COMMAND SIGNALS

The Interrogator's Read/Write commands have the following structure:

Read/Write command = Command + Address + Data + Parity (or CRC)

The commands are summarized in the table below:

TABLE 6-2: READ/WRITE COMMANDS FROM INTERROGATOR TO DEVICE

| Interrogator Command | Command Code | Address | Data | Parity or CRC | Symbol Length |
|----------------------|--------------|---------|---------|---------------|---------------|
| Unused | 0xx | xxxxx | — | — | — |
| Read 32-bit block | 110 | aaaaa | — | Parity | 3 symbols |
| Unused | 111 | 00xxx | — | — | — |
| Unused | 111 | 0100x | — | — | — |
| End Process | 111 | 01010 | — | Parity | 3 symbols |
| Unused | 111 | 01011 | — | — | — |
| Unused | 111 | 011xx | — | — | — |
| Unused | 111 | 1000x | — | — | — |
| Set Talk First Bit | 111 | 10010 | — | Parity | 3 symbols |
| Set FR Bit | 111 | 10011 | — | Parity | 3 symbols |
| Clear Talk First Bit | 111 | 10100 | — | Parity | 3 symbols |
| Clear FR Bit | 111 | 10101 | — | Parity | 3 symbols |
| Unused | 111 | 1011x | — | — | — |
| Unused | 111 | 11xxx | — | — | — |
| Unused | 100 | xxxxx | — | — | — |
| Write 32-bit block | 101 | aaaaa | 32 bits | CRC-16 | 14 symbols |

Legend: aaaaa = Block address
x = don't care

Note:

- Command and address are sent MSN (Most Significant nibble) first.
- Data and parity/CRC are sent LSN (Least Significant nibble) first.
- Calculation of Parity and CRC includes Command code, Address, and Data.
- See Microchip Application Note AN752 (DS00752) for the CRC-16 calculation algorithm.

6.2.2 STRUCTURE OF DEVICE RESPONSE

When the device receives the Interrogator command, it responds with 70 kHz Manchester encoded data having the following structures:

Device Response to FRR Command: Preamble (8 bits) + TC (3 bits) + TP (4 bits) + '0' + 32 bits of Tag ID (Block 1 data) + FRF data (32 - 96 bits) + Calculated CRC (SCRC, 16 bits) of Tag ID and FRF data = 96 - 160 bits depending on FRF data length.

Note: The preamble + TC + TP + '0' are not included for the CRC calculation.

Device Response to FRB Command: Preamble (8 bits) + '00001' + '000' + 32 bits of Tag ID (Block 1 data) + Stored CRC (SCRC, 16 bits) of Block 1 = 64 bits.

Device Response of Interrogator's Read command for Blocks 0 and 2:

Preamble (8 bits) + Block Number (5 bits) + '000' + Block Data (32 bits) + Calculated 16 bit CRC (CCRC).

Note: The CCRC is calculated by using block number and block data only. Preamble and '000' are not included in the CRC calculation.

Device Response of Interrogator's Read Command for all other blocks:

Device Response = Preamble (8 bits) + Block Number (5 bits) + '000' + Block Data (32 bits) + Stored CRC (SCRC, 16 bits) in the same block.

TABLE 6-3: INTERROGATOR COMMANDS AND DEVICE RESPONSES

| Interrogator Command | Delay | Device Response |
|--|-------------------------------|--|
| Read Block 0 and Block 2 data | TDECODE | Preamble, block #, '000', block data, CCRC |
| Read block data except for Block 0 and Block 2 | TDECODE | Preamble, block #, '000', block data, SCRC |
| Write block data | TWRITE | For Blocks 0 and 2: Preamble, block #, '000', block data, CCRC For all others: Preamble, block #, '000', block data, SCRC |
| Set Fast Read (FR) bit | TWRITE | Preamble, 1 byte '0's, Block 0 data, CCRC |
| Clear Fast Read (FR) bit | TWRITE | Preamble, 1 byte '0's, Block 0 data, CCRC |
| Set Talk First (TF) bit | TWRITE | Preamble, 1 byte '0's, Block 0 data, CCRC |
| Clear Talk First (TF) bit | TWRITE | Preamble, 1 byte '0's, Block 0 data, CCRC |
| End Process (EP) | TDECODE | Preamble |
| FRR | f(TSMAX, TCMAX, 8-bit Tag ID) | Preamble, TC, TP, '0', Tag ID, FRF, FRR_CCRC |
| FRB | TDECODE | Preamble, address of block #1 ('00001'), '000', Tag ID (32 bits), SCRC of Block 1 |

References used in this table are as follows:

Preamble = 11111110 (8 bits). '0' is transmitted last.

Block # = 5 bit addressed block, transmits Least Significant bit (LSb) first.

Block data = 32-bit data of the addressed block, transmits LSb first.

CCRC = Calculated CRC of the preceding block number and block data. Transmits LSb first.

SCRC = Stored CRC. This SCRC is the CRC of the Write command, address, and data from the Interrogator, LSb first. The device stores the received CRC for each block. See **Section 7.2 "Stored CRC (SCRC) Memory Section"** for details.

FRR_CCRC = Calculated CRC of 32-bit Tag ID and fast read field (FRF) data.

TP = Tag parameters (4 bits: '0', DF0, DF1, parity). where DF0 and DF1 determine the FR field length (see Table 7-6).

TC = Transmission counter (3 bits), transmits LSb first.

Parity = Even parity bit of TC and TP.

Tag ID = 32 bits of unique identification code of the device, transmits LSb first. This Tag ID is preprogrammed in the factory prior to shipping.

8-bit Tag ID = 8 bits of Tag ID selected from the 32 bits of the unique tag identification code. Transmits LSb first (see **Section 6.2.3.6 "Calculation Of Matching Code"** for selecting the 8 bits from the Tag ID).

FRF = Fast Read Field (Blocks 3-5), transmits LSb first (see **Section 7.0 "Memory Section"**).

f(TSMAX, TCMAX, 8-bit Tag ID) = Delay is a function of the TSMAX, TCMAX and 8-bit Tag ID.

TWRITE = Writing time for EEPROM (see Table 2-3).

TDECODE = Time requirement for command decoding (see Table 2-3).

Examples are given in **Section 9.0 "Examples"**.

MCRF450/451/452/455

6.2.3 DETECTION OF INTERROGATOR COMMANDS

The Interrogator sends commands to the device by amplitude modulating the carrier signal (gap pulse). The Interrogator uses two classes of encoding signals for modulation. They are (1) 1-of-16 PPM for data transmission, and (2) specially timed gap pulse sequence for the FRR and FRB commands. These commands consist of five gap pulses within nine possible gap pulse positions (1.575 ms). The combination of the possible gap positions determines the command type and parameters of the Fast Read command.

The Interrogator also sends TCP prior to the 1-of-16 PPM. The TCP is used to calibrate the time-base of the decoder in the device. The specifics of the two encoding methods and the TCP are described in the following sections.

6.2.3.1 Fast Read (FR) Commands

The FR commands are composed of five 175 μ s wide gap pulses (see Figure 6-2) whose spacing within 1.575 ms determines the command type and its parameters. Table 6-4 shows the specification of the gap signal for the FR commands. Two commands are used for the fast read. They are: (1) Fast Read Request (FRR) in the Detection loop, and (2) Fast Read Bypass

(FRB) in the Reactivation loop. See Tables 6-5 and 6-6 for the FRR gap pulse positions. See Figures 6-3 to 6-8 for the gap modulation patterns.

The parameters of FRR are: (1) number of time slots (TSMAX = 1, 16, or 64), (2) maximum transmission counter (TCMAX) and (3) data transmission speed. The FRB has only a data transmission speed parameter (Normal or Fast Speed mode). The device extracts these parameters based on the positions of the five gap pulses within the 1.575 ms time span, as shown in Figures 6-3 to 6-8.

TSMAX = 1 is given if there is only one device in the field. This is called "Conveyor mode" or "single tag environment". In this mode, the device responds with the FR response signal in every time slot until it receives a correct matching code, or until TCMAX is elapsed.

6.2.3.2 Data Transmission Speed

The Interrogator can send data with two different data rates: (1) Normal and (2) Fast Speed modes. The normal speed uses 2.8 ms/symbol, while the fast speed uses 160 μ s/symbol. One symbol represents one 4-bit data packet (see **Section 6.2.3.4 "1-of-16 PPM"**). The data transmission speed is a parameter of the FRR and FRB commands. This parameter indicates the data speed of subsequent Interrogator commands. The data rate of the device output (70 kHz) is not affected by this parameter.

TABLE 6-4: SPECIFICATION OF GAP SIGNAL FOR FRR AND FRB COMMANDS

| | |
|--|-------------|
| Number of gaps for one command | 5 |
| Total available number of gap positions within the command time span | 9 |
| Command time span | 1.575 ms |
| Gap pulse width | 175 μ s |

TABLE 6-5: SPECIFICATION OF MODULATION SEQUENCE FOR FRR COMMAND

| Maximum Time Slot (TSMAX) | TCMAX | Gap Pulse Position | Data Transmission Mode |
|---------------------------|-------|--------------------|------------------------|
| 1 | 1 | 1, 2, 3, 4, 6 | Normal Speed |
| | | 1, 3, 5, 6, 8 | Fast Speed |
| | 2 | 1, 2, 3, 4, 5 | Normal Speed |
| | | 1, 3, 5, 6, 7 | Fast Speed |
| | 4 | 1, 2, 3, 5, 6 | Normal Speed |
| | | 1, 3, 5, 7, 8 | Fast Speed |
| 16 | 1 | 1, 2, 4, 6, 8 | Normal Speed |
| | | 1, 3, 4, 6, 8 | Fast Speed |
| | 2 | 1, 2, 4, 6, 7 | Normal Speed |
| | | 1, 3, 4, 6, 7 | Fast Speed |
| | 4 | 1, 2, 4, 5, 6 | Normal Speed |
| | | 1, 3, 4, 5, 6 | Fast Speed |
| 64 | 1 | 1, 2, 4, 5, 7 | Normal Speed |
| | | 1, 3, 4, 5, 7 | Fast Speed |

TABLE 6-6: SPECIFICATION OF MODULATION SEQUENCE FOR FRB COMMAND

| Symbol | Gap Pulse Position | Data Transmission Mode |
|--------|--------------------|------------------------|
| FRB_N | 1, 2, 3, 5, 7 | Normal Speed |
| FRB_F | 1, 3, 5, 7, 9 | Fast Speed |

MCRF450/451/452/455

FIGURE 6-2: PULSE WAVEFORM OF GAP AND 1-OF-16 PPM SIGNALS

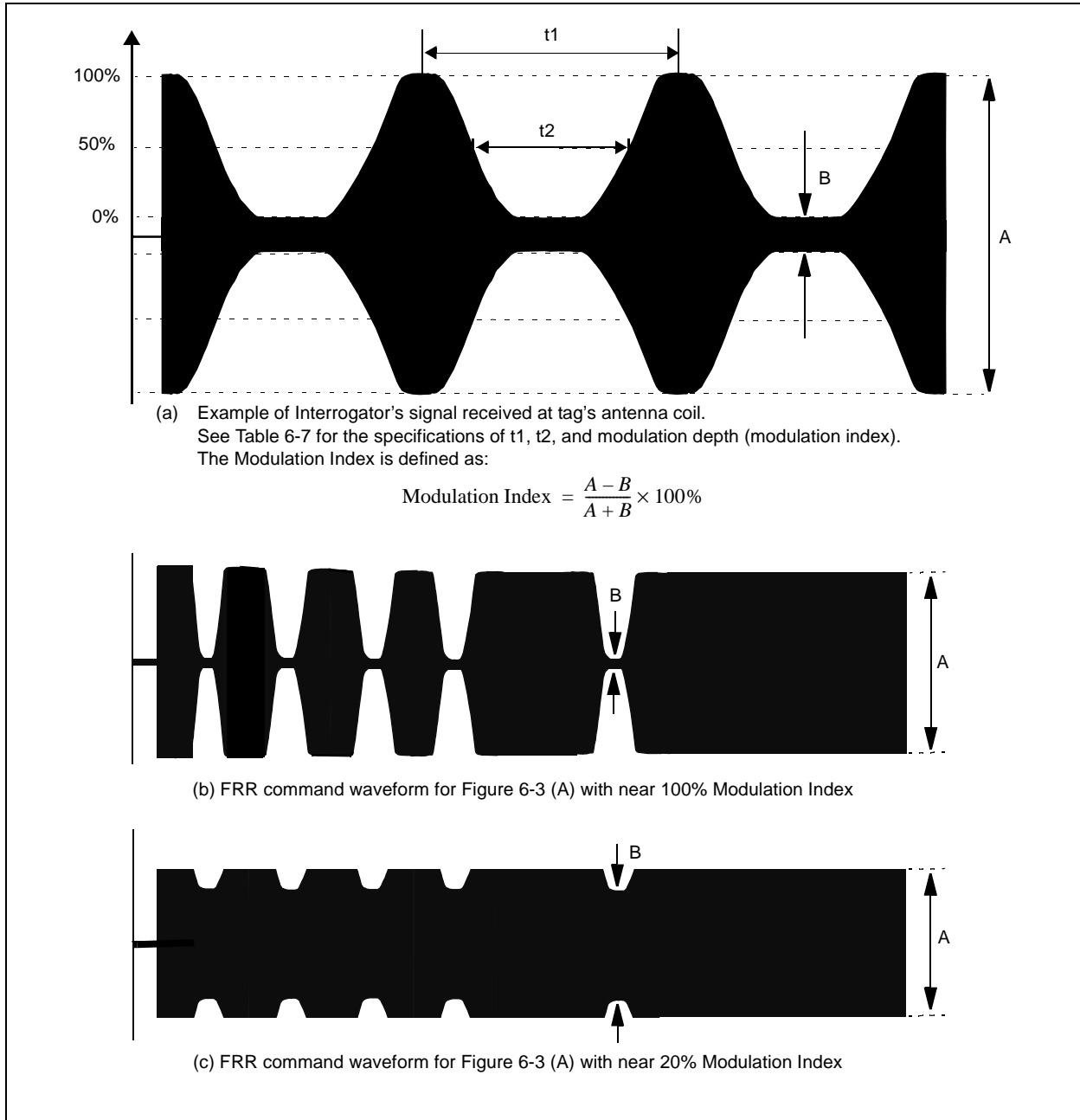


TABLE 6-7: WAVEFORM CHARACTERISTICS OF GAP AND 1-OF-16 PPM SIGNALS

| Signal | Symbol | Min | Typ | Max | Unit | Conditions |
|--|--------------|-----|-----|------|------|---|
| Gap signal and 1-of-16 PPM for Normal mode | t1 | 145 | 175 | 205 | μs | PWPPM_N |
| | t2 | 20 | 100 | 150 | μs | Measured at 50%, See Figure 6-2 GAPWIDTH_N |
| | MODINDEX_GAP | 20 | 60 | 100 | % | See Figure 6-2 |
| 1-of-16 PPM for Fast mode | t1 | 8.3 | 10 | 11.7 | μs | PWPPM_F |
| | t2 | 6.0 | 7.0 | 8.0 | μs | Measured at 50%, See Figure 6-2 GAPWIDTH_F |
| | MODINDEX_GAP | 20 | 60 | 100 | % | See Figure 6-2 |

MCRF450/451/452/455

The following figures show the various modulation patterns of the Fast Read commands (FRR and FRB). Each command consists of a combination of five gap pulses within nine possible gap positions. The pulse width of each gap is $175\ \mu\text{s}$ and the total time span of each command for the nine possible positions is $1.575\ \text{ms}$ ($175\ \mu\text{s} \times 9 = 1.575\ \text{ms}$).

In the figures, P_{mn} represents m^{th} gap pulse at n^{th} gap position in the given data packet (symbol).

FIGURE 6-3: GAP MODULATION PATTERNS FOR FRR, NORMAL SPEED, TSMAX = 1

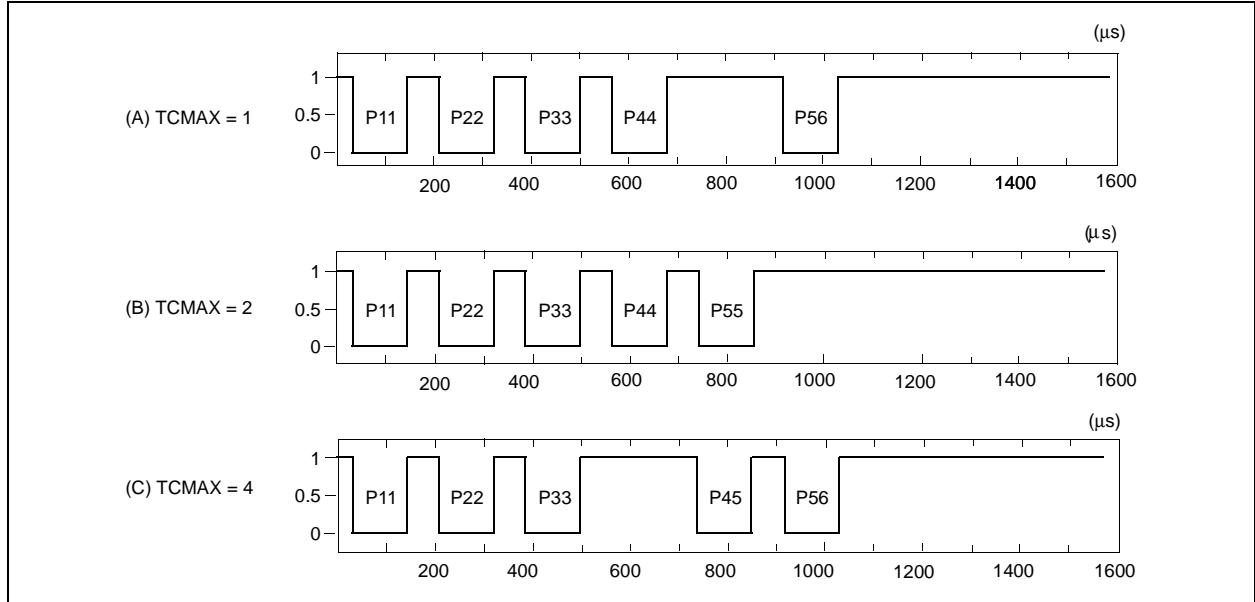
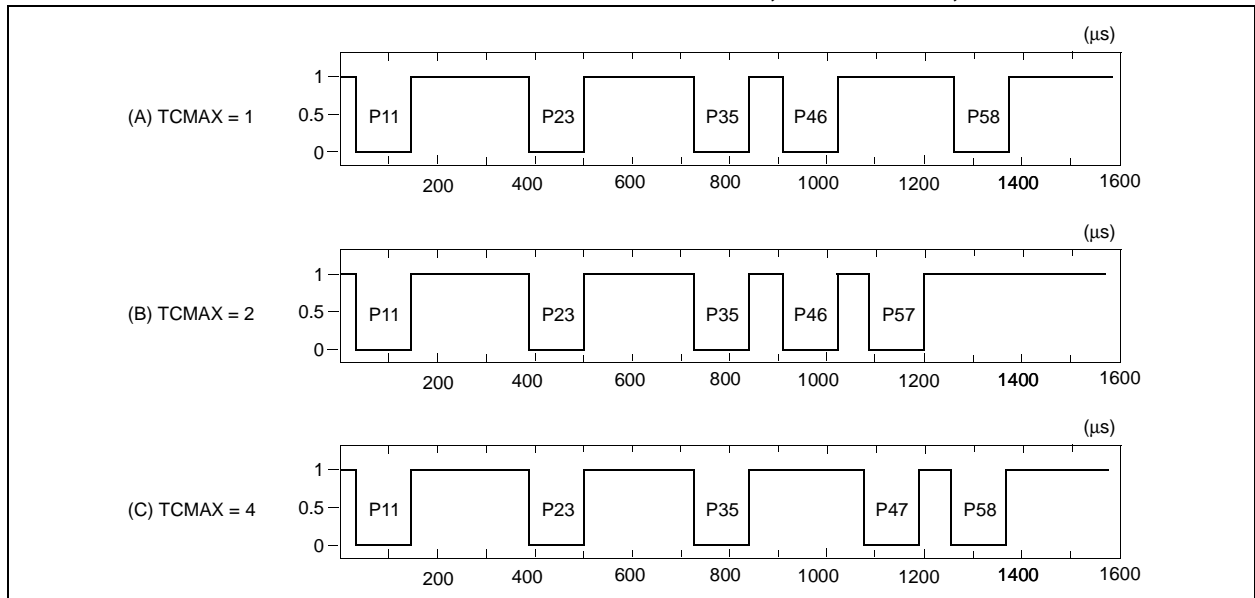


FIGURE 6-4: GAP MODULATION PATTERNS FOR FRR, FAST SPEED, TSMAX = 1



MCRF450/451/452/455

FIGURE 6-5: GAP MODULATION PATTERNS FOR FRR, NORMAL SPEED, TSMAX = 16

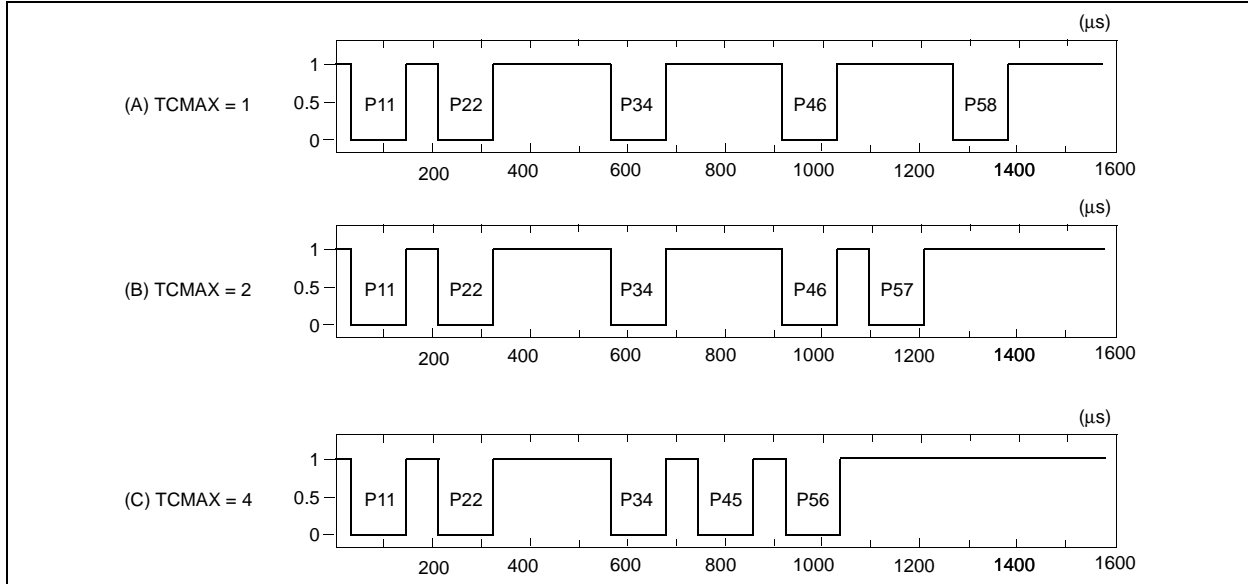


FIGURE 6-6: GAP MODULATION PATTERNS FOR FRR, FAST SPEED, TSMAX = 16

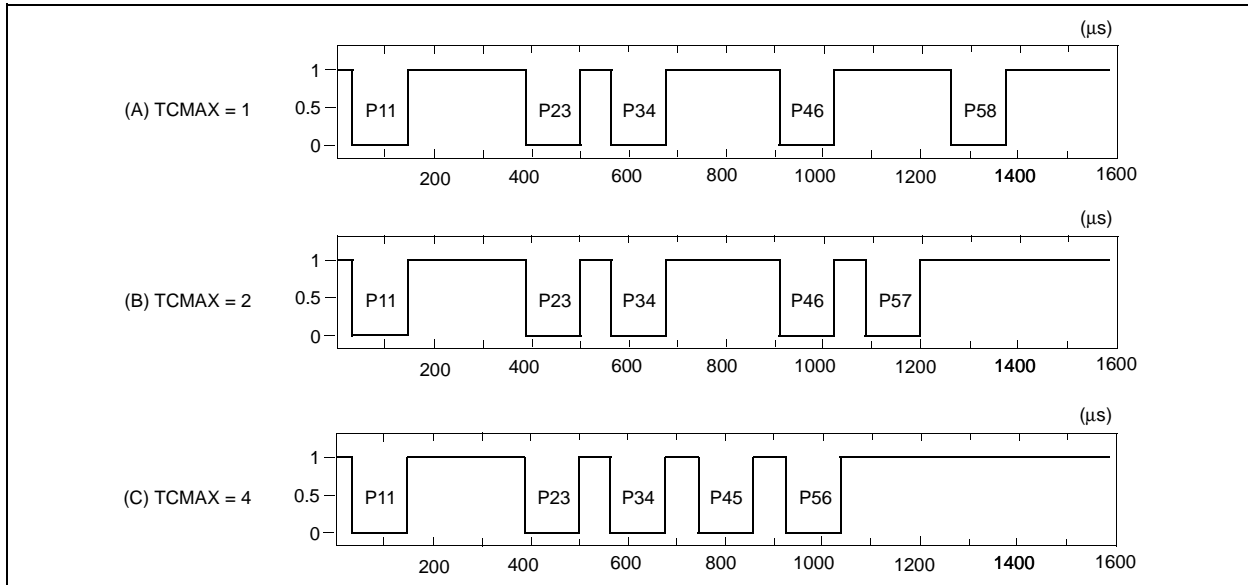


FIGURE 6-7: GAP MODULATION PATTERNS FOR FRR, TSMAX = 64, TCMAX = 1

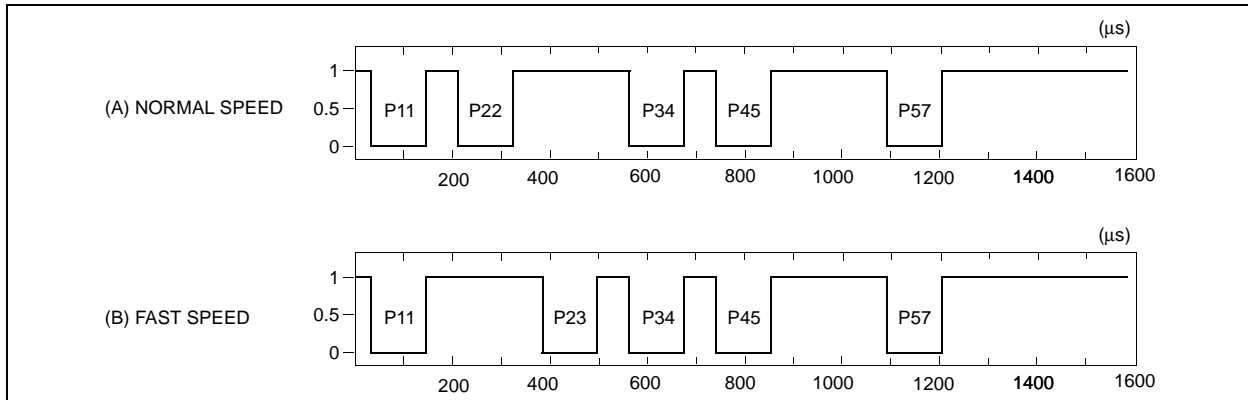
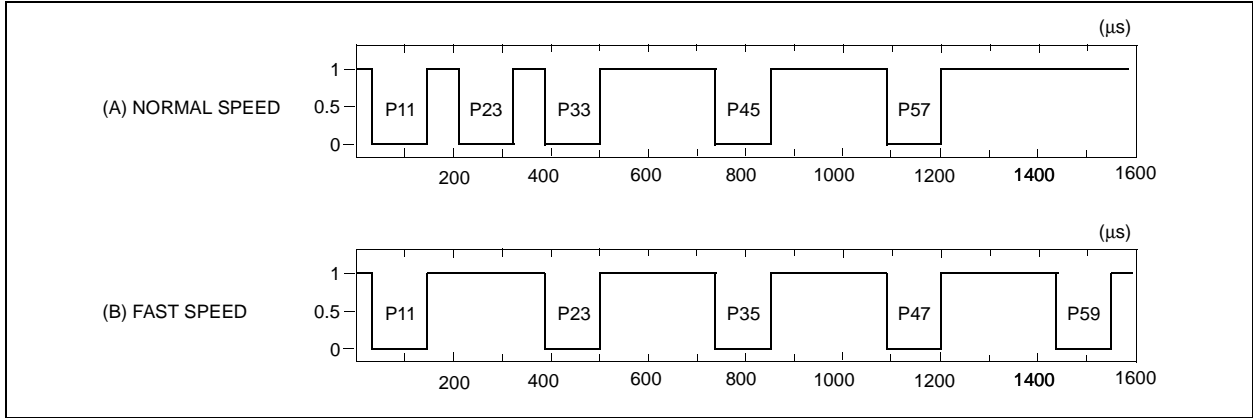


FIGURE 6-8: GAP MODULATION PATTERNS FOR FRB (FAST REQUEST BYPASS)



MCRF450/451/452/455

6.2.3.3 Usage Of TSMAX And TCMAX

The parameters of TSMAX and TCMAX are determined by an expected number of tags in the Detection Loop. The following table shows the

recommended FRR command repeat times for each of the 7 possible combinations of TSMAX and TCMAX. The command repeat time in Table 6-8 is calculated by:

EQUATION 6-1: COMMAND REPEAT TIME

$$\text{Command Repeat Time} = TSMAX \times TCMAX \times 2.5ms \times 1.17$$

Where:

1.17 is related to the tolerance of the baud rate.

TABLE 6-8: FRR COMMAND REPEAT TIME VS. (TSMAX, TCMAX)

| (TSMAX, TCMAX) | (1,1) | (1,2) | (1,4) | (16,1) | (16,2) | (16,4) | (64,1) |
|----------------------------|----------|---------|---------|---------|---------|----------|----------|
| Command Repeat Time | 2.925 ms | 5.85 ms | 11.7 ms | 46.8 ms | 93.6 ms | 187.2 ms | 187.2 ms |

6.2.3.4 1-of-16 PPM

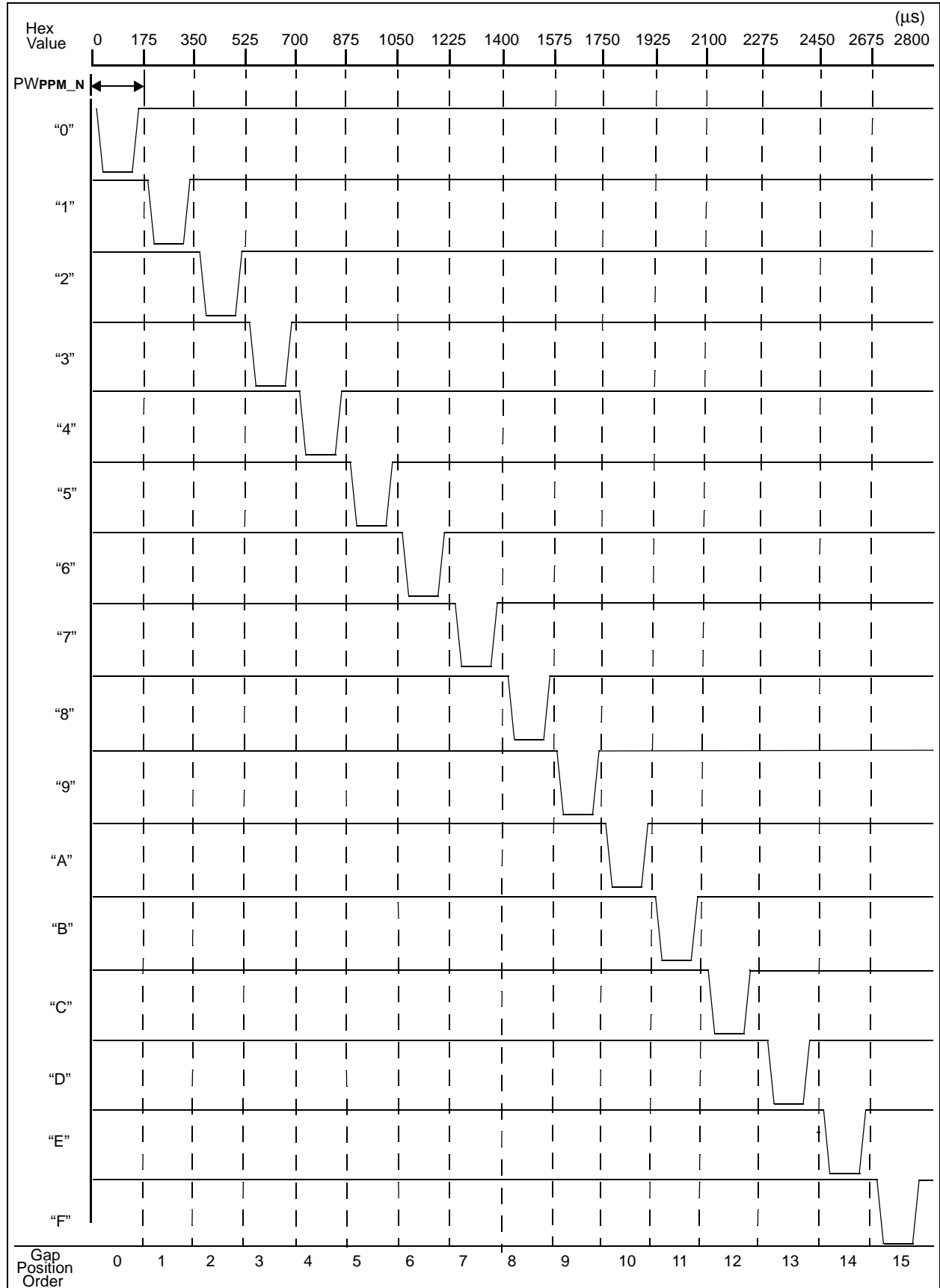
The Interrogator uses 1-of-16 Pulse Position Modulation (PPM) for MC1 and MC2 matching codes, End Process (EP) and also commands in Table 6-2. 1-of-16 PPM uses only one gap pulse in one of sixteen possible pulse positions for sending 4-bit symbols ($2^4 = 16$). This means one symbol (one data packet) represents 4 bits of binary data. One symbol lasts for 2.8 ms and 160 μ s for Normal Speed and Fast Speed mode, respectively. All communications begin with time calibration pulses (TCP) composed of three pulses in positions, zero, six and fourteen of a 1-of-16 PPM symbol, as shown in Figure 6-10.

TABLE 6-9: 1-OF-16 PPM PULSE SPECIFICATIONS

| | Normal Mode | Fast Mode |
|---------------------------------|------------------------------|------------------------------|
| Modulation depth (MODINDEX_GAP) | 100% (max) | 100% (max) |
| Pulse width | 175 μ s (typical) | 10 μ s (typical) |
| Gap width | 100 μ s (typical) | 7 μ s (typical) |
| Pulse positions per symbol | 16 | 16 |
| Symbol width | 2.8 ms (typical) | 160 μ s (typical) |
| Calibration sequence | Pulses in positions 0, 6, 14 | Pulses in positions 0, 6, 14 |

MCRF450/451/452/455

FIGURE 6-9: 1-OF-16 PPM REPRESENTATION FOR HEX VALUES FOR NORMAL SPEED MODE

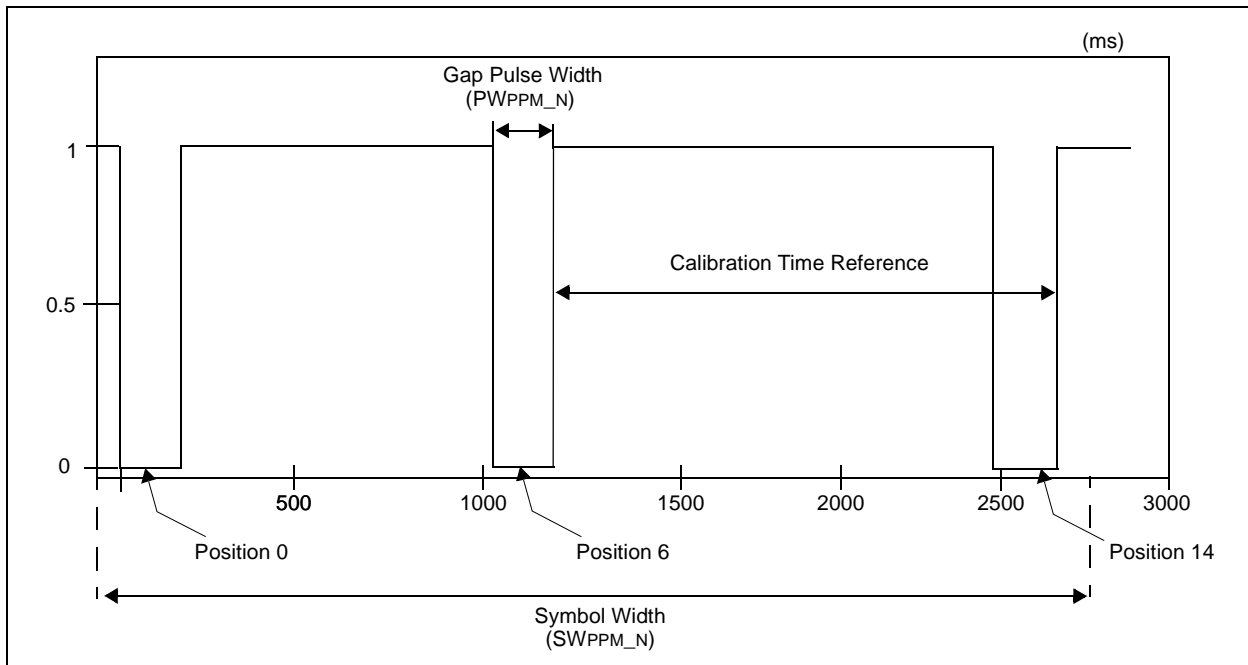


MCRF450/451/452/455

6.2.3.5 Calibration Of Time Reference For Decoding

The device uses TCP to match its internal decoder timing to the Interrogator timing. The Interrogator transmits the timing pulses at the start of all commands and at least every 17 symbols. The TCP uses a code violation of the 1-of-16 PPM signal consisting of three gap pulses within one symbol. The first gap pulse is located at position 0, the second gap pulse at position 6 and the third at position 14 of the symbol. The time period between the last two gap pulses is used to calibrate the device's timing for decoding. Figure 6-10 shows the calibration pulses for Normal Speed mode. The waveform of the gap pulses is the same as the 1-of-16 PPM signal, as shown in Figure 6-2. For Fast Speed mode, the gap positions are the same. PWPPM_F is the gap pulse width and SWPPM_F is the symbol width of the Fast mode.

FIGURE 6-10: CALIBRATION PULSES FOR NORMAL SPEED MODE



6.2.3.6 Calculation Of Matching Code

When the Interrogator receives the FR response from a device, it sends an MC to select the device. The MC is sent during the device's listening window. There are two different types of matching codes: MC1 and MC2. Both MC1 and MC2 are used in the detection loop. MC2 is used in the reactivation loop, as detailed in Figure 6-1. The MC1 command is used to send the device to the sleeping loop, while MC2 is used to send the device to the processing loop.

The MC is an 8-bit "match" of tag ID followed by 4-bit matching code type and parity bit such that:

Matching code (12 bits) = "match (8 bits of tag ID)" + matching code type (3 bits)+ parity (1-bit)

The matching code type and parity bit is bit-wise structured as follows:

- MC1: 010P
- MC2: 100P

where P represents the parity bit of all match bits (8 bits) plus the MC type (3 bits).

The "match" part of the MC is 8 bits of the 32-bit Tag ID. The Interrogator selects the 8 bits from the 32-bit Tag ID by calculating the bit range of the Tag ID. Equation 6-2 shows the equation for selecting the bit range using the transmission counter (TC). Both the

32-bit Tag ID and TC are included in the FR response. An example for the calculation of the matching code is given in Example 9-2.

EQUATION 6-2: BIT-WISE EQUATION FOR "MATCH"

| |
|--|
| "Match" = Tag ID bit range a: b |
| $\{4 \cdot TC\} \text{ modulo } 32: \{4 \cdot (TC + 1) + 3\} \text{ modulo } 32$ |

where {} modulo 32 means the remainder of {} divided by 32. For example, {28} modulo 32 and {35} modulo 32 are 28 and 3, respectively.

6.3 Time Slot Generator

This block generates time slots for the device. The time slot represents the time delay between the end of the FRR command and the beginning of the FR response. The available time slots are 1, 16 or 64. One time slot represents 2.5 ms. The device calculates the actual time slot based on the TSMAX, TC and Tag ID. The maximum time slot (TSMAX) is assigned to the device by the FRR command (see Figures 6-3 to 6-7), or set to 16, if the TF bit is set.

Four or six bits out of the 32-bit Tag ID are used to calculate the time slot, with TC being the shift parameter to choose which portion of the 32-bit Tag ID is used, as shown in Equation 6-3.

EQUATION 6-3: TIME SLOT CALCULATION

| TSMAX | Time Slot = Tag ID bit range a:b |
|-------|---|
| 64 | $\{[4 \cdot (TC + 1) + 1] \text{ modulo } 32: [4 \cdot TC] \text{ modulo } 32\} \text{ XOR TC LSB}$ |
| 16 | $\{[4 \cdot (TC + 1) - 1] \text{ modulo } 32: [4 \cdot TC] \text{ modulo } 32\} \text{ XOR TC LSB}$ |
| 1 | 0 |

Note: The exclusive-or (XOR) operation in Equation 6-3 is called "semi-inverting" in that it randomizes worst case tag IDs; for example: a Tag ID of '77777777' or '00000000'. Table 6-10 shows examples of the calculation.

TABLE 6-10: EXAMPLE: TAG ID = h'825FE1A0

| TC | Relevant Tag ID | | Selected Tag ID before XOR with LSB of TC | | Calculated Time Slot (TS) (after XOR with LSB of TC) | | | |
|----|-----------------|--------------|---|------------|--|------------|------------|------------|
| | Hexadecimal | Binary | TSMAX = 16 | TSMAX = 64 | TSMAX = 16 | TSMAX = 16 | TSMAX = 64 | TSMAX = 64 |
| 0 | h'825FE1(A0)' | b'1010 0000' | h'0' | h'20' | h'0' | d'0' | h'20' | d'32' |
| 1 | h'825FE(1A)0' | b'0001 1010' | h'A' | h'1A' | h'5' | d'5' | h'25' | d'37' |
| 2 | h'825F(E1)A0' | b'1110 0001' | h'1' | h'21' | h'1' | d'1' | h'21' | d'33' |
| 3 | h'825(FE)1A0' | b'1111 1110' | h'E' | h'3E' | h'1' | d'1' | h'01' | d'1' |
| 4 | h'82(5F)E1A0' | b'0101 1111' | h'F' | h'1F' | h'F' | d'15' | h'1F' | d'31' |
| 5 | h'8(25)FE1A0' | b'0010 0101' | h'5' | h'25' | h'A' | d'10' | h'1A' | d'26' |
| 6 | h'(82)5FE1A0' | b'1000 0010' | h'2' | h'02' | h'2' | d'2' | h'02' | d'2' |
| 7 | h'(08)25FE1A' | b'0000 1000' | h'8' | h'08' | h'7' | d'7' | h'37' | d'55' |

Legend: h'x..x' represents hexadecimal number
d'x..x' represents decimal number
b'x..x' represents binary number

Table 6-10 shows the calculated time slot (TS): 5 for TC = 1 and TSMAX = 16 with Tag ID = h'825FE1A0'. This means the device waits for 12.5 ms (5 x 2.5 ms = 12.5 ms) in a nonmodulating condition between the end of FRR and the start of the FR response.

Also, the TS is 37 for TC = 1 and TSMAX = 64. This means the device waits for 92.5 ms (37 x 2.5 ms = 92.5 ms) between the end of FRR and the start of the FR response in a nonmodulating condition.

6.4 Time Slot Counter

This section generates the Sleep time (2.5 ms x TS) of the device. During the Sleep time, the device remains in a nonmodulating condition.

MCRF450/451/452/455

7.0 MEMORY SECTION

The memory section is organized into two groups: Main Memory Section and Stored CRC (SCRC) Memory Section.

7.1 Main Memory Section

The main section is organized into 32 blocks, as shown in Table 7-1, with each block having 32 bits. Each individual block can be read and written by the Interrogator's command. The first Blocks (0-2) are used for predefined parameters and device operation. The next three Blocks (3-5) are used as the FRF data.

The Blocks from 3 to 31 (29 blocks) are used for user data memory. Bits from 0 to 15 of Block 0 also can be used for user memory. The memory is read or written in 32-bit selectable units. The exceptions are the FR bit and the TF bit of Block 0, which are individually selectable.

Each block is accessed by the Interrogator's command based on block address. The reading of FRF blocks (Blocks 3-5) can be accomplished in two different ways: (1) by FRR command or (2) by Read Block command. The device sends the FRF data when it receives the FRR command. The length of the FRF data for the FRR command is determined by DF bits (see Table 7-6).

7.2 Stored CRC (SCRC) Memory Section

This memory section is used to store the CRC of the main memory section. It is organized into 32 blocks. Each block has 16 bits and contains the CRC of the corresponding memory block.

The Stored CRC (SCRC) is the CRC of the Interrogator's writing command (Write command + block address + data). The device stores the received Interrogator's CRC and sends back verification when it sends the block data. For the Block 0 and 2, the device sends CCRC instead of the SCRC. The device sends the CRC of each block as follows:

- Blocks 0 and 2: CCRC of block number and block data.
- Other blocks except Block 0 and 2: SCRC.
- CRC for FRR response: CCRC of Tag ID and FRF (Blocks 3-5) data. The data length of the FRF is determined by DF bits (B0: 26-27).

TABLE 7-1: MEMORY ORGANIZATION

| Main Memory Section (32 blocks x 32 bits) | | | | | | | | | | | | | | | | Stored CRC Section (32 blocks x 16 bits) | | | | | | | | | | | | | | | | Comments | | | | | | | | | | | | | | | | | | | | | | | |
|--|---|---|--------------------------------|----|----|----|--------|----|----|----|--------|----|----|----|------------|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----------|---|---|---|---|---|---|---|---|--|--|---|----------------------|--|--|--|--|--|--|--|--|--|--|---|
| M | S | B | Available to user (21 Bits) | | | | | | | | | | | | | L | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | | S | 5 | 4 | 3 | 2 | 1 | 0 | | | | | | | | | | | | | | | | |
| | | | FRF | TF | DF | MT | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | TF | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Block 0 (Tag Parameters + User Memory) | | | | | | | | | | | | | | | |
| | | | Byte 3 | | | | Byte 2 | | | | Byte 1 | | | | Byte 0 | | | | | | | | | | | | | | | | | | | | | | | | | | | Block 1 (Tag ID = Serial Number) | | | | | | | | | | | | | |
| | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | | | | | | | | | | | | | | | | | | | | | | | | Block 2 (Write Protection bits) (Clear bit 2 to write-protect Block 2) |
| | | | Fast | | | | Read | | | | Field | | | | (LS Block) | | | | | | | | | | | | | | | | | | | | | | | | | | | Block 3 (FR Field Least Significant Block) | | | | | | | | | | | | | |
| | | | Fast | | | | Read | | | | Field | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Block 4 (FR Field) | | | | | | | | | | | | |
| | | | Fast | | | | Read | | | | Field | | | | (MS Block) | | | | | | | | | | | | | | | | | | | | | | | | | | | | Block 5 (FR Field Most Significant Block) | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Block 6 (User Data) | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Block 7 (User Data) | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ... | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ... | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ... | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ... | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Block 31 (User Data) | | | | | | | | | | | |

7.3 Bit Layout

7.3.1 BLOCK 0

The bit layout in Block 0 is given in the following table. FR and TF bits are not write-protectable.

TABLE 7-2: BIT LAYOUT OF BLOCK 0

| | | | | | | | |
|-------------|-------|-------|-------------|-------|-------|-------|-------|
| B0:31 | B0:30 | B0:29 | B0:28 | B0:27 | B0:26 | B0:25 | B0:24 |
| FR | TF | TFT1 | TFT0 | DF1 | DF0 | MT1* | MT0* |
| B0:23 | B0:22 | B0:21 | B0:20 | B0:19 | B0:18 | B0:17 | B0:16 |
| TM2* | TM1* | TM0* | User Memory | | | | |
| B0:15 | B0:14 | B0:13 | B0:12 | B0:11 | B0:10 | B0:9 | B0:8 |
| User Memory | | | | | | | |
| B0:7 | B0:6 | B0:5 | B0:4 | B0:3 | B0:2 | B0:1 | B0:0 |
| User Memory | | | | | | | |

Note: * These are 'hardwired' bits, not EEPROM bits.

7.3.1.1 Description Of Bits

TABLE 7-3: FR BIT (B0:31)

| FR | Reply to FRR (Fast Read Request) Command | Reply to FRB (Fast Read Bypass) Command | Application Example |
|----|---|--|---|
| 0 | No | Yes (see Example 9-1 for response) | "Item" has been purchased in retail EAS applications. |
| 1 | Yes (see Example 9-1 for response) | No | "Item" is unpaid in retail EAS applications. |

Note: FR bit is not write-protectable.

TABLE 7-4: TF BIT (B0:30)

| TF | Condition |
|----|--|
| 0 | Interrogator-Talks-First (ITF) mode: Wait for FRR command for FRR Response. |
| 1 | Tag-Talks-First (TFT) mode if FR bit is also set: Send Fast Read response without waiting for FRR command. |

Note: TF bit is not write-protectable.

TABLE 7-5: TFT BITS (B0:29 - B0:28)

| TFT1 | TFT0 | TCMAX ¹ for Tag-Talks-First mode |
|------|------|---|
| 0 | 0 | 1 |
| 0 | 1 | 2 |
| 1 | 0 | 4 |
| 1 | 1 | Never Elapses (Default) ² |

Note 1: Only applicable in TTF mode. TSMAX parameter is set to 64 for TTF mode. For the ITF mode, the TCMAX is given in the FRR command.

2: The device continuously sends its FR response until it receives its correct matching code. On average, the device will send its FR response every 80 ms.

TABLE 7-6: DF BITS (B0:27 - B0:26)

| DF1 | DF0 | FR Data Field Length |
|-----|-----|----------------------|
| 0 | 0 | 32 bits (Default) |
| 0 | 1 | 48 bits |
| 1 | 0 | 64 bits |
| 1 | 1 | 96 bits |

MCRF450/451/452/455

TABLE 7-7: MT BITS (B0:25 - B0:24)

| MT1 | MT0 | Memory Type |
|-----|-----|--|
| 0 | 0 | Single level EEPROM (Default). |
| 0 | 1 | Reserved for future uses (e.g., multi level EEPROM). |
| 1 | 0 | Reserved for future uses. |
| 1 | 1 | Reserved for future uses. |

Note: The MT bits are "hardwired".

TABLE 7-8: TM BITS (B0:23 - B0:21)

| TM2 | TM1 | TM0 | Total Memory Size |
|-----|-----|-----|-------------------|
| 0 | 0 | 0 | 512 bits |
| 0 | 0 | 1 | 1 Kbit (Default) |
| 0 | 1 | 0 | TBD |
| 0 | 1 | 1 | TBD |
| 1 | 0 | 0 | TBD |
| 1 | 0 | 1 | TBD |
| 1 | 1 | 0 | TBD |
| 1 | 1 | 1 | TBD |

Note: The TM bits are "hardwired".

TABLE 7-9: B0: (20-0)

| | |
|-----------|--------------------|
| B0:(20-0) | Available for user |
|-----------|--------------------|

7.3.2 BLOCK 1: UNIQUE 32-BIT TAG ID

Block 1 contains 32 bits of unique Tag ID with SCRC. The ID is uniquely serialized by Microchip Technology Inc.

7.3.3 BLOCK 2: WRITE-PROTECT FOR THE FIRST KBITS

Each bit corresponds to a 32-bit block, (i.e., bit '0' to Block 0, bit '1' to Block 1, etc.). Program the corresponding bit to '0' to write-protect the block. For example, program bit 10 to '0' to write-protect the Block 10. The initial value (default) of Block 2 is 'FFFFFFFD'. This means Block 1 (Tag ID) is write-protected before shipping to customer.

Write protection is a one way process, (i.e., once a block is write-protected, it cannot be modified). It should be noted that the write-protect block itself can be write-protected. TF and FR bits in Block 0 are not write-protectable, even if the write protection bit in the block is set.

TABLE 7-10: WRITE-PROTECT

| Block X Write Status | Bit X of Write-Protect Block |
|-------------------------|------------------------------|
| Block X writable | 1 |
| Block X write-protected | 0 |

7.3.4 BLOCKS 3 - 5: FAST READ FIELDS

These blocks contain data bits for the FR response. The state of the DF bits (see Table 7-6) in Block 0 determines the actual number of bits to be sent. This block can be used both as a customer ID and as additional tag ID numbers. These blocks are called Fast Read Field (FRF) because the device sends the FRF data immediately following the FRR command only (ITF mode), or as soon as energized (TTF mode), without an additional Block Read command. This means that the reading of this FRF data can be done by FRR command only. Reading of other block data requires the FRR and Block Read commands. Only the FRR device (FR bit = set) outputs the FRF data. The FRB device (FR bit = cleared) does not send the FRF data.

8.0 DEVICE TESTING

The device will be shipped to customers with the FR bit set, and with Block 1 write-protected.

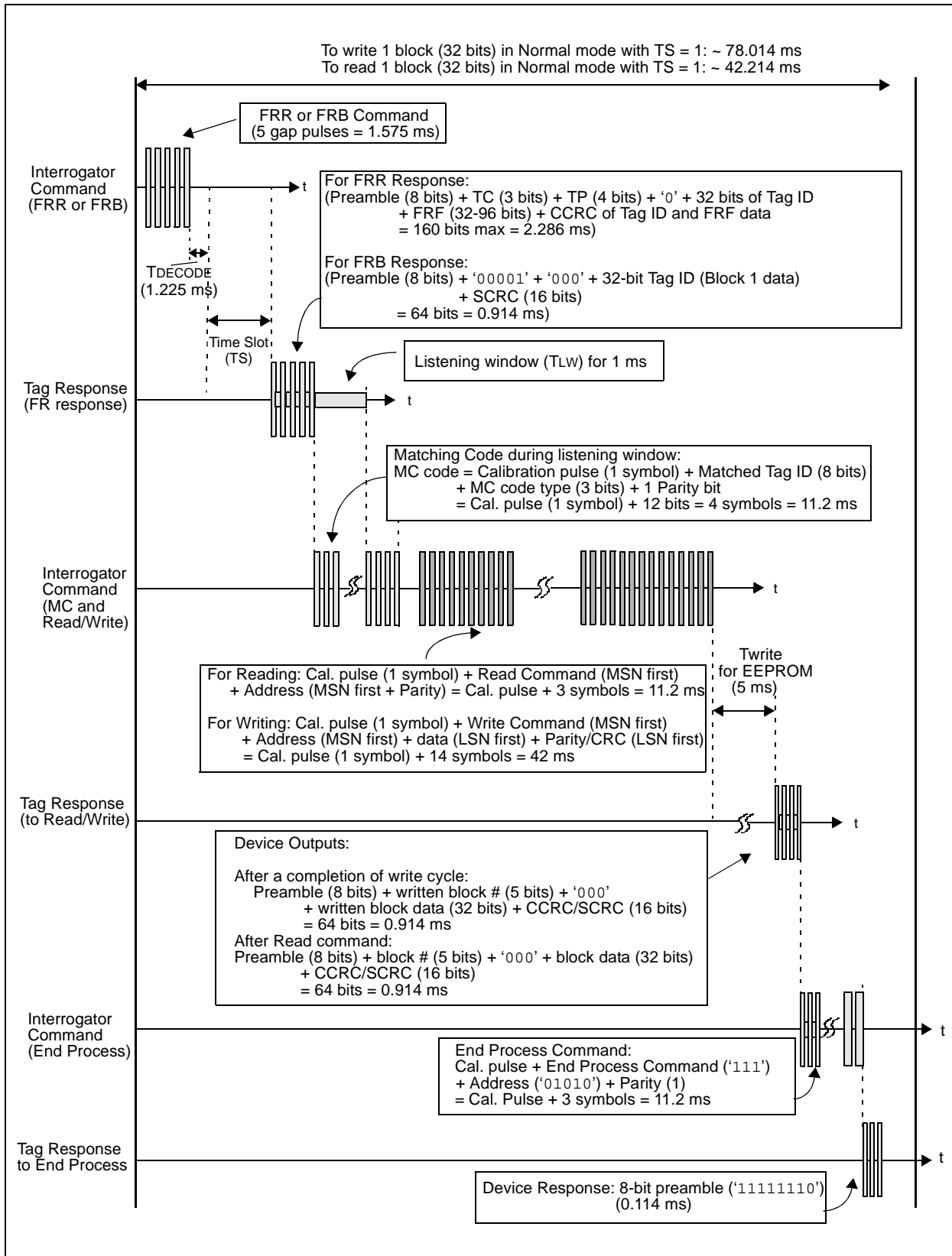
The following bits are factory programmed prior to shipping:

1. DF0 (B0:26) and DF1(B0:27) are set to '0's.
2. TFT0 (B0:28) and TFT1(B0:29) bits are set to '1's.
3. All bits in the FR field (Blocks 3-5) are programmed to '1's.
4. Failed device in the Test mode: (1) Tag ID is programmed with "BADBADBA" and (2) inked with black color on the die (see **Section 10.0 "Failed Die Identification"**, for the failed die identification).

MCRF450/451/452/455

9.0 EXAMPLES

EXAMPLE 9-1: READ/WRITE PULSE SEQUENCE



EXAMPLE 9-2: CALCULATION OF MATCHING CODE FOR TAG ID = 825FE1A0 (HEX, MSB FIRST)

The “match” part of the matching code is calculated by the Bit-Wise Equation in Equation 6-2:

$$\text{“Match (8 bits)”} = \text{Tag ID bit range a:b} = \{4(\text{TC})\} \text{ modulo } 32: \{4(\text{TC} + 1) + 3\} \text{ modulo } 32$$

For TC = 2, the above equation gives a = 8, and b = 15.

The “Match (8 bits)” is chosen from (8th 9th 10th 11th) and (12th 13th 14th 15th) bits of the Tag ID.

Therefore, for the Tag ID = 825FE1A0 (hex) = b/1000 0010 0101 1111 1110 0001 1010 0000/,

$$\text{“Match (8 bits)”} = \text{b}/1110 0001/ = 1\text{E (hex)}.$$

Using this “Match” part, a complete set of matching code is assembled as:

1E5 for MC1, and

1E9 for MC2

where:

5 in the MC1 was from b/0101/ (010 for MC1 and the last ‘1’ is a parity bit),

9 in the MC2 was from b/1001/ (100 for MC2 and the last ‘1’ is a parity bit).

Gap position in the 1-of-16 PPM signal for the calculated MC codes:

The gap position numbers in the 1-of-16 PPM for the calculated MC codes are (see Figure 6-9 for 1-of-16 PPM):

Positions 1, 14, and 5 for 1E5 for MC1 code

Positions 1, 14, and 9 for 1E9 for MC2 code.

The “Match” part of the matching code for various TCs are given in Table 9-1.

TABLE 9-1: CALCULATED “MATCH” FOR TAG ID = 825FE1A0 (HEX)

| TC | “Match (8 bits) in hex” |
|----|-------------------------|
| 0 | 0A |
| 1 | A1 |
| 2 | 1E |
| 3 | EF |
| 4 | F5 |
| 5 | 52 |
| 6 | 28 |
| 7 | 80 |

MCRF450/451/452/455

EXAMPLE 9-3: TO WRITE DATA INTO THE DEVICE

The Interrogator command structure for writing (see Section 6.2.1 “Structure of Read/Write Command Signals”) is:

Calibration pulse + Writing Command (MSN first) + Address (MSN first) + Data (LSN first) + Parity/CRC (LSN first)

If the Interrogator wants to write data “0123cdef (hex, MSB to LSB)” to Block 5, the following message will be sent:

Calibration pulse + Write Command (MSN first) + Address (MSN first) + Data (LSN first) + Parity/CRC (LSN first)
= Cal. pulse + 101 (Write command) + 00101 (address) + f e d c 3 2 1 0 (data, hex) + CRC
= Calibration pulse + a 5 f e d c 3 2 1 0 6 0 2 e (hex string)

Note: CRC = CRC for the Write command, address, and data. Calibration pulse is not included for the CRC calculation. See Application Note AN752 (DS00752) for the CRC calculation algorithm.

The hex string above is encoded with the 1-of-16 PPM signals. See Figure 6-10 for the 1-of-16 PPM representation of hex values.

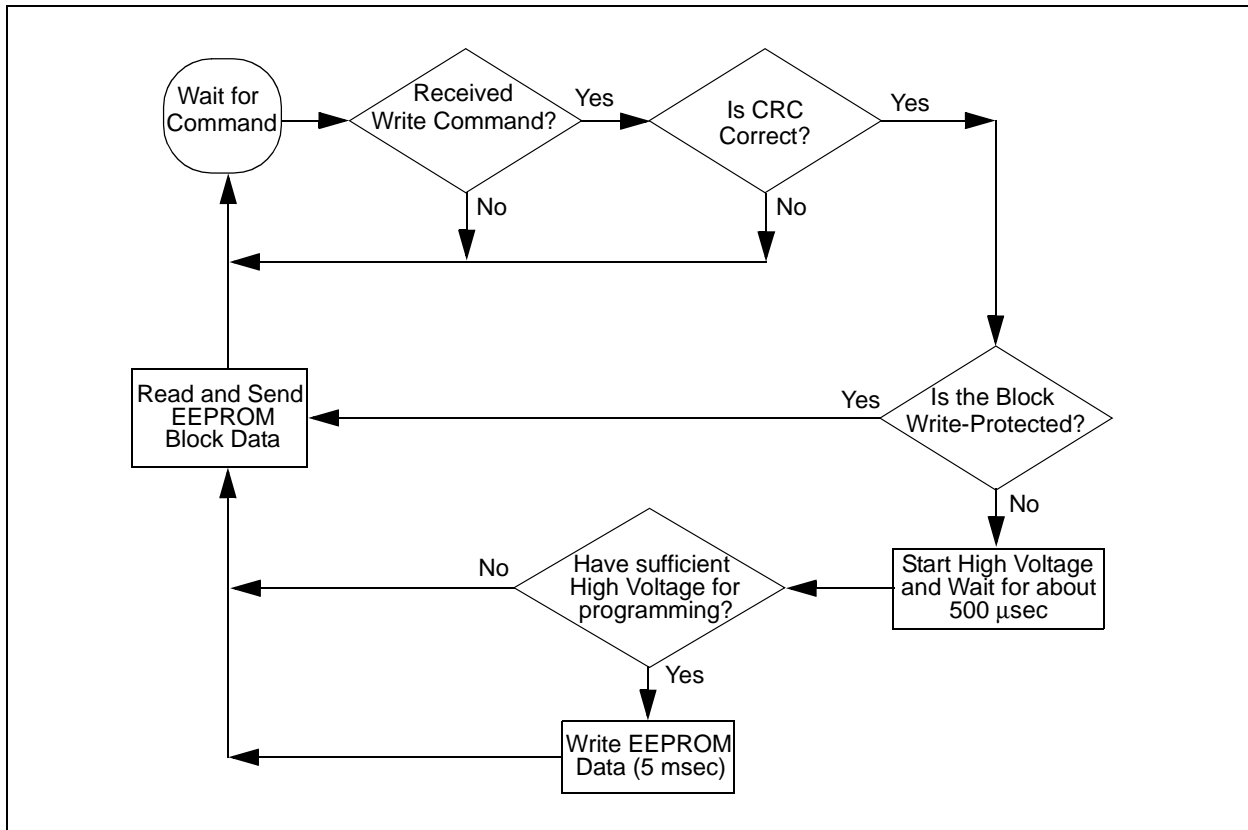
Referring to Figure 6-10, the gap positions in the 1-of-16 PPM for the above hex string are:

Positions 10 (a), 5 (5), 15 (f), 14 (e), 13 (d), 12 (c), 3 (3), 2 (2), 1 (1), 0 (0), 6 (6), 0 (0), 2 (2), e (14).

Device Response:

1. If writing is completed: The device sends the written data after 5 msec of EEPROM writing time.
2. If writing is failed due to insufficient programming voltage for unprotected block: The device sends the current block data after about 500 μ sec of delay.
3. If writing is failed because the block is write-protected block: The device sends the current block data immediately after the command.
4. If writing is failed due to incorrect CRC: The device does not respond at all.

FIGURE 9-1: FLOWCHART FOR THE DEVICE RESPONSE TO THE WRITE COMMAND



EXAMPLE 9-4: TO READ DATA FROM THE DEVICE

To read the content of Block 5 that has been programmed in the previous example, the Interrogator sends the following command:

Calibration pulse + Read Command ('110') + Address ('00101') + Parity ('0')
= Calibration pulse + C50 (hex)

The gap positions in the 1-of-16 PPM signal for the above hex string are:

12 (C), 5 (5), 0 (0).

Device Response:

When the device receives the above Interrogator command, the device outputs the following 70 kHz Manchester encoded data string (see **Section 6.2.2 "Structure of Device Response"**):

Preamble (8 bits) + Block number (5 bits, LSB first) + '000' + Block Data (32 bits, LSB first) + SCRC (16 bits)
= 1-1-1-1-1-1-1-0 (f7) + 1-0-1-0-0-0-0-0 (5 0) + 1-1-1-1 0-1-1-1 1-0-1-1... 1-0-0-0
0-0-0-0 (f e d c 3 2 1 0) + 0-1-1-0 0-0-0-0 0-1-0-0 0-1-1-1 (602e).

EXAMPLE 9-5: TO SEND THE "END PROCESS" COMMAND

The Interrogator command structure (see **Section 6.2 "Anti-Collision Command Controller"**) for the End Process is:

Calibration pulse + End Process Command ('111') + Address ('01010') + Parity (1) = Calibration pulse + EA1 (hex)

The gap positions in the 1-of-16 PPM signal for the above hex string are:

14 (E), 10 (A), 1 (1).

Device Response:

The device outputs the 8-bit preamble ('11111110') when it receives the End Process command, and enters the Sleeping Loop.

MCRF450/451/452/455

10.0 FAILED DIE IDENTIFICATION

Every die on the wafer is electrically tested according to the data sheet specifications and visually inspected to detect any mechanical damage, such as mechanical cracks and scratches.

Any failed die in the test or visual inspection is identified by black colored ink. Therefore, any die covered with black ink should not be used.

The ink dot specification:

- Ink dot size: 254 μm in circular diameter
- Position: central third of die
- Color: black

11.0 WAFER DELIVERY DOCUMENTATION

The wafer is shipped with the following information:

- Microchip Technology Inc. MP Code
- Lot Number
- Total number of wafers in the container
- Total number of good dice in the container
- Average die per wafer (DPW)
- Scribe number of wafers with number of good dice

12.0 NOTICE ON DIE AND WAFER HANDLING

The device is very susceptible to Electrostatic Discharge (ESD), which can cause a critical damage to the device. Special attention is needed during the handling process.

Any ultraviolet (UV) light can erase the memory cell contents of an unpackaged device. Fluorescent lights and sunlight can also erase the memory cell, although it takes more time than UV lamps. Therefore, keep any unpackaged device out of UV light and also avoid direct exposure of strong fluorescent lights and shining sunlight.

Certain IC manufacturing, COB, and tag assembly operations may use UV light. Operations such as backgrind de-tape, certain cleaning procedures, epoxy or glue cure should be done without exposing the die surface to UV light.

Using X-ray for die inspection will not harm the die, nor erase memory cell contents.

13.0 REFERENCES

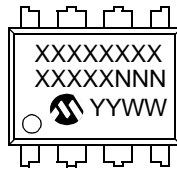
It is recommended that the reader reference the following documents.

1. "Antenna Circuit Design for RFID Applications", AN710, DS00710.
2. "RFID Tag and COB Development Guide with Microchip's RFID Devices", AN830, DS00830.
3. "CRC Algorithm for MCRF45X Read/Write Devices", AN752, DS00752.
4. "Interface Control Document for 13.56 MHz Anti-collision Interrogator", AN759, DS00759.
5. "13.56 MHz Reader Reference Design for the MCRF450/451/452/455 Read/Write Devices", DS21654.

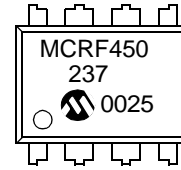
14.0 PACKAGING INFORMATION

14.1 Package Marking Information

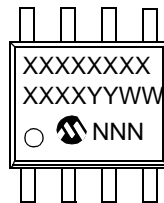
8-Lead PDIP (300 mil)



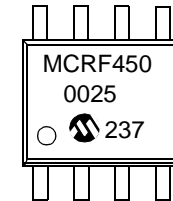
Example:



8-Lead SOIC (150 mil)



Example:



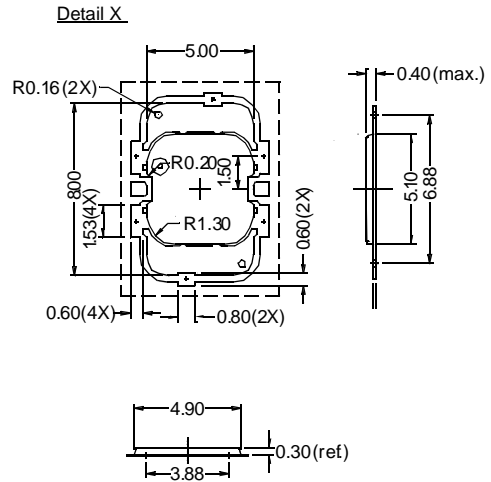
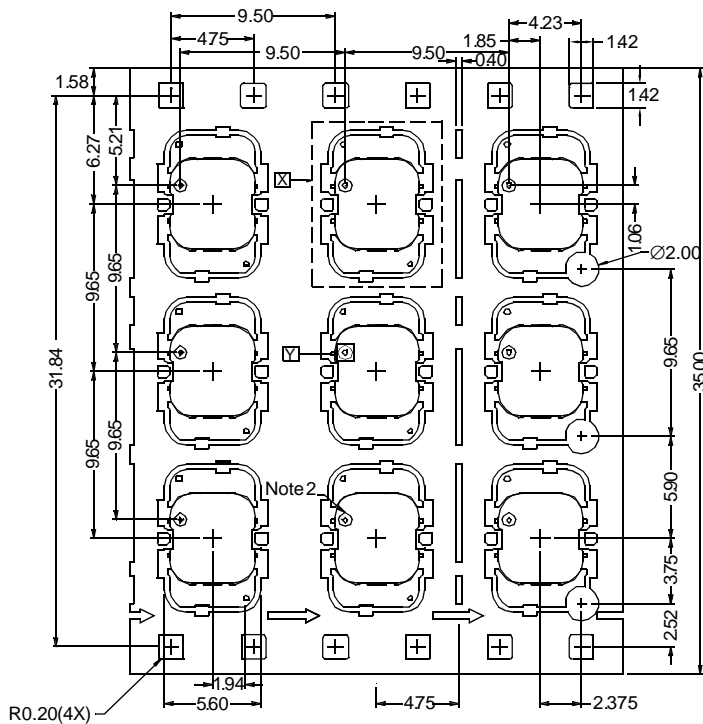
| | | |
|----------------|--|--|
| Legend: | XX...X | Customer specific information* |
| | YY | Year code (last 2 digits of calendar year) |
| | WW | Week code (week of January 1 is week '01') |
| | NNN | Alphanumeric traceability code |
| Note: | In the event the full Microchip part number cannot be marked on one line, it will be carried over to the next line thus limiting the number of available characters for customer specific information. | |

* Standard device marking consists of Microchip part number, year code, week code, and traceability code. For device marking beyond this, certain price adders apply. Please check with your Microchip Sales Office. For QTP devices, any special marking adders are included in QTP price.

MCRF450/451/452/455

Package Marking Information (Continued)

MCRF45X COB



Note:

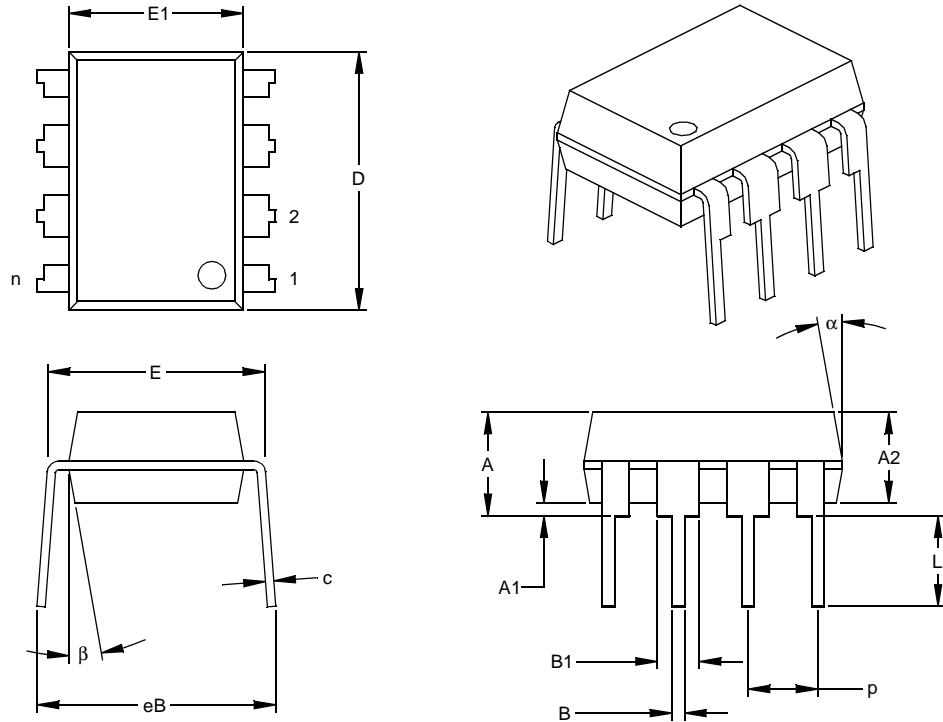
1. Reject hole by device testing
2. Top gate mark (Option)
3. Total package thickness excludes punching burr

| |
|--|
| <p>Legend:</p> <p>XX...X Customer specific information*</p> <p>YY Year code (last 2 digits of calendar year)</p> <p>WW Week code (week of January 1 is week '01')</p> <p>NNN Alphanumeric traceability code</p> |
| <p>Note: In the event the full Microchip part number cannot be marked on one line, it will be carried over to the next line thus limiting the number of available characters for customer specific information.</p> |

* Standard device marking consists of Microchip part number, year code, week code, and traceability code. For device marking beyond this, certain price adders apply. Please check with your Microchip Sales Office. For QTP devices, any special marking adders are included in QTP price.

MCRF450/451/452/455

8-Lead Plastic Dual In-line (P) – 300 mil (PDIP)



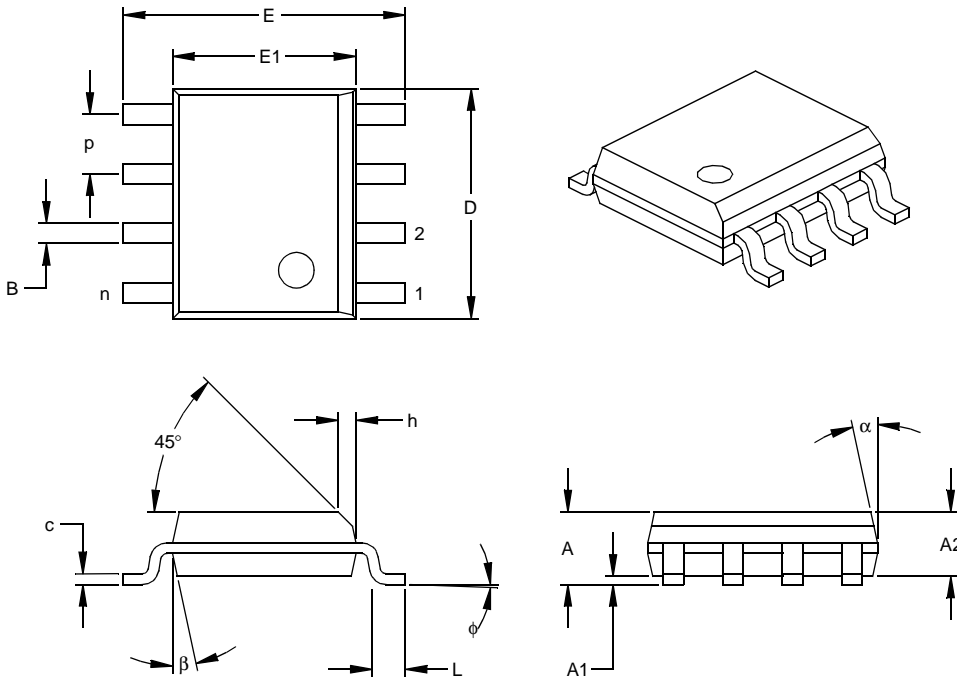
| Dimension Limits | Units | INCHES* | | | MILLIMETERS | | |
|----------------------------|-------|---------|------|------|-------------|------|-------|
| | | MIN | NOM | MAX | MIN | NOM | MAX |
| Number of Pins | n | | 8 | | | 8 | |
| Pitch | p | | .100 | | | 2.54 | |
| Top to Seating Plane | A | .140 | .155 | .170 | 3.56 | 3.94 | 4.32 |
| Molded Package Thickness | A2 | .115 | .130 | .145 | 2.92 | 3.30 | 3.68 |
| Base to Seating Plane | A1 | .015 | | | 0.38 | | |
| Shoulder to Shoulder Width | E | .300 | .313 | .325 | 7.62 | 7.94 | 8.26 |
| Molded Package Width | E1 | .240 | .250 | .260 | 6.10 | 6.35 | 6.60 |
| Overall Length | D | .360 | .373 | .385 | 9.14 | 9.46 | 9.78 |
| Tip to Seating Plane | L | .125 | .130 | .135 | 3.18 | 3.30 | 3.43 |
| Lead Thickness | c | .008 | .012 | .015 | 0.20 | 0.29 | 0.38 |
| Upper Lead Width | B1 | .045 | .058 | .070 | 1.14 | 1.46 | 1.78 |
| Lower Lead Width | B | .014 | .018 | .022 | 0.36 | 0.46 | 0.56 |
| Overall Row Spacing | § eB | .310 | .370 | .430 | 7.87 | 9.40 | 10.92 |
| Mold Draft Angle Top | α | 5 | 10 | 15 | 5 | 10 | 15 |
| Mold Draft Angle Bottom | β | 5 | 10 | 15 | 5 | 10 | 15 |

* Controlling Parameter
 § Significant Characteristic

Notes:
 Dimensions D and E1 do not include mold flash or protrusions. Mold flash or protrusions shall not exceed .010" (0.254mm) per side.
 JEDEC Equivalent: MS-001
 Drawing No. C04-018

MCRF450/451/452/455

8-Lead Plastic Small Outline (SN) – Narrow, 150 mil (SOIC)



| Dimension Limits | Units | INCHES* | | | MILLIMETERS | | |
|--------------------------|-------|---------|------|------|-------------|------|------|
| | | MIN | NOM | MAX | MIN | NOM | MAX |
| Number of Pins | n | | 8 | | | 8 | |
| Pitch | p | | .050 | | | 1.27 | |
| Overall Height | A | .053 | .061 | .069 | 1.35 | 1.55 | 1.75 |
| Molded Package Thickness | A2 | .052 | .056 | .061 | 1.32 | 1.42 | 1.55 |
| Standoff § | A1 | .004 | .007 | .010 | 0.10 | 0.18 | 0.25 |
| Overall Width | E | .228 | .237 | .244 | 5.79 | 6.02 | 6.20 |
| Molded Package Width | E1 | .146 | .154 | .157 | 3.71 | 3.91 | 3.99 |
| Overall Length | D | .189 | .193 | .197 | 4.80 | 4.90 | 5.00 |
| Chamfer Distance | h | .010 | .015 | .020 | 0.25 | 0.38 | 0.51 |
| Foot Length | L | .019 | .025 | .030 | 0.48 | 0.62 | 0.76 |
| Foot Angle | φ | 0 | 4 | 8 | 0 | 4 | 8 |
| Lead Thickness | c | .008 | .009 | .010 | 0.20 | 0.23 | 0.25 |
| Lead Width | B | .013 | .017 | .020 | 0.33 | 0.42 | 0.51 |
| Mold Draft Angle Top | α | 0 | 12 | 15 | 0 | 12 | 15 |
| Mold Draft Angle Bottom | β | 0 | 12 | 15 | 0 | 12 | 15 |

* Controlling Parameter
 § Significant Characteristic

Notes:
 Dimensions D and E1 do not include mold flash or protrusions. Mold flash or protrusions shall not exceed .010" (0.254mm) per side.
 JEDEC Equivalent: MS-012
 Drawing No. C04-057

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- Conferences for products, Development Systems, technical information and more
- Listing of seminars and events

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1-480-792-7302 for the rest of the world.

MCRF450/451/452/455

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Would you like a reply? ___Y ___N

Device: MCRF450/451/452/455 Literature Number: DS40232H

Questions:

1. What are the best features of this document?

2. How does this document meet your hardware and software development needs?

3. Do you find the organization of this document easy to follow? If not, why?

4. What additions to the document do you think would enhance the structure and subject?

5. What deletions from the document could be made without affecting the overall usefulness?

6. Is there any incorrect or misleading information (what and where)?

7. How would you improve this document?

MCRF450/451/452/455

PRODUCT IDENTIFICATION SYSTEM

To order or obtain information, e.g., on pricing or delivery, refer to the factory or the listed sales office.

| <u>PART NO.</u> | <u>X</u> | <u>/XX</u> |
|--------------------|-------------------|---|
| Device | Temperature Range | Package |
| Device: | MCRF450: | 13.56 MHz Anti-collision Read/Write MicroID device w/no internal resonant capacitor |
| | MCRF450/7M: | COB (Chip-On-Board) module with dual 68 pF capacitor |
| | MCRF451: | 13.56 MHz Anti-collision Read/Write MicroID device w/100 pF internal resonant capacitor |
| | MCRF452: | 13.56 MHz Anti-collision Read/Write MicroID device w/25 pF internal resonant capacitor |
| | MCRF455: | 13.56 MHz Anti-collision Read/Write MicroID device w/50 pF internal resonant capacitor |
| Temperature Range: | = | -20°C to +70°C |
| Package: | WF | = Sawed 8" wafer on frame (8 mil backgrind) |
| | WFB | = Bumped, sawed 8" wafer on frame (8 mil backgrind) |
| | W | = 8" wafer (11 mil backgrind) |
| | WB | = Bumped 8" wafer (8 mil backgrind) |
| | S | = Dice in wafer pack (8 mil backgrind) |
| | SB | = Bumped die in wafer pack (8 mil backgrind) |
| | X/SN | = SOIC (150 mil body), 8-lead (rotated pinout) |
| | P | = PDIP (300 mil body), 8-lead |

Examples:

- MCRF450/W: 13.56 MHz Anti-collision Read/Write MicroID device, 1 Kbit, no cap, 8" wafer, 11-mil backgrind.
- MCRF450/7M: 13.56 MHz Anti-collision Read/Write MicroID COB (IST IOA2), 1 Kbit, 68 pF dual capacitor between antenna A and B, antenna B and Vss. Thickness = 0.4 mm.
- MCRF451/WF: 13.56 MHz Anti-collision Read/Write MicroID device, 1 Kbit, 100 pF internal res cap, 8" wafer on frame, 8 mil backgrind.
- MCRF451/S: 13.56 MHz Anti-collision Read/Write MicroID device in wafer pack, 1 Kbit, 100 pF internal res cap, 8-mil thickness.
- MCRF452/WFB: 13.56 MHz Anti-collision Read/Write MicroID bumped device for flip-chip assembly, 1 Kbit, 50 pF dual (25 pF) internal res cap, Bumped 8" wafer, 8-mil backgrind wafer on frame.
- MCRF455X/SN: 13.56 MHz Anti-collision Read/Write MicroID device in SOIC package, 1k bit, 50 pF internal res cap.

Sales and Support

Data Sheets

Products supported by a preliminary Data Sheet may have an errata sheet describing minor operational differences and recommended workarounds. To determine if an errata sheet exists for a particular device, please contact one of the following:

- Your local Microchip sales office
- The Microchip Corporate Literature Center U.S. FAX: (480) 792-7277
- The Microchip Worldwide Site (www.microchip.com)

Please specify which device, revision of silicon and Data Sheet (include Literature #) you are using.

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MCRF450/451/452/455

NOTES:

CRC Algorithm for MCRF45X Read/Write Device

Author: Youbok Lee, Ph.D.
Microchip Technology Inc.

INTRODUCTION

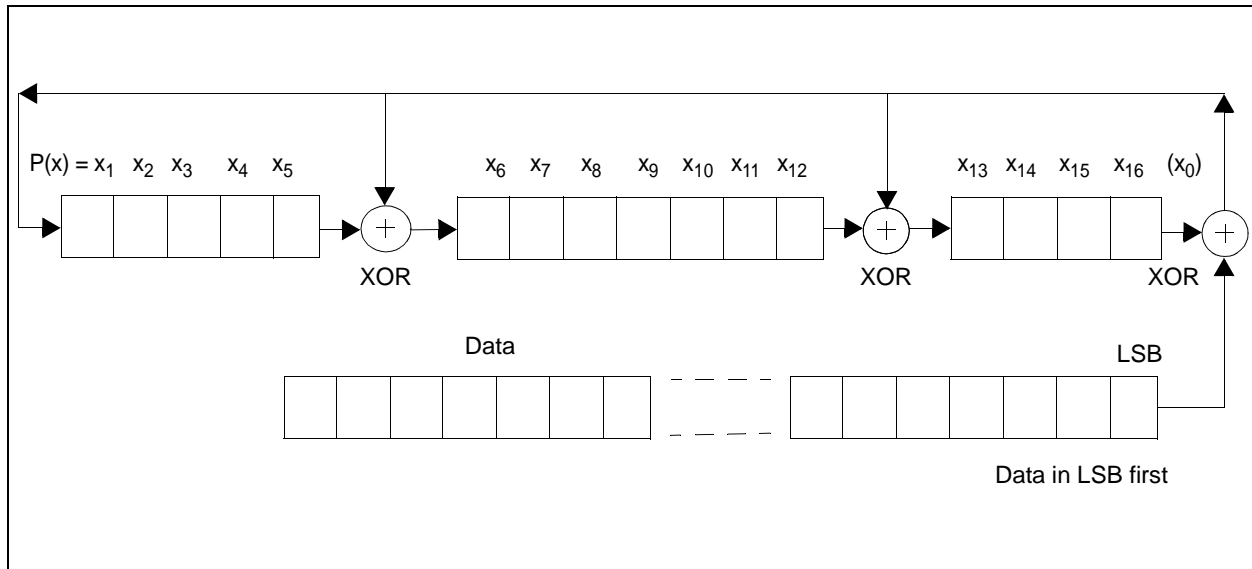
The 13.56 MHz read/write devices (MCRF4XX) use a 16-bit Cyclic Redundancy Code (CRC) to ensure the integrity of data. Its polynomial and initial values are:

CRC Polynomial: $X^0+X^5+X^{12}+X^{16} = 1000-0100-0000-1000-(1) = 8408$ (hex)

Initial Value: \$FFFF

This polynomial is also known as CRC CCITT-16. The interrogator applies the same polynomial to the incoming and transmitting data.

FIGURE 1: CCITT-16 CRC ENCODER



AN752

COMPUTATION ALGORITHM

Figure 1 shows the CCITT-16 CRC encoder. Figure 2 is the computational flow chart for computer programming.

The encoder consists of 16 shift registers and 3 exclusive-OR gates. The registers start with 1111-1111-1111-1111 (or FFFF in hex). The encoder performs XOR and shifts its content until the last bit is entered. The final register's content after the last data bit is the calculated CRC value of the data set.

Example: The following procedure shows a workout example of the CRC calculation using the encoder.

Data: 8552F189 (hex): 0001-1010-1010-0100-1111-1000-1001 (binary, LSB first for each nibble).

Table 1 shows each step of the calculation. The content of the register after the last bit is 07F1. This 07F1 is the calculated CRC of the data.

When transmitting data, this calculated CRC is attached to the data. The interrogator sends the data and CRC with LSN (Least Significant Nibble) first. Therefore, the hex string to be sent will be: 981F25581F70 and for data = 8552F189.

FIGURE 2: FLOW CHART OF CRC COMPUTATION

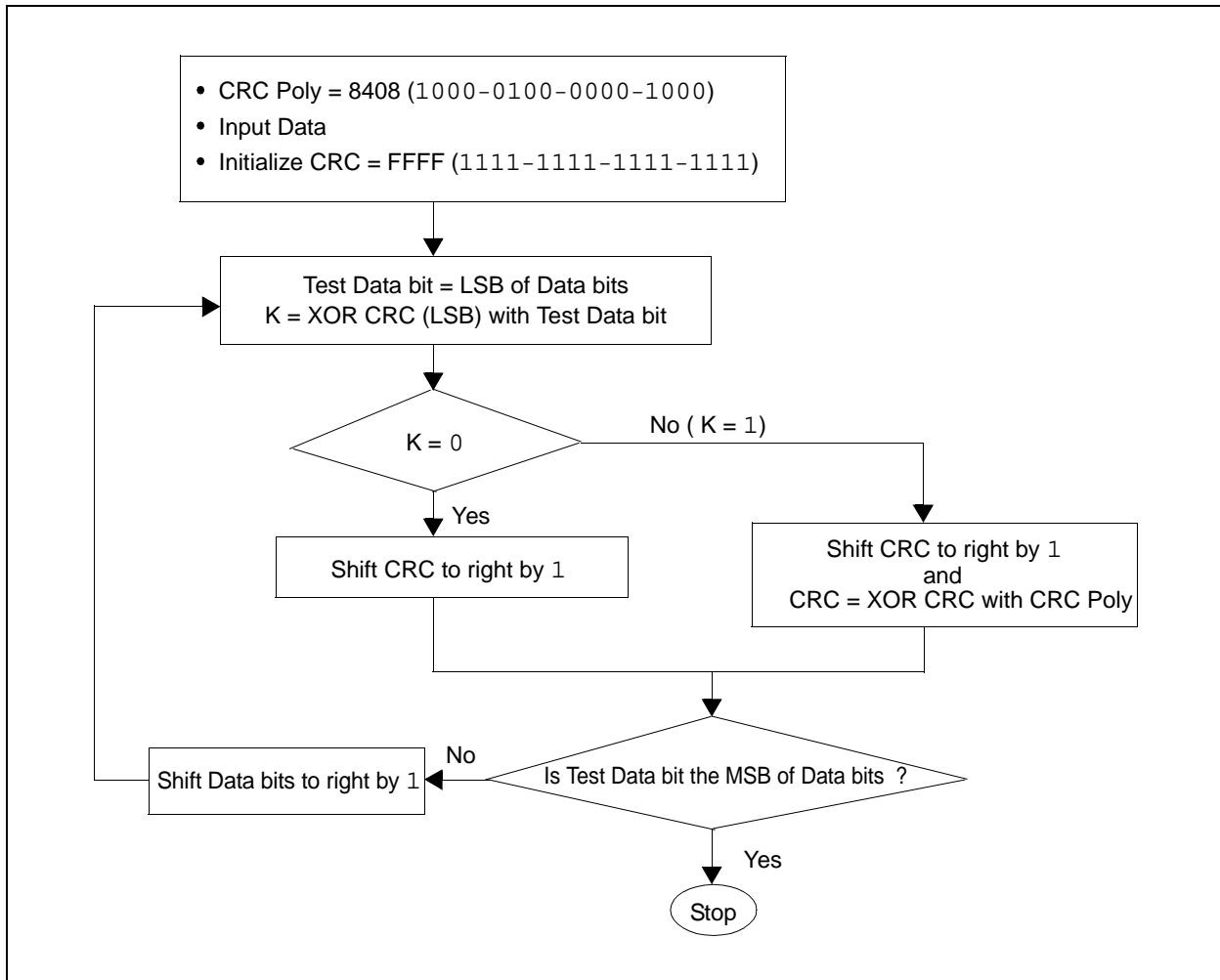


TABLE 1: CRC WORKOUT EXAMPLE FOR DATA = 8552F189 (HEX)

| Bit No. | Input Data | Register Contents | | | | | | | | | | | | | | | | Hex Value | | |
|---------|------------|-------------------|----------------|----------------|----------------|----------------|---|----------------|----------------|----------------|----------------|-----------------|-----------------|-----------------|---|-----------------|-----------------|-----------|-----------------|-----------------------------------|
| | | X ₁ | X ₂ | X ₃ | X ₄ | X ₅ | - | X ₆ | X ₇ | X ₈ | X ₉ | X ₁₀ | X ₁₁ | X ₁₂ | - | X ₁₃ | X ₁₄ | | X ₁₅ | X ₁₆ |
| Initial | | 1 | 1 | 1 | 1 | 1 | - | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - | 1 | 1 | 1 | 1 | FFFF |
| 1 | 0 | 1 | 1 | 1 | 1 | 1 | - | 0 | 1 | 1 | 1 | 1 | 1 | 1 | - | 0 | 1 | 1 | 1 | FBF7 |
| 2 | 0 | 1 | 1 | 1 | 1 | 1 | - | 0 | 0 | 1 | 1 | 1 | 1 | 1 | - | 0 | 0 | 1 | 1 | F9F3 |
| 3 | 0 | 1 | 1 | 1 | 1 | 1 | - | 0 | 0 | 0 | 1 | 1 | 1 | 1 | - | 0 | 0 | 0 | 1 | F8F1 |
| 4 | 1 | 0 | 1 | 1 | 1 | 1 | - | 1 | 0 | 0 | 0 | 1 | 1 | 1 | - | 1 | 0 | 0 | 0 | 7C78 |
| 5 | 1 | 1 | 0 | 1 | 1 | 1 | - | 0 | 1 | 0 | 0 | 0 | 1 | 1 | - | 0 | 1 | 0 | 0 | BA34 |
| 6 | 0 | 0 | 1 | 0 | 1 | 1 | - | 1 | 0 | 1 | 0 | 0 | 0 | 1 | - | 1 | 0 | 1 | 0 | 5D1A |
| 7 | 1 | 1 | 0 | 1 | 0 | 1 | - | 0 | 1 | 0 | 1 | 0 | 0 | 0 | - | 0 | 1 | 0 | 1 | AA85 |
| 8 | 0 | 1 | 1 | 0 | 1 | 0 | - | 0 | 0 | 1 | 0 | 1 | 0 | 0 | - | 1 | 0 | 1 | 0 | D14A |
| 9 | 1 | 1 | 1 | 1 | 0 | 1 | - | 1 | 0 | 0 | 1 | 0 | 1 | 0 | - | 1 | 1 | 0 | 1 | ECAD |
| 10 | 0 | 1 | 1 | 1 | 1 | 0 | - | 0 | 1 | 0 | 0 | 1 | 0 | 1 | - | 1 | 1 | 1 | 0 | F25E |
| 11 | 1 | 1 | 1 | 1 | 1 | 1 | - | 1 | 0 | 1 | 0 | 0 | 1 | 0 | - | 0 | 1 | 1 | 1 | FD27 |
| 12 | 0 | 1 | 1 | 1 | 1 | 1 | - | 0 | 1 | 0 | 1 | 0 | 0 | 1 | - | 1 | 0 | 1 | 1 | FA9B |
| 13 | 0 | 1 | 1 | 1 | 1 | 1 | - | 0 | 0 | 1 | 0 | 1 | 0 | 0 | - | 0 | 1 | 0 | 1 | F945 |
| 14 | 1 | 0 | 1 | 1 | 1 | 1 | - | 1 | 0 | 0 | 1 | 0 | 1 | 0 | - | 0 | 0 | 1 | 0 | 7CA2 |
| 15 | 1 | 0 | 0 | 1 | 1 | 1 | - | 1 | 1 | 0 | 0 | 1 | 0 | 1 | - | 0 | 0 | 0 | 1 | 3E51 |
| 16 | 0 | 1 | 0 | 0 | 1 | 1 | - | 0 | 1 | 1 | 0 | 0 | 1 | 0 | - | 0 | 0 | 0 | 0 | 9B20 |
| 17 | 1 | 1 | 1 | 0 | 0 | 1 | - | 0 | 0 | 1 | 1 | 0 | 0 | 1 | - | 1 | 0 | 0 | 0 | C998 |
| 18 | 1 | 1 | 1 | 1 | 0 | 0 | - | 0 | 0 | 0 | 1 | 1 | 0 | 0 | - | 0 | 1 | 0 | 0 | E0C4 |
| 19 | 1 | 1 | 1 | 1 | 1 | 0 | - | 1 | 0 | 0 | 0 | 1 | 1 | 0 | - | 1 | 0 | 1 | 0 | F46A |
| 20 | 1 | 1 | 1 | 1 | 1 | 1 | - | 1 | 1 | 0 | 0 | 0 | 1 | 1 | - | 1 | 1 | 0 | 1 | FE3D |
| 21 | 1 | 0 | 1 | 1 | 1 | 1 | - | 1 | 1 | 1 | 0 | 0 | 0 | 1 | - | 1 | 1 | 1 | 0 | 7F1E |
| 22 | 0 | 0 | 0 | 1 | 1 | 1 | - | 1 | 1 | 1 | 1 | 0 | 0 | 0 | - | 1 | 1 | 1 | 1 | 3F8F |
| 23 | 0 | 1 | 0 | 0 | 1 | 1 | - | 0 | 1 | 1 | 1 | 1 | 0 | 0 | - | 1 | 1 | 1 | 1 | 9BCF |
| 24 | 0 | 1 | 1 | 0 | 0 | 1 | - | 0 | 0 | 1 | 1 | 1 | 1 | 0 | - | 1 | 1 | 1 | 1 | C9EF |
| 25 | 0 | 1 | 1 | 1 | 0 | 0 | - | 0 | 0 | 0 | 1 | 1 | 1 | 1 | - | 1 | 1 | 1 | 1 | E0FF |
| 26 | 0 | 1 | 1 | 1 | 1 | 0 | - | 1 | 0 | 0 | 0 | 1 | 1 | 1 | - | 0 | 1 | 1 | 1 | F477 |
| 27 | 0 | 1 | 1 | 1 | 1 | 1 | - | 1 | 1 | 0 | 0 | 0 | 1 | 1 | - | 0 | 0 | 1 | 1 | FE33 |
| 28 | 1 | 0 | 1 | 1 | 1 | 1 | - | 1 | 1 | 1 | 0 | 0 | 0 | 1 | - | 1 | 0 | 0 | 1 | 7F19 |
| 29 | 1 | 0 | 0 | 1 | 1 | 1 | - | 1 | 1 | 1 | 1 | 0 | 0 | 0 | - | 1 | 1 | 0 | 0 | 3F8C |
| 30 | 0 | 0 | 0 | 0 | 1 | 1 | - | 1 | 1 | 1 | 1 | 1 | 0 | 0 | - | 0 | 1 | 1 | 0 | 1FC6 |
| 31 | 0 | 0 | 0 | 0 | 0 | 1 | - | 1 | 1 | 1 | 1 | 1 | 1 | 0 | - | 0 | 0 | 1 | 1 | 0FE3 |
| 32 | 1 | 0 | 0 | 0 | 0 | 0 | - | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - | 0 | 0 | 0 | 1 | 07F1 (CRC Value) |

APPENDIX A: EXAMPLE WITH C-SOURCE CODE FOR CRC CALCULATION

```
# include <stdio.h>
# include <stdlib.h>
# include "onescnt.h"
# define NULL 0
# define true 1
# define false 0
void main (int argc, char *argv[ ])
{
int i, j, k, message[40], num_bits, bitcount, bytecount, crc, next_bit, crc_temp, message_temp;
int maskreg[8] = {1, 2, 4, 8, 16, 32, 64, 128};
int crc_nibble[4];
char ch
FILE *fin;
if (argc != 2)
{ printf ("proper usage is CCITT {indata file with data in hex}\n"); abort (); }
if ( (fin =fopen(argv[1], "r")) ==NULL)
    {printf("Can't open %s\n", argv[1]; abort();}

i = 0;
while ( (ch=fgetc(fin)) !=EOF)
{
message_temp = 0;
//retrieve the input data field and convert to an integer message field
if ((ch >= 'a') && (ch <= 'f')) ch = ch - 0x20
if ((ch >= 'A') && (ch <= 'F')) ch = ch - 0x70
if ((ch >= '0') && (ch <= '?'))
{
message_temp = ch - '0';
message[i++] = message_temp;
}
}
// At this point, message[ ] holds data with nibbles (4 bits on each array). This will be used for
CRC calculation
message[ i ] = -1;
k = i
// The above is used for array checking and k value is the total number of nibbles.
printf ("Read in %d nibbles. \n", k);
printf ("Original data in hex read in from data file: \n");
for (i = 0; i < k; i++)
printf("%x ", message[ i ]);
printf("\n\n");

// Now computing the CRC of data
//----- Initialization -----
crc = 0xffff; //initial CRC value
crc_poly = 0x8408; //1000-0100-0000-1000
//-----
printf ("Initial CRC value in hex: %x ... \n", crc);
num_bits = k*4;
for ( i = 0; i < num_bits; i++)
{
bitcount = i % 4;
bytecount = i/4;
next_bit = (message[bytecount] & maskreg[bitcount]); //This will find the next data bit to apply
next_bit = ((next_bit >> bitcount) & 1); //This will move the current data bit to LSB of next_bit
// and make all bits except LSB bit to zero
crc_temp = crc^next_bit; //xor the last nibble of crc (actually the last bit of CRC) with next_bit
if (crc_temp & 1)
{
printf ("xor = 1\n");
crc = crc >> 1; //Shift the crc by 1 to right
crc = crc^crc_poly ; //xor current crc with crc_poly
}
```

```
crc = crc|0x8000; //this may not be necessary
}
// if it is zero, just shift crc by 1
if (!(crc_temp &1))
{
printf ("xor = 0\n");
crc = crc >> 1;
crc = crc & 0x7fff;// this may not be necessary
}
printf("Temp CRC after iteration %d: ", i);
for (j = i; j<num_bits; j++)
printf(" ");
}
printf("%d\n", crc);
}
crc_nibble [0] = crc & x000f;
crc_nibble [1] = (crc & x000f >> 4;
crc_nibble [2] = (crc & x000f >> 8;
crc_nibble [3] = (crc & x000f >> 12;
printf("Bit order for shifting in nibbles in LSB first. \n");
printf ("\n CRC at end: %x ", crc);
printf ("Send %x %x %x %x \n", crc_nibble[0], crc_nibble[1],crc_nibble[2],crc_nibble[3],);
printf("\n\n");
fclose(fin);
}
```

AN752

NOTES:

MCRF 355/360 Application Note: Mode of Operation and External Resonant Circuit

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INTRODUCTION

The MCRF355 passive RFID device is designed for low cost, multiple reading, and various high volume tagging applications using a frequency band of 13.56 MHz. The device has a total of 154 memory bits that can be reprogrammed by a contact programmer. The device operates with a 70 kHz data rate, and asynchronously with respect to the reader's carrier. The device turns on when the coil voltage reaches 4 V_{PP} and outputs data with a Manchester format (see Figure 2-3 in the data sheet). With the given data rate (70 kHz), it takes about 2.2 ms to transmit all 154 bits of the data. After transmitting all data, the device goes into a sleep mode for 100 ms +/- 50%.

The MCRF355 needs only an external parallel LC resonant circuit that consists of an antenna coil and a capacitor for operation. The external LC components must be connected between antenna A, B, and ground pads. The circuit formed between Antenna Pad A and the ground pad must be tuned to the operating frequency of the reader antenna.

MODE OF OPERATION

The device transmits data by tuning and detuning the resonant frequency of the external circuit. This process is accomplished by using an internal modulation gate

(CMOS), that has a very low turn-on resistance (2 ~ 4 ohms) between Drain and Source. This gate turns on during a logic "High" period of the modulation signal and off otherwise. When the gate turns on, its low turn-on resistance shorts the external circuit between Antenna Pad B and the ground pad. Therefore, the resonant frequency of the circuit changes. This is called *detuned* or *cloaking*. Since the detuned tag is out of the frequency band of the reader, the reader can't see it.

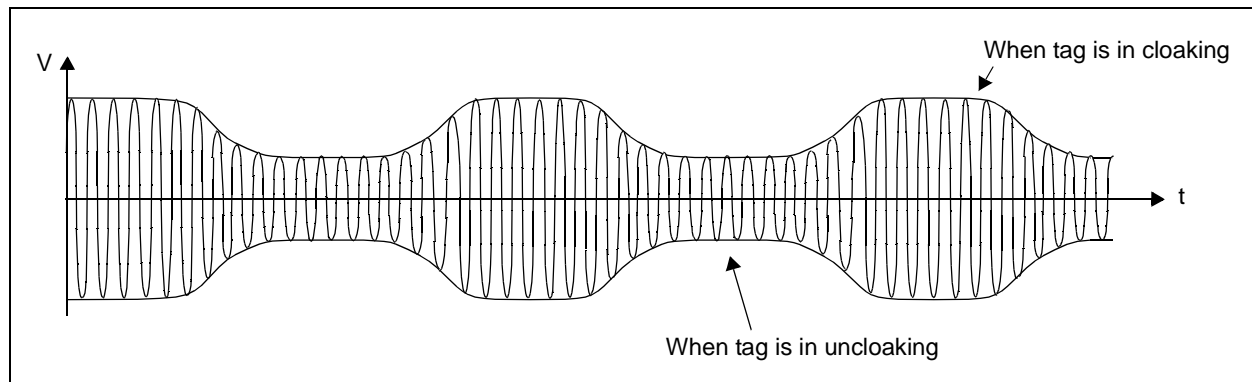
The modulation gate turns off as the modulation signal goes to a logic "Low." This turn-off condition again tunes the resonant circuit to the frequency of the reader antenna. Therefore the reader sees the tag again. This is called *tuned* or *uncloaking*.

The tag coil induces maximum voltage during "uncloaking (tuned)" and minimum voltage during cloaking (detuned). Therefore, the cloaking and uncloaking events develop an amplitude modulation signal in the tag coil.

This amplitude modulated signal in the tag coil perturbs the voltage envelope in the reader coil. The reader coil has maximum voltage during cloaking (detuned) and minimum voltage during uncloaking (tuned). By detecting the voltage envelope, the data signal from the tag can be readily reconstructed.

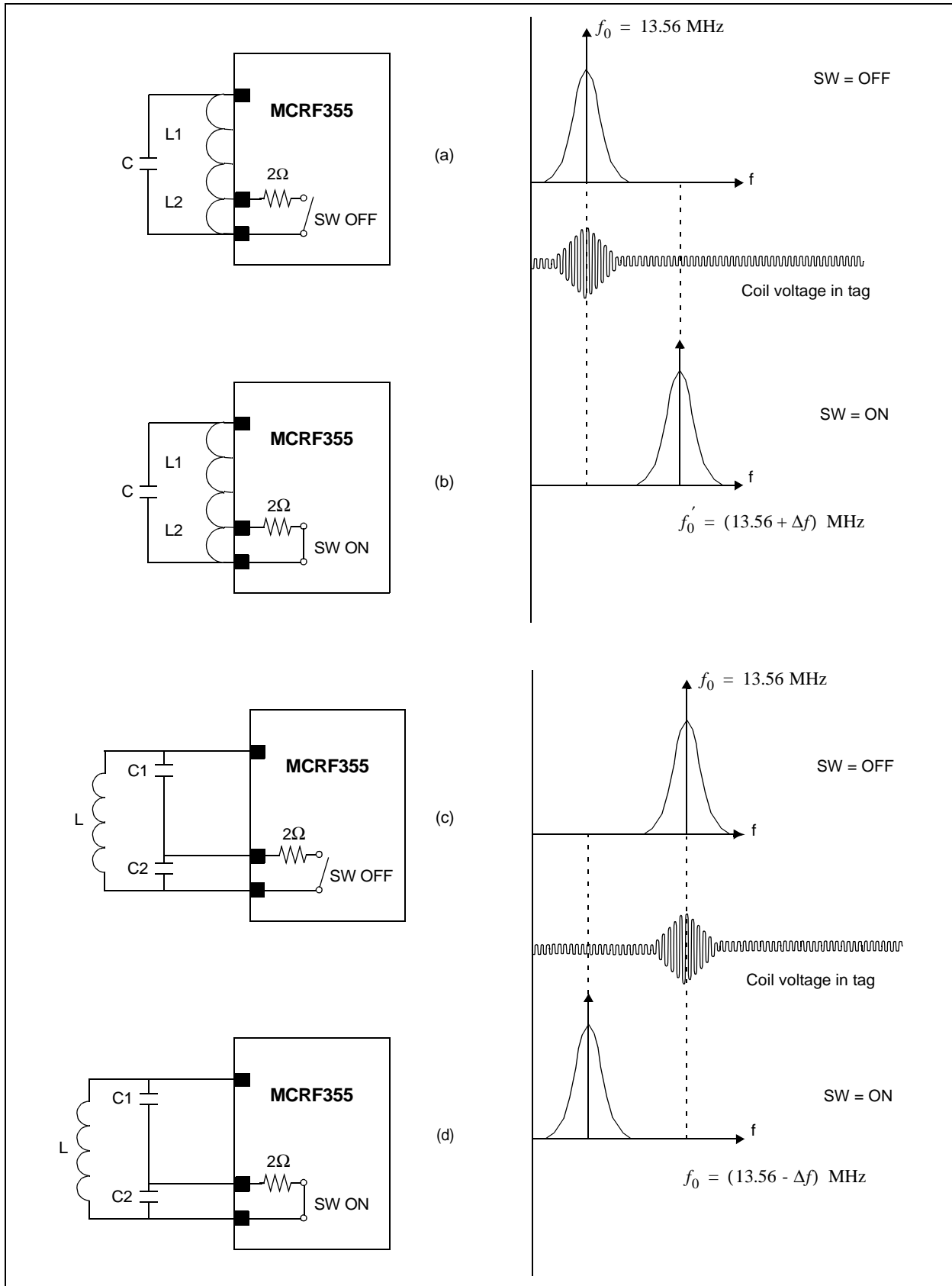
Once the device transmits all 154 bits of data, it goes into "sleep mode" for about 100 ms. The tag wakes up from sleep time (100 ms) and transmits the data package for 2.2 ms and goes into sleep mode again. The device repeats the transmitting and sleep cycles as long as it is energized.

FIGURE 1: VOLTAGE ENVELOPE IN READER COIL



AN707

FIGURE 2: (A) UNCLOAKING (TUNED) AND (B) CLOAKING (DETUNED) MODES AND THEIR RESONANT FREQUENCIES

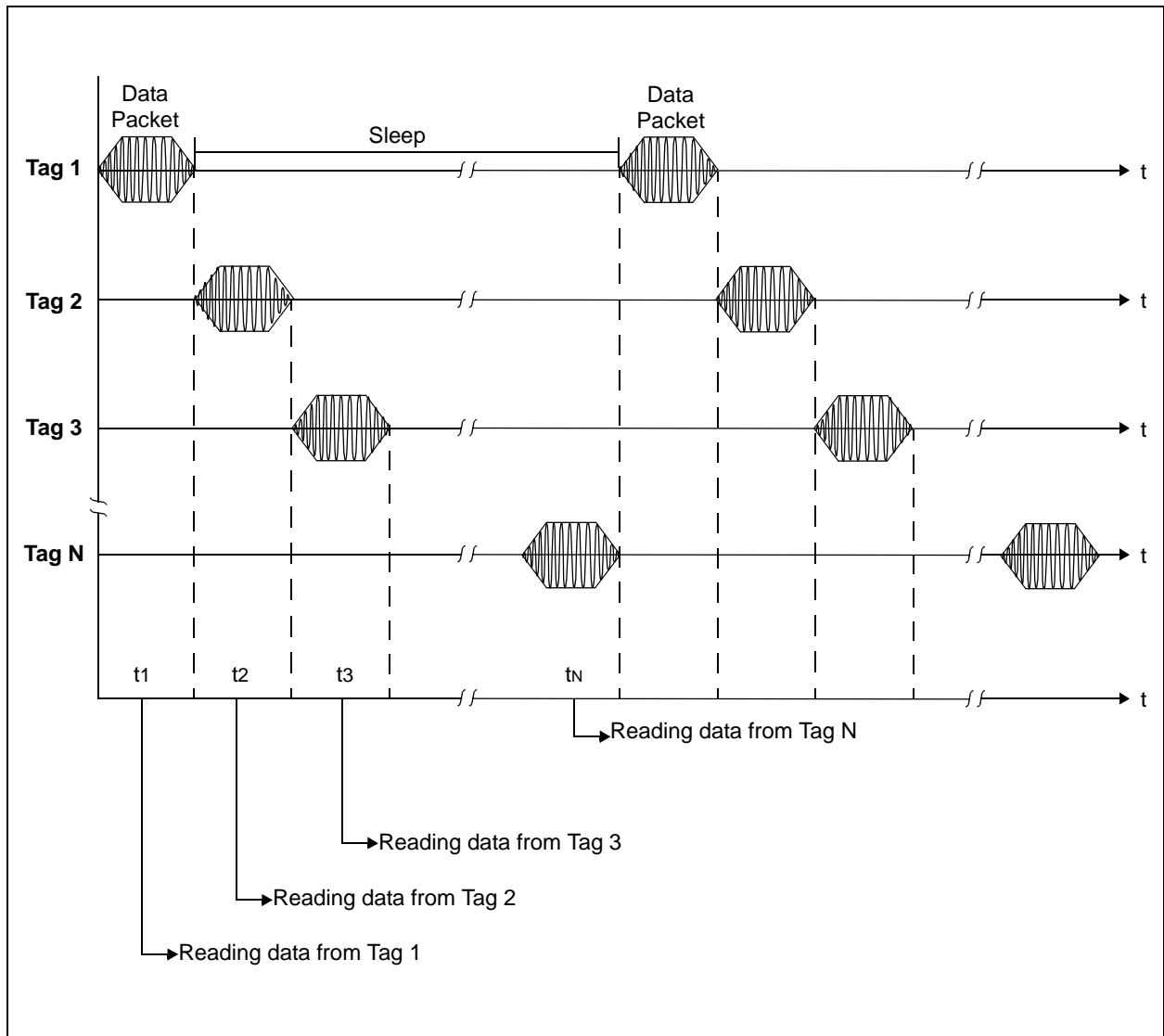


ANTI-COLLISION FEATURES

During sleep mode, the device remains in a cloaked state where the circuit is detuned. Therefore, the reader can't see the tag during sleep time. While one tag is in sleep mode, the reader can receive data from other tags. This enables the reader to receive clean data from many tags without any data collision. This ability to read multiple tags in the same RF field is

called *anti-collision*. Theoretically, more than 50 tags can be read in the same RF field. However, it is affected by distance from the tag to the reader, angular orientation, movement of the tags, and spacial distribution of the tags.

FIGURE 3: EXAMPLE OF READING MULTIPLE TAGS



EXTERNAL CIRCUIT CONFIGURATION

Since the device transmits data by tuning and detuning the antenna circuit, caution must be given in the external circuit configuration. For a better modulation index, the differences between the tuned and detuned frequencies must be wide enough (about 3 ~ 6 MHz).

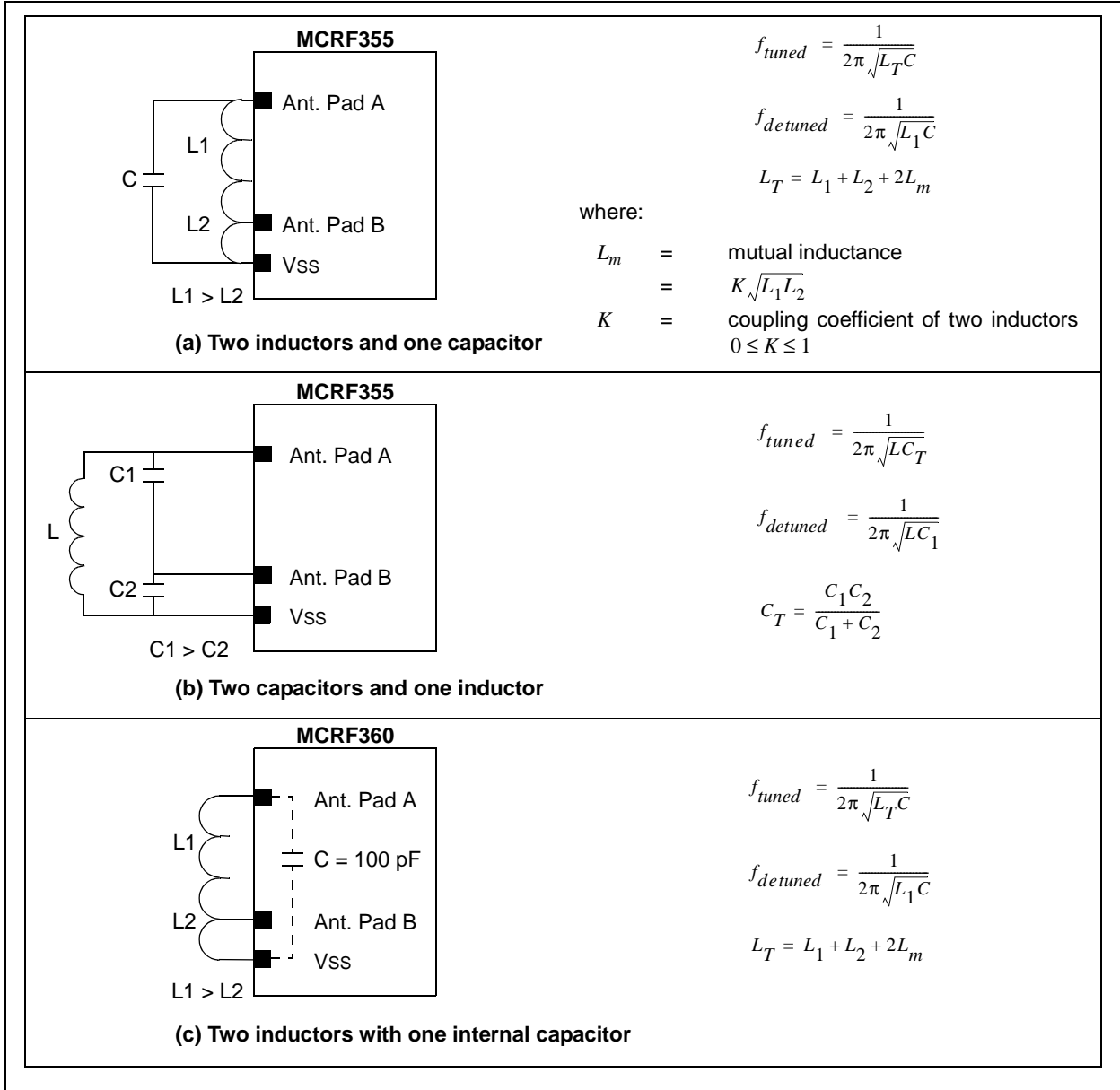
Figure 4 shows various configurations of the external circuit. The choice of the configuration must be chosen depending on the form-factor of the tag. For example, (a) is a better choice for printed circuit tags while, (b) is a better candidate for coil-wound tags. Both (a) and (b) relate to the MCRF355.

In configuration (a), the tuned resonance frequency is determined by a total capacitance and inductance from Antenna Pad A to Vss. During cloaking, the internal switch (modulation gate) shorts Antenna Pad B and Vss. Therefore, the inductance L2 is shorted out. As a result, the detuned frequency is determined by the total capacitance and inductance L1. When shorting the inductance between Antenna Pad B and Vss, the detuned (cloak) frequency is higher than the tuned (uncloak) frequency

In configuration (b), the tuned frequency (uncloak) is determined by the inductance L and the total capacitance between Antenna Pad A and Vss. The circuit detunes (cloak) when C2 is shorted. This detuned frequency (cloak) is lower than the tuned (uncloak) frequency.

The MCRF360 includes a 100 pF internal capacitor. This device needs only an external inductor for operation. The explanation on tuning and detuning is the same as for configuration (a).

FIGURE 4: VARIOUS EXTERNAL CIRCUIT CONFIGURATIONS



PROGRAMMING OF DEVICE

All of the memory bits in the are reprogrammable by a contact programmer or by factory programming prior to shipment, known as Serialized Quick Turn ProgrammingSM (SQTPSM). For more information about contact programming, see the *microID*[®] 13.56 MHz System Design Guide (DS21299). For information about SQTP programming, please see *TB032* (DS91032), of the design guide.

Antenna Circuit Design for RFID Applications

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INTRODUCTION

Passive RFID tags utilize an induced antenna coil voltage for operation. This induced AC voltage is rectified to provide a voltage source for the device. As the DC voltage reaches a certain level, the device starts operating. By providing an energizing RF signal, a reader can communicate with a remotely located device that has no external power source such as a battery. Since the energizing and communication between the reader and tag is accomplished through antenna coils, it is important that the device must be equipped with a proper antenna circuit for successful RFID applications.

An RF signal can be radiated effectively if the linear dimension of the antenna is comparable with the wavelength of the operating frequency. However, the wavelength at 13.56 MHz is 22.12 meters. Therefore, it is difficult to form a true antenna for most RFID applications. Alternatively, a small loop antenna circuit that is resonating at the frequency is used. A current flowing into the coil radiates a near-field magnetic field that falls off with r^{-3} . This type of antenna is called a *magnetic dipole antenna*.

For 13.56 MHz passive tag applications, a few microhenries of inductance and a few hundred pF of resonant capacitor are typically used. The voltage transfer between the reader and tag coils is accomplished through inductive coupling between the two coils. As in a typical transformer, where a voltage in the primary coil transfers to the secondary coil, the voltage in the reader antenna coil is transferred to the tag antenna coil and vice versa. The efficiency of the voltage transfer can be increased significantly with high Q circuits.

This section is written for RF coil designers and RFID system engineers. It reviews basic electromagnetic theories on antenna coils, a procedure for coil design, calculation and measurement of inductance, an antenna tuning method, and read range in RFID applications.

REVIEW OF A BASIC THEORY FOR RFID ANTENNA DESIGN

Current and Magnetic Fields

Ampere's law states that current flowing in a conductor produces a magnetic field around the conductor. The magnetic field produced by a current element, as shown in Figure 1, on a round conductor (wire) with a finite length is given by:

EQUATION 1:

$$B_{\phi} = \frac{\mu_0 I}{4\pi r} (\cos \alpha_2 - \cos \alpha_1) \quad (\text{Weber}/m^2)$$

where:

- I = current
- r = distance from the center of wire
- μ_0 = permeability of free space and given as $4\pi \times 10^{-7}$ (Henry/meter)

In a special case with an infinitely long wire where:

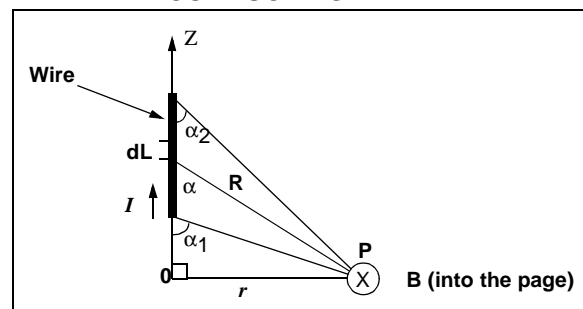
$$\begin{aligned} \alpha_1 &= -180^\circ \\ \alpha_2 &= 0^\circ \end{aligned}$$

Equation 1 can be rewritten as:

EQUATION 2:

$$B_{\phi} = \frac{\mu_0 I}{2\pi r} \quad (\text{Weber}/m^2)$$

FIGURE 1: CALCULATION OF MAGNETIC FIELD B AT LOCATION P DUE TO CURRENT I ON A STRAIGHT CONDUCTING WIRE



AN710

The magnetic field produced by a circular loop antenna is given by:

EQUATION 3:

$$B_z = \frac{\mu_o I N a^2}{2(a^2 + r^2)^{3/2}}$$
$$= \frac{\mu_o I N a^2}{2} \left(\frac{1}{r^3} \right) \text{ for } r^2 \gg a^2$$

where

- I = current
- a = radius of loop
- r = distance from the center of loop
- μ_0 = permeability of free space and given as $4 \pi \times 10^{-7}$ (Henry/meter)

The above equation indicates that the magnetic field strength decays with $1/r^3$. A graphical demonstration is shown in Figure 3. It has maximum amplitude in the plane of the loop and directly proportional to both the current and the number of turns, N .

Equation 3 is often used to calculate the ampere-turn requirement for read range. A few examples that calculate the ampere-turns and the field intensity necessary to power the tag will be given in the following sections.

FIGURE 2: CALCULATION OF MAGNETIC FIELD B AT LOCATION P DUE TO CURRENT I ON THE LOOP

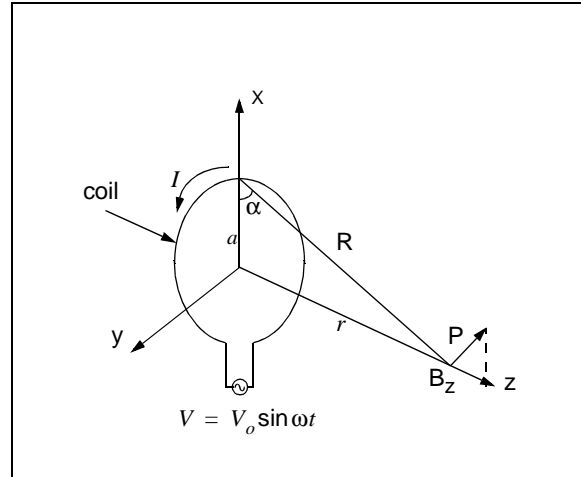
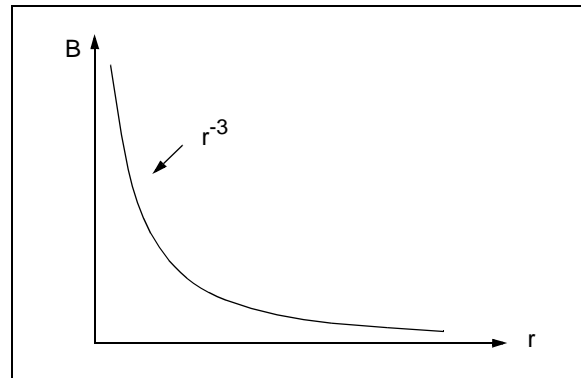


FIGURE 3: DECAYING OF THE MAGNETIC FIELD B VS. DISTANCE r



INDUCED VOLTAGE IN AN ANTENNA COIL

Faraday's law states that a time-varying magnetic field through a surface bounded by a closed path induces a voltage around the loop.

Figure 4 shows a simple geometry of an RFID application. When the tag and reader antennas are in close proximity, the time-varying magnetic field B that is produced by a reader antenna coil induces a voltage (called electromotive force or simply EMF) in the closed tag antenna coil. The induced voltage in the coil causes a flow of current on the coil. This is called Faraday's law. The induced voltage on the tag antenna coil is equal to the time rate of change of the magnetic flux Ψ .

EQUATION 4:

$$V = -N \frac{d\Psi}{dt}$$

where:

- N = number of turns in the antenna coil
- Ψ = magnetic flux through each turn

The negative sign shows that the induced voltage acts in such a way as to oppose the magnetic flux producing it. This is known as Lenz's law and it emphasizes the fact that the direction of current flow in the circuit is such that the induced magnetic field produced by the induced current will oppose the original magnetic field.

The magnetic flux Ψ in Equation 4 is the total magnetic field B that is passing through the entire surface of the antenna coil, and found by:

EQUATION 5:

$$\Psi = \int B \cdot dS$$

where:

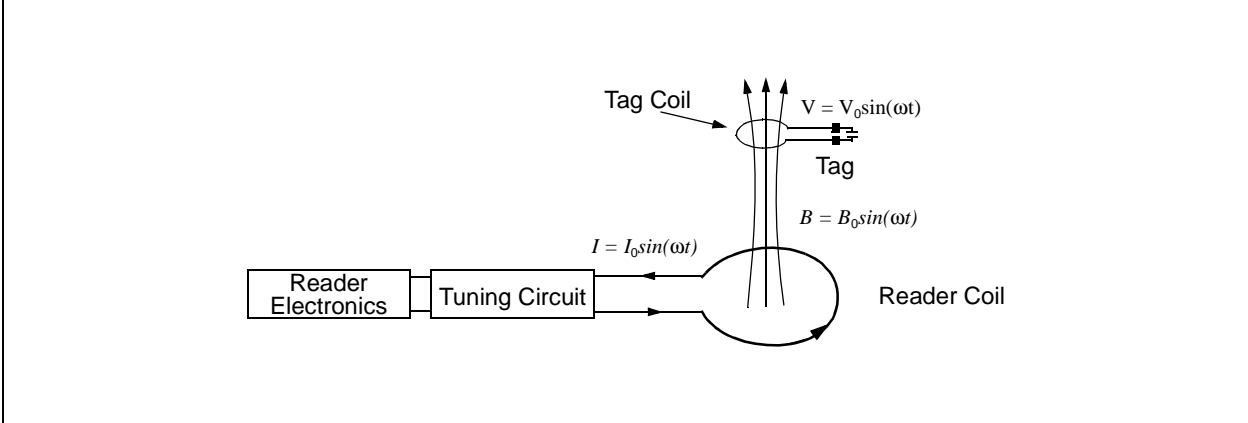
- B = magnetic field given in Equation 2
- S = surface area of the coil
- \cdot = inner product (*cosine angle between two vectors*) of vectors B and surface area S

Note: Both magnetic field B and surface S are vector quantities.

The presentation of inner product of two vectors in Equation 5 suggests that the total magnetic flux ψ that is passing through the antenna coil is affected by an orientation of the antenna coils. The inner product of two vectors becomes minimized when the cosine angle between the two are 90 degrees, or the two (B field and the surface of coil) are perpendicular to each other and maximized when the cosine angle is 0 degrees.

The maximum magnetic flux that is passing through the tag coil is obtained when the two coils (reader coil and tag coil) are placed in parallel with respect to each other. This condition results in maximum induced voltage in the tag coil and also maximum read range. The inner product expression in Equation 5 also can be expressed in terms of a mutual coupling between the reader and tag coils. The mutual coupling between the two coils is maximized in the above condition.

FIGURE 4: A BASIC CONFIGURATION OF READER AND TAG ANTENNAS IN RFID APPLICATIONS



AN710

Using Equations 3 and 5, Equation 4 can be rewritten as:

EQUATION 6:

$$\begin{aligned}
 V &= - N_2 \frac{d\Psi_{21}}{dt} = - N_2 \frac{d}{dt} \left(\int B \cdot dS \right) \\
 &= - N_2 \frac{d}{dt} \left[\int \frac{\mu_o i_1 N_1 a^2}{2(a^2 + r^2)^{3/2}} \cdot dS \right] \\
 &= - \left[\frac{\mu_o N_1 N_2 a^2 (\pi b^2)}{2(a^2 + r^2)^{3/2}} \right] \frac{di_1}{dt} \\
 &= - M \frac{di_1}{dt}
 \end{aligned}$$

where:

- V = voltage in the tag coil
- i_1 = current on the reader coil
- a = radius of the reader coil
- b = radius of tag coil
- r = distance between the two coils
- M = mutual inductance between the tag and reader coils, and given by:

EQUATION 7:

$$M = \left[\frac{\mu_o \pi N_1 N_2 (ab)^2}{2(a^2 + r^2)^{3/2}} \right]$$

The above equation is equivalent to a voltage transformation in typical transformer applications. The current flow in the primary coil produces a magnetic flux that causes a voltage induction at the secondary coil.

As shown in Equation 6, the tag coil voltage is largely dependent on the mutual inductance between the two coils. The mutual inductance is a function of coil geometry and the spacing between them. The induced voltage in the tag coil decreases with r^{-3} . Therefore, the read range also decreases in the same way.

From Equations 4 and 5, a generalized expression for induced voltage V_o in a tuned loop coil is given by:

EQUATION 8:

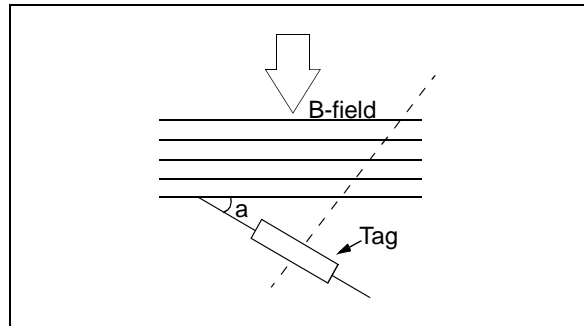
$$V_o = 2\pi f N S Q B_o \cos \alpha$$

where:

- f = frequency of the arrival signal
- N = number of turns of coil in the loop
- S = area of the loop in square meters (m^2)
- Q = quality factor of circuit
- B_o = strength of the arrival signal
- α = angle of arrival of the signal

In the above equation, the quality factor Q is a measure of the selectivity of the frequency of the interest. The Q will be defined in Equations 43 through 59.

FIGURE 5: ORIENTATION DEPENDENCY OF THE TAG ANTENNA



The induced voltage developed across the loop antenna coil is a function of the angle of the arrival signal. The induced voltage is maximized when the antenna coil is placed in parallel with the incoming signal where $\alpha = 0$.

EXAMPLE 1: CALCULATION OF B-FIELD IN A TAG COIL

The MCRF355 device turns on when the antenna coil develops 4 VPP across it. This voltage is rectified and the device starts to operate when it reaches 2.4 VDC. The B-field to induce a 4 VPP coil voltage with an ISO standard 7810 card size (85.6 x 54 x 0.76 mm) is calculated from the coil voltage equation using Equation 8.

EQUATION 9:

$$V_o = 2\pi fNSQB_o \cos\alpha = 4$$

and

$$B_o = \frac{4/(\sqrt{2})}{2\pi fNSQ \cos\alpha} = 0.0449 \quad (\mu\text{wbm}^{-2})$$

where the following parameters are used in the above calculation:

| | |
|--------------------------------------|--|
| Tag coil size = | (85.6 x 54) mm ² (ISO card size) = 0.0046224 m ² |
| Frequency = | 13.56 MHz |
| Number of turns = | 4 |
| Q of tag antenna coil = | 40 |
| AC coil voltage to turn on the tag = | 4 VPP |
| cos α = | 1 (normal direction, α = 0). |

EXAMPLE 2: NUMBER OF TURNS AND CURRENT (AMPERE-TURNS)

Assuming that the reader should provide a read range of 15 inches (38.1 cm) for the tag given in the previous example, the current and number of turns of a reader antenna coil is calculated from Equation 3:

EQUATION 10:

$$\begin{aligned} (NI)_{rms} &= \frac{2B_z(a^2 + r^2)^{3/2}}{\mu a^2} \\ &= \frac{2(0.0449 \times 10^{-6})(0.1^2 + (0.38)^2)^{3/2}}{(4\pi \times 10^{-7})(0.1^2)} \\ &= 0.43(\text{ampere} - \text{turns}) \end{aligned}$$

The above result indicates that it needs a 430 mA for 1 turn coil, and 215 mA for 2-turn coil.

EXAMPLE 3: OPTIMUM COIL DIAMETER OF THE READER COIL

An optimum coil diameter that requires the minimum number of ampere-turns for a particular read range can be found from Equation 3 such as:

EQUATION 11:

$$NI = K \frac{(a^2 + r^2)^{3/2}}{a^2}$$

here: $K = \frac{2B_z}{\mu_o}$

By taking derivative with respect to the radius a ,

$$\begin{aligned} \frac{d(NI)}{da} &= K \frac{3/2(a^2 + r^2)^{1/2}(2a^3) - 2a(a^2 + r^2)^{3/2}}{a^4} \\ &= K \frac{(a^2 - 2r^2)(a^2 + r^2)^{1/2}}{a^3} \end{aligned}$$

The above equation becomes minimized when:

The above result shows a relationship between the read range versus optimum coil diameter. The optimum coil diameter is found as:

EQUATION 12:

$$a = \sqrt{2}r$$

where:

a = radius of coil
 r = read range.

The result indicates that the optimum loop radius, a , is 1.414 times the demanded read range r .

WIRE TYPES AND OHMIC LOSSES

DC Resistance of Conductor and Wire Types

The diameter of electrical wire is expressed as the American Wire Gauge (AWG) number. The gauge number is inversely proportional to diameter, and the diameter is roughly doubled every six wire gauges. The wire with a smaller diameter has a higher DC resistance. The DC resistance for a conductor with a uniform cross-sectional area is found by:

EQUATION 13: DC Resistance of Wire

$$R_{DC} = \frac{l}{\sigma S} = \frac{l}{\sigma \pi a^2} \quad (\Omega)$$

where:

- l = total length of the wire
- σ = conductivity of the wire (mho/m)
- S = cross-sectional area = πr^2
- a = radius of wire

For a The resistance must be kept small as possible for higher Q of antenna circuit. For this reason, a larger diameter coil as possible must be chosen for the RFID circuit. Table 5 shows the diameter for bare and enamel-coated wires, and DC resistance.

AC Resistance of Conductor

At DC, charge carriers are evenly distributed through the entire cross section of a wire. As the frequency increases, the magnetic field is increased at the center of the inductor. Therefore, the reactance near the center of the wire increases. This results in higher impedance to the current density in the region. Therefore, the charge moves away from the center of the wire and towards the edge of the wire. As a result, the current density decreases in the center of the wire and increases near the edge of the wire. This is called a *skin effect*. The depth into the conductor at which the current density falls to 1/e, or 37% (= 0.3679) of its value along the surface, is known as the *skin depth* and is a function of the frequency and the permeability and conductivity of the medium. The net result of skin effect is an effective decrease in the cross sectional area of the conductor. Therefore, a net increase in the AC resistance of the wire. The skin depth is given by:

EQUATION 14:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

where:

- f = frequency
- μ = permeability (F/m) = $\mu_0 \mu_r$
- μ_0 = Permeability of air = $4 \pi \times 10^{-7}$ (h/m)
- μ_r = 1 for Copper, Aluminum, Gold, etc
= 4000 for pure Iron
- σ = Conductivity of the material (mho/m)
= 5.8×10^7 (mho/m) for Copper
= 3.82×10^7 (mho/m) for Aluminum
= 4.1×10^7 (mho/m) for Gold
= 6.1×10^7 (mho/m) for Silver
= 1.5×10^7 (mho/m) for Brass

EXAMPLE 4:

The skin depth for a copper wire at 13.56 MHz and 125 kHz can be calculated as:

EQUATION 15:

$$\begin{aligned} \delta &= \frac{1}{\sqrt{\pi f (4\pi \times 10^{-7}) (5.8 \times 10^7)}} \\ &= \frac{0.0661}{\sqrt{f}} \quad (m) \\ &= 0.018 \text{ (mm)} \quad \text{for 13.56 MHz} \\ &= 0.187 \text{ (mm)} \quad \text{for 125 kHz} \end{aligned}$$

As shown in Example 4, 63% of the RF current flowing in a copper wire will flow within a distance of 0.018 mm of the outer edge of wire for 13.56 MHz and 0.187 mm for 125 kHz.

The wire resistance increases with frequency, and the resistance due to the skin depth is called an AC resistance. An approximated formula for the AC resistance is given by:

EQUATION 16:

$$\begin{aligned}
 R_{ac} &= \frac{l}{\sigma A_{active}} \approx \frac{l}{2\pi a \delta \sigma} \quad (\Omega) \\
 &= \frac{l}{2a} \sqrt{\frac{f\mu}{\pi\sigma}} \quad (\Omega) \\
 &= (R_{dc}) \frac{a}{2\delta} \quad (\Omega)
 \end{aligned}$$

where the skin depth area on the conductor is,

$$A_{active} \approx 2\pi a \delta$$

The AC resistance increases with the square root of the operating frequency.

For the conductor etched on dielectric, substrate is given by:

EQUATION 17:

$$R_{ac} = \frac{l}{\sigma(w+t)\delta} = \frac{l}{(w+t)} \sqrt{\frac{\pi f \mu}{\sigma}} \quad (\Omega)$$

where w is the width and t is the thickness of the conductor.

Resistance of Conductor with Low Frequency Approximation

When the skin depth is almost comparable to the radius of conductor, the resistance can be obtained with a low frequency approximation^[5]:

EQUATION 18:

$$R_{low\ freq} \approx \frac{l}{\sigma \pi a^2} \left[1 + \frac{1}{48} \left(\frac{a}{\delta} \right)^2 \right] \quad (\Omega)$$

The first term of the above equation is the DC resistance, and the second term represents the AC resistance.

AN710

TABLE 5: AWG WIRE CHART

| Wire Size (AWG) | Dia. in Mils (bare) | Dia. in Mils (coated) | Ohms/ 1000 ft. |
|-----------------|---------------------|-----------------------|----------------|
| 1 | 289.3 | — | 0.126 |
| 2 | 287.6 | — | 0.156 |
| 3 | 229.4 | — | 0.197 |
| 4 | 204.3 | — | 0.249 |
| 5 | 181.9 | — | 0.313 |
| 6 | 162.0 | — | 0.395 |
| 7 | 166.3 | — | 0.498 |
| 8 | 128.5 | 131.6 | 0.628 |
| 9 | 114.4 | 116.3 | 0.793 |
| 10 | 101.9 | 106.2 | 0.999 |
| 11 | 90.7 | 93.5 | 1.26 |
| 12 | 80.8 | 83.3 | 1.59 |
| 13 | 72.0 | 74.1 | 2.00 |
| 14 | 64.1 | 66.7 | 2.52 |
| 15 | 57.1 | 59.5 | 3.18 |
| 16 | 50.8 | 52.9 | 4.02 |
| 17 | 45.3 | 47.2 | 5.05 |
| 18 | 40.3 | 42.4 | 6.39 |
| 19 | 35.9 | 37.9 | 8.05 |
| 20 | 32.0 | 34.0 | 10.1 |
| 21 | 28.5 | 30.2 | 12.8 |
| 22 | 25.3 | 28.0 | 16.2 |
| 23 | 22.6 | 24.2 | 20.3 |
| 24 | 20.1 | 21.6 | 25.7 |
| 25 | 17.9 | 19.3 | 32.4 |

| Wire Size (AWG) | Dia. in Mils (bare) | Dia. in Mils (coated) | Ohms/ 1000 ft. |
|-----------------|---------------------|-----------------------|----------------|
| 26 | 15.9 | 17.2 | 41.0 |
| 27 | 14.2 | 15.4 | 51.4 |
| 28 | 12.6 | 13.8 | 65.3 |
| 29 | 11.3 | 12.3 | 81.2 |
| 30 | 10.0 | 11.0 | 106.0 |
| 31 | 8.9 | 9.9 | 131 |
| 32 | 8.0 | 8.8 | 162 |
| 33 | 7.1 | 7.9 | 206 |
| 34 | 6.3 | 7.0 | 261 |
| 35 | 5.6 | 6.3 | 331 |
| 36 | 5.0 | 5.7 | 415 |
| 37 | 4.5 | 5.1 | 512 |
| 38 | 4.0 | 4.5 | 648 |
| 39 | 3.5 | 4.0 | 847 |
| 40 | 3.1 | 3.5 | 1080 |
| 41 | 2.8 | 3.1 | 1320 |
| 42 | 2.5 | 2.8 | 1660 |
| 43 | 2.2 | 2.5 | 2140 |
| 44 | 2.0 | 2.3 | 2590 |
| 45 | 1.76 | 1.9 | 3350 |
| 46 | 1.57 | 1.7 | 4210 |
| 47 | 1.40 | 1.6 | 5290 |
| 48 | 1.24 | 1.4 | 6750 |
| 49 | 1.11 | 1.3 | 8420 |
| 50 | 0.99 | 1.1 | 10600 |

Note: mil = 2.54×10^{-3} cm

INDUCTANCE OF VARIOUS ANTENNA COILS

An electric current element that flows through a conductor produces a magnetic field. This time-varying magnetic field is capable of producing a flow of current through another conductor – this is called *inductance*. The inductance L depends on the physical characteristics of the conductor. A coil has more inductance than a straight wire of the same material, and a coil with more turns has more inductance than a coil with fewer turns. The inductance L of inductor is defined as the ratio of the total magnetic flux linkage to the current I through the inductor:

EQUATION 19:

$$L = \frac{N\Psi}{I} \quad (\text{Henry})$$

where:

N = number of turns

I = current

Ψ = the magnetic flux

For a coil with multiple turns, the inductance is greater as the spacing between turns becomes smaller. Therefore, the tag antenna coil that has to be formed in a limited space often needs a multilayer winding to reduce the number of turns.

Calculation of Inductance

Inductance of the coil can be calculated in many different ways. Some are readily available from references^[1-7]. It must be remembered that for RF coils the actual resulting inductance may differ from the calculated true result because of distributed capacitance. For that reason, inductance calculations are generally used only for a starting point in the final design.

INDUCTANCE OF A STRAIGHT WOUND WIRE

The inductance of a straight wound wire shown in Figure 1 is given by:

EQUATION 20:

$$L = 0.002l \left[\log_e \frac{2l}{a} - \frac{3}{4} \right] \quad (\mu H)$$

where:

l and a = length and radius of wire in cm, respectively.

EXAMPLE 6: INDUCTANCE CALCULATION FOR A STRAIGHT WIRE:

The inductance of a wire with 10 feet (304.8cm) long and 2 mm in diameter is calculated as follows:

EQUATION 21:

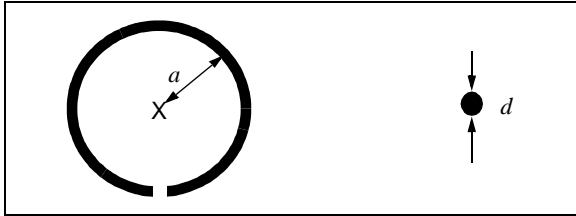
$$\begin{aligned} L &= 0.002(304.8) \left[\ln \left(\frac{2(304.8)}{0.1} \right) - \frac{3}{4} \right] \\ &= 0.60967(7.965) \\ &= 4.855(\mu H) \end{aligned}$$

AN710

INDUCTANCE OF A SINGLE TURN CIRCULAR COIL

The inductance of a single turn circular coil shown in Figure 6 can be calculated by:

FIGURE 6: A CIRCULAR COIL WITH SINGLE TURN



EQUATION 22:

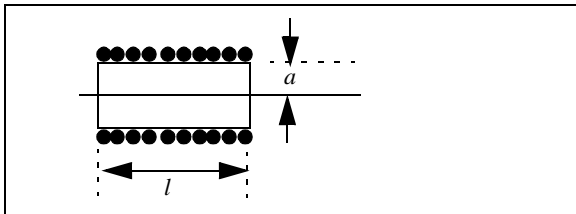
$$L = 0.01257(a) \left[2.303 \log_{10} \left(\frac{16a}{d} - 2 \right) \right] \quad (\mu H)$$

where:

- a = mean radius of loop in (cm)
- d = diameter of wire in (cm)

INDUCTANCE OF AN N-TURN SINGLE LAYER CIRCULAR COIL

FIGURE 7: A CIRCULAR COIL WITH SINGLE TURN



EQUATION 23:

$$L = \frac{(aN)^2}{22.9a + 25.4l} \quad (\mu H)$$

where:

- N = number of turns
- l = length in cm
- a = the radius of coil in cm

INDUCTANCE OF N-TURN MULTILAYER CIRCULAR COIL

FIGURE 8: N-TURN MULTILAYER CIRCULAR COIL

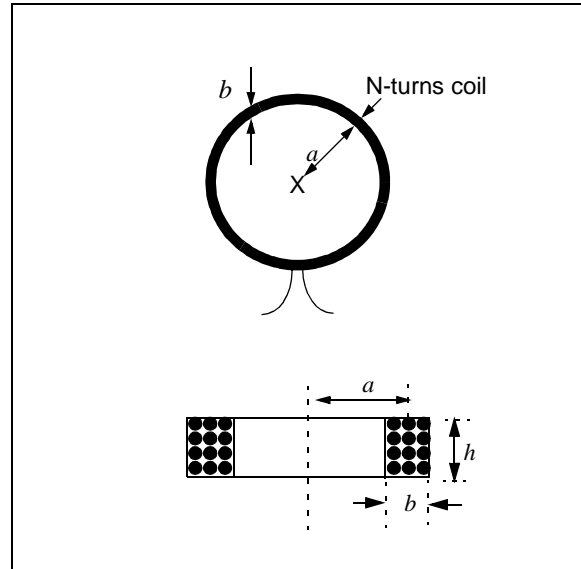


Figure 8 shows an N-turn inductor of circular coil with multilayer. Its inductance is calculated by:

EQUATION 24:

$$L = \frac{0.31(aN)^2}{6a + 9h + 10b} \quad (\mu H)$$

where:

- a = average radius of the coil in cm
- N = number of turns
- b = winding thickness in cm
- h = winding height in cm

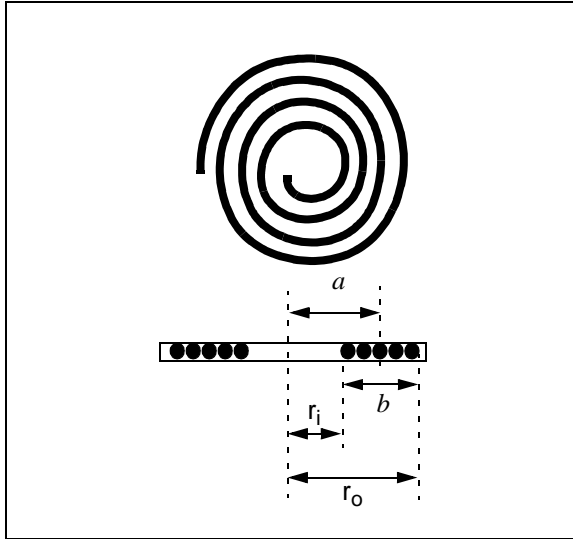
INDUCTANCE OF SPIRAL WOUND COIL WITH SINGLE LAYER

The inductance of a spiral inductor is calculated by:

EQUATION 25:

$$L = \frac{(0.3937)(aN)^2}{8a + 11b} \quad (\mu H)$$

FIGURE 9: A SPIRAL COIL



where:

$$a = (r_i + r_o)/2$$

$$b = r_o - r_i$$

r_i = Inner radius of the spiral

r_o = Outer radius of the spiral

Note: All dimensions are in cm

INDUCTANCE OF N-TURN SQUARE LOOP COIL WITH MULTILAYER

Inductance of a multilayer square loop coil is calculated by:

EQUATION 26:

$$L = 0.008aN^2 \left\{ 2.303 \log_{10} \left(\frac{a}{b+c} \right) + 0.2235 \frac{b+c}{a} + 0.726 \right\} (\mu H)$$

where:

N = number of turns

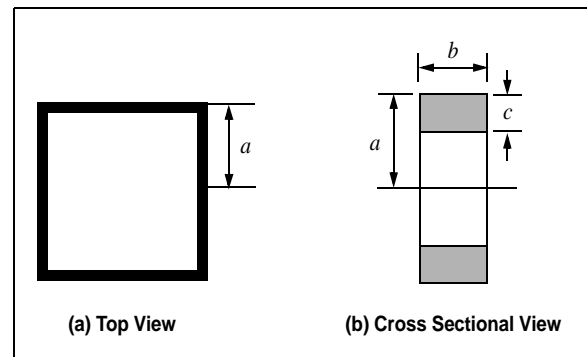
a = side of square measured to the center of the rectangular cross section of winding

b = winding length

c = winding depth as shown in Figure 10

Note: All dimensions are in cm

FIGURE 10: N-TURN SQUARE LOOP COIL WITH MULTILAYER



AN710

INDUCTANCE OF N-TURN RECTANGULAR COIL WITH MULTILAYER

Inductance of a multilayer rectangular loop coil is calculated by:

EQUATION 27:

$$L = \frac{0.0276 (CN)^2}{1.908C + 9b + 10h} \quad (\mu H)$$

where:

N = number of turns

C = $x + y + 2h$

x = width of coil

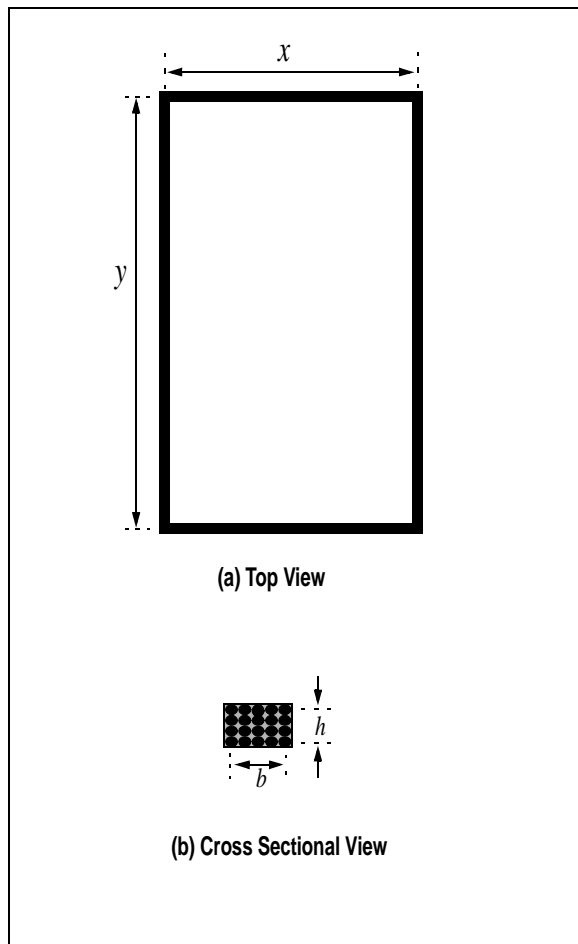
y = length of coil

b = width of cross section

h = height (coil build up) of cross section

Note: All dimensions are in cm

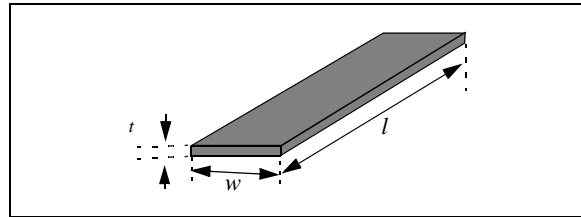
FIGURE 11: N-TURN SQUARE LOOP COIL WITH MULTILAYER



INDUCTANCE OF THIN FILM INDUCTOR WITH A RECTANGULAR CROSS SECTION

Inductance of a conductor with rectangular cross section as shown in Figure 12 is calculated as:

FIGURE 12: A STRAIGHT THIN FILM INDUCTOR



EQUATION 28:

$$L = 0.002l \left\{ \ln \left(\frac{2l}{w+t} \right) + 0.50049 + \frac{w+t}{3l} \right\} \quad (\mu H)$$

where:

w = width in cm

t = thickness in cm

l = length of conductor in cm

INDUCTANCE OF A FLAT SQUARE COIL

Inductance of a flat square coil of rectangular cross section with N turns is calculated by^[2]:

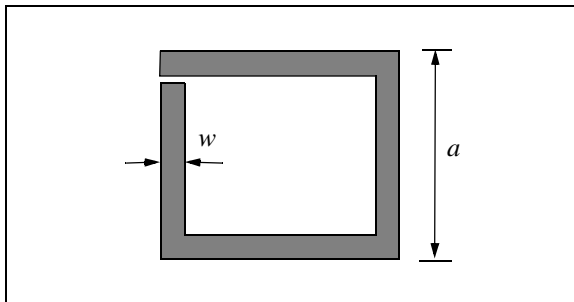
EQUATION 29:

$$L = 0.0467aN^2 \left\{ \log_{10} \left(2 \frac{a^2}{t+w} \right) - \log_{10}(2.414a) \right\} + 0.02032aN^2 \left\{ 0.914 + \left[\frac{0.2235}{a}(t+w) \right] \right\}$$

where:

- L = in μH
- a = side length in inches
- t = thickness in inches
- w = width in inches
- N = total number of turns

FIGURE 13: SQUARE LOOP INDUCTOR WITH A RECTANGULAR CROSS SECTION

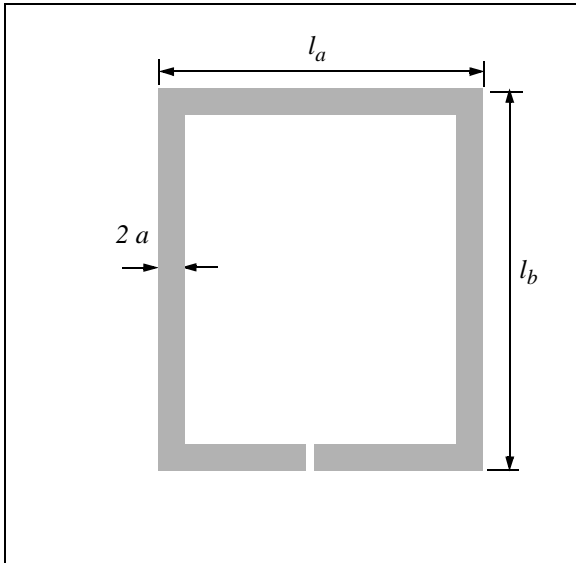


AN710

EXAMPLE ON ONE TURN READER ANTENNA

If reader antenna is made of a rectangular loop composed of a thin wire or a thin plate element, its inductance can be calculated by the following simple formula [5]:

FIGURE 14: ONE TURN READER ANTENNA



EQUATION 30:

$$L = 4 \left\{ l_b \ln \left(\frac{2A}{a(l_b + l_c)} \right) + l_a \ln \left(\frac{2A}{a(l_a + l_c)} \right) + 2 [a + l_c - (l_a + l_b)] \right\} \quad (nH)$$

where

units are all in cm, and a = radius of wire in cm.

$$l_c = \sqrt{l_a^2 + l_b^2}$$
$$A = l_a \times l_b$$

Example with dimension:

One-turn rectangular shape with $l_a = 18.887$ cm, $l_b = 25.4$ cm, width $a = 0.254$ cm gives 653 (nH) using the above equation.

INDUCTANCE OF N-TURN PLANAR SPIRAL COIL

Inductance of planar structure is well calculated in Reference [4]. Consider an inductor made of straight segments as shown in Figure 15. The inductance is the sum of self inductances and mutual inductances^[4]:

EQUATION 31:

$$L_T = L_o - M_+ - M_- \quad (\mu H)$$

where:

- L_T = Total Inductance
- L_o = Sum of self inductances of all straight segments
- M_+ = Sum of positive mutual inductances
- M_- = Sum of negative mutual inductances

The mutual inductance is the inductance that is resulted from the magnetic fields produced by adjacent conductors. The mutual inductance is positive when the directions of current on conductors are in the same direction, and negative when the directions of currents are opposite directions. The mutual inductance between two parallel conductors is a function of the length of the conductors and of the geometric mean distance between them. The mutual inductance of two conductors is calculated by:

EQUATION 32:

$$M = 2lF \quad (nH)$$

where l is the length of conductor in centimeter. F is the mutual inductance parameter and calculated as:

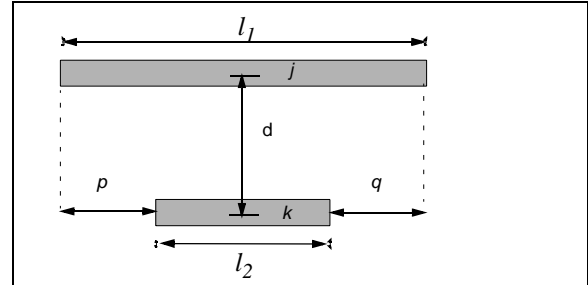
EQUATION 33:

$$F = \ln \left\{ \left(\frac{l}{d} \right) + \left[1 + \left(\frac{l}{d} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{l}{d} \right)^2 \right]^{1/2} + \left(\frac{d}{l} \right)$$

where d is the geometric mean distance between two conductors, which is approximately equal to the distance between the track center of the conductors.

Let us consider the two conductor segments shown in Figure 15:

FIGURE 15: TWO CONDUCTOR SEGMENTS FOR MUTUAL INDUCTANCE CALCULATION



j and k in the above figure are indices of conductor, and p and q are the indices of the length for the difference in the length of the two conductors.

The above configuration (with partial segments) occurs between conductors in multiple turn spiral inductor. The mutual inductance of conductors j and k in the above configuration is:

EQUATION 34:

$$\begin{aligned} M_{j,k} &= \frac{1}{2} \{ (M_{k+p} + M_{k+q}) - (M_p + M_q) \} \\ &= \frac{1}{2} \{ (M_j + M_k) - M_q \} \quad \text{for } p = 0 \quad (a) \\ &= \frac{1}{2} \{ (M_j + M_k) - M_p \} \quad \text{for } q = 0 \quad (b) \\ &= M_{k+p} - M_p \quad \text{for } p = q \quad (c) \\ &= M_k \quad \text{for } p = q = 0 \quad (d) \end{aligned}$$

If the length of l_1 and l_2 are the same ($l_1 = l_2$), then Equation 34 (d) is used. Each mutual inductance term in the above equation is calculated as follows by using Equations 33 and 34:

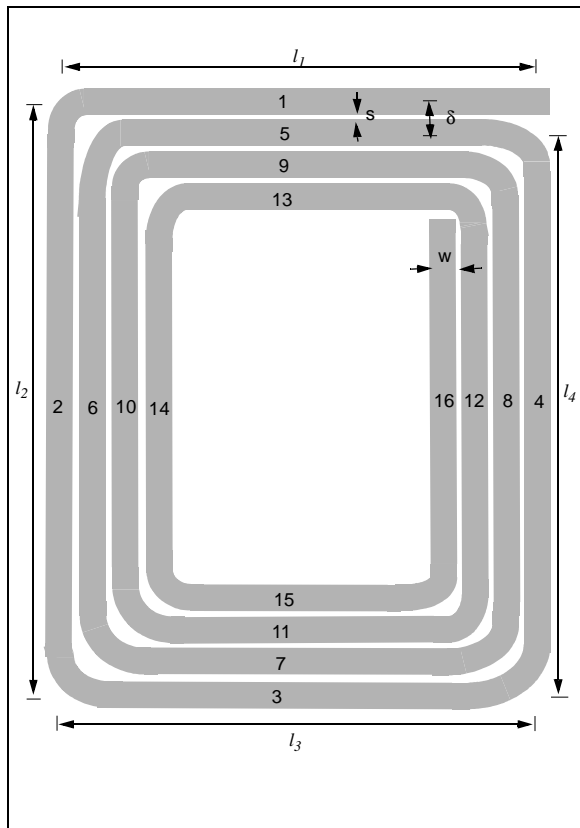
EQUATION 35:

$$\begin{aligned} M_{k+p} &= 2l_{k+p} F_{k+p} \\ \text{where} \\ F_{k+p} &= \ln \left\{ \left(\frac{l_{k+p}}{d_{j,k}} \right) + \left[1 + \left(\frac{l_{k+p}}{d_{j,k}} \right)^2 \right]^{1/2} \right\} \\ &\quad - \left[1 + \left(\frac{d_{j,k}}{l_{k+p}} \right)^2 \right]^{1/2} + \left(\frac{d_{j,k}}{l_{k+p}} \right) \end{aligned}$$

The following examples shows how to use the above formulas to calculate the inductance of a 4-turn rectangular spiral inductor.

AN710

EXAMPLE 7: INDUCTANCE OF RECTANGULAR PLANAR SPIRAL INDUCTOR



1, 2, 3, ..., 16 are indices of conductor. For four full turn inductor, there are 16 straight segments. s is the spacing between conductor, and $\delta (= s + w)$ is the distance of track centers between two adjacent conductors. l_1 is the length of conductor 1, l_2 is the length of conductor 2, and so on. The length of conductor segments are:

$$\begin{aligned} l_3 &= l_1, \quad l_4 = l_2 - \delta, \quad l_5 = l_1 - \delta, \quad l_6 = l_4 - \delta, \\ l_7 &= l_5 - \delta, \quad l_8 = l_6 - \delta, \quad l_9 = l_7 - \delta, \\ l_{10} &= l_8 - \delta, \quad l_{11} = l_9 - \delta, \quad l_{12} = l_{10} - \delta, \\ l_{13} &= l_{11} - \delta, \quad l_{14} = l_{12} - \delta, \quad l_{15} = l_{13} - \delta, \\ l_{16} &= l_{14} - \delta \end{aligned}$$

The total inductance of the coil is equal to the sum of the self inductance of each straight segment ($L_0 = L1 + L2 + L3 + L4 + \dots + L16$) plus all the mutual inductances between these segments as shown in Equation 31.

The self inductance is calculated by Equation (28), and the mutual inductances are calculated by Equations (32) - (34).

For the four-turn spiral, there are both positive and negative mutual inductances. The positive mutual inductance (M_+) is the mutual inductance between conductors that have the same current direction. For example, the current on segments 1 and 5 are in the same direction. Therefore, the mutual inductance between the two conductor segments is positive. On

the other hand, the currents on segments 1 and 15 are in the opposite direction. Therefore, the mutual inductance between conductors 1 and 15 is negative term.

The mutual inductance is maximized if the two segments are in parallel, and minimum if they are placed in orthogonal (in 90 degrees). Therefore the mutual inductance between segments 1 and 2, 1 and 6, 1 and 10, 1 and 14, etc, are negligible in calculation.

In Example 7, the total positive mutual inductance terms are:

EQUATION 36:

$$\begin{aligned} M_+ &= 2(M_{1,5} + M_{1,9} + M_{1,13}) \\ &+ 2(M_{5,9} + M_{5,13} + M_{9,13}) \\ &+ 2(M_{3,7} + M_{3,11} + M_{3,15}) \\ &+ 2(M_{7,11} + M_{7,15} + M_{11,15}) \\ &+ 2(M_{2,6} + M_{2,10} + M_{2,14}) \\ &+ 2(M_{6,10} + M_{6,14} + M_{10,14}) \\ &+ 2(M_{4,8} + M_{4,12} + M_{4,16}) \\ &+ 2(M_{8,12} + M_{8,16} + M_{12,16}) \end{aligned}$$

The total negative mutual inductance terms are:

EQUATION 37:

$$\begin{aligned} M_- &= 2(M_{1,3} + M_{1,7} + M_{1,11} + M_{1,15}) \\ &+ 2(M_{5,3} + M_{5,7} + M_{5,11} + M_{5,15}) \\ &+ 2(M_{9,3} + M_{9,7} + M_{9,11} + M_{9,15}) \\ &+ 2(M_{13,15} + M_{13,11} + M_{13,7} + M_{13,3}) \\ &+ 2(M_{2,4} + M_{2,8} + M_{2,12} + M_{2,16}) \\ &+ 2(M_{6,4} + M_{6,8} + M_{6,12} + M_{6,16}) \\ &+ 2(M_{10,4} + M_{10,8} + M_{10,12} + M_{10,16}) \\ &+ 2(M_{14,4} + M_{14,8} + M_{14,12} + M_{14,16}) \end{aligned}$$

See Appendix A for calculation of each individual mutual inductance term in Equations (36) - (37).

EXAMPLE 8: INDUCTANCE CALCULATION INCLUDING MUTUAL INDUCTANCE TERMS FOR A RECTANGULAR SHAPED ONE TURN READER ANTENNA

Let us calculate the Inductance of one turn loop etched antenna on PCB board for reader antenna (for example, the MCRF450 reader antenna in the DV103006 development kit) with the following parameters:

$$l_2 = l_4 = 10'' = 25.4 \text{ cm}$$

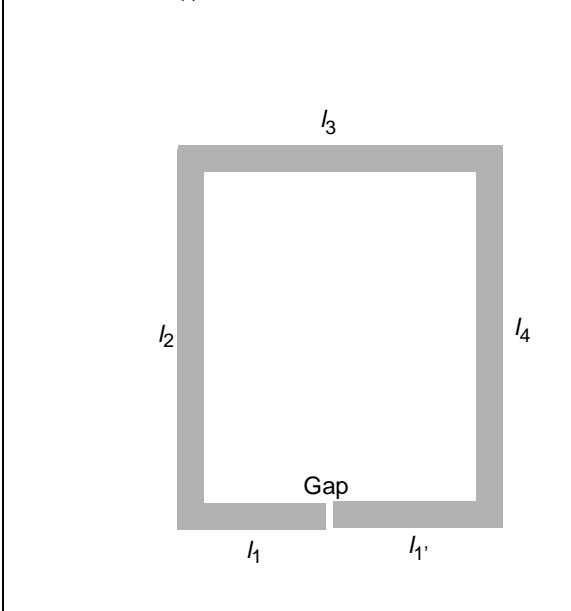
$$l_3 = 7.436'' = 18.887 \text{ cm}$$

$$l_1 = l_{1'} = 3'' = 7.62$$

$$\text{gap} = 1.4536'' = 3.692 \text{ cm}$$

$$\text{trace width (w)} = 0.508 \text{ cm}$$

$$\text{trace thickness (t)} = 0.0001 \text{ cm}$$



In the one turn rectangular shape inductor, there are four sides. Because of the gap, there are a total of 5 conductor segments. In one-turn inductor, the direction of current on each conductor segment is all opposite directions to each other. For example, the direction of current on segment 2 and 4, 1 and 3, 1' and 3 are opposite. There is no conductor segments that have the same current direction. Therefore, there is no positive mutual inductance.

From Equation 31, the total inductance is:

EQUATION 38:

$$L_T = L_o + M_+ - M_- \quad (\mu H)$$

$$= L_o - M_- \quad (\mu H)$$

where $M_+ = 0$ since the direction of current on each segment is opposite with respect to the currents on other segments.

$$L_o = L_1 + L_{1'} + L_2 + L_3 + L_4$$

By solving the self inductance using Equation (28),

$$L_1 = L_{1'} = 59.8 \quad (nH)$$

$$L_2 = L_4 = 259.7 \quad (nH)$$

$$L_3 = 182 \quad (nH)$$

$$L_o = 821 \quad (nH)$$

Negative mutual inductances are solved as follows:

$$M_- = 2(M_{1,3} + M_{1',3} + M_{2,4})$$

$$M_{2,4} = 2l_2 F_{2,4}$$

$$M_{1,3} = \frac{1}{2}(M_3 + M_1 - M_{1'+\text{gap}})$$

$$M_{1',3} = \frac{1}{2}(M_3 + M_{1'} - M_{1+\text{gap}})$$

$$F_{2,4} = \ln \left\{ \frac{l_2}{d_{2,4}} + \left[1 + \left(\frac{l_2}{d_{2,4}} \right)^2 \right]^{\frac{1}{2}} \right\} - \left[1 + \left(\frac{d_{2,4}}{l_2} \right)^2 \right]^{\frac{1}{2}} + \frac{l_2}{d_{2,4}}$$

$$F_3 = \ln \left\{ \frac{l_3}{d_{1,3}} + \left[1 + \left(\frac{l_3}{d_{1,3}} \right)^2 \right]^{\frac{1}{2}} \right\} - \left[1 + \left(\frac{d_{1,3}}{l_3} \right)^2 \right]^{\frac{1}{2}} + \frac{l_3}{d_{1,3}}$$

$$F_1 = \ln \left\{ \frac{l_1}{d_{1,3}} + \left[1 + \left(\frac{l_1}{d_{1,3}} \right)^2 \right]^{\frac{1}{2}} \right\} - \left[1 + \left(\frac{d_{1,3}}{l_1} \right)^2 \right]^{\frac{1}{2}} + \frac{l_1}{d_{1,3}}$$

$$F_{1'} = \ln \left\{ \frac{l_{1'}}{d_{1',3}} + \left[1 + \left(\frac{l_{1'}}{d_{1',3}} \right)^2 \right]^{\frac{1}{2}} \right\} - \left[1 + \left(\frac{d_{1',3}}{l_{1'}} \right)^2 \right]^{\frac{1}{2}} + \frac{l_{1'}}{d_{1',3}}$$

$$M_1 = 2l_1 F_1$$

$$M_{1'} = 2l_{1'} F_{1'}$$

$$M_{1'+\text{gap}} = 2l_{1'+\text{gap}} F_{1'+\text{gap}}$$

$$F_{1'+\text{gap}} = \ln \left\{ \frac{l_{1'+\text{gap}}}{d_{1'+\text{gap},3}} + \left[1 + \left(\frac{l_{1'+\text{gap}}}{d_{1'+\text{gap},3}} \right)^2 \right]^{\frac{1}{2}} \right\} + \frac{l_{1'}}{d_{1',3}} - \left[1 + \left(\frac{d_{1'+\text{gap},3}}{l_{1'+\text{gap}}} \right)^2 \right]^{\frac{1}{2}}$$

AN710

By solving the above equation, the mutual inductance between each conductor are:

$$\begin{aligned}M_{2,4} &= 30.1928 \text{ (nH)}, \\M_{1,3} &= 5.1818 \text{ (nH)} = M_{1',3}\end{aligned}$$

Therefore, the total inductance of the antenna is:

$$\begin{aligned}L_T &= L_o - M. = L_o - 2(M_{2,4} + M_{1,3}) = \\&= 797.76 - 81.113 = 716.64 \text{ (nH)}\end{aligned}$$

It has been found that the inductance calculated using Equation (38) has about 9% higher than the result using Equation (30) for the same physical dimension. The resulting difference of the two formulas is contributed mainly by the mutual inductance terms. Equation (38) is recommended if it needs very accurate calculation while Equation (30) gives quick answers within about 10 percent of error.

The computation software using Matlab is shown in Appendix B.

The formulas for inductance are widely published and provide a reasonable approximation for the relationship between inductance and the number of turns for a given physical size^[1-7]. When building prototype coils, it is wise to exceed the number of calculated turns by about 10% and then remove turns to achieve a right value. For production coils, it is best to specify an inductance and tolerance rather than a specific number of turns.

CONFIGURATION OF ANTENNA CIRCUITS

Reader Antenna Circuits

The inductance for the reader antenna coil for 13.56 MHz is typically in the range of a few microhenries (μH). The antenna can be formed by air-core or ferrite core inductors. The antenna can also be formed by a metallic or conductive trace on PCB board or on flexible substrate.

The reader antenna can be made of either a single coil, that is typically forming a series or a parallel resonant circuit, or a double loop (transformer) antenna coil. Figure 16 shows various configurations of reader antenna circuit. The coil circuit must be tuned to the operating frequency to maximize power efficiency. The tuned LC resonant circuit is the same as the band-pass filter that passes only a selected frequency. The Q of the tuned circuit is related to both read range and bandwidth of the circuit. More on this subject will be discussed in the following section.

Choosing the size and type of antenna circuit depends on the system design topology. The series resonant circuit results in minimum impedance at the resonance frequency. Therefore, it draws a maximum current at

the resonance frequency. Because of its simple circuit topology and relatively low cost, this type of antenna circuit is suitable for proximity reader antenna.

On the other hand, a parallel resonant circuit results in maximum impedance at the resonance frequency. Therefore, maximum voltage is available at the resonance frequency. Although it has a minimum resonant current, it still has a strong circulating current that is proportional to Q of the circuit. The double loop antenna coil that is formed by two parallel antenna circuits can also be used.

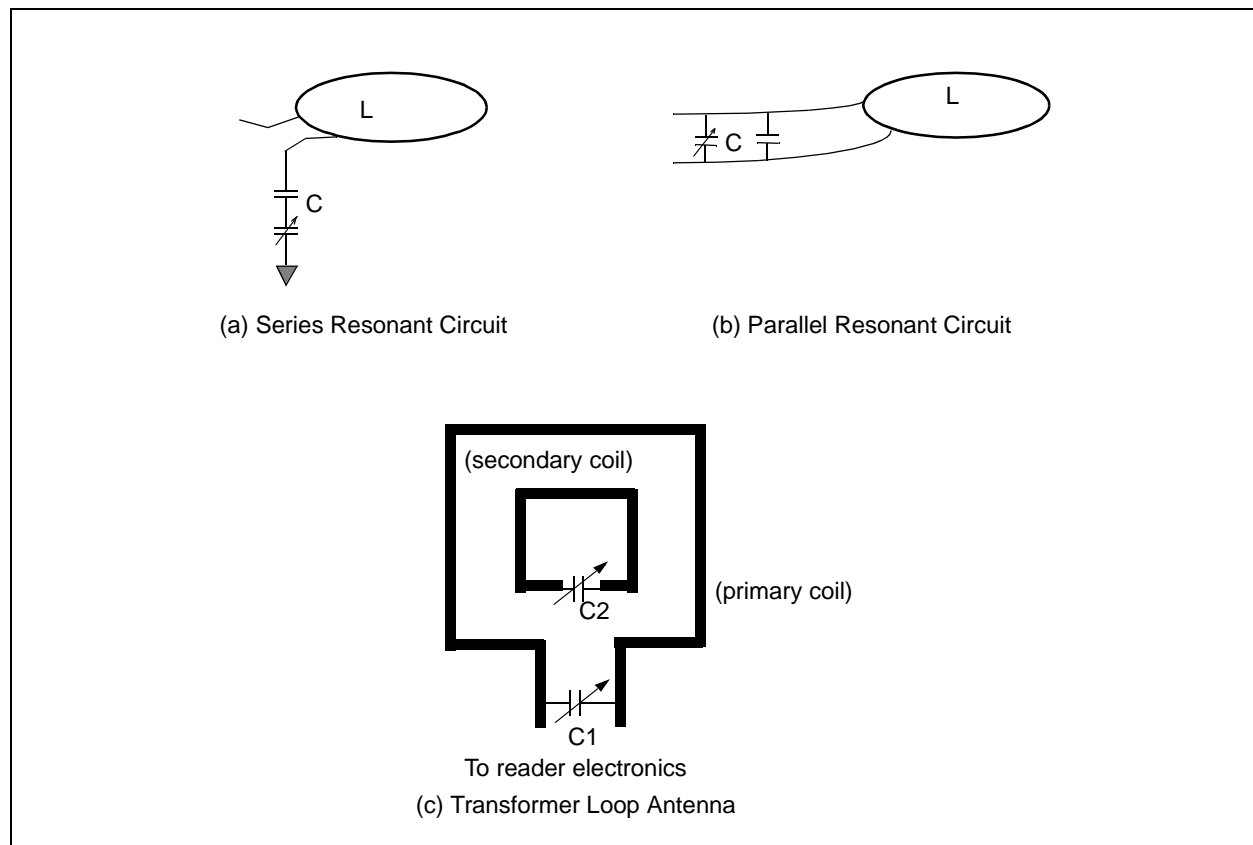
The frequency tolerance of the carrier frequency and output power level from the read antenna is regulated by government regulations (e.g., FCC in the USA).

FCC limits for 13.56 MHz frequency band are as follows:

1. Tolerance of the carrier frequency: $13.56 \text{ MHz} \pm 0.01\% = \pm 1.356 \text{ kHz}$.
2. Frequency bandwidth: $\pm 7 \text{ kHz}$.
3. Power level of fundamental frequency: 10 mv/m at 30 meters from the transmitter.
4. Power level for harmonics: -50.45 dB down from the fundamental signal.

The transmission circuit including the antenna coil must be designed to meet the FCC limits.

FIGURE 16: VARIOUS READER ANTENNA CIRCUITS



AN710

Tag Antenna Circuits

The MCRF355 device communicates data by tuning and detuning the antenna circuit (see AN707). Figure 17 shows examples of the external circuit arrangement.

The external circuit must be tuned to the resonant frequency of the reader antenna. In a detuned condition, a circuit element between the antenna B and Vss pads is shorted. The frequency difference (delta frequency) between tuned and detuned frequencies must be adjusted properly for optimum operation. It has been found that maximum modulation index and maximum read range occur when the tuned and detuned frequencies are separated by 3 to 6 MHz.

The tuned frequency is formed from the circuit elements between the antenna A and Vss pads without shorting the antenna B pad. The detuned frequency is found when the antenna B pad is shorted. This detuned frequency is calculated from the circuit between antenna A and Vss pads excluding the circuit element between antenna B and Vss pads.

In Figure 17 (a), the tuned resonant frequency is:

EQUATION 39:

$$f_o = \frac{1}{2\pi\sqrt{L_T C}}$$

where:

- L_T = $L_1 + L_2 + 2L_M$ = Total inductance between antenna A and Vss pads
- L_1 = inductance between antenna A and antenna B pads
- L_2 = inductance between antenna B and Vss pads
- M = mutual inductance between coil 1 and coil 2
- = $k\sqrt{L_1 L_2}$
- k = coupling coefficient between the two coils
- C = tuning capacitance

and detuned frequency is:

EQUATION 40:

$$f_{detuned} = \frac{1}{2\pi\sqrt{L_1 C}}$$

In this case, $f_{detuned}$ is higher than f_{tuned} .

Figure 17(b) shows another example of the external circuit arrangement. This configuration controls C_2 for tuned and detuned frequencies. The tuned and untuned frequencies are:

EQUATION 41:

$$f_{tuned} = \frac{1}{2\pi\sqrt{\left(\frac{C_1 C_2}{C_1 + C_2}\right) L}}$$

and

EQUATION 42:

$$f_{detuned} = \frac{1}{2\pi\sqrt{L C_1}}$$

A typical inductance of the coil is about a few microhenry with a few turns. Once the inductance is determined, the resonant capacitance is calculated from the above equations. For example, if a coil has an inductance of 1.3 μH , then it needs a 106 pF of capacitance to resonate at 13.56 MHz.

CONSIDERATION ON QUALITY FACTOR Q AND BANDWIDTH OF TUNING CIRCUIT

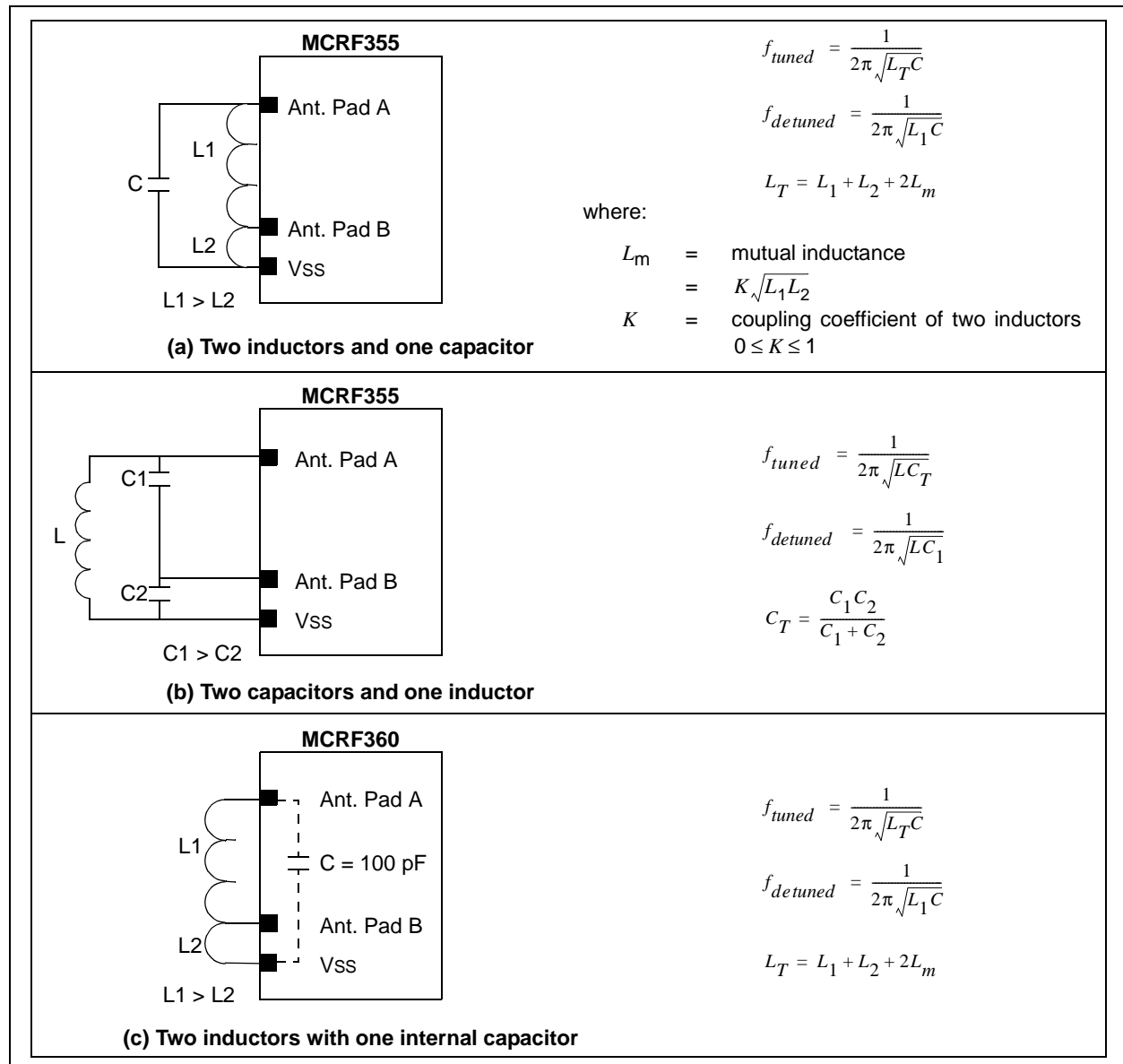
The voltage across the coil is a product of quality factor Q of the circuit and input voltage. Therefore, for a given input voltage signal, the coil voltage is directly proportional to the Q of the circuit. In general, a higher Q

results in longer read range. However, the Q is also related to the bandwidth of the circuit as shown in the following equation.

EQUATION 43:

$$Q = \frac{f_o}{B}$$

FIGURE 17: VARIOUS EXTERNAL CIRCUIT CONFIGURATIONS



AN710

Bandwidth requirement and limit on circuit Q for MCRF355

Since the MCRF355 operates with a data rate of 70 kHz, the reader antenna circuit needs a bandwidth of at least twice of the data rate. Therefore, it needs:

EQUATION 44:

$$B_{\text{minimum}} = 140 \text{ kHz}$$

Assuming the circuit is turned at 13.56 MHz, the maximum attainable Q is obtained from Equations 43 and 44:

EQUATION 45:

$$Q_{\text{max}} = \frac{f_o}{B} = 96.8$$

In a practical LC resonant circuit, the range of Q for 13.56 MHz band is about 40. However, the Q can be significantly increased with a ferrite core inductor. The system designer must consider the above limits for optimum operation.

RESONANT CIRCUITS

Once the frequency and the inductance of the coil are determined, the resonant capacitance can be calculated from:

EQUATION 46:

$$C = \frac{1}{L(2\pi f_o)^2}$$

In practical applications, parasitic (distributed) capacitance is present between turns. The parasitic capacitance in a typical tag antenna coil is a few (pF). This parasitic capacitance increases with operating frequency of the device.

There are two different resonant circuits: parallel and series. The parallel resonant circuit has maximum impedance at the resonance frequency. It has a minimum current and maximum voltage at the resonance frequency. Although the current in the circuit is minimum at the resonant frequency, there are a circulation current that is proportional to Q of the circuit. The parallel resonant circuit is used in both the tag and the high power reader antenna circuit.

On the other hand, the series resonant circuit has a minimum impedance at the resonance frequency. As a result, maximum current is available in the circuit. Because of its simplicity and the availability of the high current into the antenna element, the series resonant circuit is often used for a simple proximity reader.

Parallel Resonant Circuit

Figure 18 shows a simple parallel resonant circuit. The total impedance of the circuit is given by:

EQUATION 47:

$$Z(j\omega) = \frac{j\omega L}{(1 - \omega^2 LC) + j\frac{\omega L}{R}} \quad (\Omega)$$

where ω is an angular frequency given as $\omega = 2\pi f$.

The maximum impedance occurs when the denominator in the above equation is minimized. This condition occurs when:

EQUATION 48:

$$\omega^2 LC = 1$$

This is called a resonance condition, and the resonance frequency is given by:

EQUATION 49:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

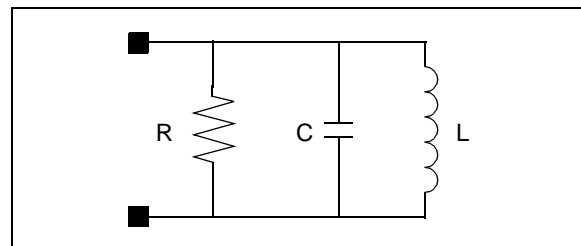
By applying Equation 48 into Equation 47, the impedance at the resonance frequency becomes:

EQUATION 50:

$$Z = R$$

where R is the load resistance.

FIGURE 18: PARALLEL RESONANT CIRCUIT



The R and C in the parallel resonant circuit determine the bandwidth, B , of the circuit.

EQUATION 51:

$$B = \frac{1}{2\pi RC} \quad (\text{Hz})$$

The quality factor, Q , is defined by various ways such as:

EQUATION 52:

$$Q = \frac{\text{Energy Stored in the System per One Cycle}}{\text{Energy Dissipated in the System per One Cycle}}$$

$$= \frac{\text{reactance}}{\text{resistance}}$$

$$= \frac{\omega L}{r} \quad \text{For inductance}$$

$$= \frac{1}{\omega cr} \quad \text{For capacitance}$$

$$= \frac{f_0}{B}$$

where:

$$\omega = 2\pi f = \text{angular frequency}$$

$$f_0 = \text{resonant frequency}$$

$$B = \text{bandwidth}$$

$$r = \text{ohmic losses}$$

By applying Equation 49 and Equation 51 into Equation 52, the Q in the parallel resonant circuit is:

EQUATION 53:

$$Q = R \sqrt{\frac{C}{L}}$$

The Q in a parallel resonant circuit is proportional to the load resistance R and also to the ratio of capacitance and inductance in the circuit.

When this parallel resonant circuit is used for the tag antenna circuit, the voltage drop across the circuit can be obtained by combining Equations 8 and 53:

EQUATION 54:

$$V_o = 2\pi f_o N Q S B_o \cos \alpha$$

$$= 2\pi f_o N \left(R \sqrt{\frac{C}{L}} \right) S B_o \cos \alpha$$

The above equation indicates that the induced voltage in the tag coil is inversely proportional to the square root of the coil inductance, but proportional to the number of turns and surface area of the coil.

Series Resonant Circuit

A simple series resonant circuit is shown in Figure 19. The expression for the impedance of the circuit is:

EQUATION 55:

$$Z(j\omega) = r + j(X_L - X_C) \quad (\Omega)$$

where:

$$r = \text{a DC ohmic resistance of coil and capacitor}$$

$$X_L \text{ and } X_C = \text{the reactance of the coil and capacitor, respectively, such that:}$$

EQUATION 56:

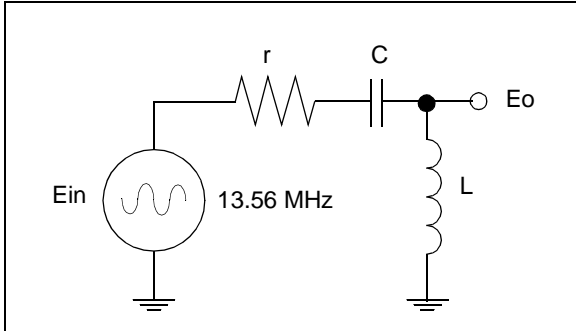
$$X_L = 2\pi f_o L \quad (\Omega)$$

EQUATION 57:

$$X_c = \frac{1}{2\pi f_o C} \quad (\Omega)$$

The impedance in Equation 55 becomes minimized when the reactance component cancelled out each other such that $X_L = X_C$. This is called a resonance condition. The resonance frequency is same as the parallel resonant frequency given in Equation 49.

FIGURE 19: SERIES RESONANCE CIRCUIT



The half power frequency bandwidth is determined by r and L , and given by:

EQUATION 58:

$$B = \frac{r}{2\pi L} \quad (\text{Hz})$$

The quality factor, Q , in the series resonant circuit is given by:

$$Q = \frac{f_0}{B} = \frac{\omega L}{r} = \frac{1}{r\omega C}$$

The series circuit forms a voltage divider, the voltage drops in the coil is given by:

EQUATION 59:

$$V_o = \frac{jX_L}{r + jX_L - jX_C} V_{in}$$

When the circuit is tuned to a resonant frequency such as $X_L = X_C$, the voltage across the coil becomes:

EQUATION 60:

$$V_o = \frac{jX_L}{r} V_{in}$$

$$= jQV_{in}$$

The above equation indicates that the coil voltage is a product of input voltage and Q of the circuit. For example, a circuit with Q of 40 can have a coil voltage that is 40 times higher than input signal. This is because all energy in the input signal spectrum becomes squeezed into a single frequency band.

EXAMPLE 9: CIRCUIT PARAMETERS

If the DC ohmic resistance r is 5Ω , then the L and C values for 13.56 MHz resonant circuit with $Q = 40$ are:

EQUATION 61:

$$X_L = Qr_s = 200\Omega$$

$$L = \frac{X_L}{2\pi f} = \frac{200}{2\pi(13.56\text{MHz})} = 2.347 \quad (\mu\text{H})$$

$$C = \frac{1}{2\pi f X_L} = \frac{1}{2\pi(13.56\text{MHz})(200)} = 58.7 \quad (\text{pF})$$

TUNING METHOD

The circuit must be tuned to the resonance frequency for a maximum performance (read range) of the device. Two examples of tuning the circuit are as follows:

- **Voltage Measurement Method:**

- Set up a voltage signal source at the resonance frequency.
- Connect a voltage signal source across the resonant circuit.
- Connect an Oscilloscope across the resonant circuit.
- Tune the capacitor or the coil while observing the signal amplitude on the Oscilloscope.
- Stop the tuning at the maximum voltage.

- **S-Parameter or Impedance Measurement Method using Network Analyzer:**

- Set up an S-Parameter Test Set (Network Analyzer) for S11 measurement, and do a calibration.
- Measure the S11 for the resonant circuit.
- Reflection impedance or reflection admittance can be measured instead of the S11.
- Tune the capacitor or the coil until a maximum null (S11) occurs at the resonance frequency, f_0 . For the impedance measurement, the maximum peak will occur for the parallel resonant circuit, and minimum peak for the series resonant circuit.

FIGURE 20: VOLTAGE VS. FREQUENCY FOR RESONANT CIRCUIT

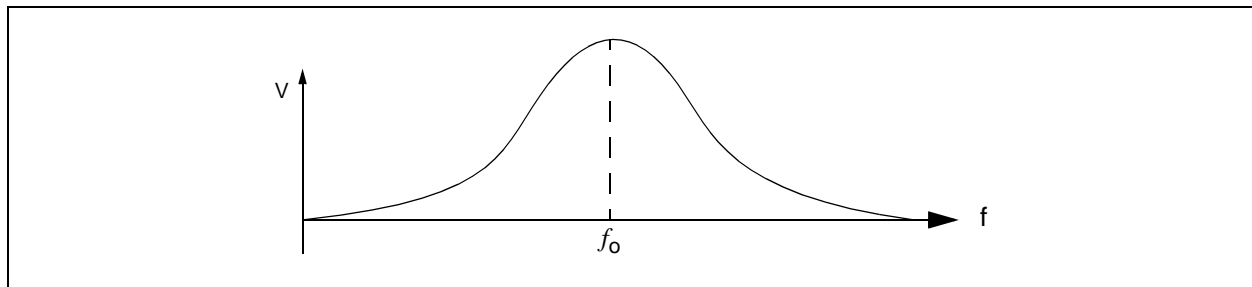
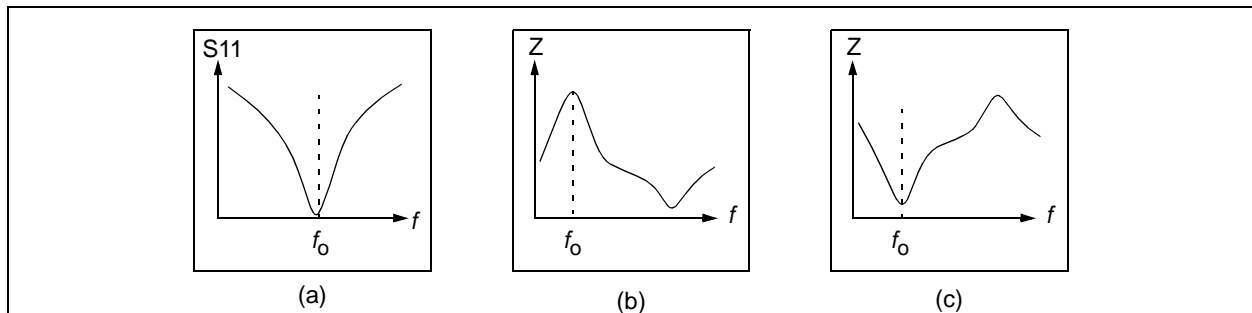


FIGURE 21: FREQUENCY RESPONSES FOR RESONANT CIRCUIT



Note 1: (a) S11 Response, (b) Impedance Response for a Parallel Resonant Circuit, and (c) Impedance Response for a Series Resonant Circuit.

- 2:** In (a), the null at the resonance frequency represents a minimum input reflection at the resonance frequency. This means the circuit absorbs the signal at the frequency while other frequencies are reflected back. In (b), the impedance curve has a peak at the resonance frequency. This is because the parallel resonant circuit has a maximum impedance at the resonance frequency. (c) shows a response for the series resonant circuit. Since the series resonant circuit has a minimum impedance at the resonance frequency, a minimum peak occurs at the resonance frequency.

AN710

READ RANGE OF RFID DEVICES

Read range is defined as a maximum communication distance between the reader and tag. In general, the read range of passive RFID products varies, depending on system configuration and is affected by the following parameters:

- Operating frequency and performance of antenna coils
- Q of antenna and tuning circuit
- Antenna orientation
- Excitation current
- Sensitivity of receiver
- Coding (or modulation) and decoding (or demodulation) algorithm
- Number of data bits and detection (interpretation) algorithm
- Condition of operating environment (electrical noise), etc.

The read range of 13.56 MHz is relatively longer than that of 125 kHz device. This is because the antenna efficiency increases as the frequency increases. With a given operating frequency, the conditions (a – c) are related to the antenna configuration and tuning circuit. The conditions (d – e) are determined by a circuit topology of reader. The condition (f) is a communication protocol of the device, and (g) is related to a firmware software program for data detection.

Assuming the device is operating under a given condition, the read range of the device is largely affected by the performance of the antenna coil. It is always true that a longer read range is expected with the larger size of the antenna with a proper antenna design. Figures 22 and 23 show typical examples of the read range of various passive RFID devices.

FIGURE 22: READ RANGE VS. TAG SIZE FOR TYPICAL PROXIMITY APPLICATIONS*

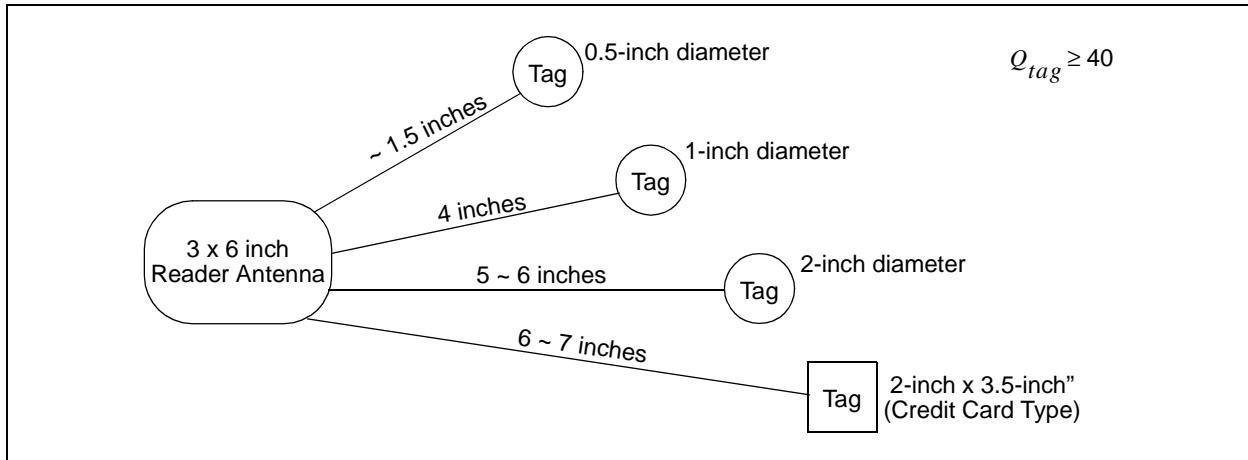
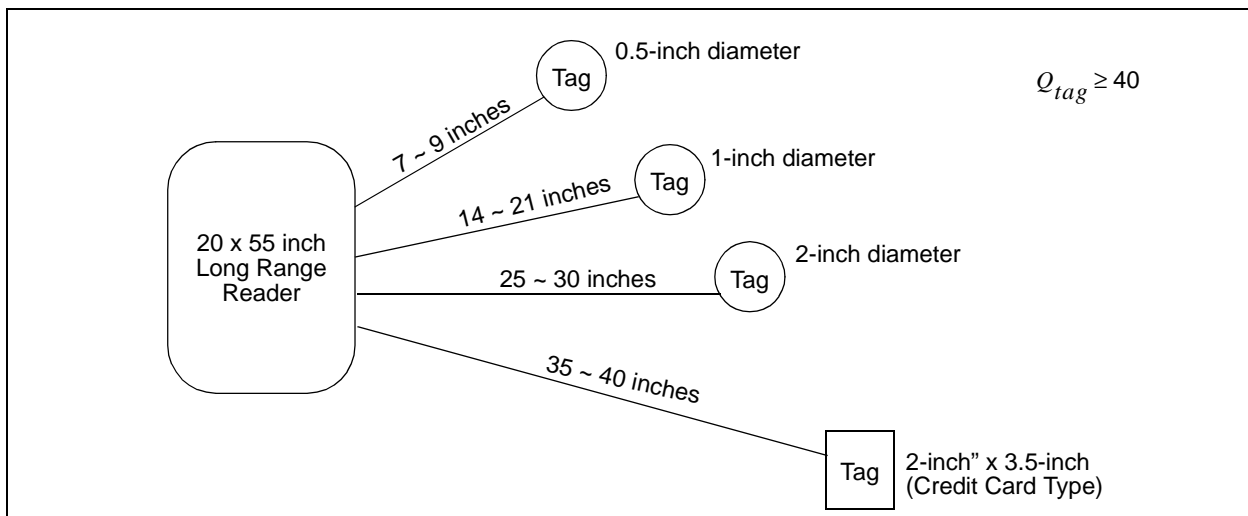


FIGURE 23: READ RANGE VS. TAG SIZE FOR TYPICAL LONG RANGE APPLICATIONS*



Note: Actual results may be shorter or longer than the range shown, depending upon factors discussed above.

APPENDIX A: CALCULATION OF MUTUAL INDUCTANCE TERMS IN EQUATIONS 36 AND 37

Positive Mutual Inductance Terms:

EQUATION A.1 Mutual Inductance Between Conductors 1 and 5

$$M_{1,5} = \frac{1}{2} \left\{ (M_1^{1,5} + M_5^{1,5}) - M_\delta^{1,5} \right\}$$

where:

$$M_1^{1,5} = 2l_1 F_1^{1,5}$$

$$M_5^{1,5} = 2l_5 F_5^{1,5}$$

$$M_\delta^{1,5} = 2d_{1,5} F_\delta^{1,5}$$

$$F_1^{1,5} = \ln \left\{ \frac{l_1}{d_{1,5}} + \left[1 + \left(\frac{l_1}{d_{1,5}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,5}}{l_1} \right)^2 \right]^{1/2} + \left(\frac{d_{1,5}}{l_1} \right)$$

$$F_5^{1,5} = \ln \left\{ \frac{l_5}{d_{1,5}} + \left[1 + \left(\frac{l_5}{d_{1,5}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,5}}{l_5} \right)^2 \right]^{1/2} + \left(\frac{d_{1,5}}{l_5} \right)$$

$$F_\delta^{1,5} = \ln \left\{ \frac{l_\delta}{d_{1,5}} + \left[1 + \left(\frac{l_\delta}{d_{1,5}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,5}}{l_\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{1,5}}{l_\delta} \right)$$

$$\delta = w + s$$

$$l_\delta = \delta$$

where $d_{1,5}$ is the distance between track centers of conductor l_1 and l_5 . s is the interspacing between conductors l_1 and l_5 , w is the width of track, δ is $s + w$.

$F_1^{1,5}$ is the mutual inductance parameter between conductor segments 1 and 5 by viewing from conductor 1.

$F_5^{1,5}$ is the mutual inductance parameter between conductor segments 1 and 5 by viewing from conductor 5.

$F_\delta^{1,5}$ is the mutual inductance parameter between conductor segments 1 and 5 by viewing from the length difference between the two conductors.

EQUATION A.2 Mutual Inductance Between Conductors 1 and 9

$$M_{1,9} = \frac{1}{2} \left\{ (M_{9+2\delta}^{1,9} + M_{9+\delta}^{1,9}) - (M_{2\delta}^{1,9} + M_\delta^{1,9}) \right\}$$

where:

$$M_{9+2\delta}^{1,9} = 2l_{9+2\delta} F_{9+2\delta}^{1,9}$$

$$M_{9+\delta}^{1,9} = 2l_{9+\delta} F_{9+\delta}^{1,9}$$

$$M_{2\delta}^{1,9} = 2d_{1,9} F_{2\delta}^{1,9}$$

$$M_\delta^{1,9} = 2d_{1,9} F_\delta^{1,9}$$

$$F_{9+2\delta}^{1,9} = \ln \left\{ \frac{l_{9+2\delta}}{d_{1,9}} + \left[1 + \left(\frac{l_{9+2\delta}}{d_{1,9}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,9}}{l_{9+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{1,9}}{l_{9+2\delta}} \right)$$

$$F_{9+\delta}^{1,9} = \ln \left\{ \frac{l_{9+\delta}}{d_{1,9}} + \left[1 + \left(\frac{l_{9+\delta}}{d_{1,9}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,9}}{l_{9+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{1,9}}{l_{9+\delta}} \right)$$

$$F_{2\delta}^{1,9} = \ln \left\{ \frac{l_{2\delta}}{d_{1,9}} + \left[1 + \left(\frac{l_{2\delta}}{d_{1,9}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,9}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{1,9}}{l_{2\delta}} \right)$$

$$F_\delta^{1,9} = \ln \left\{ \frac{l_\delta}{d_{1,9}} + \left[1 + \left(\frac{l_\delta}{d_{1,9}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,9}}{l_\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{1,9}}{l_\delta} \right)$$

EQUATION A.3 Mutual Inductance Between Conductors 1 and 13

$$M_{1,13} = \frac{1}{2} \left\{ \left(M_{13+3\delta}^{1,13} + M_{13+2\delta}^{1,13} \right) - \left(M_{3\delta}^{1,13} + M_{2\delta}^{1,13} \right) \right\}$$

where:

$$M_{13+3\delta}^{1,13} = 2l_{13+3\delta} F_{13+3\delta}^{1,13}$$

$$M_{13+2\delta}^{1,13} = 2l_{13+2\delta} F_{13+2\delta}^{1,13}$$

$$M_{3\delta}^{1,13} = 2d_{1,13} F_{3\delta}^{1,13}$$

$$M_{2\delta}^{1,13} = 2d_{1,13} F_{2\delta}^{1,13}$$

$$F_{13+3\delta}^{1,13} = \ln \left\{ \frac{l_{13+3\delta}}{d_{1,13}} + \left[1 + \left(\frac{l_{13+3\delta}}{d_{1,13}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,13}}{l_{13+3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{1,13}}{l_{13+3\delta}} \right)$$

$$F_{13+\delta}^{1,13} = \ln \left\{ \frac{l_{13+\delta}}{d_{1,13}} + \left[1 + \left(\frac{l_{13+\delta}}{d_{1,13}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,13}}{l_{13+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{1,13}}{l_{13+\delta}} \right)$$

$$F_{3\delta}^{1,13} = \ln \left\{ \frac{l_{3\delta}}{d_{1,13}} + \left[1 + \left(\frac{l_{3\delta}}{d_{1,13}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,13}}{l_{3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{1,13}}{l_{3\delta}} \right)$$

$$F_{2\delta}^{1,13} = \ln \left\{ \frac{l_{2\delta}}{d_{1,13}} + \left[1 + \left(\frac{l_{2\delta}}{d_{1,13}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,13}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{1,13}}{l_{2\delta}} \right)$$

EQUATION A.4 Mutual Inductance Between Conductors 5 and 9

$$M_{5,9} = M_{9+\delta}^{5,9} - M_{\delta}^{5,9}$$

where:

$$M_{9+\delta}^{5,9} = 2l_1 F_{9+\delta}^{5,9}$$

$$M_{\delta}^{5,9} = 2l_1 F_{\delta}^{5,9}$$

$$F_{9+\delta}^{5,9} = \ln \left\{ \frac{l_{9+\delta}}{d_{5,9}} + \left[1 + \left(\frac{l_{9+\delta}}{d_{5,9}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,9}}{l_{9+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{5,9}}{l_{9+\delta}} \right)$$

$$F_{\delta}^{5,9} = \ln \left\{ \frac{l_{\delta}}{d_{5,9}} + \left[1 + \left(\frac{l_{\delta}}{d_{5,9}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,9}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{5,9}}{l_{\delta}} \right)$$

EQUATION A.5 Mutual Inductance Between Conductors 5 and 13

$$M_{5,13} = M_{13+2\delta}^{5,13} - M_{2\delta}^{5,13}$$

where:

$$M_{13+2\delta}^{5,13} = 2l_{13+2\delta} F_{13+2\delta}^{5,13}$$

$$M_{2\delta}^{5,13} = 2l_{2\delta} F_{2\delta}^{5,13}$$

$$F_{13+2\delta}^{5,13} = \ln \left\{ \frac{l_{13+2\delta}}{d_{5,13}} + \left[1 + \left(\frac{l_{13+2\delta}}{d_{5,13}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,13}}{l_{13+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{5,13}}{l_{13+2\delta}} \right)$$

$$F_{2\delta}^{5,13} = \ln \left\{ \frac{l_{2\delta}}{d_{5,13}} + \left[1 + \left(\frac{l_{2\delta}}{d_{5,13}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,13}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{5,13}}{l_{2\delta}} \right)$$

EQUATION A.6 Mutual Inductance Between Conductors 9 and 13

$$M_{9,13} = M_{13+\delta}^{9,13} - M_{\delta}^{9,13}$$

where:

$$M_{13+\delta}^{9,13} = 2l_{13+\delta} F_{13+\delta}^{9,13}$$

$$M_{\delta}^{9,13} = 2l_{\delta} F_{\delta}^{9,13}$$

$$F_{13+\delta}^{9,13} = \ln \left\{ \frac{l_{13+\delta}}{d_{9,13}} + \left[1 + \left(\frac{l_{13+\delta}}{d_{9,13}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,13}}{l_{13+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,13}}{l_{13+\delta}} \right)$$

$$F_{\delta}^{9,13} = \ln \left\{ \frac{l_{\delta}}{d_{9,13}} + \left[1 + \left(\frac{l_{\delta}}{d_{9,13}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,13}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,13}}{l_{\delta}} \right)$$

EQUATION A.7 Mutual Inductance Between Conductors 3 and 7

$$M_{3,7} = M_{7+\delta}^{3,7} - M_{\delta}^{3,7}$$

where:

$$M_{7+\delta}^{3,7} = 2l_{7+\delta} F_{7+\delta}^{3,7}$$

$$M_{\delta}^{3,7} = 2l_{\delta} F_{\delta}^{3,7}$$

$$F_{7+\delta}^{3,7} = \ln \left\{ \frac{l_{7+\delta}}{d_{3,7}} + \left[1 + \left(\frac{l_{7+\delta}}{d_{3,7}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{3,7}}{l_{7+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{3,7}}{l_{7+\delta}} \right)$$

$$F_{\delta}^{3,7} = \ln \left\{ \frac{l_{\delta}}{d_{3,7}} + \left[1 + \left(\frac{l_{\delta}}{d_{3,7}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{3,7}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,13}}{l_{\delta}} \right)$$

EQUATION A.8 Mutual Inductance Between Conductors 3 and 11

$$M_{3,11} = M_{11+2\delta}^{3,11} - M_{2\delta}^{3,11}$$

where:

$$M_{11+2\delta}^{3,11} = 2l_{11+2\delta} F_{11+2\delta}^{3,11}$$

$$M_{2\delta}^{3,11} = 2l_{2\delta} F_{2\delta}^{3,11}$$

$$F_{11+2\delta}^{3,11} = \ln \left\{ \frac{l_{11+2\delta}}{d_{3,11}} + \left[1 + \left(\frac{l_{11+2\delta}}{d_{3,11}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{3,11}}{l_{11+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{3,11}}{l_{11+2\delta}} \right)$$

$$F_{2\delta}^{3,11} = \ln \left\{ \frac{l_{2\delta}}{d_{3,11}} + \left[1 + \left(\frac{l_{2\delta}}{d_{3,11}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{3,11}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{3,11}}{l_{2\delta}} \right)$$

EQUATION A.9 Mutual Inductance Between Conductors 3 and 15

$$M_{3,15} = M_{15+3\delta}^{3,15} - M_{3\delta}^{3,15}$$

where:

$$M_{15+3\delta}^{3,15} = 2l_{15+3\delta} F_{15+3\delta}^{3,15}$$

$$M_{3\delta}^{3,15} = 2l_{3\delta} F_{3\delta}^{3,15}$$

$$F_{15+3\delta}^{3,15} = \ln \left\{ \frac{l_{15+3\delta}}{d_{3,15}} + \left[1 + \left(\frac{l_{15+3\delta}}{d_{3,15}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{3,15}}{l_{15+3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{3,15}}{l_{15+3\delta}} \right)$$

$$F_{3\delta}^{3,15} = \ln \left\{ \frac{l_{3\delta}}{d_{3,15}} + \left[1 + \left(\frac{l_{3\delta}}{d_{3,15}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{3,15}}{l_{3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{3,15}}{l_{3\delta}} \right)$$

$$\delta = w + s$$

EQUATION A.10 Mutual Inductance Between Conductors 7 and 11

$$M_{7,11} = M_{11+\delta}^{7,11} - M_{\delta}^{7,11}$$

where:

$$M_{11+\delta}^{7,11} = 2l_{11+\delta} F_{11+\delta}^{7,11}$$

$$M_{\delta}^{7,11} = 2l_{\delta} F_{\delta}^{7,11}$$

$$F_{11+\delta}^{7,11} = \ln \left\{ \frac{l_{11+\delta}}{d_{7,11}} + \left[1 + \left(\frac{l_{11+\delta}}{d_{7,11}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{7,11}}{l_{11+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{7,11}}{l_{11+\delta}} \right)$$

$$F_{\delta}^{7,11} = \ln \left\{ \frac{l_{\delta}}{d_{7,11}} + \left[1 + \left(\frac{l_{\delta}}{d_{7,11}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{7,11}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{7,11}}{l_{\delta}} \right)$$

EQUATION A.11 Mutual Inductance Between Conductors 7 and 15

$$M_{7,15} = M_{15+2\delta}^{7,15} - M_{2\delta}^{7,15}$$

where:

$$M_{15+2\delta}^{7,15} = 2l_{15+2\delta} F_{15+2\delta}^{7,15}$$

$$M_{2\delta}^{7,15} = 2l_{2\delta} F_{2\delta}^{7,15}$$

$$F_{15+2\delta}^{7,15} = \ln \left\{ \frac{l_{15+2\delta}}{d_{7,15}} + \left[1 + \left(\frac{l_{15+2\delta}}{d_{7,15}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{7,15}}{l_{15+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{7,15}}{l_{15+2\delta}} \right)$$

$$F_{2\delta}^{7,15} = \ln \left\{ \frac{l_{2\delta}}{d_{7,15}} + \left[1 + \left(\frac{l_{2\delta}}{d_{7,15}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{7,15}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{7,15}}{l_{2\delta}} \right)$$

EQUATION A.12 Mutual Inductance Between Conductors 11 and 15

$$M_{11,15} = M_{15+\delta}^{11,15} - M_{\delta}^{11,15}$$

where:

$$M_{15+\delta}^{11,15} = 2l_{15+\delta} F_{15+\delta}^{11,15}$$

$$M_{\delta}^{11,15} = 2l_{\delta} F_{\delta}^{11,15}$$

$$F_{15+\delta}^{11,15} = \ln \left\{ \frac{l_{15+\delta}}{d_{11,15}} + \left[1 + \left(\frac{l_{15+\delta}}{d_{11,15}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{11,15}}{l_{15+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{11,15}}{l_{15+\delta}} \right)$$

$$F_{\delta}^{11,15} = \ln \left\{ \frac{l_{\delta}}{d_{11,15}} + \left[1 + \left(\frac{l_{\delta}}{d_{11,15}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{11,15}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{11,15}}{l_{\delta}} \right)$$

EQUATION A.13 Mutual Inductance Between Conductors 2 and 6

$$M_{2,6} = M_{6+\delta}^{2,6} - M_{\delta}^{2,6}$$

where:

$$M_{6+\delta}^{2,6} = 2l_{6+\delta} F_{6+\delta}^{2,6}$$

$$M_{\delta}^{2,6} = 2l_{\delta} F_{\delta}^{2,6}$$

$$F_{6+\delta}^{2,6} = \ln \left\{ \frac{l_{6+\delta}}{d_{2,6}} + \left[1 + \left(\frac{l_{6+\delta}}{d_{2,6}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,6}}{l_{6+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,6}}{l_{6+\delta}} \right)$$

$$F_{\delta}^{2,6} = \ln \left\{ \frac{l_{\delta}}{d_{2,6}} + \left[1 + \left(\frac{l_{\delta}}{d_{2,6}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,6}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,6}}{l_{\delta}} \right)$$

EQUATION A.14 Mutual Inductance Between Conductors 2 and 10

$$M_{2,10} = M_{10+2\delta}^{2,10} - M_{2\delta}^{2,10}$$

where:

$$M_{10+2\delta}^{2,10} = 2l_{10+2\delta} F_{10+2\delta}^{2,10}$$

$$M_{2\delta}^{2,10} = 2l_{2\delta} F_{2\delta}^{2,10}$$

$$F_{10+2\delta}^{2,10} = \ln \left\{ \frac{l_{10+2\delta}}{d_{2,10}} + \left[1 + \left(\frac{l_{10+2\delta}}{d_{2,10}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,10}}{l_{10+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,10}}{l_{10+2\delta}} \right)$$

$$F_{2\delta}^{2,10} = \ln \left\{ \frac{l_{2\delta}}{d_{2,10}} + \left[1 + \left(\frac{l_{2\delta}}{d_{2,10}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,10}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,10}}{l_{2\delta}} \right)$$

EQUATION A.15 Mutual Inductance Between Conductors 2 and 14

$$M_{2,14} = M_{14+3\delta}^{2,14} - M_{3\delta}^{2,14}$$

where:

$$M_{14+3\delta}^{2,14} = 2l_{14+3\delta} F_{14+3\delta}^{2,14}$$

$$M_{3\delta}^{2,14} = 2l_{3\delta} F_{3\delta}^{2,14}$$

$$F_{14+3\delta}^{2,14} = \ln \left\{ \frac{l_{14+3\delta}}{d_{2,14}} + \left[1 + \left(\frac{l_{14+3\delta}}{d_{2,14}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{2,14}}{l_{14+3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,14}}{l_{14+3\delta}} \right)$$

$$F_{3\delta}^{2,14} = \ln \left\{ \frac{l_{3\delta}}{d_{2,14}} + \left[1 + \left(\frac{l_{3\delta}}{d_{2,14}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{2,14}}{l_{3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,14}}{l_{3\delta}} \right)$$

EQUATION A.17 Mutual Inductance Between Conductors 6 and 14

$$M_{6,14} = M_{14+2\delta}^{6,14} - M_{2\delta}^{6,14}$$

where:

$$M_{14+2\delta}^{6,14} = 2l_{14+2\delta} F_{14+2\delta}^{6,14}$$

$$M_{2\delta}^{6,14} = 2l_{2\delta} F_{2\delta}^{6,14}$$

$$F_{14+2\delta}^{6,14} = \ln \left\{ \frac{l_{14+2\delta}}{d_{6,14}} + \left[1 + \left(\frac{l_{14+2\delta}}{d_{6,14}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{6,14}}{l_{14+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,14}}{l_{14+2\delta}} \right)$$

$$F_{2\delta}^{6,14} = \ln \left\{ \frac{l_{2\delta}}{d_{6,14}} + \left[1 + \left(\frac{l_{2\delta}}{d_{6,14}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{6,14}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,14}}{l_{2\delta}} \right)$$

EQUATION A.16 Mutual Inductance Between Conductors 6 and 10

$$M_{6,10} = M_{10+\delta}^{6,10} - M_{\delta}^{6,10}$$

where:

$$M_{10+\delta}^{6,10} = 2l_{10+\delta} F_{10+\delta}^{6,10}$$

$$M_{\delta}^{6,10} = 2l_{\delta} F_{\delta}^{6,10}$$

$$F_{10+\delta}^{6,10} = \ln \left\{ \frac{l_{10+\delta}}{d_{6,10}} + \left[1 + \left(\frac{l_{10+\delta}}{d_{6,10}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{6,10}}{l_{10+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,10}}{l_{10+\delta}} \right)$$

$$F_{\delta}^{6,10} = \ln \left\{ \frac{l_{\delta}}{d_{6,10}} + \left[1 + \left(\frac{l_{\delta}}{d_{6,10}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{6,10}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,10}}{l_{\delta}} \right)$$

EQUATION A.18 Mutual Inductance Between Conductors 10 and 14

$$M_{10,14} = M_{14+\delta}^{10,14} - M_{\delta}^{10,14}$$

where:

$$M_{14+\delta}^{10,14} = 2l_{14+\delta} F_{14+\delta}^{10,14}$$

$$M_{\delta}^{10,14} = 2l_{\delta} F_{\delta}^{10,14}$$

$$F_{14+\delta}^{10,14} = \ln \left\{ \frac{l_{14+\delta}}{d_{10,14}} + \left[1 + \left(\frac{l_{14+\delta}}{d_{10,14}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{10,14}}{l_{14+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,14}}{l_{14+\delta}} \right)$$

$$F_{\delta}^{10,14} = \ln \left\{ \frac{l_{\delta}}{d_{10,14}} + \left[1 + \left(\frac{l_{\delta}}{d_{10,14}} \right)^2 \right]^{1/2} \right\} \left[1 + \left(\frac{d_{10,14}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,14}}{l_{\delta}} \right)$$

EQUATION A.19 Mutual Inductance Between Conductors 4 and 8

$$M_{4,8} = M_{8+\delta}^{4,8} - M_{\delta}^{4,8}$$

where:

$$M_{8+\delta}^{4,8} = 2l_{8+\delta} F_{8+\delta}^{4,8}$$

$$M_{\delta}^{4,8} = 2l_{\delta} F_{\delta}^{4,8}$$

$$F_{8+\delta}^{4,8} = \ln \left\{ \frac{l_{8+\delta}}{d_{4,8}} + \left[1 + \left(\frac{l_{8+\delta}}{d_{4,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{4,8}}{8+\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{4,8}}{8+\delta} \right)$$

$$F_{\delta}^{4,8} = \ln \left\{ \frac{l_{\delta}}{d_{4,8}} + \left[1 + \left(\frac{l_{\delta}}{d_{4,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{4,8}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{4,8}}{l_{\delta}} \right)$$

EQUATION A.20 Mutual Inductance Between Conductors 4 and 12

$$M_{4,12} = M_{12+2\delta}^{4,12} - M_{2\delta}^{4,12}$$

where:

$$M_{12+2\delta}^{4,12} = 2l_{12+2\delta} F_{12+2\delta}^{4,12}$$

$$M_{2\delta}^{4,12} = 2l_{2\delta} F_{2\delta}^{4,12}$$

$$F_{12+2\delta}^{4,12} = \ln \left\{ \frac{l_{12+2\delta}}{d_{4,12}} + \left[1 + \left(\frac{l_{12+2\delta}}{d_{4,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{4,12}}{12+2\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{4,12}}{12+2\delta} \right)$$

$$F_{2\delta}^{4,12} = \ln \left\{ \frac{l_{2\delta}}{d_{4,12}} + \left[1 + \left(\frac{l_{2\delta}}{d_{4,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{4,12}}{2\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{4,12}}{2\delta} \right)$$

EQUATION A.21 Mutual Inductance Between Conductors 4 and 16

$$M_{4,16} = M_{16+3\delta}^{4,16} - M_{3\delta}^{4,16}$$

where:

$$M_{16+3\delta}^{4,16} = 2l_{16+3\delta} F_{16+3\delta}^{4,16}$$

$$M_{3\delta}^{4,16} = 2l_{3\delta} F_{3\delta}^{4,16}$$

$$F_{16+3\delta}^{4,16} = \ln \left\{ \frac{l_{16+3\delta}}{d_{4,16}} + \left[1 + \left(\frac{l_{16+3\delta}}{d_{4,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{4,16}}{16+3\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{4,16}}{16+3\delta} \right)$$

$$F_{3\delta}^{4,16} = \ln \left\{ \frac{l_{3\delta}}{d_{4,16}} + \left[1 + \left(\frac{l_{3\delta}}{d_{4,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{4,16}}{3\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{4,16}}{3\delta} \right)$$

EQUATION A.22 Mutual Inductance Between Conductors 8 and 12

$$M_{8,12} = M_{14+\delta}^{8,12} - M_{\delta}^{8,12}$$

where:

$$M_{14+\delta}^{8,12} = 2l_{10+\delta} F_{12+\delta}^{8,12}$$

$$M_{\delta}^{8,12} = 2l_{\delta} F_{\delta}^{8,12}$$

$$F_{12+\delta}^{8,12} = \ln \left\{ \frac{l_{12+\delta}}{d_{8,12}} + \left[1 + \left(\frac{l_{12+\delta}}{d_{8,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{8,12}}{12+\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{8,12}}{12+\delta} \right)$$

$$F_{\delta}^{8,12} = \ln \left\{ \frac{l_{\delta}}{d_{8,12}} + \left[1 + \left(\frac{l_{\delta}}{d_{8,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{8,12}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{8,12}}{l_{\delta}} \right)$$

EQUATION A.23 Mutual Inductance Between Conductors 8 and 16

$$M_{8,16} = M_{14+2\delta}^{8,16} - M_{2\delta}^{8,16}$$

where:

$$M_{16+2\delta}^{8,16} = 2l_{16+2\delta} F_{16+2\delta}^{8,16}$$

$$M_{2\delta}^{8,16} = 2l_{2\delta} F_{2\delta}^{8,16}$$

$$F_{16+2\delta}^{8,16} = \ln \left\{ \frac{l_{16+2\delta}}{d_{8,16}} + \left[1 + \left(\frac{l_{16+2\delta}}{d_{8,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{8,16}}{l_{16+2\delta}} \right)^2 \right]^{-1/2} + \left(\frac{d_{8,16}}{l_{16+2\delta}} \right)$$

$$F_{2\delta}^{8,16} = \ln \left\{ \frac{l_{2\delta}}{d_{8,16}} + \left[1 + \left(\frac{l_{2\delta}}{d_{8,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{8,16}}{l_{2\delta}} \right)^2 \right]^{-1/2} + \left(\frac{d_{8,16}}{l_{2\delta}} \right)$$

EQUATION A.24 Mutual Inductance Between Conductors 12 and 16

$$M_{12,16} = M_{14+\delta}^{12,16} - M_{\delta}^{12,16}$$

where:

$$M_{16+\delta}^{12,16} = 2l_{16+\delta} F_{16+\delta}^{12,16}$$

$$M_{\delta}^{12,16} = 2l_{\delta} F_{\delta}^{12,16}$$

$$F_{16+\delta}^{12,16} = \ln \left\{ \frac{l_{16+\delta}}{d_{12,16}} + \left[1 + \left(\frac{l_{16+\delta}}{d_{12,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{12,16}}{l_{16+\delta}} \right)^2 \right]^{-1/2} + \left(\frac{d_{12,16}}{l_{16+\delta}} \right)$$

$$F_{\delta}^{12,16} = \ln \left\{ \frac{l_{\delta}}{d_{12,16}} + \left[1 + \left(\frac{l_{\delta}}{d_{12,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{12,16}}{l_{\delta}} \right)^2 \right]^{-1/2} + \left(\frac{d_{12,16}}{l_{\delta}} \right)$$

EQUATION A.25 Mutual Inductance Between Conductors 1 and 3

$$M_{1,3} = M_1^{1,3} = M_3^{1,3} = 2l_1 F_1^{1,3}$$

where:

$$F_1^{1,3} = \ln \left\{ \frac{l_1}{d_{1,3}} + \left[1 + \left(\frac{l_1}{d_{1,3}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,3}}{l_1} \right)^2 \right]^{-1/2} + \left(\frac{d_{1,3}}{l_1} \right)$$

EQUATION A.26 Mutual Inductance Between Conductors 1 and 7

$$M_{1,7} = M_{7+\delta}^{1,7} - M_{\delta}^{1,7}$$

where:

$$M_{7+\delta}^{1,7} = 2l_{7+\delta} F_{7+\delta}^{1,7}$$

$$M_{\delta}^{1,7} = 2l_{\delta} F_{\delta}^{1,7}$$

$$F_{7+\delta}^{1,7} = \ln \left\{ \frac{l_{7+\delta}}{d_{1,7}} + \left[1 + \left(\frac{l_{7+\delta}}{d_{1,7}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,7}}{l_{7+\delta}} \right)^2 \right]^{-1/2} + \left(\frac{d_{1,7}}{l_{7+\delta}} \right)$$

$$F_{\delta}^{1,7} = \ln \left\{ \frac{l_{\delta}}{d_{1,7}} + \left[1 + \left(\frac{l_{\delta}}{d_{1,7}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{1,7}}{l_{\delta}} \right)^2 \right]^{-1/2} + \left(\frac{d_{1,7}}{l_{\delta}} \right)$$

EQUATION A.27 Mutual Inductance Between Conductors 1 and 11

$$M_{1,11} = M_{11+2\delta}^{1,11} - M_{2\delta}^{1,11}$$

where:

$$M_{11+2\delta}^{1,11} = 2l_{11+2\delta}F_{11+2\delta}^{1,11}$$

$$M_{2\delta}^{1,11} = 2l_{2\delta}F_{2\delta}^{1,11}$$

$$F_{11+2\delta}^{1,11} = \ln\left\{\frac{l_{11+2\delta}}{d_{1,11}} + \left[1 + \left(\frac{l_{11+2\delta}}{d_{1,11}}\right)^2\right]^{1/2}\right\} - \left[1 + \left(\frac{d_{1,11}}{l_{11+2\delta}}\right)^2\right]^{1/2} + \left(\frac{d_{1,11}}{l_{11+2\delta}}\right)$$

$$F_{2\delta}^{1,11} = \ln\left\{\frac{l_{2\delta}}{d_{1,11}} + \left[1 + \left(\frac{l_{2\delta}}{d_{1,11}}\right)^2\right]^{1/2}\right\} - \left[1 + \left(\frac{d_{1,11}}{l_{2\delta}}\right)^2\right]^{1/2} + \left(\frac{d_{1,11}}{l_{2\delta}}\right)$$

EQUATION A.28 Mutual Inductance Between Conductors 1 and 15

$$M_{1,15} = M_{15+3\delta}^{1,15} - M_{3\delta}^{1,15}$$

where:

$$M_{15+3\delta}^{1,15} = 2l_{15+3\delta}F_{15+3\delta}^{1,15}$$

$$M_{3\delta}^{1,15} = 2l_{3\delta}F_{3\delta}^{1,15}$$

$$F_{15+3\delta}^{1,15} = \ln\left\{\frac{l_{15+3\delta}}{d_{1,15}} + \left[1 + \left(\frac{l_{15+3\delta}}{d_{1,15}}\right)^2\right]^{1/2}\right\} - \left[1 + \left(\frac{d_{1,15}}{l_{15+3\delta}}\right)^2\right]^{1/2} + \left(\frac{d_{1,15}}{l_{15+3\delta}}\right)$$

$$F_{3\delta}^{1,15} = \ln\left\{\frac{l_{3\delta}}{d_{1,15}} + \left[1 + \left(\frac{l_{3\delta}}{d_{1,15}}\right)^2\right]^{1/2}\right\} - \left[1 + \left(\frac{d_{1,15}}{l_{3\delta}}\right)^2\right]^{1/2} + \left(\frac{d_{1,15}}{l_{3\delta}}\right)$$

EQUATION A.29 Mutual Inductance Between Conductors 5 and 3

$$M_{5,3} = \frac{1}{2}\left[(M_5^{5,3} + M_3^{5,3}) - M_{\delta}^{5,3}\right]$$

where:

$$M_5^{5,3} = 2l_5F_5^{5,3}$$

$$M_3^{5,3} = 2l_3F_3^{5,3}$$

$$M_{\delta}^{5,3} = 2l_{\delta}F_{\delta}^{5,3}$$

$$F_5^{5,3} = \ln\left\{\frac{l_5}{d_{5,3}} + \left[1 + \left(\frac{l_5}{d_{5,3}}\right)^2\right]^{1/2}\right\} - \left[1 + \left(\frac{d_{5,3}}{l_5}\right)^2\right]^{1/2} + \left(\frac{d_{5,3}}{l_5}\right)$$

$$F_3^{5,3} = \ln\left\{\frac{l_3}{d_{5,3}} + \left[1 + \left(\frac{l_3}{d_{5,3}}\right)^2\right]^{1/2}\right\} - \left[1 + \left(\frac{d_{5,3}}{l_3}\right)^2\right]^{1/2} + \left(\frac{d_{5,3}}{l_3}\right)$$

$$F_{\delta}^{5,3} = \ln\left\{\frac{l_{\delta}}{d_{5,3}} + \left[1 + \left(\frac{l_{\delta}}{d_{5,3}}\right)^2\right]^{1/2}\right\} - \left[1 + \left(\frac{d_{5,3}}{l_{\delta}}\right)^2\right]^{1/2} + \left(\frac{d_{5,3}}{l_{\delta}}\right)$$

EQUATION A.30 Mutual Inductance Between Conductors 5 and 7

$$M_{5,7} = \frac{1}{2}\left[(M_5^{5,7} + M_7^{5,7}) - M_{\delta}^{5,7}\right]$$

where:

$$M_5^{5,7} = 2l_5F_5^{5,7}$$

$$M_7^{5,7} = 2l_7F_7^{5,7}$$

$$M_{\delta}^{5,7} = 2l_{\delta}F_{\delta}^{5,7}$$

$$F_5^{5,7} = \ln\left\{\frac{l_5}{d_{5,7}} + \left[1 + \left(\frac{l_5}{d_{5,7}}\right)^2\right]^{1/2}\right\} - \left[1 + \left(\frac{d_{5,7}}{l_5}\right)^2\right]^{1/2} + \left(\frac{d_{5,7}}{l_5}\right)$$

$$F_7^{5,7} = \ln\left\{\frac{l_7}{d_{5,7}} + \left[1 + \left(\frac{l_7}{d_{5,7}}\right)^2\right]^{1/2}\right\} - \left[1 + \left(\frac{d_{5,7}}{l_7}\right)^2\right]^{1/2} + \left(\frac{d_{5,7}}{l_7}\right)$$

$$F_{\delta}^{5,7} = \ln\left\{\frac{l_{\delta}}{d_{5,7}} + \left[1 + \left(\frac{l_{\delta}}{d_{5,7}}\right)^2\right]^{1/2}\right\} - \left[1 + \left(\frac{d_{5,7}}{l_{\delta}}\right)^2\right]^{1/2} + \left(\frac{d_{5,7}}{l_{\delta}}\right)$$

EQUATION A.31 Mutual Inductance Between Conductors 5 and 11

$$M_{5,11} = \frac{1}{2} \left\{ \left(M_{11+2\delta}^{5,11} + M_{11+\delta}^{5,11} \right) - \left(M_{2\delta}^{5,11} + M_{\delta}^{5,11} \right) \right\}$$

where:

$$M_{11+2\delta}^{5,11} = 2l_{11+2\delta} F_{11+2\delta}^{5,11}$$

$$M_{11+\delta}^{5,11} = 2l_{11+\delta} F_{11+\delta}^{5,11}$$

$$M_{2\delta}^{5,11} = 2l_{2\delta} F_{2\delta}^{5,11}$$

$$M_{\delta}^{5,11} = 2l_{\delta} F_{\delta}^{5,11}$$

$$F_{11+2\delta}^{5,11} = \ln \left\{ \frac{l_{11+2\delta}}{d_{5,11}} + \left[1 + \left(\frac{l_{11+2\delta}}{d_{5,11}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,11}}{l_{11+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{5,11}}{l_{11+2\delta}} \right)$$

$$F_{11+\delta}^{5,11} = \ln \left\{ \frac{l_{11+\delta}}{d_{5,11}} + \left[1 + \left(\frac{l_{11+\delta}}{d_{5,11}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,11}}{l_{11+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{5,11}}{l_{11+\delta}} \right)$$

$$F_{2\delta}^{5,11} = \ln \left\{ \frac{2\delta}{d_{5,11}} + \left[1 + \left(\frac{2\delta}{d_{5,11}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,11}}{2\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{5,11}}{2\delta} \right)$$

$$F_{\delta}^{5,11} = \ln \left\{ \frac{\delta}{d_{5,11}} + \left[1 + \left(\frac{\delta}{d_{5,11}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,11}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{5,11}}{\delta} \right)$$

EQUATION A.32 Mutual Inductance Between Conductors 2 and 4

$$M_{2,4} = \frac{1}{2} \left\{ \left(M_2^{2,4} + M_4^{2,4} \right) - M_{\delta}^{2,4} \right\}$$

where:

$$M_2^{2,4} = 2l_2 F_2^{2,4} \quad M_4^{2,4} = 2l_4 F_4^{2,4}$$

$$M_{\delta}^{2,4} = 2l_{\delta} F_{\delta}^{2,4}$$

$$F_2^{2,4} = \ln \left\{ \frac{l_2}{d_{2,4}} + \left[1 + \left(\frac{l_2}{d_{2,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,4}}{l_2} \right)^2 \right]^{1/2} + \left(\frac{d_{2,4}}{l_2} \right)$$

$$F_4^{2,4} = \ln \left\{ \frac{l_4}{d_{2,4}} + \left[1 + \left(\frac{l_4}{d_{2,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,4}}{l_4} \right)^2 \right]^{1/2} + \left(\frac{d_{2,4}}{l_4} \right)$$

$$F_{\delta}^{2,4} = \ln \left\{ \frac{l_{\delta}}{d_{2,4}} + \left[1 + \left(\frac{l_{\delta}}{d_{2,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,4}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,4}}{l_{\delta}} \right)$$

EQUATION A.33 Mutual Inductance Between Conductors 5 and 15

$$M_{5,15} = \frac{1}{2} \left\{ \left(M_{15+3\delta}^{5,15} + M_{15+2\delta}^{5,15} \right) - \left(M_{3\delta}^{5,15} + M_{2\delta}^{5,15} \right) \right\}$$

where:

$$M_{15+3\delta}^{5,15} = 2l_{15+3\delta} F_{15+3\delta}^{5,15}$$

$$M_{15+2\delta}^{5,15} = 2l_{15+2\delta} F_{15+2\delta}^{5,15}$$

$$M_{3\delta}^{5,15} = 2l_{3\delta} F_{3\delta}^{5,15}, \quad M_{2\delta}^{5,15} = 2l_{2\delta} F_{2\delta}^{5,15}$$

$$F_{15+3\delta}^{5,15} = \ln \left\{ \frac{l_{15+3\delta}}{d_{5,15}} + \left[1 + \left(\frac{l_{15+3\delta}}{d_{5,15}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,15}}{15+3\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{5,15}}{15+3\delta} \right)$$

$$F_{15+2\delta}^{5,15} = \ln \left\{ \frac{l_{15+2\delta}}{d_{5,15}} + \left[1 + \left(\frac{l_{15+2\delta}}{d_{5,15}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,15}}{15+2\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{5,15}}{15+2\delta} \right)$$

$$F_{2\delta}^{5,15} = \ln \left\{ \frac{2\delta}{d_{5,15}} + \left[1 + \left(\frac{2\delta}{d_{5,15}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,15}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{5,15}}{l_{2\delta}} \right)$$

$$F_{\delta}^{5,15} = \ln \left\{ \frac{\delta}{d_{5,15}} + \left[1 + \left(\frac{\delta}{d_{5,15}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{5,15}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{5,15}}{\delta} \right)$$

EQUATION A.34 Mutual Inductance Between Conductors 9 and 7

$$M_{9,7} = \frac{1}{2} \left\{ \left(M_9^{9,7} + M_7^{9,7} \right) - M_{\delta}^{9,7} \right\}$$

where:

$$M_9^{9,7} = 2l_9 F_9^{9,7}, \quad M_7^{9,7} = 2l_7 F_7^{9,7}$$

$$M_{\delta}^{9,7} = 2l_{\delta} F_{\delta}^{9,7}$$

$$F_9^{9,7} = \ln \left\{ \frac{l_9}{d_{9,7}} + \left[1 + \left(\frac{l_9}{d_{9,7}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,7}}{l_9} \right)^2 \right]^{1/2} + \left(\frac{d_{9,7}}{l_9} \right)$$

$$F_7^{9,7} = \ln \left\{ \frac{l_7}{d_{9,7}} + \left[1 + \left(\frac{l_7}{d_{9,7}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,7}}{l_7} \right)^2 \right]^{1/2} + \left(\frac{d_{9,7}}{l_7} \right)$$

$$F_{\delta}^{9,7} = \ln \left\{ \frac{l_{\delta}}{d_{9,7}} + \left[1 + \left(\frac{l_{\delta}}{d_{9,7}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,7}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,7}}{l_{\delta}} \right)$$

EQUATION A.35 Mutual Inductance Between Conductors 9 and 3

$$M_{9,3} = \frac{1}{2} \left\{ \left(M_{9+2\delta}^{9,3} + M_{9+\delta}^{9,3} \right) - \left(M_{2\delta}^{9,3} + M_{\delta}^{9,3} \right) \right\}$$

where:

$$M_{9+2\delta}^{9,3} = 2l_{9+2\delta} F_{9+2\delta}^{9,3}, \quad M_{9+\delta}^{9,3} = 2l_{9+\delta} F_{9+\delta}^{9,3}$$

$$M_{2\delta}^{9,3} = 2l_{2\delta} F_{2\delta}^{9,3}, \quad M_{\delta}^{9,3} = 2l_{\delta} F_{\delta}^{9,3}$$

$$F_{9+2\delta}^{9,3} = \ln \left\{ \frac{l_{9+2\delta}}{d_{9,3}} + \left[1 + \left(\frac{l_{9+2\delta}}{d_{9,3}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,3}}{l_{9+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,3}}{l_{9+2\delta}} \right)$$

$$F_{9+\delta}^{9,3} = \ln \left\{ \frac{l_{9+\delta}}{d_{9,3}} + \left[1 + \left(\frac{l_{9+\delta}}{d_{9,3}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,3}}{l_{9+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,3}}{l_{9+\delta}} \right)$$

$$F_{2\delta}^{9,3} = \ln \left\{ \frac{2\delta}{d_{9,3}} + \left[1 + \left(\frac{2\delta}{d_{9,3}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,3}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,3}}{l_{2\delta}} \right)$$

$$F_{\delta}^{9,3} = \ln \left\{ \frac{\delta}{d_{9,3}} + \left[1 + \left(\frac{\delta}{d_{9,3}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,3}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{9,3}}{\delta} \right)$$

EQUATION A.36 Mutual Inductance Between Conductors 9 and 11

$$M_{9,11} = \frac{1}{2} \left\{ \left(M_9^{9,11} + M_{11}^{9,11} \right) - M_{\delta}^{9,11} \right\}$$

where:

$$M_9^{9,11} = 2l_9 F_9^{9,11}, \quad M_{11}^{9,11} = 2l_{11} F_{11}^{9,11}$$

$$M_{\delta}^{9,11} = 2l_{\delta} F_{\delta}^{9,11}$$

$$F_9^{9,11} = \ln \left\{ \frac{l_9}{d_{9,11}} + \left[1 + \left(\frac{l_9}{d_{9,11}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,11}}{l_9} \right)^2 \right]^{1/2} + \left(\frac{d_{9,11}}{l_9} \right)$$

$$F_{11}^{9,11} = \ln \left\{ \frac{l_{11}}{d_{9,11}} + \left[1 + \left(\frac{l_{11}}{d_{9,11}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,11}}{l_{11}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,11}}{l_{11}} \right)$$

$$F_{\delta}^{9,11} = \ln \left\{ \frac{l_{\delta}}{d_{9,11}} + \left[1 + \left(\frac{l_{\delta}}{d_{9,11}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{9,11}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,11}}{l_{\delta}} \right)$$

EQUATION A.37 Mutual Inductance Between Conductors 9 and 15

$$M_{9,15} = \frac{1}{2} \left\{ \left(M_{15+2\delta}^{9,15} + M_{15+\delta}^{9,15} \right) - \left(M_{2\delta}^{9,15} + M_{\delta}^{9,15} \right) \right\}$$

where:

$$M_{15+2\delta}^{9,15} = 2l_{15+2\delta} F_{15+2\delta}^{9,15}, \quad M_{15+\delta}^{9,15} = 2l_{15+\delta} F_{15+\delta}^{9,15}$$

$$M_{2\delta}^{9,15} = 2l_{2\delta} F_{2\delta}^{9,15}, \quad M_{\delta}^{9,15} = 2l_{\delta} F_{\delta}^{9,15}$$

$$F_{9+2\delta}^{9,15} = \ln \left\{ \frac{l_{9+2\delta}}{d_{9,15}} + \left[1 + \left(\frac{l_{9+2\delta}}{d_{9,15}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{9,15}}{l_{9+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,15}}{l_{9+2\delta}} \right)$$

$$F_{9+\delta}^{9,15} = \ln \left\{ \frac{l_{9+\delta}}{d_{9,15}} + \left[1 + \left(\frac{l_{9+\delta}}{d_{9,15}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{9,15}}{l_{9+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{9,15}}{l_{9+\delta}} \right)$$

$$F_{2\delta}^{9,15} = \ln \left\{ \frac{2\delta}{d_{9,15}} + \left[1 + \left(\frac{2\delta}{d_{9,15}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{9,15}}{2\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{9,15}}{2\delta} \right)$$

$$F_{\delta}^{9,15} = \ln \left\{ \frac{\delta}{d_{9,15}} + \left[1 + \left(\frac{\delta}{d_{9,15}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{9,15}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{9,15}}{\delta} \right)$$

EQUATION A.38 Mutual Inductance Between Conductors 13 and 15

$$M_{13,15} = \frac{1}{2} \left\{ \left(M_{13}^{13,15} + M_{15}^{13,15} \right) - M_{\delta}^{13,15} \right\}$$

where:

$$M_{13}^{13,15} = 2l_{13} F_{13}^{13,15}, \quad M_{15}^{13,15} = 2l_{15} F_{15}^{13,15}$$

$$M_{\delta}^{13,15} = 2l_{\delta} F_{\delta}^{13,15}$$

$$F_{13}^{13,15} = \ln \left\{ \frac{l_{13}}{d_{13,15}} + \left[1 + \left(\frac{l_{13}}{d_{13,15}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{13,15}}{l_{13}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,15}}{l_{13}} \right)$$

$$F_{15}^{13,15} = \ln \left\{ \frac{l_{15}}{d_{13,15}} + \left[1 + \left(\frac{l_{15}}{d_{13,15}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{13,15}}{l_{15}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,15}}{l_{15}} \right)$$

$$F_{\delta}^{13,15} = \ln \left\{ \frac{l_{\delta}}{d_{13,15}} + \left[1 + \left(\frac{l_{\delta}}{d_{13,15}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{13,15}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,15}}{l_{\delta}} \right)$$

EQUATION A.39 Mutual Inductance Between Conductors 13 and 11

$$M_{13,11} = \frac{1}{2} \left\{ \left(M_{13}^{13,11} + M_{11}^{13,11} \right) - M_{\delta}^{13,11} \right\}$$

where:

$$M_{13}^{13,11} = 2l_{13} F_{13}^{13,11}, \quad M_{11}^{13,11} = 2l_{11} F_{11}^{13,11}$$

$$M_{\delta}^{13,11} = 2l_{\delta} F_{\delta}^{13,11}$$

$$F_{13}^{13,11} = \ln \left\{ \frac{l_{13}}{d_{13,11}} + \left[1 + \left(\frac{l_{13}}{d_{13,11}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{13,11}}{l_{13}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,11}}{l_{13}} \right)$$

$$F_{11}^{13,11} = \ln \left\{ \frac{l_{11}}{d_{13,11}} + \left[1 + \left(\frac{l_{11}}{d_{13,11}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{13,11}}{l_{11}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,11}}{l_{11}} \right)$$

$$F_{\delta}^{13,11} = \ln \left\{ \frac{l_{\delta}}{d_{13,11}} + \left[1 + \left(\frac{l_{\delta}}{d_{13,11}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{13,11}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,11}}{l_{\delta}} \right)$$

EQUATION A.40 Mutual Inductance Between Conductors 13 and 7

$$M_{13,7} = \frac{1}{2} \left\{ \left(M_{13+2\delta}^{13,7} + M_{13+\delta}^{13,7} \right) - \left(M_{2\delta}^{13,7} + M_{\delta}^{13,7} \right) \right\}$$

where:

$$M_{13+2\delta}^{13,7} = 2l_{13+2\delta} F_{13+2\delta}^{13,7}, \quad M_{13+\delta}^{13,7} = 2l_{13+\delta} F_{13+\delta}^{13,7}$$

$$M_{2\delta}^{13,7} = 2l_{2\delta} F_{2\delta}^{13,7}, \quad M_{\delta}^{13,7} = 2l_{\delta} F_{\delta}^{13,7}$$

$$F_{13+2\delta}^{13,7} = \ln \left\{ \frac{l_{13+2\delta}}{d_{13,7}} + \left[1 + \left(\frac{l_{13+2\delta}}{d_{13,7}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{13,7}}{l_{13+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,7}}{l_{13+2\delta}} \right)$$

$$F_{13+\delta}^{13,7} = \ln \left\{ \frac{l_{13+\delta}}{d_{13,7}} + \left[1 + \left(\frac{l_{13+\delta}}{d_{13,7}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{13,7}}{l_{13+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,7}}{l_{13+\delta}} \right)$$

$$F_{2\delta}^{13,7} = \ln \left\{ \frac{2\delta}{d_{13,7}} + \left[1 + \left(\frac{2\delta}{d_{13,7}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{13,7}}{2\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{13,7}}{2\delta} \right)$$

$$F_{\delta}^{13,7} = \ln \left\{ \frac{\delta}{d_{13,7}} + \left[1 + \left(\frac{\delta}{d_{13,7}} \right)^2 \right]^{1/2} \right\}$$

$$\quad - \left[1 + \left(\frac{d_{13,7}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{13,7}}{\delta} \right)$$

EQUATION A.41 Mutual Inductance Between Conductors 13 and 3

$$M_{13,3} = \frac{1}{2} \left\{ \left(M_{13+3\delta}^{13,3} + M_{13+2\delta}^{13,3} \right) - \left(M_{3\delta}^{13,3} + M_{2\delta}^{13,3} \right) \right\}$$

where:

$$M_{13+3\delta}^{13,3} = 2l_{13+3\delta} F_{13+3\delta}^{13,3}$$

$$M_{13+2\delta}^{13,3} = 2l_{13+2\delta} F_{13+2\delta}^{13,3}$$

$$M_{3\delta}^{13,3} = 2l_{3\delta} F_{3\delta}^{13,3}, \quad M_{2\delta}^{13,3} = 2l_{2\delta} F_{2\delta}^{13,3}$$

$$F_{13+3\delta}^{13,3} = \ln \left\{ \frac{l_{13+3\delta}}{d_{13,3}} + \left[1 + \left(\frac{l_{13+3\delta}}{d_{13,3}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{13,3}}{l_{13+3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,3}}{l_{13+3\delta}} \right)$$

$$F_{13+2\delta}^{13,3} = \ln \left\{ \frac{l_{13+2\delta}}{d_{13,3}} + \left[1 + \left(\frac{l_{13+2\delta}}{d_{13,3}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{13,3}}{l_{13+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,3}}{l_{13+2\delta}} \right)$$

$$F_{2\delta}^{13,3} = \ln \left\{ \frac{2\delta}{d_{13,3}} + \left[1 + \left(\frac{2\delta}{d_{13,3}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{13,3}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{13,3}}{l_{2\delta}} \right)$$

$$F_{\delta}^{13,3} = \ln \left\{ \frac{\delta}{d_{13,3}} + \left[1 + \left(\frac{\delta}{d_{13,3}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{13,3}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{13,3}}{\delta} \right)$$

EQUATION A.42 Mutual Inductance Between Conductors 6 and 4

$$M_{6,4} = \frac{1}{2} \left\{ \left(M_6^{6,4} + M_4^{6,4} \right) - M_{\delta}^{6,4} \right\}$$

where:

$$M_6^{6,4} = 2l_6 F_6^{6,4}$$

$$M_4^{6,4} = 2l_4 F_4^{6,4}$$

$$M_{\delta}^{6,4} = 2l_{\delta} F_{\delta}^{6,4}$$

$$F_6^{6,4} = \ln \left\{ \frac{l_6}{d_{6,4}} + \left[1 + \left(\frac{l_6}{d_{6,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{6,4}}{l_6} \right)^2 \right]^{1/2} + \left(\frac{d_{6,4}}{l_6} \right)$$

$$F_4^{6,4} = \ln \left\{ \frac{l_4}{d_{6,4}} + \left[1 + \left(\frac{l_4}{d_{6,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{6,4}}{l_4} \right)^2 \right]^{1/2} + \left(\frac{d_{6,4}}{l_4} \right)$$

$$F_{\delta}^{6,4} = \ln \left\{ \frac{l_{\delta}}{d_{6,4}} + \left[1 + \left(\frac{l_{\delta}}{d_{6,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{6,4}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,4}}{l_{\delta}} \right)$$

EQUATION A.43 Mutual Inductance Between Conductors 2 and 8

$$M_{2,8} = \frac{1}{2} \left\{ \left(M_{8+2\delta}^{2,8} + M_{8+\delta}^{2,8} \right) - \left(M_{2\delta}^{2,8} + M_{\delta}^{2,8} \right) \right\}$$

where:

$$M_{8+2\delta}^{2,8} = 2l_{8+2\delta} F_{8+2\delta}^{2,8}, \quad M_{8+\delta}^{2,8} = 2l_{8+\delta} F_{8+\delta}^{2,8}$$

$$M_{2\delta}^{2,8} = 2l_{2\delta} F_{2\delta}^{2,8}, \quad M_{\delta}^{2,8} = 2l_{\delta} F_{\delta}^{2,8}$$

$$F_{8+2\delta}^{2,8} = \ln \left\{ \frac{l_{8+2\delta}}{d_{2,8}} + \left[1 + \left(\frac{l_{8+2\delta}}{d_{2,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,8}}{l_{8+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,8}}{l_{8+2\delta}} \right)$$

$$F_{8+\delta}^{2,8} = \ln \left\{ \frac{l_{8+\delta}}{d_{2,8}} + \left[1 + \left(\frac{l_{8+\delta}}{d_{2,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,8}}{l_{8+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,8}}{l_{8+\delta}} \right)$$

$$F_{2\delta}^{2,8} = \ln \left\{ \frac{2\delta}{d_{2,8}} + \left[1 + \left(\frac{2\delta}{d_{2,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,8}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,8}}{l_{2\delta}} \right)$$

$$F_{\delta}^{2,8} = \ln \left\{ \frac{\delta}{d_{2,8}} + \left[1 + \left(\frac{\delta}{d_{2,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,8}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{2,8}}{\delta} \right)$$

EQUATION A.44 Mutual Inductance Between Conductors 10 and 8

$$M_{10,8} = \frac{1}{2} \left\{ \left(M_{10}^{10,8} + M_8^{10,8} \right) - M_{\delta}^{10,8} \right\}$$

where:

$$M_{10}^{10,8} = 2l_6 F_6^{10,8}, \quad M_8^{10,8} = 2l_8 F_8^{10,8}$$

$$M_{\delta}^{10,8} = 2l_{\delta} F_{\delta}^{10,8}$$

$$F_6^{10,8} = \ln \left\{ \frac{l_6}{d_{10,8}} + \left[1 + \left(\frac{l_6}{d_{10,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,8}}{l_6} \right)^2 \right]^{1/2} + \left(\frac{d_{10,8}}{l_6} \right)$$

$$F_8^{10,8} = \ln \left\{ \frac{l_8}{d_{10,8}} + \left[1 + \left(\frac{l_8}{d_{10,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,8}}{l_8} \right)^2 \right]^{1/2} + \left(\frac{d_{10,8}}{l_8} \right)$$

$$F_{\delta}^{10,8} = \ln \left\{ \frac{l_{\delta}}{d_{10,8}} + \left[1 + \left(\frac{l_{\delta}}{d_{10,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,8}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,8}}{l_{\delta}} \right)$$

EQUATION A.45 Mutual Inductance Between Conductors 2 and 12

$$M_{2,12} = \frac{1}{2} \left\{ \left(M_{12+3\delta}^{2,12} + M_{12+2\delta}^{2,12} \right) - \left(M_{3\delta}^{2,12} + M_{2\delta}^{2,12} \right) \right\}$$

where:

$$M_{12+3\delta}^{2,12} = 2l_{12+3\delta} F_{12+3\delta}^{2,12}$$

$$M_{12+2\delta}^{2,12} = 2l_{15+2\delta} F_{12+2\delta}^{2,12}$$

$$M_{3\delta}^{2,12} = 2l_{3\delta} F_{3\delta}^{2,12}, \quad M_{2\delta}^{2,12} = 2l_{2\delta} F_{2\delta}^{2,12}$$

$$F_{12+3\delta}^{2,12} = \ln \left\{ \frac{l_{12+3\delta}}{d_{2,12}} + \left[1 + \left(\frac{l_{12+3\delta}}{d_{2,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,12}}{l_{12+3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,12}}{l_{12+3\delta}} \right)$$

$$F_{12+2\delta}^{2,12} = \ln \left\{ \frac{l_{12+2\delta}}{d_{2,12}} + \left[1 + \left(\frac{l_{12+2\delta}}{d_{2,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,12}}{l_{12+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,12}}{l_{12+2\delta}} \right)$$

$$F_{2\delta}^{2,12} = \ln \left\{ \frac{2\delta}{d_{2,12}} + \left[1 + \left(\frac{2\delta}{d_{2,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,12}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,12}}{l_{2\delta}} \right)$$

$$F_{2\delta}^{2,12} = \ln \left\{ \frac{\delta}{d_{2,12}} + \left[1 + \left(\frac{\delta}{d_{2,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,12}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{2,12}}{\delta} \right)$$

EQUATION A.46 Mutual Inductance Between Conductors 6 and 8

$$M_{6,8} = \frac{1}{2} \left\{ \left(M_6^{6,8} + M_4^{6,8} \right) - M_\delta^{6,8} \right\}$$

where:

$$M_6^{6,8} = 2l_6 F_6^{6,8}$$

$$M_8^{6,8} = 2l_8 F_8^{6,8}$$

$$M_\delta^{6,8} = 2l_\delta F_\delta^{6,8}$$

$$F_6^{6,8} = \ln \left\{ \frac{l_6}{d_{6,8}} + \left[1 + \left(\frac{l_6}{d_{6,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{6,8}}{l_6} \right)^2 \right]^{1/2} + \left(\frac{d_{6,8}}{l_6} \right)$$

$$F_8^{6,8} = \ln \left\{ \frac{l_8}{d_{6,8}} + \left[1 + \left(\frac{l_8}{d_{6,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{6,8}}{l_8} \right)^2 \right]^{1/2} + \left(\frac{d_{6,8}}{l_8} \right)$$

$$F_\delta^{6,8} = \ln \left\{ \frac{l_\delta}{d_{6,8}} + \left[1 + \left(\frac{l_\delta}{d_{6,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{6,8}}{l_\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{6,8}}{l_\delta} \right)$$

EQUATION A.47 Mutual Inductance Between Conductors 2 and 16

$$M_{2,16} = \frac{1}{2} \left\{ \left(M_{16+3\delta}^{2,16} + M_{16+4\delta}^{2,16} \right) - \left(M_{3\delta}^{2,16} + M_{4\delta}^{2,16} \right) \right\}$$

where:

$$M_{16+3\delta}^{2,16} = 2l_{16+3\delta} F_{16+3\delta}^{2,16}$$

$$M_{16+4\delta}^{2,16} = 2l_{16+4\delta} F_{16+4\delta}^{2,16}$$

$$M_{3\delta}^{2,16} = 2l_{3\delta} F_{3\delta}^{2,16}, \quad M_{4\delta}^{2,16} = 2l_{4\delta} F_{4\delta}^{2,16}$$

$$F_{16+3\delta}^{2,16} = \ln \left\{ \frac{l_{16+3\delta}}{d_{2,16}} + \left[1 + \left(\frac{l_{16+3\delta}}{d_{2,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,16}}{l_{16+3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,16}}{l_{16+3\delta}} \right)$$

$$F_{16+4\delta}^{2,16} = \ln \left\{ \frac{l_{16+4\delta}}{d_{2,16}} + \left[1 + \left(\frac{l_{16+4\delta}}{d_{2,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,16}}{l_{16+4\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,16}}{l_{16+4\delta}} \right)$$

$$F_{2\delta}^{2,16} = \ln \left\{ \frac{2\delta}{d_{2,16}} + \left[1 + \left(\frac{2\delta}{d_{2,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,16}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{2,16}}{l_{2\delta}} \right)$$

$$F_\delta^{2,16} = \ln \left\{ \frac{\delta}{d_{2,16}} + \left[1 + \left(\frac{\delta}{d_{2,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{2,16}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{2,16}}{\delta} \right)$$

EQUATION A.48 Mutual Inductance Between Conductors 14 and 16

$$M_{14,16} = \frac{1}{2} \left\{ \left(M_{14}^{14,16} + M_{12}^{14,16} \right) - M_{\delta}^{14,16} \right\}$$

where:

$$M_{14}^{14,16} = 2l_{14}F_{14}^{14,16}, \quad M_{12}^{14,16} = 2l_{12}F_{12}^{14,16}$$

$$M_{\delta}^{14,16} = 2l_{\delta}F_{\delta}^{14,16}$$

$$F_{14}^{14,16} = \ln \left\{ \frac{l_{14}}{d_{14,16}} + \left[1 + \left(\frac{l_{14}}{d_{14,16}} \right)^2 \right]^{1/2} \right\}$$

$$- \left[1 + \left(\frac{d_{14,16}}{l_{14}} \right)^2 \right]^{1/2} + \left(\frac{d_{14,16}}{l_{14}} \right)$$

$$F_{16}^{14,16} = \ln \left\{ \frac{l_{16}}{d_{14,16}} + \left[1 + \left(\frac{l_{16}}{d_{14,16}} \right)^2 \right]^{1/2} \right\}$$

$$- \left[1 + \left(\frac{d_{14,16}}{l_{16}} \right)^2 \right]^{1/2} + \left(\frac{d_{14,16}}{l_{16}} \right)$$

$$F_{\delta}^{14,16} = \ln \left\{ \frac{l_{\delta}}{d_{14,16}} + \left[1 + \left(\frac{l_{\delta}}{d_{14,16}} \right)^2 \right]^{1/2} \right\}$$

$$- \left[1 + \left(\frac{d_{14,16}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{14,16}}{l_{\delta}} \right)$$

EQUATION A.50 Mutual Inductance Between Conductors 10 and 12

$$M_{10,12} = \frac{1}{2} \left\{ \left(M_{10}^{10,12} + M_{12}^{10,12} \right) - M_{\delta}^{10,12} \right\}$$

where:

$$M_{10}^{10,12} = 2l_{10}F_{10}^{10,12}, \quad M_{12}^{10,12} = 2l_{12}F_{12}^{10,12}$$

$$M_{\delta}^{10,12} = 2l_{\delta}F_{\delta}^{10,12}$$

$$F_{10}^{10,12} = \ln \left\{ \frac{l_{10}}{d_{10,12}} + \left[1 + \left(\frac{l_{10}}{d_{10,12}} \right)^2 \right]^{1/2} \right\}$$

$$- \left[1 + \left(\frac{d_{10,12}}{l_{10}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,12}}{l_{10}} \right)$$

$$F_{12}^{10,12} = \ln \left\{ \frac{l_{12}}{d_{10,12}} + \left[1 + \left(\frac{l_{12}}{d_{10,12}} \right)^2 \right]^{1/2} \right\}$$

$$- \left[1 + \left(\frac{d_{10,12}}{l_{12}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,12}}{l_{12}} \right)$$

$$F_{\delta}^{10,12} = \ln \left\{ \frac{l_{\delta}}{d_{10,12}} + \left[1 + \left(\frac{l_{\delta}}{d_{10,12}} \right)^2 \right]^{1/2} \right\}$$

$$- \left[1 + \left(\frac{d_{10,12}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,12}}{l_{\delta}} \right)$$

EQUATION A.49 Mutual Inductance Between Conductors 6 and 12

$$M_{6,12} = \frac{1}{2} \left\{ \left(M_{12+2\delta}^{6,12} + M_{12+\delta}^{6,12} \right) - \left(M_{2\delta}^{6,12} + M_{\delta}^{6,12} \right) \right\}$$

where:

$$M_{12+2\delta}^{6,12} = 2l_{12+2\delta}F_{12+2\delta}^{6,12}, \quad M_{12+\delta}^{6,12} = 2l_{12+\delta}F_{12+\delta}^{6,12}$$

$$M_{2\delta}^{6,12} = 2l_{2\delta}F_{2\delta}^{6,12}, \quad M_{\delta}^{6,12} = 2l_{\delta}F_{\delta}^{6,12}$$

$$F_{12+2\delta}^{6,12} = \ln \left\{ \frac{l_{12+2\delta}}{d_{6,12}} + \left[1 + \left(\frac{l_{12+2\delta}}{d_{6,12}} \right)^2 \right]^{1/2} \right\}$$

$$- \left[1 + \left(\frac{d_{6,12}}{l_{12+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,12}}{l_{12+2\delta}} \right)$$

$$F_{12+\delta}^{6,12} = \ln \left\{ \frac{l_{12+\delta}}{d_{6,12}} + \left[1 + \left(\frac{l_{12+\delta}}{d_{6,12}} \right)^2 \right]^{1/2} \right\}$$

$$- \left[1 + \left(\frac{d_{6,12}}{l_{12+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,12}}{l_{12+\delta}} \right)$$

$$F_{2\delta}^{6,12} = \ln \left\{ \frac{2\delta}{d_{6,12}} + \left[1 + \left(\frac{2\delta}{d_{6,12}} \right)^2 \right]^{1/2} \right\}$$

$$- \left[1 + \left(\frac{d_{6,12}}{2\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{6,12}}{2\delta} \right)$$

$$F_{\delta}^{6,12} = \ln \left\{ \frac{\delta}{d_{6,12}} + \left[1 + \left(\frac{\delta}{d_{6,12}} \right)^2 \right]^{1/2} \right\}$$

$$- \left[1 + \left(\frac{d_{6,12}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{6,12}}{\delta} \right)$$

EQUATION A.51 Mutual Inductance Between Conductors 6 and 16

$$M_{6,16} = \frac{1}{2} \left\{ \left(M_{16+3\delta}^{6,16} + M_{16+2\delta}^{6,16} \right) - \left(M_{3\delta}^{6,16} + M_{2\delta}^{6,16} \right) \right\}$$

where:

$$M_{16+3\delta}^{6,16} = 2l_{16+3\delta} F_{16+3\delta}^{6,16}$$

$$M_{16+2\delta}^{6,16} = 2l_{16+2\delta} F_{16+2\delta}^{6,16}$$

$$M_{3\delta}^{6,16} = 2l_{3\delta} F_{3\delta}^{6,16}, \quad M_{2\delta}^{6,16} = 2l_{2\delta} F_{2\delta}^{6,16}$$

$$F_{16+3\delta}^{6,16} = \ln \left\{ \frac{l_{16+3\delta}}{d_{6,16}} + \left[1 + \left(\frac{l_{16+3\delta}}{d_{6,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{6,16}}{l_{16+3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,16}}{l_{16+3\delta}} \right)$$

$$F_{16+2\delta}^{6,16} = \ln \left\{ \frac{l_{16+2\delta}}{d_{6,16}} + \left[1 + \left(\frac{l_{16+2\delta}}{d_{6,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{6,16}}{l_{16+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,16}}{l_{16+2\delta}} \right)$$

$$F_{3\delta}^{6,16} = \ln \left\{ \frac{l_{3\delta}}{d_{6,16}} + \left[1 + \left(\frac{l_{3\delta}}{d_{6,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{6,16}}{l_{3\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,16}}{l_{3\delta}} \right)$$

$$F_{2\delta}^{6,16} = \ln \left\{ \frac{l_{2\delta}}{d_{6,16}} + \left[1 + \left(\frac{l_{2\delta}}{d_{6,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{6,16}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{6,16}}{l_{2\delta}} \right)$$

EQUATION A.52 Mutual Inductance Between Conductors 10 and 4

$$M_{10,4} = \frac{1}{2} \left\{ \left(M_{12+2\delta}^{10,4} + M_{12+\delta}^{10,4} \right) - \left(M_{2\delta}^{10,4} + M_{\delta}^{10,4} \right) \right\}$$

where:

$$M_{10+2\delta}^{10,4} = 2l_{10+2\delta} F_{10+2\delta}^{10,4}, \quad M_{\delta}^{10,4} = 2l_{\delta} F_{\delta}^{10,4}$$

$$M_{2\delta}^{10,4} = 2l_{2\delta} F_{2\delta}^{10,4}, \quad M_{10+\delta}^{10,4} = 2l_{10+\delta} F_{10+\delta}^{10,4}$$

$$F_{10+2\delta}^{10,4} = \ln \left\{ \frac{l_{10+2\delta}}{d_{10,4}} + \left[1 + \left(\frac{l_{10+2\delta}}{d_{10,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,4}}{l_{10+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,4}}{l_{10+2\delta}} \right)$$

$$F_{10+\delta}^{10,4} = \ln \left\{ \frac{l_{10+\delta}}{d_{10,4}} + \left[1 + \left(\frac{l_{10+\delta}}{d_{10,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,4}}{l_{10+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,4}}{l_{10+\delta}} \right)$$

$$F_{2\delta}^{10,4} = \ln \left\{ \frac{2\delta}{d_{10,4}} + \left[1 + \left(\frac{2\delta}{d_{10,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,4}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,4}}{l_{2\delta}} \right)$$

$$F_{\delta}^{10,4} = \ln \left\{ \frac{\delta}{d_{10,4}} + \left[1 + \left(\frac{\delta}{d_{10,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,4}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{10,4}}{\delta} \right)$$

EQUATION A.53 Mutual Inductance Between Conductors 10 and 8

$$M_{14,12} = \frac{1}{2} \left\{ (M_{14}^{14,12} + M_{12}^{14,12}) - M_{\delta}^{14,12} \right\}$$

where:

$$M_{14}^{14,12} = 2l_{14}F_{14}^{14,12}, \quad M_{12}^{14,12} = 2l_{12}F_{12}^{14,12}$$

$$M_{\delta}^{14,12} = 2l_{\delta}F_{\delta}^{14,12}$$

$$F_{14}^{14,12} = \ln \left\{ \frac{l_{14}}{d_{14,12}} + \left[1 + \left(\frac{l_{14}}{d_{14,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,12}}{l_{14}} \right)^2 \right]^{1/2} + \left(\frac{d_{14,12}}{l_{14}} \right)$$

$$F_{12}^{14,12} = \ln \left\{ \frac{l_{12}}{d_{10,8}} + \left[1 + \left(\frac{l_{12}}{d_{14,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,12}}{l_{12}} \right)^2 \right]^{1/2} + \left(\frac{d_{14,12}}{l_{12}} \right)$$

$$F_{\delta}^{14,12} = \ln \left\{ \frac{l_{\delta}}{d_{14,12}} + \left[1 + \left(\frac{l_{\delta}}{d_{14,12}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,12}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{14,12}}{l_{\delta}} \right)$$

EQUATION A.54 Mutual Inductance Between Conductors 10 and 16

$$M_{10,16} = \frac{1}{2} \left\{ (M_{16+2\delta}^{10,16} + M_{16+\delta}^{10,16}) - (M_{2\delta}^{10,16} + M_{\delta}^{10,16}) \right\}$$

where:

$$M_{16+2\delta}^{10,16} = 2l_{16+2\delta}F_{16+2\delta}^{10,16}, \quad M_{16+\delta}^{10,16} = 2l_{16+\delta}F_{16+\delta}^{10,16}$$

$$M_{2\delta}^{10,16} = 2l_{2\delta}F_{2\delta}^{10,16}, \quad M_{\delta}^{10,16} = 2l_{\delta}F_{\delta}^{10,16}$$

$$F_{16+2\delta}^{10,16} = \ln \left\{ \frac{l_{16+2\delta}}{d_{10,16}} + \left[1 + \left(\frac{l_{16+2\delta}}{d_{10,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,16}}{l_{16+2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,16}}{l_{16+2\delta}} \right)$$

$$F_{16+\delta}^{10,16} = \ln \left\{ \frac{l_{16+\delta}}{d_{10,16}} + \left[1 + \left(\frac{l_{16+\delta}}{d_{10,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,16}}{l_{16+\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,16}}{l_{16+\delta}} \right)$$

$$F_{2\delta}^{10,16} = \ln \left\{ \frac{l_{2\delta}}{d_{10,16}} + \left[1 + \left(\frac{l_{2\delta}}{d_{10,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,16}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{10,16}}{l_{2\delta}} \right)$$

$$F_{\delta}^{10,16} = \ln \left\{ \frac{\delta}{d_{10,16}} + \left[1 + \left(\frac{\delta}{d_{10,16}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{10,16}}{\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{10,16}}{\delta} \right)$$

EQUATION A.55 Mutual Inductance Between Conductor 1 and other Conductors

$$M_{1,3} = M_1^{1,3} = M_3^{1,3} = 2l_1F_1^{1,3}$$

$$M_{1,5} = \frac{1}{2} \{ (M_1^{1,5} + M_5^{1,5}) - M_d^{1,5} \}$$

$$M_{1,7} = M_{7+d}^{1,7} - M_d^{1,7}$$

$$M_{1,9} = \frac{1}{2} \{ (M_{9+2d}^{1,9} + M_{9+d}^{1,9}) - (M_{2d}^{1,9} + M_d^{1,9}) \}$$

$$M_{1,11} = M_{11+2d}^{1,11} - M_{2d}^{1,11}$$

$$M_{1,13} = \frac{1}{2} \{ (M_{13+3d}^{1,13} + M_{13+2d}^{1,13}) - (M_{3d}^{1,13} + M_{2d}^{1,13}) \}$$

$$M_{1,15} = M_{15+3d}^{1,15} - M_{3d}^{1,15}$$

EQUATION A.56 Mutual Inductance Between Conductors 14 and 4

$$M_{14,4} = \frac{1}{2} \left\{ (M_{14+3\delta}^{14,4} + M_{14+2\delta}^{14,4}) - (M_{3\delta}^{14,4} + M_{2\delta}^{14,4}) \right\}$$

where:

$$M_{16+3\delta}^{14,4} = 2l_{16+3\delta} F_{16+3\delta}^{14,4}$$

$$M_{16+2\delta}^{14,4} = 2l_{16+2\delta} F_{16+2\delta}^{14,4}$$

$$M_{3\delta}^{14,4} = 2l_{3\delta} F_{3\delta}^{14,4}, \quad M_{2\delta}^{14,4} = 2l_{2\delta} F_{2\delta}^{14,4}$$

$$F_{14+3\delta}^{14,4} = \ln \left\{ \frac{l_{14+3\delta}}{d_{14,4}} + \left[1 + \left(\frac{l_{14+3\delta}}{d_{14,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,4}}{14+3\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{14,4}}{14+3\delta} \right)$$

$$F_{14+2\delta}^{14,4} = \ln \left\{ \frac{l_{14+2\delta}}{d_{14,4}} + \left[1 + \left(\frac{l_{14+2\delta}}{d_{14,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,4}}{14+2\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{14,4}}{14+2\delta} \right)$$

$$F_{2\delta}^{14,4} = \ln \left\{ \frac{l_{2\delta}}{d_{14,4}} + \left[1 + \left(\frac{l_{2\delta}}{d_{14,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,4}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{14,4}}{l_{2\delta}} \right)$$

$$F_{2\delta}^{14,4} = \ln \left\{ \frac{l_{2\delta}}{d_{14,4}} + \left[1 + \left(\frac{l_{2\delta}}{d_{14,4}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,4}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{14,4}}{l_{2\delta}} \right)$$

EQUATION A.57 Mutual Inductance Between Conductor 2 and other Conductors

$$M_{2,6} = M_{\delta+d}^{2,6} - M_d^{2,6}$$

$$M_{2,4} = \frac{1}{2} \{ (M_2^{2,4} + M_4^{2,4}) - M_d^{2,4} \}$$

$$M_{2,10} = M_{10+2d}^{2,10} - M_{2d}^{2,10}$$

$$M_{2,12} = \frac{1}{2} \{ (M_{12+2d}^{2,12} + M_{12+3d}^{2,12}) - (M_{2d}^{2,12} + M_{3d}^{2,12}) \}$$

$$M_{2,14} = M_{14+3d}^{2,14} - M_{3d}^{2,14}$$

$$M_{2,16} = \frac{1}{2} \{ (M_{16+3d}^{2,16} + M_{16+4d}^{2,16}) - (M_{3d}^{2,16} + M_{2d}^{2,16}) \}$$

$$M_{2,8} = \frac{1}{2} \{ (M_{8+2\delta}^{2,8} + M_{8+\delta}^{2,8}) - (M_{2\delta}^{2,8} + M_{\delta}^{2,8}) \}$$

EQUATION A.58 Mutual Inductance Between Conductors 14 and 8

$$M_{14,8} = \frac{1}{2} \left\{ (M_{14+2\delta}^{14,8} + M_{14+\delta}^{14,8}) - (M_{2\delta}^{14,8} + M_{\delta}^{14,8}) \right\}$$

where:

$$M_{14+2\delta}^{14,8} = 2l_{14+2\delta} F_{14+2\delta}^{14,8}, \quad M_{14+\delta}^{14,8} = 2l_{14+\delta} F_{14+\delta}^{14,8}$$

$$M_{2\delta}^{14,8} = 2l_{2\delta} F_{2\delta}^{14,8}, \quad M_{\delta}^{14,8} = 2l_{\delta} F_{\delta}^{14,8}$$

$$F_{14+2\delta}^{14,8} = \ln \left\{ \frac{l_{14+2\delta}}{d_{14,8}} + \left[1 + \left(\frac{l_{14+2\delta}}{d_{14,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,8}}{14+2\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{14,8}}{14+2\delta} \right)$$

$$F_{14+\delta}^{14,8} = \ln \left\{ \frac{l_{14+\delta}}{d_{14,8}} + \left[1 + \left(\frac{l_{14+\delta}}{d_{14,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,8}}{14+\delta} \right)^2 \right]^{1/2} + \left(\frac{d_{14,8}}{14+\delta} \right)$$

$$F_{2\delta}^{14,8} = \ln \left\{ \frac{l_{2\delta}}{d_{14,8}} + \left[1 + \left(\frac{l_{2\delta}}{d_{14,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,8}}{l_{2\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{14,8}}{l_{2\delta}} \right)$$

$$F_{\delta}^{14,8} = \ln \left\{ \frac{l_{\delta}}{d_{14,8}} + \left[1 + \left(\frac{l_{\delta}}{d_{14,8}} \right)^2 \right]^{1/2} \right\} - \left[1 + \left(\frac{d_{14,8}}{l_{\delta}} \right)^2 \right]^{1/2} + \left(\frac{d_{14,8}}{l_{\delta}} \right)$$

EQUATION A.59 Mutual Inductance Between Conductor 5 and other Conductors

$$M_{5,9} = M_{9+d}^{5,9} - M_d^{5,9}$$

$$M_{5,7} = \frac{1}{2} \{ (M_5^{5,7} + M_7^{5,7}) - M_d^{5,7} \}$$

$$M_{5,3} = \frac{1}{2} \{ (M_5^{5,3} + M_3^{5,3}) - M_d^{5,3} \}$$

$$M_{5,11} = \frac{1}{2} \{ (M_{11+d}^{5,11} + M_{11+2d}^{5,11}) - (M_d^{5,11} + M_{2d}^{5,11}) \}$$

$$M_{5,13} = M_{13+2d}^{5,13} - M_{2d}^{5,13}$$

$$M_{5,15} = \frac{1}{2} \{ (M_{15+2d}^{5,15} + M_{15+3d}^{5,15}) - (M_{3d}^{5,15} + M_{2d}^{5,15}) \}$$

EQUATION A.60 Mutual Inductance Between Conductor 9 and other Conductors

$$M_{9,3} = \frac{1}{2} \{ (M_{9+2d}^{9,3} + M_{9+d}^{9,3}) - (M_{2d}^{9,3} + M_d^{9,3}) \}$$

$$M_{9,7} = \frac{1}{2} \{ (M_9^{9,7} + M_7^{9,7}) - M_d^{9,7} \}$$

$$M_{9,11} = \frac{1}{2} \{ (M_9^{9,11} + M_{11}^{9,11}) - M_d^{9,11} \}$$

$$M_{9,13} = M_{13+d}^{9,13} - M_d^{9,13}$$

EQUATION A.61 Mutual Inductance Between Conductor 13 and other Conductors

$$M_{13,3} = \frac{1}{2} \{ (M_{13+3d}^{13,3} + M_{13+2d}^{13,3}) - (M_{3d}^{13,3} + M_{2d}^{13,3}) \}$$

$$M_{13,7} = \frac{1}{2} \{ (M_{13+2d}^{13,7} + M_{13+d}^{13,7}) - (M_{2d}^{13,7} + M_d^{13,7}) \}$$

$$M_{13,11} = \frac{1}{2} \{ (M_{13}^{13,11} + M_{11}^{13,11}) - M_d^{13,11} \}$$

$$M_{13,15} = \frac{1}{2} \{ (M_{13}^{13,15} + M_{15}^{13,15}) - M_d^{13,15} \}$$

EQUATION A.62 Mutual Inductance Between Conductors 15, 11, 7 and other Conductors

$$M_{15,11} = M_{15+d}^{15,11} - M_d^{15,11}$$

$$M_{15,7} = M_{15+2d}^{15,7} - M_{2d}^{15,7}$$

$$M_{15,3} = M_{15+3d}^{15,3} - M_{3d}^{15,3}$$

$$M_{11,7} = M_{11+d}^{11,7} - M_d^{11,7}$$

$$M_{11,3} = M_{11+2d}^{11,3} - M_{2d}^{11,3}$$

$$M_{7,3} = M_{7+d}^{7,3} - M_d^{7,3}$$

EQUATION A.63 Mutual Inductance Between Conductor 6 and other Conductors

$$M_{6,10} = M_{10+d}^{6,10} - M_d^{6,10}$$

$$M_{6,14} = M_{14+2d}^{6,14} - M_{2d}^{6,14}$$

$$M_{6,16} = \frac{1}{2} \{ (M_{16+2d}^{6,16} + M_{16+3d}^{6,16}) - (M_{2d}^{6,16} + M_{3d}^{6,16}) \}$$

$$M_{6,12} = \frac{1}{2} \{ (M_{12+2d}^{6,12} + M_{12+d}^{6,12}) - (M_{2d}^{6,12} + M_d^{6,12}) \}$$

$$M_{6,8} = \frac{1}{2} \{ (M_6^{6,8} + M_8^{6,8}) - M_d^{6,8} \}$$

$$M_{6,4} = \frac{1}{2} \{ (M_6^{6,4} + M_4^{6,4}) - M_d^{6,4} \}$$

EQUATION A.64 Mutual Inductance Between Conductor 10 and other Conductors

$$M_{10,14} = M_{14+d}^{10,14} - M_d^{10,14}$$

$$M_{10,16} = \frac{1}{2} \{ (M_{16+2d}^{10,16} + M_{16+d}^{10,16}) - (M_{2d}^{10,16} + M_d^{10,16}) \}$$

$$M_{10,12} = \frac{1}{2} \{ (M_{10}^{10,12} + M_{12}^{10,12}) - M_d^{10,12} \}$$

$$M_{10,8} = \frac{1}{2} \{ (M_{10}^{10,8} + M_8^{10,8}) - M_d^{10,8} \}$$

$$M_{10,4} = \frac{1}{2} \{ (M_{10+d}^{10,4} + M_{10+2d}^{10,4}) - (M_d^{10,4} + M_{2d}^{10,4}) \}$$

EQUATION A.65 Mutual Inductance Between Conductors 16, 12, 8 and other Conductors

$$M_{16,12} = M_{16+d}^{16,12} - M_d^{16,12}$$

$$M_{16,8} = M_{16+2d}^{16,8} - M_{2d}^{16,8}$$

$$M_{16,4} = M_{16+3d}^{16,4} - M_{3d}^{16,4}$$

$$M_{12,8} = M_{12+d}^{12,8} - M_d^{12,8}$$

$$M_{12,4} = M_{12+2d}^{12,4} - M_{2d}^{12,4}$$

$$M_{8,4} = M_{8+d}^{8,4} - M_d^{8,4}$$

APPENDIX B: MATHLAB PROGRAM EXAMPLE FOR EXAMPLE 8

```

% One_turn.m
% Inductance calculation with mutual inductance terms
% for 1 turn rectangular shape.
% Inductor type = Etched MCRF450 reader antenna
%
% Youbok Lee
%
% Microchip Technology Inc.
%-----
% L_T = L_o + M_+ M_- (nH)
% unit = cm
% where
% L_o = L1 + L2 + L3+ L4 = (self inductance)
% M_- = Negative mutual inductance
% M_+ = positive mutual inductance = 0 for 1 turn coil
%
%----- Length of each conductor -----
% l_1a = l_1b = 3" = 7.62 Cm
% l_2 = l_4 = 10" = 25.4 Cm
% l_4 = 7.436" = 18.887 Cm
% gap = 3.692 cm
%-----Define segment length (cm) -----
w = 0.508
t = 0.0001
gap = 3.692
l_1A = 7.62 - w/2.
l_1B = 7.62 - w/2.
l_2 = 25.4 - w
l_3 = 18.887 - w
l_4 = 25.4 - w
%----- distance between branches (cm) -----
d13 = l_2
d24 = l_3
%-----calculate self inductance -----
L1A = 2*l_1A*(log((2*l_1A)/(w+t)) + 0.50049 + (w+t)/(3*l_1A))
L1B = 2*l_1B*(log((2*l_1B)/(w+t)) + 0.50049 + (w+t)/(3*l_1B))

L2 = 2*l_2*(log((2*l_2)/(w+t)) + 0.50049 + (w+t)/(3*l_2))
L3 = 2*l_3*(log((2*l_3)/(w+t)) + 0.50049 + (w+t)/(3*l_3))

L4 = 2*l_4*(log((2*l_4)/(w+t)) + 0.50049 + (w+t)/(3*l_4))

```

AN710

$$L_o = L1A + L1B + L2 + L3 + L4$$

%----- calculate mutual inductance parameters ----

$$Q1A_3 = \log((l_{1A}/d13) + (1 + (l_{1A}/d13)^2)^{0.5}) - (1 + (d13/l_{1A})^2)^{0.5} + (d13/l_{1A})$$

$$Q1B_3 = \log((l_{1B}/d13) + (1 + (l_{1B}/d13)^2)^{0.5}) - (1 + (d13/l_{1B})^2)^{0.5} + (d13/l_{1B})$$

$$Q_1A_gap = \log(((l_{1A}+gap)/d13) + (1 + ((l_{1A}+gap)/d13)^2)^{0.5}) - (1 + (d13/(l_{1A}+gap))^2)^{0.5} + (d13/(l_{1A}+gap))$$

$$Q_1B_gap = \log(((l_{1B}+gap)/d13) + (1 + ((l_{1B}+gap)/d13)^2)^{0.5}) - (1 + (d13/(l_{1B}+gap))^2)^{0.5} + (d13/(l_{1B}+gap))$$

$$Q3 = \log((l_3/d13) + (1 + (l_3/d13)^2)^{0.5}) - (1 + (d13/l_3)^2)^{0.5} + (d13/l_3)$$

$$Q2_4 = \log((l_2/d24) + (1 + (l_2/d24)^2)^{0.5}) - (1 + (d24/l_2)^2)^{0.5} + (d24/l_2)$$

%----- calculate negative mutual inductance -----

%

$$M1A = 2 * l_{1A} * Q1A_3$$

$$M1B = 2 * l_{1B} * Q1B_3$$

$$M1A_gap = 2 * (l_{1A}+gap) * Q_1A_gap$$

$$M1B_gap = 2 * (l_{1B}+gap) * Q_1B_gap$$

$$M3 = 2 * l_3 * Q3$$

$$M1A_3 = (M1A + M3 - M1B_gap) / 2.$$

$$M1B_3 = (M1B + M3 - M1A_gap) / 2.$$

$$M2_4 = 2 * (l_2 * Q2_4)$$

$$M_T = 2 * (M1A_3 + M1B_3 + M2_4)$$

%----- Total Inductance (nH) -----

$$L_T = L_o - M_T$$

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AN710

NOTES:



MICROCHIP MCRF355/360 REFERENCE DESIGN

MCRF355/360 Reader Reference Design

1.0 INTRODUCTION

This chapter provides a reference guide for the 13.56 MHz reader designer. The schematic included in this chapter is for the 13.56 MHz Reference Reader included in the DV103003 microID[®] Developer's Kit. The circuit is designed for short read-range applications. The basic design can be modified for long-range or other applications with MCRF355/360 devices. An electronic copy of the PICmicro[®] microcontroller source code is available upon request.

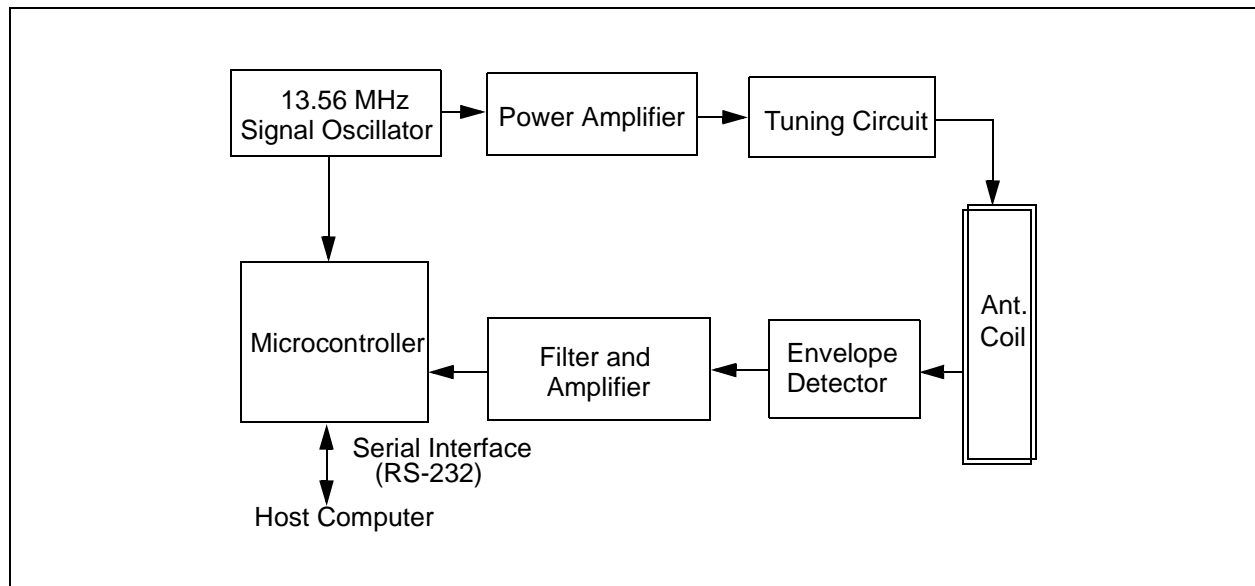
2.0 READER CIRCUITS

The RFID reader consists of transmitting and receiving sections. It transmits a carrier signal (13.56 MHz), receives the backscattered signal from the tag, and performs data processing. The reader also communicates with an external host computer. A basic block diagram of a typical RFID reader is shown in Figure 2-1.

The transmitting section contains a 13.56 MHz signal oscillator (74HC04), power amplifier (Q2), and RF tuning circuits. The tuning circuit matches impedance between the antenna coil circuit and the power driver at 13.56 MHz. The radiating signal strength from the antenna must comply with government regulations. For best performance, the antenna coil circuit must be tuned to the same frequency of the tag. The design for antenna circuits is given in Application Note AN710 (DS00710).

The receiving section contains an envelope detector (D6), hi-pass filters, and amplifiers (U2 and U3). When the tag is energized, it transmits 154 bits of data that is encoded in Biphase-L (Manchester). In the Manchester encoding, data '1' is represented by a logic high-to-low level change at midclock, and data '0' is represented by a low-to-high level change at midclock. There is always a level change at middle of every bit clock.

FIGURE 2-1: FUNCTIONAL BLOCK DIAGRAM OF TYPICAL RFID READER



MCRF355/360 REFERENCE DESIGN

FIGURE 2-2: SIGNAL WAVEFORMS

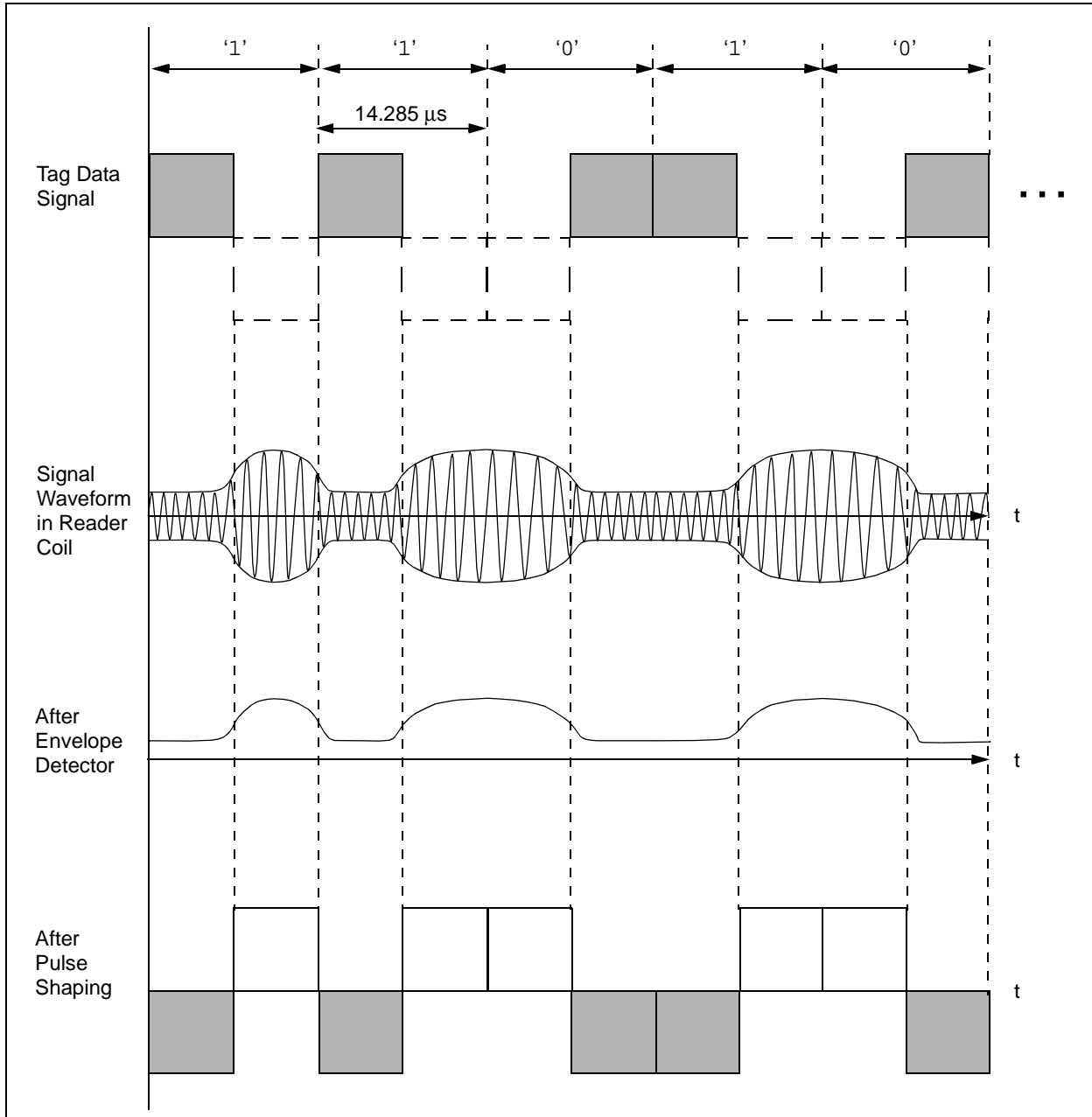
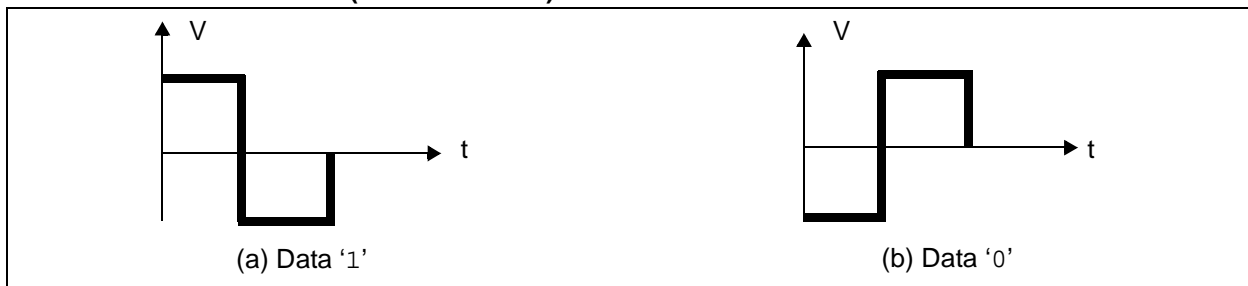


FIGURE 2-3: BIPHASE-L (MANCHESTER) SIGNAL



When the tag is energized by the reader's carrier signal, it transmits back with an amplitude modulated signal. This results in a perturbation in the voltage amplitude across the reader antenna coil. The envelope detector detects the changes in the voltage amplitude and passes it into an RC filter (R7, C11). The charged signal in the capacitor passes through active filters and amplifiers. The signal that is passing through this receiving section is the data signal. This filtered-shaped data signal is fed into Pin 10 of the microcontroller for data processing.

2.1 FCC Specifications on Transmitting Signal

Each country limits the signal strength of the radio frequency signal that is intentionally radiated from the device. In the USA, the maximum signal strength that is radiated from the device is regulated by Federal Communication Commission (FCC). Any device operating at 13.56 MHz frequency band must comply with the FCC Part 15.225 of the federal regulation. FCC limits for 13.56 MHz frequency band are as follows:

1. Tolerance of the carrier frequency: 13.56 MHz
+/- 0.01% = +/- 7 kHz.
2. Frequency bandwidth: +/- 7 kHz.
3. Power level of fundamental frequency: 10 mv/m at 30 meters from the transmitter.
4. Power level for harmonics: -50.45 dB down from the fundamental signal.

The transmission circuit including the antenna coil must be designed to meet the FCC limits.

3.0 OPTIMIZATION FOR LONG-RANGE APPLICATIONS

The reader circuit provided is designed for about a 5-inch read-range, using a 2-inch by 2-inch tag coil that is printed on PCB with the MCRF355. The read-range can be increased by increasing the reader power, sensitivity, and antenna size. A read-range of more than 30-inches can be achieved with the MCRF355 and an optimized reader. In order to optimize the reader circuit for long-range applications, the following aspects may be considered:

1. **Optimize the output power level within FCC limits.** The reader should provide a sufficient signal level to the tag. The tag needs about 4 V_{PP} across the coil circuit for operation. The power level radiating from the reader antenna must comply to the government regulations such as FCC specifications in the USA. The FCC limits for 13.56 MHz band are described in Section 2.1. For long-range applications, the designer may start with about 50 V_{PP} of antenna voltage and optimize the signal strength for a read-range within the government regulations.
2. **Increase the size of the antenna.** The read-range, in general, is proportional to the size of the reader coil (see Equation 12 in Application Note 710). An optimum radius of antenna is 1.414 times of the read-range.
3. **Increase the Q of the antenna circuit.** The read-range increases with Q of the antenna circuit. This is because the induced voltage is directly proportional to Q of the circuit. The recommended Q for long-range applications is as follows:

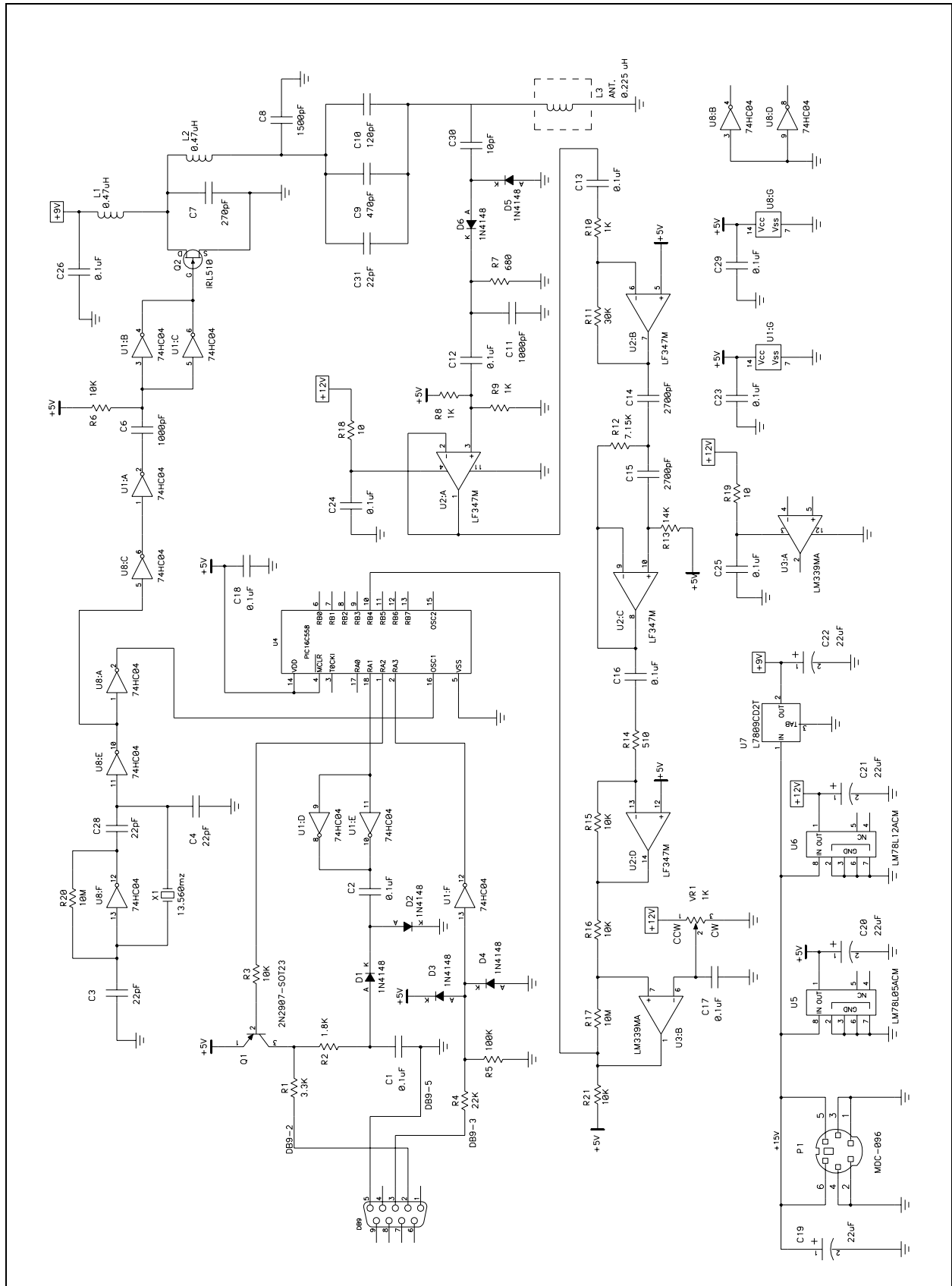
$$\begin{array}{ll} 40 < Q < 96 & \text{for reader} \\ 40 < Q & \text{for tag} \end{array}$$

MCRF355/360 REFERENCE DESIGN

4. **Optimize the input sensitivity of the reader.** The sensitivity is a measure of how weak a signal can be and still be satisfactorily received. The sensitivity is proportional to the carrier power and square of the modulation index (1 for 100% modulation such as MCRF355). It is inversely proportional to the noise signal. The limit to the sensitivity of the receiving section of the reader is noise, both external and internal. The external noises may come from various sources such as computers, televisions, appliances, motors, power lines, transformers, etc. The internal noise is mostly due to a thermal noise of components. To reduce noise, the reader should be operated a distance away from the noise sources. The receiving section may have a 70 kHz bandpass filter to reduce the noises. The 70 kHz bandpass filter will pass only the 70 kHz data signal for processing. The receiving section should have sensitivity of about -120 dBm for long-range applications.
5. **Optimize the amplitude gain circuit.** The receiving circuit amplifies the modulated signals before data processing. The input signal contains both real data and noise. Typically, op amplifiers are used for both as a gain amplifier and filter. The gain must be optimized within the circuit to obtain gains only at the real data signal.

MCRF355/360 REFERENCE DESIGN

4.0 READER SCHEMATIC



MCRF355/360 REFERENCE DESIGN

5.0 READER BILL OF MATERIALS

| Assembly # | Line # | Qty | Part # | Part Description | Reference Designator |
|------------|--------|-----|-----------------|---|---|
| 02-01523 | 1 | 1 | 02-01523-D | PCB ASSY DWG, MCRF355 microID READER | — |
| 02-01523 | 2 | 1 | 03-01523 | SCHEMATIC, MCRF355 microID READER | — |
| 02-01523 | 3 | 1 | 04-01523 | PCB FABRICATION, MCRF355 microID READER | — |
| 02-01523 | 4 | 2 | MM74HC04M | IC, SMT, CMOS HEX INVERTER, 14P SOIC | U1, U8 |
| 02-01523 | 5 | 1 | LF347M | IC, SMT, QUAD BI-FET OP AMP, 14P SOIC | U2 |
| 02-01523 | 6 | 1 | LM339M | IC, SMT, LOW POWER LOW OFFSET VOLT QUAD COMPARATORS, 14P SOIC | U3 |
| 02-01523 | 7 | 1 | PIC16C558-20/SO | IC, PIC16C558-20/SO EPROM-BASED 8-BIT CMOS MICROCONTROLLER | U4 |
| 02-01523 | 8 | 1 | LM78L05ACM | IC, REG, +5V 100 mA REGULATOR | U5 |
| 02-01523 | 9 | 1 | LM78L12ACM | IC, REG, +12V 100 mA REGULATOR | U6 |
| 02-01523 | 10 | 1 | L7809CD2T | IC, +9V, REG 1.5A TO-263 | U7 |
| 02-01523 | 11 | 1 | MMBT2907ALT1 | TRANSISTOR, PNP, 2N2907A, SOT-23 | Q1 Flip upside and bend legs toward the PCB |
| 02-01523 | 12 | 1 | IRL510 | TRANSISTOR, N-CHANNEL HEX FET, TO220AB | Q2 |
| 02-01523 | 13 | 6 | RLS4148TE11C | DIODE SMT, ROHM DIODE LL-34 SIG DIODE | D1-D6 |
| 02-01523 | 14 | 1 | ERJ-3GSYJ332V | RES SMT, 3.3K OHM, 1/16W, 5%, 0603 | R1 |
| 02-01523 | 15 | 1 | ERJ-3GSYJ182V | RES SMT, 1.8K OHM, 1/16W, 5%, 0603 | R2 |
| 02-01523 | 16 | 5 | ERJ-3GSYJ103V | RES SMT, 10K OHM, 1/16 W, 5%, 0603 | R3, R6, R15, R16, R21 |
| 02-01523 | 17 | 1 | ERJ-3GSYJ223V | RES SMT, 22K OHM, 5% 0603 | R4 |
| 02-01523 | 18 | 1 | ERJ-3GSYJ104V | RES SMT, 100K OHM 1/16W 5% TYPE 0603 | R5 |
| 02-01523 | 19 | 1 | ERJ-3GSYJ681V | RES SMT, 680 OHM 1/16W 5% 0603 | R7 |
| 02-01523 | 20 | 3 | ERJ-3GSYJ102V | RES SMT, 1K OHM 1/16W 5% 0603 | R8-R10 |
| 02-01523 | 21 | 1 | ERJ-3GSYJ303V | RES SMT, 30K OHM 1/16W 5% 0603 | R11 |
| 02-01523 | 22 | 1 | ERJ-3EKF7151V | RES SMT, 7.15K OHM 1/16W 1% 0603 | R12 |
| 02-01523 | 23 | 1 | MFR-25FRF 14K0 | RES, 14K OHM 1/4W 1% MF | R13, connected from U2 pin 12 to top pad of R13 |
| 02-01523 | 24 | 2 | RM73B1JT106J | RES SMT, 10M OHM 1/16W 5% 0603 | R17, R20 |
| 02-01523 | 25 | 2 | ERJ-3GSYJ100V | RES SMT, 10 OHM 1/16W 5% 0603 | R18, R19 |
| 02-01523 | 26 | 1 | EVM-7JSX30B13 | RES SMT, POT, 1K OHM 3MM SEALED, 3 TT | VR1 |
| 02-01523 | 27 | 12 | ECU-V1H104KBW | CAP SMT, 0.1uF 50V 10%, X7R CER 1206 | C1, C2, C12, C13, C16-18, C23-C26, C29 |
| 02-01523 | 28 | 3 | ECU-V1H220JCV | CAP SMT, 22 pF CERAMIC 5% 50V 0603 NPO | C3, C4, C28 |
| 02-01523 | 29 | 2 | ECU-V1H102KBV | CAP SMT, 1000 pF 50V CERAMIC 10% 0603 X7R | C6, C11 |

MCRF355/360 REFERENCE DESIGN

| Assembly # | Line # | Qty | Part # | Part Description | Reference Designator |
|------------|--------|-----|-------------------------|---|----------------------|
| 02-01523 | 30 | 1 | ECU-V1H271JCV | CAP SMT, 270 pF 50V CERAMIC 5% 0603 NPO | C7 |
| 02-01523 | 31 | 1 | ECU-V1H152KBV | CAP SMT, 1500 pF 50V CERAMIC 10% 0603 X7R | C8 |
| 02-01523 | 32 | 1 | GRM42- 6C0G471G500AL | CAP SMT, 470 pF 500V 2% 1206 C0G | C9 |
| 02-01523 | 33 | 1 | GRM42- 6C0G121J500AL | CAP SMT, 120 pF 500V 5% 1206 C0G | C10 |
| 02-01523 | 34 | 2 | ECU-V1H272KBV | CAP SMT, 2700PF 50V CERAMIC 10% 0603 XR7 | C14, C15 |
| 02-01523 | 35 | 4 | ECE-A1EU220 | CAP, 22UF 25V RADIAL ELECTROLYTIC 20% | C19-C22 |
| 02-01523 | 36 | 1 | GRM42- 6C0G100J500AL | CAP SMT, 10 pF 500V 5% 1206 C0G | C30 |
| 02-01523 | 37 | 1 | GRM42- 6C0G220J500AL | CAP SMT, 22 pF 500V 5% 1206 C0G | C31 (AS NEEDED) |
| 02-01523 | 38 | 2 | 43LS477 | INDUCTOR, 0.47 μ H | L1, L2 |
| 02-01523 | 39 | 1 | MCX0001 | OSCILLATOR, CUSTOM 13.560 MHz, PARALLEL MODE, 22 pF LOAD, HC49 CASE, 30 PPM | X1 |
| 02-01523 | 40 | 1 | MDC-096 | CONN, MINI-DIN, 6-PIN | P1 |
| 02-01523 | 41 | 1 | KF22-E9S-NJ | CONN, D-SUB 9P RECPT RT ANGLE WITH JACK SCREWS | DB9 |
| 02-01523 | 42 | 1 | 08-00170 | LABEL, MCRF355 READER FIRM- WARE, 355READ.HEX, 1/25/99, U4 | @ U4 |
| 02-01523 | 43 | 1 | ERJ-3GSYJ511V | RES SMT, 510 OHM 1/16W 5% 0603 | R14 |

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6.0 READER SOURCE CODE FOR THE PICmicro[®] MCU

```
;receiver.asm

;Processor: PIC16C558 operating at 13.56 MHz
;      Ti= 295 nsec

      processor 16c558
      #include "P16c558.inc"
      __config h'3ff2' ;protection off,PWRT enabled,watchdog disabled,HS oscillator

#define _CARRY          STATUS,0
#define _ZERO           STATUS,2

#define _125KHZ         PORTA,1
#define _RS232TX        PORTA,2
#define _RS232RX        PORTA,3
#define _RS232          PORTA
#define SIGNAL          PORTB,4
invmask          = h'2'
;.....
;Define variables and constants here--
delay            =h'20'
wait             =h'21'
acctime         =h'22' ;accumulated sync interval sum--also used as halfbit interval threshold
#define halfthr      acctime ;halfbit interval threshold
halfthr         =acctime ;halfbit interval threshold
rcv_csumhi      =h'23' ;2 bytes for storing received checksum
rcv_csumlo      =h'24'
bitcnt          =h'25' ;RS232 bit counter
cycle_cnt       =h'26'
halfthr         =h'27' ;threshold value between halfbit and fullbit intervals
ptr1            =h'28' ;temporary FSR storage
ptr2            =h'29' ;temporary FSR storage
TXchar          =h'2a' ;character to transmit over RS232
temp            =h'2b' ;temporary storage
shiftcnt        =h'2c' ;used to strip the framing '0' bits from the rec'd data array
letters         =h'2d' ;storage area for next character to send
charcnt         =h'2e'
lastbit         =h'2f' ;the LSB stores the last rec'd bit--flip it by complementing f

;!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
;Note that s/w tests for MSb to detect end of area--be careful if move to different
;processor or relocate this storage area
rcvbits         =h'40' ;32 bytes set aside for storing the received bits--actual number of bytes
                  ;in transmission is 18
;Note that main loop uses bit tests to determine bit receive or runaway condition (to limit
;processing time). Keep this in mind if rcvbits storage area changed in the future.
```

MCRF355/360 REFERENCE DESIGN

```
;;40h-60h is reserved for received bits--actual bit receiving area 40h-51h, rest is overrun area

;;52h-73h set aside for ASCII conversion of received bytes before RS232 transmission. Note that
;;52h-60h contains no useful information from the use during receive of demodulated bits. Also,
;; bits are not being received while the ASCII conversion and serial transmission are
;; taking place.
;; 'G' 1st character: "go"
;; Character 2-37: ASCII representation of received 18 bytes (until checksum used)
;; Character 38: '\n' newline

sendascii =h'52' ;begin of storage area for ASCII conversion of received bytes
xfercnt =d'14' ;defines number of received bytes to convert to ASCII & transmit
```

```
.....

;.....
;Overall function- To recover Manchester encoded RFID message after AM demodulation and
; comparator decision. The comparator input trips the interrupt on PORTB change.
;The steps are:
;
; 1- Initialize registers to seek synch field.
; 2- Determine bit width from synch field by averaging the periods between transitions
; over the synch field. TMR0 is cleared at each edge. If the timer overflows before
; the next edge, synch seek starts over. The synch field is composed of 9 bits.
; 3- Use the measured bit width to establish a threshold period between repeat bits and
; complement of previous bit. This is due to the Manchester encoding method. Since there
; is always a transition in the middle of each bit interval transmitted, a repeated bit
; will appear as a pair of edges that occur with a halfbit interval period. A bit that
; is the complement of the last received bit will appear as an interval between edges
; of a full bit interval period.
; 4- Shift in bits as they are received into the storage array. When the timer overflows,
; consider the data field over. The received data format is MSb to LSb, where the MSb
; is the first bit received.
; 5- There are 16 bytes in the message, followed by a 16 bit checksum of the message
; contents. The remaining bit is unused.
; 6- Compute the checksum of the received 16 byte message and compare to the received
; checksum.
; 7- If checksums match, convert the message and the checksum into ASCII form and transmit
; over the RS232 serial link. The message format is:
; "GG" :the go characters (start of message)
; 36 bytes which are the ASCII representation of the 18 bytes received
; "\n" : closing newline character
; The serial data rate is 9600 bps, 8 data bits, 1 stop, no parity
;.....
```

```
org h'000' ;RESET vector location
goto init
org h'004' ;interrupt vector location
```

```
=====
;;isr(): interrupt service routine
; interrupts enabled for transition on PORTB
;
; 1- BEWARE! To minimize interrupt response time, the w & status register are NOT
; archived.
; 2- The isr execution path is determined by w register and uses calculated goto's.
; The w for next isr is set at end of current isr execution and is dependent on
; signal context (i.e. sync start, w/in sync, w/in data, etc.)
; Be very cautious here--must stay w/in 255 instructions for this to work!
; 3- Sync field processed as follows:
; -Ignore the first 4 transitions, they may be in response to tag power on reset
; -Accumulate the sum of next 8 intervals
; -Establish half bit width from full bit width threshold value based on
; average interval measured above. Due to Manchester encoding, repeat of previous
```

MCRF355/360 REFERENCE DESIGN

```
;          bit will be a series of 2 halfbit width intervals, complement of previous bit
;          will be a fullbit width interval. halfbit defined as 1.5x(average sync).
;          -wait for interval over the fullbit threshold. This is end of sync. In accordance
;          w/ Manchester encoding, the sync field will be: 1 1 1 1 1 1 1 0
;=====
isr
    addwf PCL,f          ;4 calculated goto
;first sync edge is calculated goto here
    clrf TMR0           ;5
    movf PORTB,f        ;6 must read PORTB before clearing RBIF
    bcf INTCON,RBIF ;7 just in case timer interrupt happened just at 1st edge
    bcf INTCON,T0IF ;8
    movlw (first_cycle - isr-d'1') ;9 next isr calculated goto offset
    clrf lastbit        ;10 lastbit @ end of sync = 0
    retfie              ;12
;end of first cycle here. Note that first 4 transitions are ignored, because sync start is
;corrupted by tag power on reset.
first_cycle
    clrf TMR0           ;5
    movf PORTB,f        ;6 must read PORTB before clearing RBIF
    bcf INTCON,RBIF ;7
    movlw (second_cycle - isr-d'1') ;8 next isr calculated goto offset
    retfie              ;10
;end of 2nd cycle here. Note that first 4 transitions are ignored, because sync start is
;corrupted by tag power on reset.
second_cycle
    clrf TMR0           ;5
    movf PORTB,f        ;6 must read PORTB before clearing RBIF
    bcf INTCON,RBIF ;7
    movlw recvbits      ;8
    movwf FSR           ;9 set up to store data bits
    movlw (third_cycle - isr-d'1') ;10 next isr calculated goto offset
    retfie              ;12
;end of 3rd cycle here. Note that first 4 transitions are ignored, because sync start is
;corrupted by tag power on reset. The 3rd cycle is the 4th transition, so from here we measure
;the longest interval in sync field.
third_cycle
    clrf TMR0           ;5
    movf PORTB,f        ;6 must read PORTB before clearing RBIF
    bcf INTCON,RBIF ;7
    clrf acctime        ;8 reset accumulated sync interval for average
    movlw (fourth_cycle - isr-d'1') ;9 next isr calculated goto offset
    retfie              ;11
;end of 4th cycle here. Start looking for longest sync interval here.
fourth_cycle
    movf TMR0,w         ;5
    clrf TMR0           ;6
    movf PORTB,f        ;7
    bcf INTCON,RBIF ;8
    addwf acctime,f     ;9 first measured sync cycle, must be the largest
    movlw (fifth_cycle - isr-d'1') ;10
    retfie              ;12
;end of 5th cycle here.
fifth_cycle
    movf TMR0,w         ;5
    clrf TMR0           ;6
    movf PORTB,f        ;7
    bcf INTCON,RBIF ;8
    addwf acctime,f     ;9 acctime = acctime + TMR0
    movlw (sixth_cycle - isr-d'1') ;10
    retfie              ;12
;end of 6th cycle here.
sixth_cycle
    movf TMR0,w         ;5
    clrf TMR0           ;6
```

MCRF355/360 REFERENCE DESIGN

```
    movf    PORTB,f    ;7
    bcf     INTCON,RBIF ;8
    addwf  acctime,f   ;9    acctime = acctime + TMRO
    movlw  (seventh_cycle - isr-d'1') ;10
    retfie                ;12
;end of 7th cycle here.
seventh_cycle
    movf    TMR0,w    ;5
    clrf   TMR0      ;6
    movf    PORTB,f   ;7
    bcf     INTCON,RBIF ;8
    addwf  acctime,f   ;9    acctime = acctime + TMRO
    movlw  (eighth_cycle - isr-d'1') ;10
    retfie                ;12
;end of 8th cycle here.
eighth_cycle
    movf    TMR0,w    ;5
    clrf   TMR0      ;6
    movf    PORTB,f   ;7
    bcf     INTCON,RBIF ;8
    addwf  acctime,f   ;9    acctime = acctime + TMRO
    movlw  (ninth_cycle - isr-d'1') ;10
    retfie                ;12
;end of 9th cycle here.
ninth_cycle
    movf    TMR0,w    ;5
    clrf   TMR0      ;6
    movf    PORTB,f   ;7
    bcf     INTCON,RBIF ;8
    addwf  acctime,f   ;9    acctime = acctime + TMRO
    movlw  (tenth_cycle - isr-d'1') ;10
    retfie                ;12
;end of 10th cycle here.
tenth_cycle
    movf    TMR0,w    ;5
    clrf   TMR0      ;6
    movf    PORTB,f   ;7
    bcf     INTCON,RBIF ;8
    addwf  acctime,f   ;9    acctime = acctime + TMRO
    movlw  (eleventh_cycle - isr-d'1') ;10
    retfie                ;12
;end of 11th cycle here. --this is last of sync cycles to be accumulated. Average the result
;and determine halfbit threshold in remaining sync cycles.
eleventh_cycle
    movf    TMR0,w    ;5
    clrf   TMR0      ;6
    movf    PORTB,f   ;7
    bcf     INTCON,RBIF ;8
    addwf  acctime,f   ;9    acctime = acctime + TMRO
    movlw  (twelfth_cycle - isr-d'1') ;10
    retfie                ;12
;end of 12th cycle here. Start averaging the sync interval accumulated time
twelfth_cycle
    movf    PORTB,f   ;5
    bcf     INTCON,RBIF ;6
    rrf    acctime,f   ;7    acctime/2
    rrf    acctime,f   ;8    acctime/4
    rrf    acctime,f   ;9    avg interval = acctime/8
    movlw  h'1f'      ;10    clear 3 MSBs that may have been set by carry
    andwf  acctime,f   ;11
    movlw  (cycle13 - isr-d'1') ;12
    retfie                ;14
;end of 13th cycle here. Calculate the halfbit threshold = 1.5(sync interval avg) Note that
;that the threshold value will be kept in acctime (=halfthr)
cycle13
```

MCRF355/360 REFERENCE DESIGN

```
    clr  TMR0           ;5
    movf PORTB,f       ;6
    bcf  INTCON,RBIF   ;7
    rrf  acctime,w     ;8 half the sync interval avg
    addwf acctime,f    ;9 halfthr = 1+1.5x(sync interval avg)
    incf acctime,f     ;10
    movlw (sync_end - h'100'-h'1'-isr) ;11
    bsf  PCLATH,0      ;12 adjust for origin @ 100h
    retfie             ;14

    org  h'100'
;sync end wait. End of sync is distinguished by a fullbit interval. ( T > halfthr )
sync_end
    movf TMR0,w       ;5
    clr  TMR0         ;6
    movf PORTB,f      ;7
    bcf  INTCON,RBIF  ;8
    subwf halfthr,w   ;9 Test interval to detect end of sync field (halfthr - w)
    movlw (sync_end - h'100'-isr-d'1') ;10
    btfss STATUS,C    ;12 Carry set for halfthr >= w
    movlw (bit1 - h'100'-isr-h'1');12 If T > halfbit, end of sync detected. Proceed to data
processing
    retfie            ;14
;rec'd bit processing here --bit1 is 1st bit of 8 bit block
bit1
    movf TMR0,w       ;5
    clr  TMR0         ;6
    movf PORTB,f      ;7
    bcf  INTCON,RBIF  ;8
    subwf halfthr,w   ;9 Test interval to determine bit. C = 1 for repeated bit
    btfsc STATUS,C    ;11
    goto halfabit1    ;12
;fullbit processing here
    comf lastbit,f     ;12 Complement lastbit for fullbit measurement
    rrf  lastbit,w     ;13
    rlf  INDF,f        ;14 shift in the new bit
    movlw (bit2 - h'100'-isr-h'1') ;15
    retfie             ;17
halfabit1
;repeated bit (1 of 8)
    rrf  lastbit,w     ;13
    rlf  INDF,f        ;14
    movlw (half21-h'100'-isr-h'1') ;15
    retfie             ;17
;2nd half of bit interval processing
half21 ;2nd half, bit1
    clr  TMR0           ;5
    movf PORTB,f       ;6
    bcf  INTCON,RBIF   ;7
    movlw (bit2-h'100'-isr-h'1');8
    retfie             ;10

;rec'd bit processing here --bit2 is 2nd bit of 8 bit block
bit2
    movf TMR0,w       ;5
    clr  TMR0         ;6
    movf PORTB,f      ;7
    bcf  INTCON,RBIF  ;8
    subwf halfthr,w   ;9 Test interval to determine bit. C = 1 for repeated bit
    btfsc STATUS,C    ;11
    goto halfabit2    ;12
;fullbit processing here
    comf lastbit,f     ;12 Complement lastbit for fullbit measurement
    rrf  lastbit,w     ;13
    rlf  INDF,f        ;14 shift in the new bit
```

MCRF355/360 REFERENCE DESIGN

```
        movlw (bit3 - h'100'-isr-h'1') ;15
        retfie          ;17
halfabit2
;repeated bit (2 of 8)
        rrf  lastbit,w  ;13
        rlf  INDF,f    ;14
        movlw (half22-h'100'-isr-h'1') ;15
        retfie          ;17
;2nd half of bit interval processing
half22      ;2nd half, bit2
        clrf  TMR0      ;5
        movf  PORTB,f   ;6
        bcf  INTCON,RBIF ;7
        movlw (bit3-h'100'-isr-h'1') ;8
        retfie          ;10
;rec'd bit processing here --bit3 is 3rd bit of 8 bit block
bit3
        movf  TMR0,w    ;5
        clrf  TMR0      ;6
        movf  PORTB,f   ;7
        bcf  INTCON,RBIF ;8
        subwf halfthr,w ;9   Test interval to determine bit. C = 1 for repeated bit
        btfs  STATUS,C  ;11
        goto  halfabit3 ;12
;fullbit processing here
        comf  lastbit,f  ;12  Complement lastbit for fullbit measurement
        rrf  lastbit,w  ;13
        rlf  INDF,f    ;14  shift in the new bit
        movlw (bit4 - h'100'-isr-h'1') ;15
        retfie          ;17
halfabit3
;repeated bit (3 of 8)
        rrf  lastbit,w  ;13
        rlf  INDF,f    ;14
        movlw (half23-h'100'-isr-h'1') ;15
        retfie          ;17
;2nd half of bit interval processing
half23      ;2nd half, bit3
        clrf  TMR0      ;5
        movf  PORTB,f   ;6
        bcf  INTCON,RBIF ;7
        movlw (bit4-h'100'-isr-h'1') ;8
        retfie          ;10
;rec'd bit processing here --bit4 is 4th bit of 8 bit block
bit4
        movf  TMR0,w    ;5
        clrf  TMR0      ;6
        movf  PORTB,f   ;7
        bcf  INTCON,RBIF ;8
        subwf halfthr,w ;9   Test interval to determine bit. C = 1 for repeated bit
        btfs  STATUS,C  ;11
        goto  halfabit4 ;12
;fullbit processing here
        comf  lastbit,f  ;12  Complement lastbit for fullbit measurement
        rrf  lastbit,w  ;13
        rlf  INDF,f    ;14  shift in the new bit
        movlw (bit5 - h'100'-isr-h'1') ;15
        retfie          ;17
halfabit4
;repeated bit (4 of 8)
        rrf  lastbit,w  ;13
        rlf  INDF,f    ;14
        movlw (half24-h'100'-isr-h'1') ;15
        retfie          ;17
;2nd half of bit interval processing
```

MCRF355/360 REFERENCE DESIGN

```
half24      ;2nd half, bit4
    clrf TMR0      ;5
    movf PORTB,f   ;6
    bcf  INTCON,RBIF ;7
    movlw (bit5-h'100'-isr-h'1') ;8
    retfie          ;10
;rec'd bit processing here --bit5 is 5th bit of 8 bit block
bit5
    movf TMR0,w    ;5
    clrf TMR0      ;6
    movf PORTB,f   ;7
    bcf  INTCON,RBIF ;8
    subwf halfthr,w ;9   Test interval to determine bit. C = 1 for repeated bit
    btfs STATUS,C  ;11
    goto halfabit5 ;12
;fullbit processing here
    comf lastbit,f ;12 Complement lastbit for fullbit measurement
    rrf  lastbit,w ;13
    rlf  INDF,f    ;14 shift in the new bit
    movlw (bit6 - h'100'-isr-h'1') ;15
    retfie          ;17
halfabit5
;repeated bit (5 of 8)
    rrf  lastbit,w ;13
    rlf  INDF,f    ;14
    movlw (half25-h'100'-isr-h'1') ;15
    retfie          ;17
;2nd half of bit interval processing
half25      ;2nd half, bit5
    clrf TMR0      ;5
    movf PORTB,f   ;6
    bcf  INTCON,RBIF ;7
    movlw (bit6-h'100'-isr-h'1') ;8
    retfie          ;10

;rec'd bit processing here --bit6 is 6th bit of 8 bit block
bit6
    movf TMR0,w    ;5
    clrf TMR0      ;6
    movf PORTB,f   ;7
    bcf  INTCON,RBIF ;8
    subwf halfthr,w ;9   Test interval to determine bit. C = 1 for repeated bit
    btfs STATUS,C  ;11
    goto halfabit6 ;12
;fullbit processing here
    comf lastbit,f ;12 Complement lastbit for fullbit measurement
    rrf  lastbit,w ;13
    rlf  INDF,f    ;14 shift in the new bit
    movlw (bit7 - h'100'-isr-h'1') ;15
    retfie          ;17
halfabit6
;repeated bit (6 of 8)
    rrf  lastbit,w ;13
    rlf  INDF,f    ;14
    movlw (half26-h'100'-isr-h'1') ;15
    retfie          ;17
;2nd half of bit interval processing
half26      ;2nd half, bit6
    clrf TMR0      ;5
    movf PORTB,f   ;6
    bcf  INTCON,RBIF ;7
    movlw (bit7-h'100'-isr-h'1') ;8
    retfie          ;10
;rec'd bit processing here --bit7 is 7th bit of 8 bit block
bit7
```


MCRF355/360 REFERENCE DESIGN

```
    movf TMR0,w      ;5
    clrf TMR0       ;6
    movf PORTB,f    ;7
    bcf  INTCON,RBIF ;8
    subwf halfthr,w ;9  Test interval to determine bit. C = 1 for repeated bit
    btfsc STATUS,C  ;11
    goto halfabit7  ;12
;fullbit processing here
    comf lastbit,f  ;12 Complement lastbit for fullbit measurement
    rrf  lastbit,w  ;13
    rlf  INDF,f     ;14 shift in the new bit
    movlw (bit8 - h'100'-isr-h'1') ;15
    retfie          ;17
halfabit7
;repeated bit (7 of 8)
    rrf  lastbit,w  ;13
    rlf  INDF,f     ;14
    movlw (half27-h'100'-isr-h'1') ;15
    retfie          ;17
;2nd half of bit interval processing
half27      ;2nd half, bit7
    clrf TMR0       ;5
    movf PORTB,f    ;6
    bcf  INTCON,RBIF ;7
    movlw (bit8-h'100'-isr-h'1') ;8
    retfie          ;10
;rec'd bit processing here --bit8 is 8th bit of 8 bit block
bit8
    movf TMR0,w      ;5
    clrf TMR0       ;6
    movf PORTB,f    ;7
    bcf  INTCON,RBIF ;8
    subwf halfthr,w ;9  Test interval to determine bit. C = 1 for repeated bit
    btfsc STATUS,C  ;11
    goto halfabit8  ;12
;fullbit processing here
    comf lastbit,f  ;12 Complement lastbit for fullbit measurement
    rrf  lastbit,w  ;13
    rlf  INDF,f     ;14 shift in the new bit
    movlw (bit1 - h'100'-isr-h'1') ;15
    incf FSR,f      ;16
    retfie          ;18
halfabit8
;repeated bit (8 of 8)
    rrf  lastbit,w  ;13
    rlf  INDF,f     ;14
    movlw (half28-h'100'-isr-h'1') ;15
    retfie          ;17
;2nd half of bit interval processing
half28      ;2nd half, bit8
    clrf TMR0       ;5
    movf PORTB,f    ;6
    bcf  INTCON,RBIF ;7
    movlw (bit1-h'100'-isr-h'1') ;8
    incf FSR,f      ;9  advance to next byte in recvbits storage array
    retfie          ;11

;The negative RS232 supply is generated by an inverter clocked at ~125 KHz by port pin RA1.
    ;first pump up the -5V, i.e. generate 125 KHz clock (T=8 usec, ~27 Ti)
    ;run for a total of 128 cycles before sending data
    ;put line at stop bit level
```

alphabet

MCRF355/360 REFERENCE DESIGN

```
    clrwdt
    bcf  INTCON,GIE ;make sure interrupts are off
    movlw sendascii
    movwf FSR

    movlw xfercnt    ;# of ASCII represented received bytes to xfer
    addlw xfercnt    ;x2
    addlw h'3'       ;plus 2 start character "G" and newline character at end
    movwf charcnt

;set up registers in bank 1
    bsf  STATUS,RP0 ;point to bank 1
    movlw h'8'
    movwf TRISA     ;RA3 input, RA2-0 output
    movlw h'10'
    movwf TRISB     ;RB7-5,3-0 output, RB4 input
    movlw b'00001100' ;set up timer option for internal clock, prescale-->watchdog/16
    movwf OPTION_REG ;port B pullups enabled
    bcf  STATUS,RP0 ;point back to bank 0
;done setting up registers in bank 1, back to bank 0
    bsf  _RS232TX ;default is mark mode
    call gen125khz

;start the test transmission
sendA
    movf  INDF,w
    movwf TXchar
    movlw d'8'
    movwf bitcnt
;stop bit last
    bsf  _RS232TX
    call TX_RS232 ;stop bit = 3Ti

    call ti17 ;burn 17Ti (includes the 2Ti for the call)
;start bit first
    bcf  _RS232TX
    call TX_RS232
    call ti17 ;burn 17Ti (includes the 2Ti for the call, adjusts the bit timing)
sendchar
    btfsc TXchar,0 ;1Ti
    goto setbit ;3Ti
    bcf  _RS232TX
    goto nextbit
setbit
    bsf  _RS232TX ;4Ti
nextbit
    call TX_RS232 ;6Ti
    rrf  TXchar,f ;7Ti
    call ti10 ;17Ti
    decfsz bitcnt,f ;18Ti
    goto sendchar ;20Ti
;stop bit last
    bsf  _RS232TX
    call TX_RS232 ;stop bit = 3Ti

    incf  FSR,f ;1
    decfsz charcnt,f ;2
    goto inalpha ;4
    movlw d'255'
    movwf charcnt
    movlw d'10'
    movwf bitcnt
waiting
    call ti17
```

MCRF355/360 REFERENCE DESIGN

```
    decfsz charcnt,f
    goto waiting
    decfsz bitcnt,f
    goto waiting
    goto seekinit
inalpha
    call ti10
    goto sendA

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;
;;subroutine--RS232 bit timing & 125 KHz voltage inverter maintenance
;;      baud rate set to 9600 bps--this is a bit time of 104 usec
;;      Timing for this subroutine: to104 loop is 5.605 usec, additional setup
;;      overhead is 1.77 usec. If do 17 to104 loops,
;;      that leaves 5.844 usec to make up in the calling
;;      routine to meet 104 usec target. 5.844= 19.8 Ti
;;      (20 Ti)
;;      Note that 5.844 is not evenly divisible by the
;;      instruction cycle time. Need to save one
;;      instruction every 5th bit sent--w/ the stop & start
;;      bit overhead, easier to save 2 extra instructions
;;      every character sent (10 bits)
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;
TX_RS232
    movlw d'17'      ;time out 104 usec, Ti=295 nsec
    movwf wait

to104
    movlw invmask   ;flip voltage inverter bit
    xorwf _RS232,f
    movlw d'4'
    movwf delay

wait4usec
    decfsz delay,f   ;4 usec is half inverter clock period
    goto wait4usec
    decfsz wait,f
    goto to104
    movlw invmask
    xorwf _RS232,f
    nop
    nop
    nop
    return

;;=====

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;
;;subroutine--generates 128 cycles at ~125 KHz for the RS232 voltage inverter
gen125khz
    movlw d'128'
    movwf cycle_cnt

next125
    bsf    _125KHZ
    movlw d'4'
    movwf delay

highside
    decfsz delay,f
    goto highside
    bcf    _125KHZ
    movlw d'4'
```

MCRF355/360 REFERENCE DESIGN

```
        movwf  delay
lowside
        decfsz delay,f
        goto  lowside
        decfsz cycle_cnt,f
        goto  next125
        return
;;end gen125khz
subroutine;
;
;
;
;subroutine-ti17: burn 17 Ti--includes the 2Ti to call this subroutine
;;      ti15: burn 15 Ti, including call
;;      ti10: burn 10 Ti, including call
;
ti17
        movlw  d'3'      ;1
        movwf  delay     ;2
burn9
        decfsz delay,f
        goto  burn9      ;11
        clrwdt          ;12
        nop            ;13
        return          ;15+2 for call ti17=17Ti

ti15
        movlw  d'3'      ;1
        movwf  delay     ;2
burn9Ti
        decfsz delay,f
        goto  burn9Ti    ;11
        return          ;13+2 for call ti15=15Ti

ti12
        nop
        clrwdt
ti10
        goto  dly1       ;2Ti
dly1
        goto  dly2       ;4Ti
dly2
        goto  leaveti10 ;6Ti
leaveti10
        return          ;8Ti+2Ti=10Ti

;=====
;;initialization
;=====
init
        ;1st set up the I/O configuration--note that setting PORTB 7,6,5,4,0 as outputs disables
        ;them as external interrupt sources. In this application PORTB-4 is utilized as an
        ;external interrupt source upon change of state. All other external interrupt sources are
        ;set as outputs to disable them as interrupts.

;;set up registers in bank 1
        bsf    STATUS,RP0 ;point to bank 1
        movlw  h'8'
        movwf  TRISA      ;RA3 input, RA2-0 output
        movlw  h'10'
        movwf  TRISB     ;RB7-5,3-0 output, RB4 input
        movlw  b'00001000' ;set up timer option for internal clock, no prescaler
```

MCRF355/360 REFERENCE DESIGN

```
        movwf  OPTION_REG  ;port B pullups enabled
        bcf   STATUS,RP0  ;point back to bank 0
;;done setting up registers in bank 1, back to bank 0
        movlw HIGH isr
        movwf PCLATH      ;setup for calculated goto's dependent on context when entering
                          ;isr
;=====
;;initialization for sync field search- done @ turn on & after data recovery complete (or failed)
;=====
seekinit
        clrwdt
        movlw d'19'
        movwf bitcnt      ;clear the bit storage field
        movlw recvbits
        movwf FSR
clrbits
        clrf   INDF
        incf   FSR,f
        decfsz bitcnt,f
        goto  clrbits

        movlw recvbits
        movwf FSR          ;start of the received bits field
        movf   PORTB,w ;read PORTB before clearing INTCON to be sure RBIF=0
        clrf   INTCON
        clrf   TMR0
;=====
; From here on, the w register represents the PCL offset when answering the isr.
; It is to be used for no other purpose until interrupts are disabled.
;=====
        movlw d'0'
        clrf   PCLATH
        bsf   INTCON,RBIE ;enable portB change interrupt enable
        bsf   INTCON,GIE  ;global interrupts are now enabled.

;=====
;;tag word search
;=====
;The main loop monitors the T0IF flag to detect successfully received word (subject to
;checksum test). Tag word processing is isr driven. A calculated goto method is used for
;position context in tag word for speed. FOR THIS REASON, THE W REGISTER CANNOT BE USED
;BY THE MAIN LOOP! If the main loop detects a timer overflow, the w register is cleared to
;return processing to first sync edge search.
;Also, expect recvbits area to be @ 40h-52h while receiving data. The ptr will be tested to
;determine this bitwise (because w can't be used in the main loop).
;=====
seeksync
        bcf   INTCON,RBIE
        movlw d'0' ;calculated goto offset for 1st sync edge processing
        clrf   PCLATH
        clrf   FSR ;FSR = 0 to indicate not gathering bits
        bsf   INTCON,RBIE
        bcf   INTCON,T0IF
main
        clrwdt
        btfsc FSR,6
        goto  datamain ;receiving data, monitor progress
        btfsc INTCON,T0IF
        goto  seeksync ;if TMR0 overflows w/o receiving bits, seeksync
        goto  main
;check for done receiving bits using TMR0 overflow as indicator. Also test for overflow from
;proper bit storage area for runaway condition (non tag noise tripping comparator)
datamain
```

MCRF355/360 REFERENCE DESIGN

```
    clrwdt
    btfsc  INTCON,T0IF
    goto  calc_checksum ;if timer overflows, calculate checksum of received data
    btfsc  FSR,5        ;if bit 5 set, FSR > 5fh and has overrun its proper area.
    goto  seeksync     ;search for sync.
    goto  datamain

;Data received at this point. Two processing tasks remain:
;1- the framing '0' bits must be removed from the received 14 data bytes and 16 bit checksum
;2- the checksum of the 14 data bytes must be calculated and compared to the received
; 16 bit checksum
;If checksums match, transmit data over RS232 link.

calc_checksum
    clrf  INTCON
clrgie
    bcf  INTCON,GIE
        btfsc  INTCON,GIE  ;make sure it's clear before proceeding
    goto  clrgie
    movf  PORTB,f
    clrf  INTCON          ;disable all interrupts while processing received data
;remove the framing '0' bits by bit shifting the data array left until all framing 0s are
;shifted out

    movlw  d'17'
    movwf  bitcnt
    movwf  shiftcnt
shiftout
    movlw  recvbits+d'17'
    movwf  FSR
roll_left
    rlf  INDF,f
    decf  FSR,f
    decfsz shiftcnt,f
    goto  roll_left      ;rotate left shiftcnt # of bytes
    decfsz bitcnt,f
    goto  next_RL
    goto  framestripped
;bit shift left through the array (successively 1 byte less each time)
next_RL
    movf  bitcnt,w
    movwf  shiftcnt
    goto  shiftout
framestripped

;1st check for all 0s in data--This is an illegal combination
    movlw  recvbits
    movwf  FSR
    movlw  d'14'
    movwf  bitcnt
zerotest
    movf  INDF,w
    btfss STATUS,Z
    goto  nonzero
    decfsz bitcnt,f
    goto  zerotest
    goto  seekinit      ;all zeros received. Ignore the message
nonzero
;do 16 bit checksum of first 14 bytes received. It should match the last 2 bytes received.
    movlw  recvbits
    movwf  FSR
    movlw  d'14'
    movwf  bitcnt
    clrf  recv_csumlo
    clrf  recv_csumhi
sumbytes
```

MCRF355/360 REFERENCE DESIGN

```
movf    INDF,w
addwf  recv_csumlo,f
btfsc  STATUS,C
incf   recv_csumhi,f ;carry into high byte as necessary
incf   FSR,f         ;point to next data byte
decfsz bitcnt,f
goto   sumbytes
;now compare the received checksum w/ the calculated checksum. Transmit data if they match.
movf   recv_csumhi,w
subwf  INDF,f
btfss  STATUS,Z
goto   seekinit
incf   FSR,f         ;point to received checksum LSB
movf   recv_csumlo,w
subwf  INDF,f
btfss  STATUS,Z
goto   seekinit
;message passes checksum. Convert to ASCII and transmit.
;now convert to ASCII form
movlw  recvbits
movwf  ptr1          ;keep track of where in conversion
movlw  sendascii
movwf  ptr2
movwf  FSR
movlw  "G"
movwf  INDF
incf   ptr2,f
incf   FSR,f
movwf  INDF          ;double "G" to indicate start
incf   ptr2,f        ;next ascii character
movlw  xfercnt       ;how many bytes to convert to ASCII
movwf  bitcnt
movlw  h'4'
movwf  PCLATH        ;set up PCLATH for lookup table
asciiconv
movf   ptr1,w
movwf  FSR
swapf  INDF,w
andlw  h'f'          ;isolate the MSN
call   hex2ascii
movwf  temp          ;hold the ASCII character
movf   ptr2,w
movwf  FSR
movf   temp,w        ;store ASCII representation of received byte MSN
movwf  INDF
incf   ptr2,f        ;advance ASCII ptr
movf   ptr1,w        ;back to received bytes
movwf  FSR
movf   INDF,w
andlw  h'f'          ;isolate the LSN
call   hex2ascii
movwf  temp
movf   ptr2,w
movwf  FSR
movf   temp,w        ;store ASCII representation of received byte LSN
movwf  INDF
incf   ptr2,f        ;advance ASCII ptr
incf   ptr1,f        ;advance received byte ptr
decfsz bitcnt,f
goto   asciiconv
;done data conversion, now indicate newline before sending
movlw  "\n"          ;newline character
incf   FSR,f
movwf  INDF
```

MCRF355/360 REFERENCE DESIGN

```
;cleared for RS232 transmission
    goto    alphabet

;hexadecimal to ASCII conversion table
    org     h'3ff'
hex2ascii
    addwf   PCL,f
    retlw   "0" ;ascii 0
    retlw   "1" ;ascii 1
    retlw   "2" ;ascii 2
    retlw   "3" ;ascii 3
    retlw   "4" ;ascii 4
    retlw   "5" ;ascii 5
    retlw   "6" ;ascii 6
    retlw   "7" ;ascii 7
    retlw   "8" ;ascii 8
    retlw   "9" ;ascii 9
    retlw   "A" ;ascii A
    retlw   "B" ;ascii B
    retlw   "C" ;ascii C
    retlw   "D" ;ascii D
    retlw   "E" ;ascii E
    retlw   "F" ;ascii F

    end
```




**13.56 MHz Reader Reference Design for the MCRF450/451/452/455
Read/Write Devices and MCRF355/360 Read-Only Devices**

1.0 INTRODUCTION

The anti-collision interrogator in the DV103006 Development Kit is for Microchip Technology Inc.'s 13.56 MHz RFID devices (MCRF35X/360 and MCRF45X). The interrogator is used in conjunction with rLAB™ software version 3.2 or above. The user must select the device type in the rLAB menu bar for either the MCRF35X/360 or MCRF45X device.

In the MCRF35X/360 mode, the interrogator transmits 13.56 MHz carrier signal continuously and receives tag's responses. This is often called "Tag Talks First" (TTF). The interrogator is working as the reader in the DV103003 kit that is for read-only devices (MCRF35X and MCRF360).

In the MCRF45X mode, the interrogator sends commands for reading or writing block data. Interrogator uses amplitude modulation for the commands. To initiate communications, the interrogator sends specially timed gap pulses: FRR (Fast Read Request) and FRB (Fast Read Bypass). These pulses consist of 5 gaps within 1.575 ms time span. Each gap pulse is 175 μs wide with 100% modulation depth. Gap means an absence of RF field. See Figures 4-3 thru 4-8 in the MCRF45X data sheet for details.

1-of-16 PPM (Pulse Position Modulation) is used for data and commands such as Read/Write command for block data, command to set/clear TF (Tag Talks First) and FR (Fast Read) bits, and command for end process. The 1-of-16 PPM signal consists of one gap pulse within 2.8 ms time span for a normal mode and 160 μs for a fast mode. The gap's position within 16 possible locations determines its representation for hex value. See Figure 4-9 in the MCRF45X data sheet (DS40232) for details.

The interrogator also sends a time reference pulse before the commands and data. This time reference signal consists of three gap pulses within 2.8 ms time span for a normal mode and 160 μs for a fast mode. See Figure 4-10 in the MCRF45X data sheet for details. Figure 1-1 shows the read/write pulse sequence between the interrogator and device.

The demo interrogator communicates with the device in conjunction with the rLAB.

The rLAB is a menu driven software package. Once the "MCRF450" - "Continuous" - "Run" menus are selected, the interrogator transmits FRR command continuously. Tags respond to the FRR command with a maximum of 160 bits of data, including its unique ID number (32 bits). To read or write a specific memory block, users must select the tag ID and block number.

The demo interrogator, along with the rLAB included in the DV103006 kit, is made as a reference material for various applications. The demo interrogator is designed for a general purpose utilizing all possible features shown in the data sheet. Both firmware and schematics can be modified for each individual application.

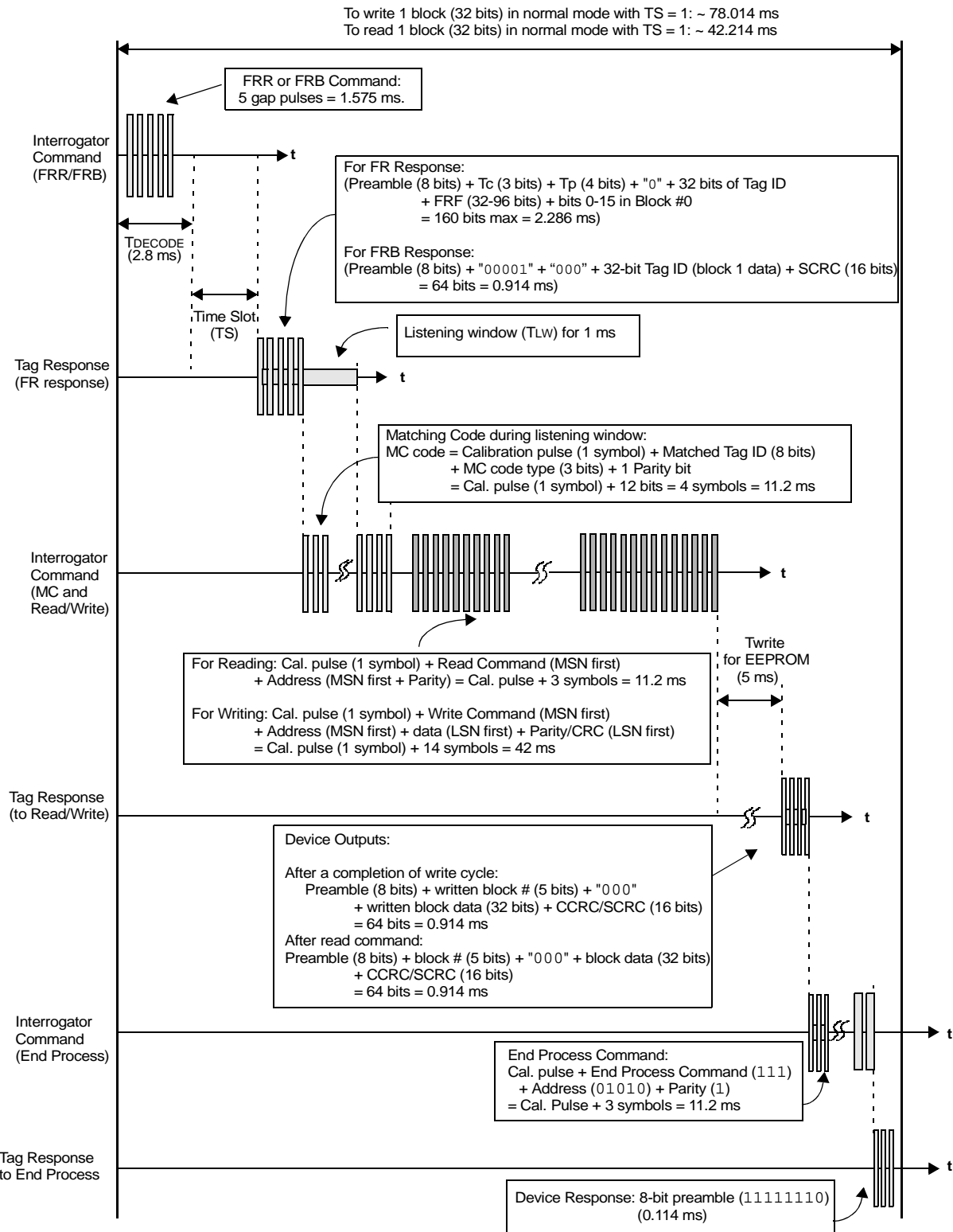
The interrogator uses two PICmicro® microcontrollers (MCUs) to communicate with a host computer, to send commands and data to the tag, and to receive and process the data from the tag.

The U17 includes the anti-collision algorithm shown in Figure 4-1 of the MCRF45X data sheet. It controls all functions of the interrogator except decoding the received Manchester data which is done by the U14.

The circuit is designed for medium read/write range applications (about 15" with 2" x 2" tag). The circuit can be optimized for lower cost or modified for long-range applications. Electronic copies of the PICmicro MCU source codes, schematics and Bill of Material (BOM) are available for download and contained on the CD provided in the DV103006 developer kit.

MCRF45X REFERENCE DESIGN

FIGURE 1-1: READ/WRITE PULSE SEQUENCE



MCRF45X REFERENCE DESIGN

2.0 INTERROGATOR CIRCUITS

The interrogator circuit consists of (1) transmitting, (2) receiving and (3) command control/data processing sections.

2.1 RF Transmission Section

U6:A and 13.56 MHz crystal form a crystal oscillator and output a 13.56 MHz signal. The output signal is fed into pin 1 of U7. The input signal on pin 2 of U7 is coming from U17 (master microcontroller). The following is the output of U17 for pin 2 of U7.

- MCRF45X mode: Modulation signal for commands and block data for writing.
- Standby mode: Logic "HIGH".
- MCRF35X/360 mode: Logic "HIGH".

Therefore, U7 outputs (a) a modulated RF signal (for command or write data) or (b) continuous RF signals during the standby and MCRF35X/360 operation. The output signal of the U7 is fed into the gate of RF power amplifier U8 through U6:D, E and F. Splitting the output of U6:C using U6:D, E and F is helpful for preventing excessive heat on U6.

U4 is an adjustable voltage regulator and supplies the DC power supply voltage for U8. The U4 is controlled by U17 through U16 (DAC) and U3. The main idea of using the adjustable voltage regulator is to adjust the RF output signal level of U8. The power level is adjusted by the following procedure in the rfLAB menu:

"Configure" -> "Carrier Strength"

User can select the "Carrier Strength" from 0%-100% (from the above menu). Default is set to 100%. The interrogator outputs the maximum power level at this setting.

rfLAB sends the Carrier Strength information to U17 which adjusts U4's output voltage through U16 and U3.

This corresponds to about 12.37 VDC at pin 2 of U4 for the 15 VDC input voltage.

The purpose of adjusting the carrier signal level is to reduce a possible near-field problem which may result in an irregular clock rate of the RFID device. This is due to an excessive input voltage to the device when the tag is placed too close to the reader antenna. In this case, the output power level from the interrogator should be decreased. However, for a longer read range, it is often necessary to output a higher power level so that it can detect tags in the far range.

Adjusting the carrier signal level is an optional choice. Therefore, the circuit components (U16, U3 and U4) associated with this feature can be easily removed. In this case, +15 VDC or 9 VDC should be directly applied to L9 for U8.

The RF output voltage from U8 is fed into the antenna circuit formed by C1, C2, C3, C4, C5 and antenna coil L.

The demo unit has three different sizes of antenna. Each one has one turn inductor along the edge of the PCB board. The metal trace is embedded inside the PCB.

Figure 2-1 shows the antenna circuit. The impedance of LC circuit is given by:

EQUATION 2-1:

$$Z(\omega) = \frac{\frac{1}{C_4} \left(j\omega L + \frac{1}{j\omega C_S} \right)}{-\omega^2 L + \left(\frac{1}{C_S} + \frac{1}{C_4} \right)}$$

where

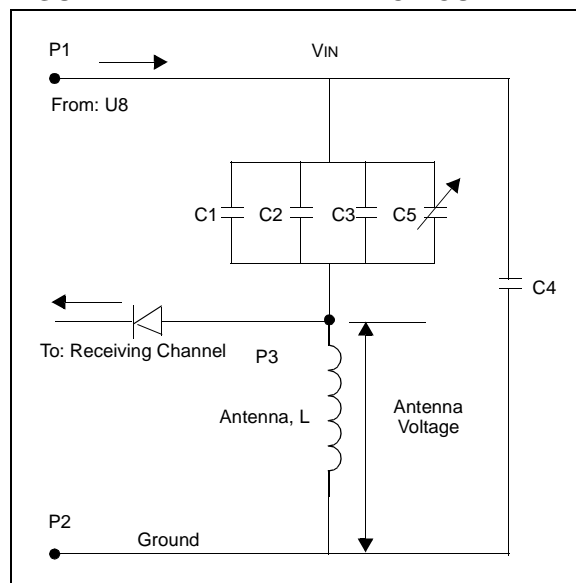
$$C_S = C_1 + C_2 + C_3 + C_5$$

$$\omega = 2 \pi f$$

f = output carrier frequency

The resonant frequency of the antenna circuit in the interrogator is given by solving the impedance equation in Equation 2-1. In Equation 2-1, the impedance $Z(\omega)$ has poles and zeroes. The poles are found at the condition when the denominator goes to zero and the zeroes are found when the numerator goes to zero. The poles result in a maximum impedance, since the denominator goes to zero. Therefore, the frequencies at the poles are the parallel resonant frequencies. The zeroes result in a minimum impedance since the numerator goes to zero. Thus, the frequencies at the zeroes are series resonant frequencies.

FIGURE 2-1: ANTENNA CIRCUIT



MCRF45X REFERENCE DESIGN

The resonant frequencies by solving the poles and zeroes are:

EQUATION 2-2:

$$f_{series} = \frac{1}{2\pi\sqrt{LC_S}} = \frac{1}{2\pi\sqrt{L(C_1 + C_2 + C_3 + C_5)}}$$

and

EQUATION 2-3:

$$f_{parallel} = \frac{1}{2\pi\sqrt{L\left(C_S\left(1 + \frac{C_S}{C_4}\right)\right)}}$$

where

$$C_S = C_1 + C_2 + C_3 + C_5$$

Equation 2-3 is used for the antenna circuit of the interrogator in the DEV103005 kit.

The antenna voltage across the L is given:

EQUATION 2-4:

$$V_{Ant} = \frac{jX_L}{r + j(X_L - X_{C_S})} V_{in}$$

where

r = Ohmic resistance of L and C

$$X_L = 2\pi f L (\Omega)$$

$$X_{C_S} = (2\pi f C_S)^{-1} (\Omega)$$

V_{IN} = AC voltage at points between P1 and P2.

The antenna voltage measured between P3 and P2 contributes the radiating RF field from the antenna. The voltage is about 60 V_{PP}-80 V_{PP}. C₅ can be adjusted to get the maximum voltage across the antenna. The current that flows along antenna L generates magnetic fields.

Each interrogator unit may have a slightly different output parasitic capacitor. As a result, there will be a chance of tuning variation when the antenna is attached to the unit. This results in shorter read range. In this case, C₅ in the circuit should be adjusted properly.

2.2 Receiving Section

The receiving section receives 70 kHz Manchester data from tag in the field. D1, C4 and R3 collectively form an envelope detector.

L1 and C3 forms a 70 kHz band-pass filter. D4 and D2 are used to limit signal amplitude level which prevents U1:A from going into a saturation condition. L3, C33 and C47 form a 13.56 MHz notch filter and bypass the induced carrier signal into ground. FB1 is an RF choker that gives high attenuation to high frequency signal. U1:A is a gain amplifier that gives about 26 dB voltage gain. U1: B is a unit gain second-order high-pass filter. U1:C is a gain amplifier with about 29 dB voltage gain. U1:D is a unit gain second-order low-pass filter. U1:B and D result in a band-pass filter for the 70 kHz Manchester data.

U11:A, B, T1 and T2 circuits are used to find a midpoint of the input data voltage. The resulting average voltage, (V_{P+} + V_{P-})/2, is used as a reference voltage for the voltage comparator U2. The output of U2 is fed into the PICmicro microcontroller U17 for data decoding.

2.3 Command Control and Data Decoding Section

The interrogator uses two PICmicro MCUs (PIC16F876-20/SP) for the command controls, data decoding and communication with a host computer.

The U17 includes PIC[®] code routines to follow the device's read/write anti-collision algorithm as shown in Figure 4-1 in the data sheet. The U14 performs bit timing calculation for the received Manchester code.

The U17 does the following tasks:

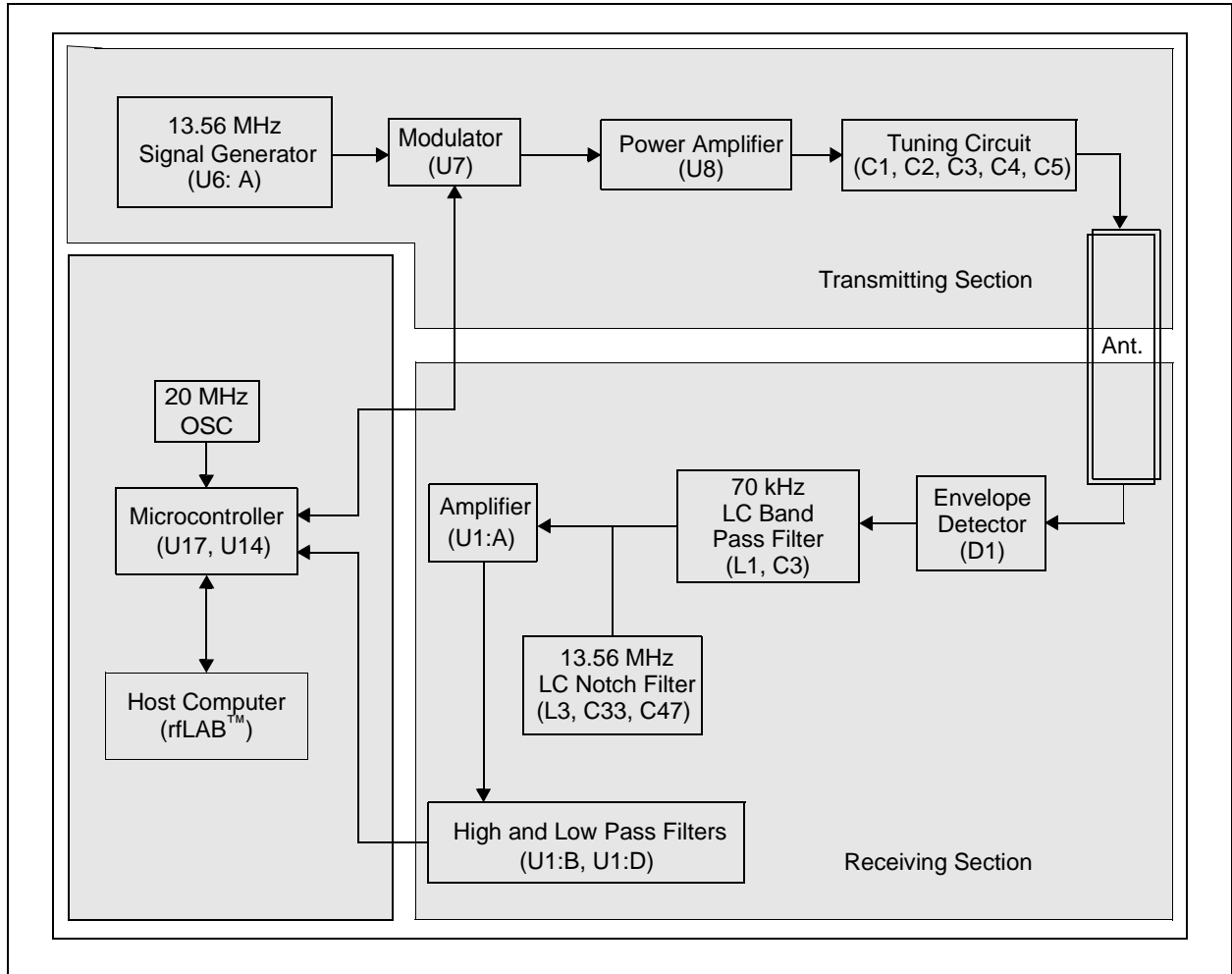
- Communicate with a host computer
- Encode and transmit:
 - FRR and FRB Commands
 - Calculate/Send MC1 and MC2
 - Read/Write/End Commands
 - Calibration Pulse
 - Data and CRC
- Decode receiving data
- Calculate CRC for transmitting data and receiving data. CRC look-up table is used for the calculation.
- Give a received data stream to U14 for decoding of the Manchester data.

The flow charts of the PICmicro microcontroller routines for U14 and U17 are shown in AN760 (DS00760). The source codes are available for download and contained on the CD provided in the DV103006 develop kit.

Figure 2-2 shows the functional block diagram of the interrogator.

MCRF45X REFERENCE DESIGN

FIGURE 2-2: FUNCTIONAL BLOCK DIAGRAM OF DEMO INTERROGATOR



MCRF45X REFERENCE DESIGN

FIGURE 2-3: DATA SIGNAL WAVEFORMS FROM TAG

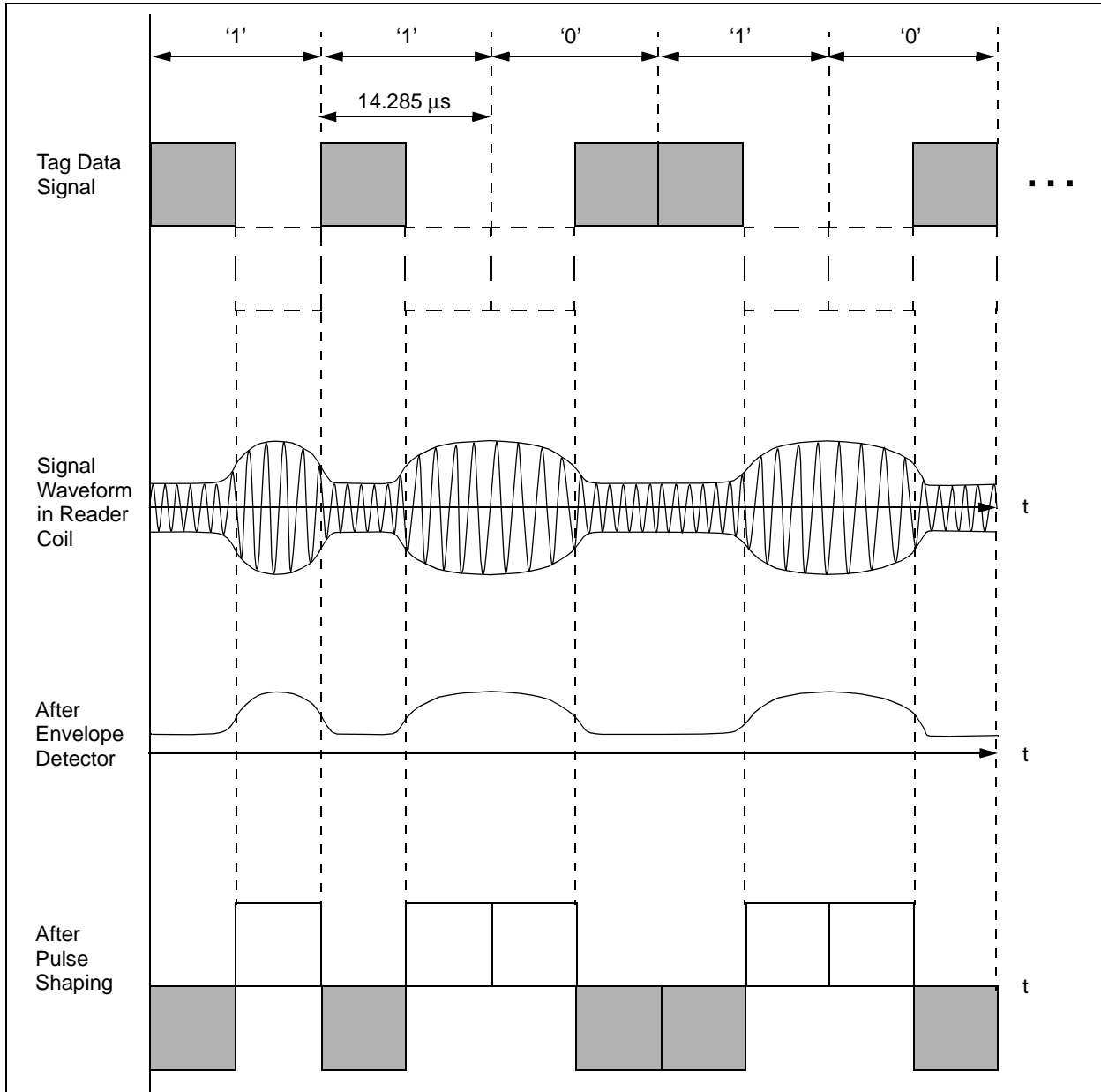
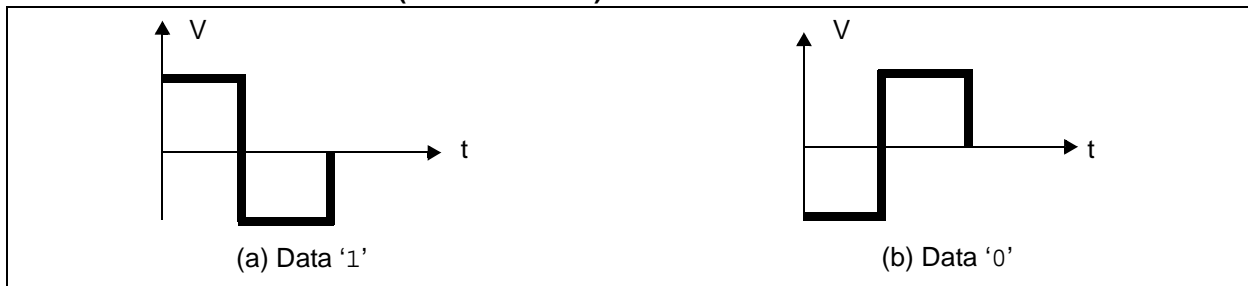
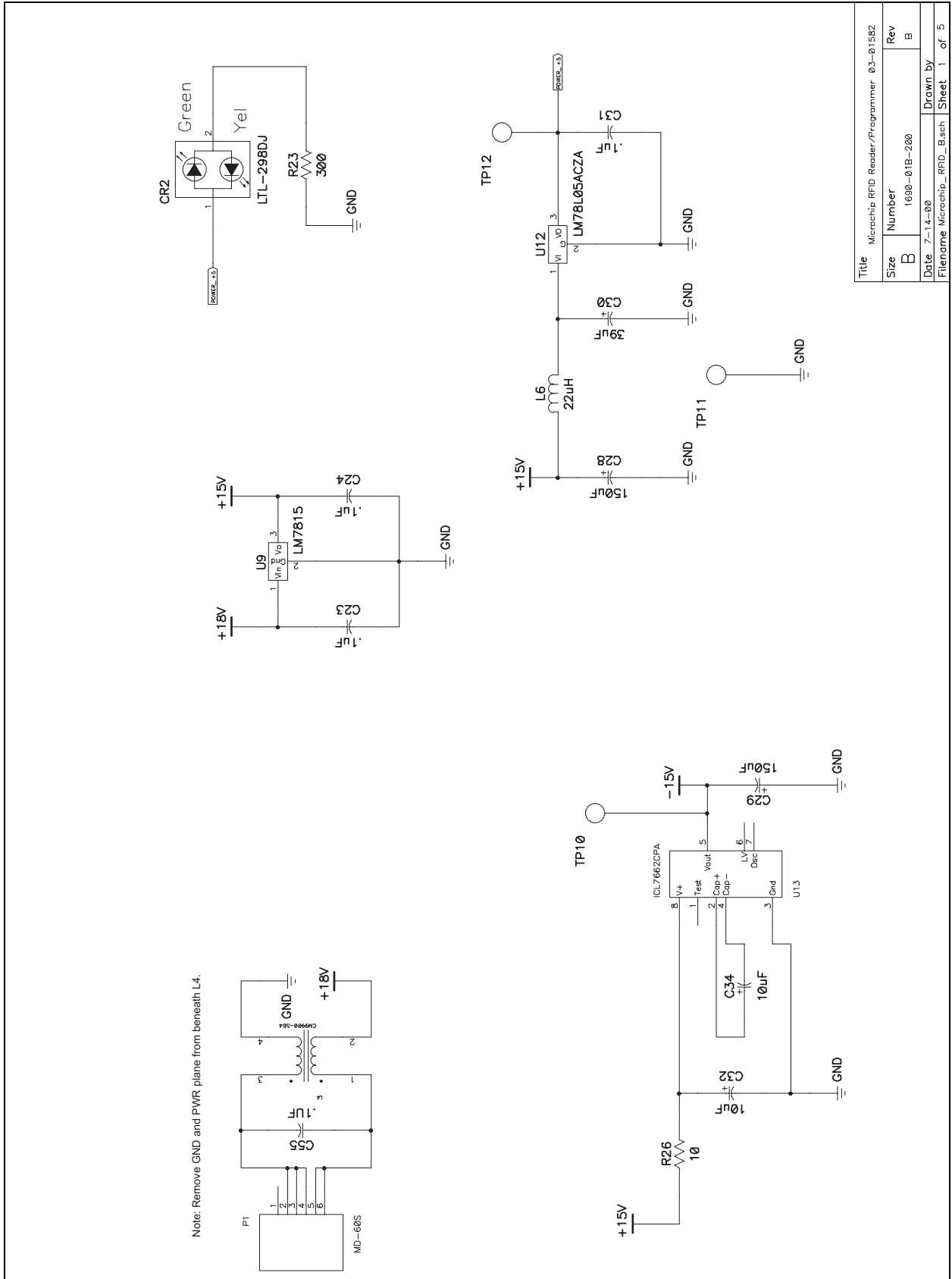


FIGURE 2-4: BIPHASE-L (MANCHESTER) SIGNAL

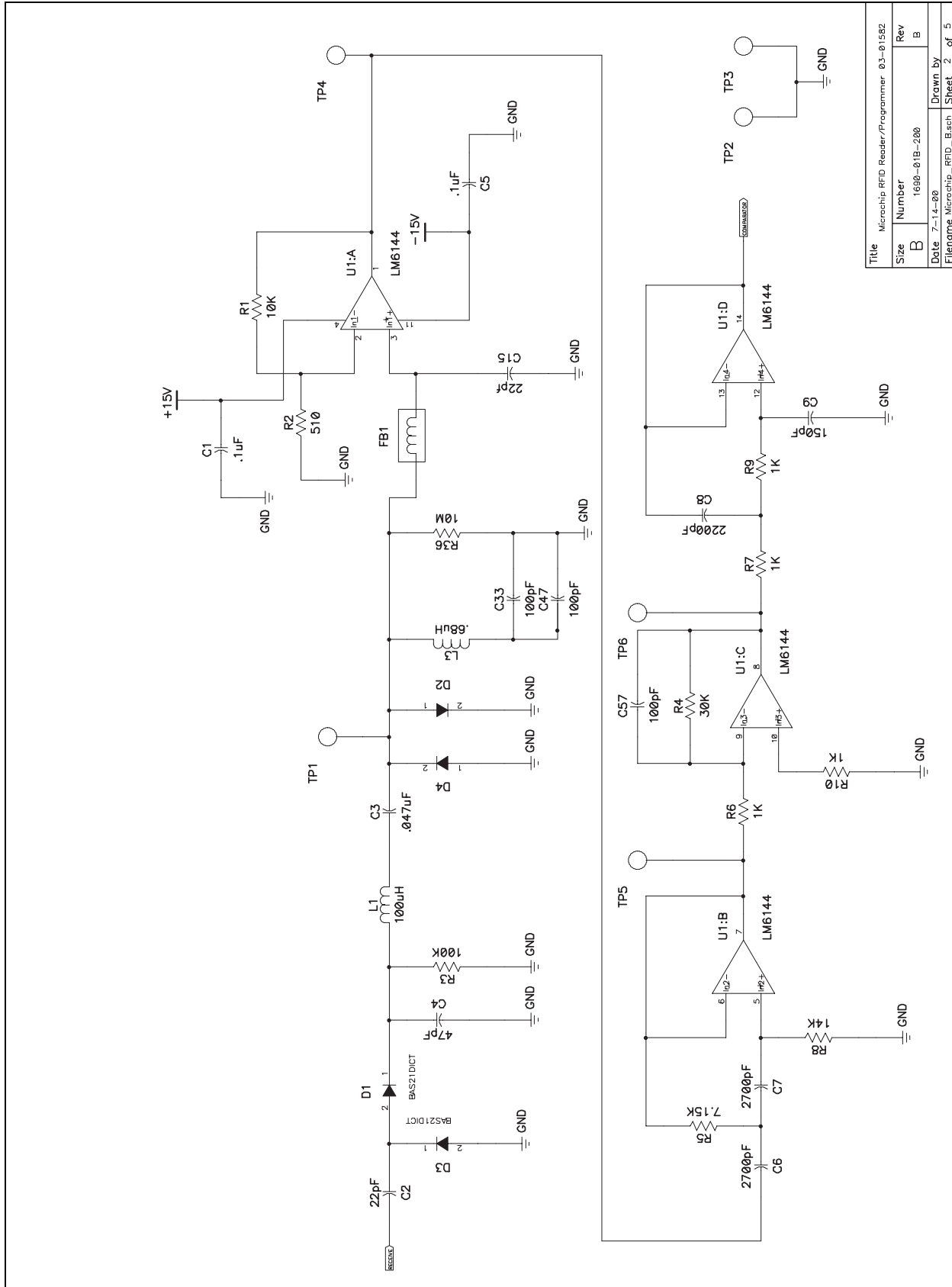


MCRF45X REFERENCE DESIGN



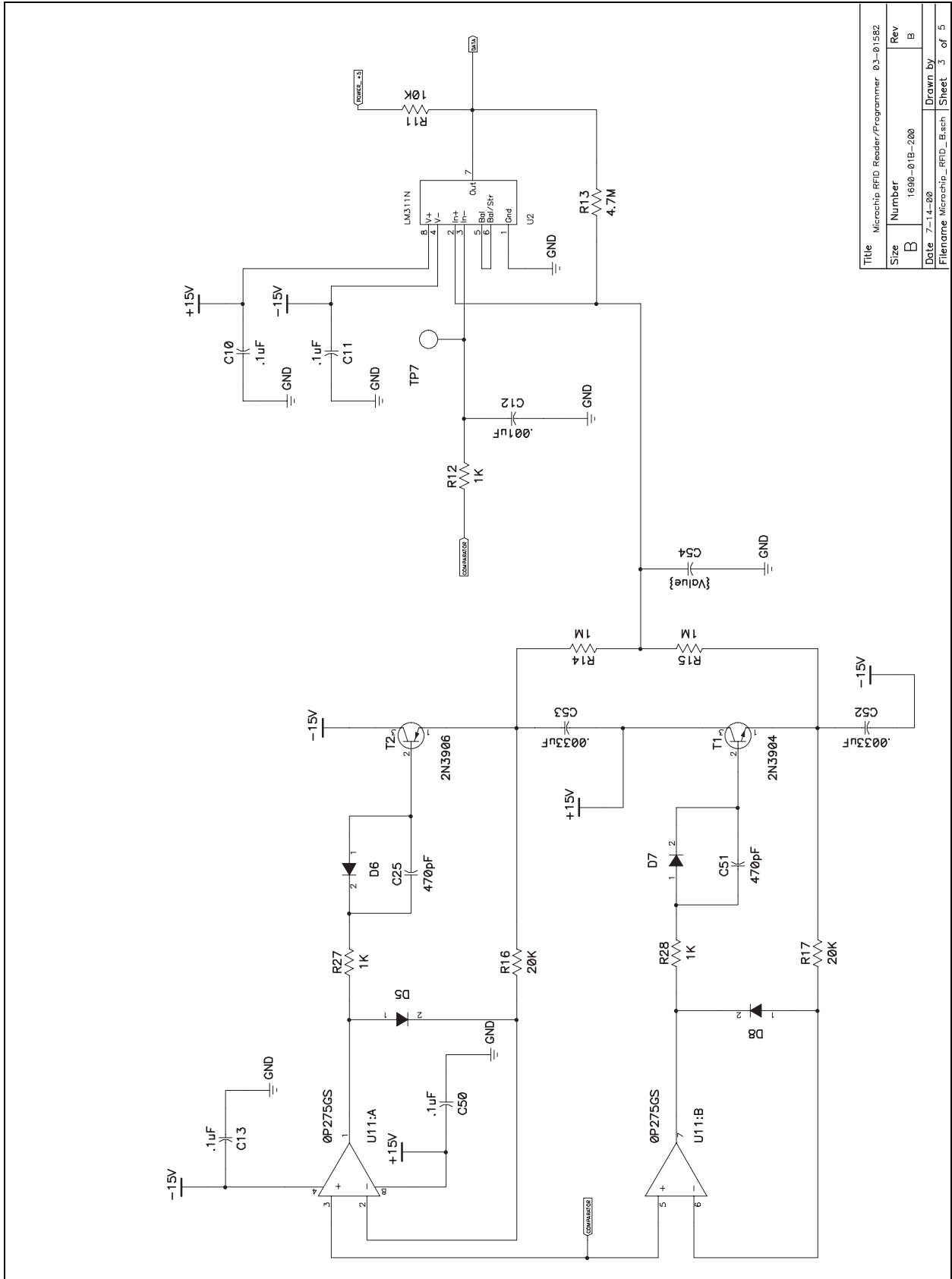
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| Number | 1690-01B-200 |
| Date | 7-14-00 |
| Drawn by | Sheet 1 of 5 |

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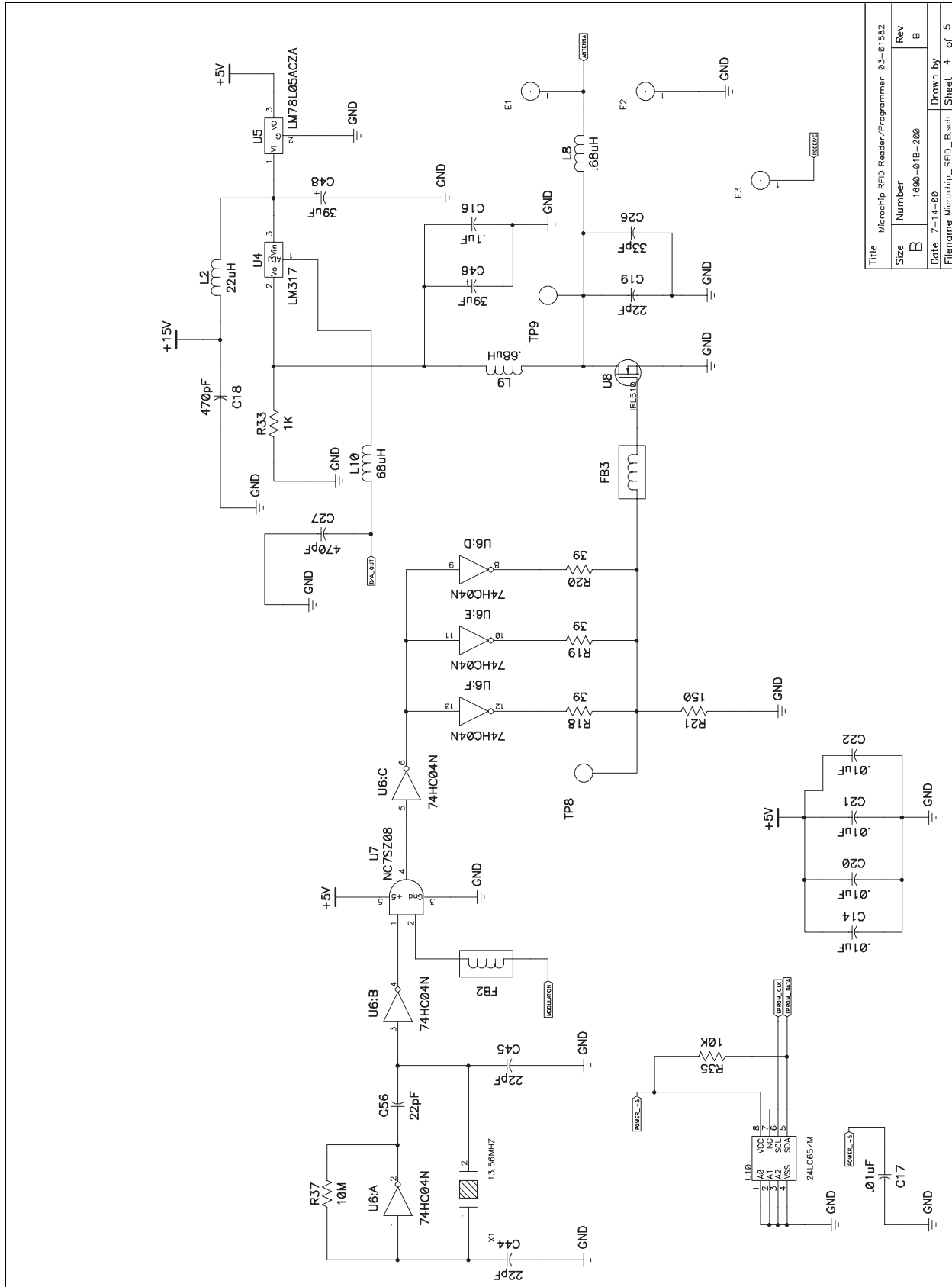
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| Title | | Microchip RFID Reader/Programmer 03-01582 | |
| Size | Number | Rev | |
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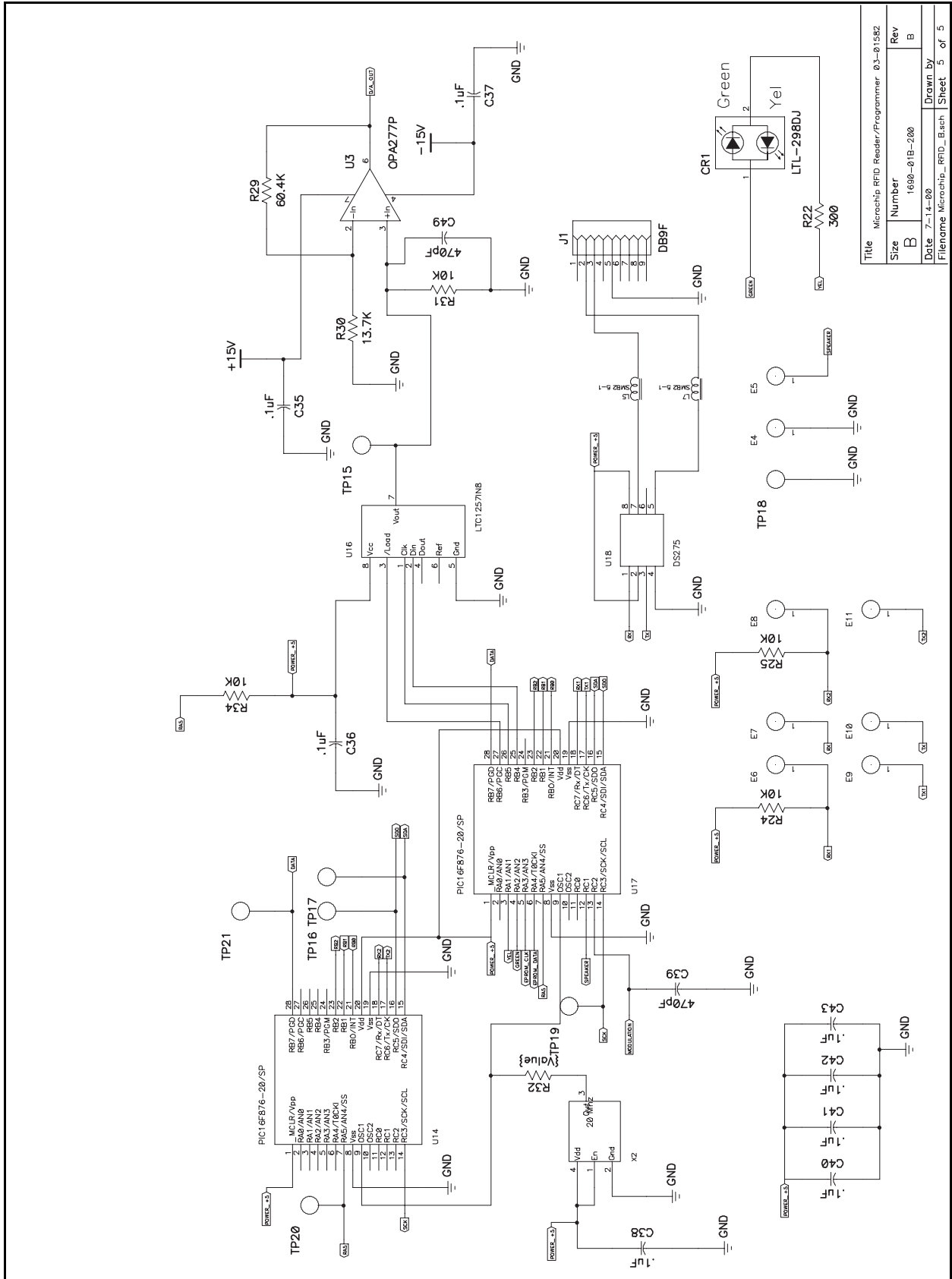
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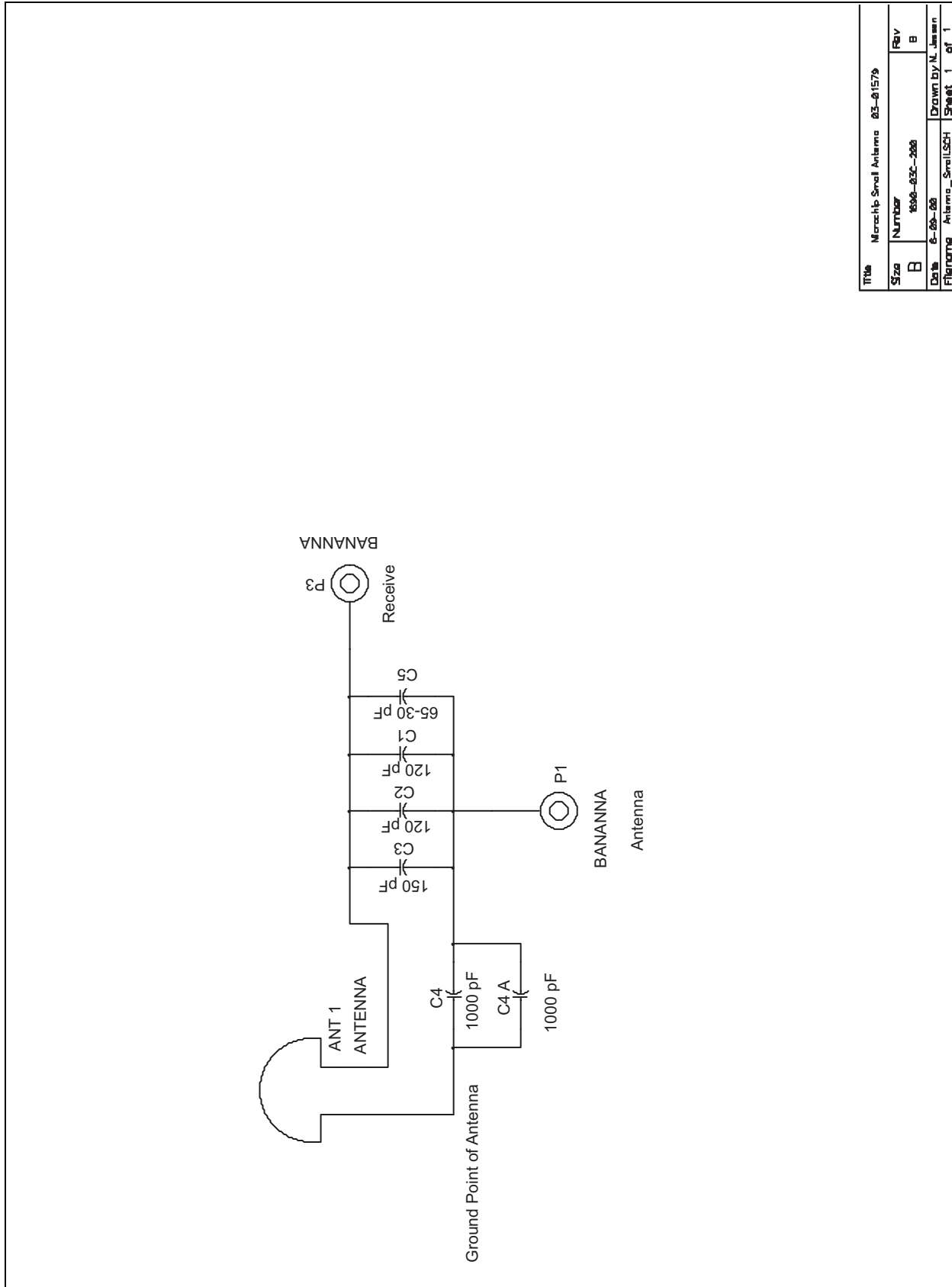
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MCRF45X REFERENCE DESIGN



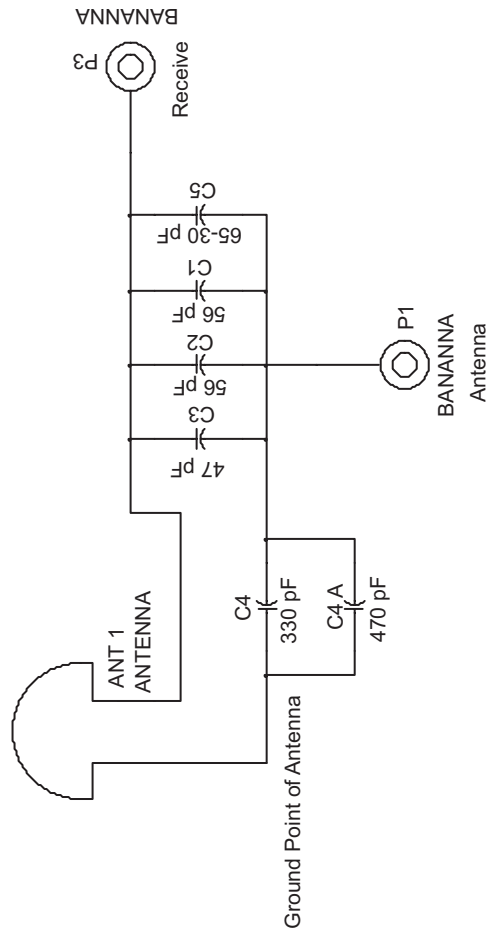
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| Sheet | 5 of 5 |

MCRF45X REFERENCE DESIGN



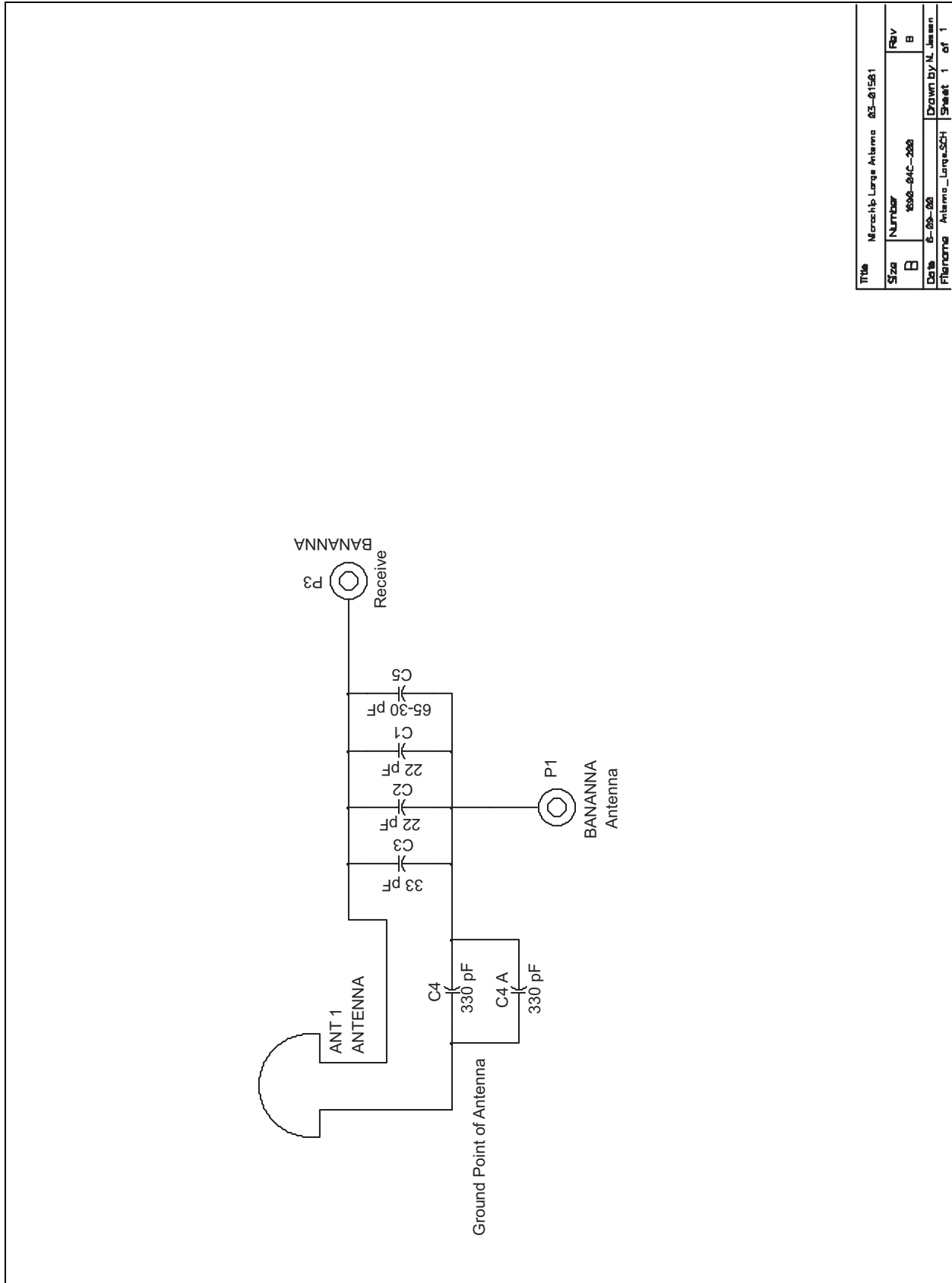
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|----------|-------------------------|--------------------|
| Title | Microchip Small Antenna | DS-01579 |
| Size | Number | Rev |
| B | 1000-02C-200 | B |
| Date | 6-03-03 | Drawn by N. Jansen |
| Filename | Antenna_SmallSCH | Sheet 1 of 1 |

MCRF45X REFERENCE DESIGN



| | | |
|----------|--------------------------|--------------------|
| Title | Microchip Medium Antenna | 03-01580 |
| Size | Number | Rev |
| B | 1000-02C-300 | B |
| Date | 6-28-00 | Drawn by N. Jensen |
| Filename | Antenna_Nat1SCH | Sheet 1 of 1 |

MCRF45X REFERENCE DESIGN



| | | |
|----------|-------------------------|--------------------|
| Title | Microchip Large Antenna | 05-01561 |
| Size | Number | Rev |
| B | 1000-04C-200 | B |
| Date | 6-08-00 | Drawn by N. Jansen |
| Filename | Antenna_Large.SCH | Sheet 1 of 1 |

Interface Control Document for the 13.56 MHz Anti-Collision Interrogator

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SCOPE

This document specifies the external interface requirements for the MCRF4XX and MCRF355/360 Interrogator of the RFID development kits (DV103005 and DV103006). A description of the RS232 interface messages, their bit fields and meanings are described in this document.

Identification

This interface control document is applicable to the Microchip's 13.56 MHz RFID Reader/Writer.

System Overview

The RFID Reader/Writer will support both reading and writing of the MCRF355/360 and MCRF4XX RFID devices. The RFID Reader/Writer will support communication for commands and data via the RS232 interface, using standard protocol settings.

EXTERNAL INTERFACES

Electrical Interfaces

SERIAL COMPUTER INTERFACE

The RFID Reader/Writer communicates with the external host computer via the RS232 interface. The interface settings will be 19.2 Kbaud, 8 bits, no parity and one stop bit. All characters transmitted should be within the ASCII character set, with values less than 127.

TEST INTERFACE

The RFID Reader/Writer provides discrete LEDs that give simple status of the RFID Reader/Writer, independent of an attached PC.

Communication Protocol/Messages

The packet protocol for the RFID Reader/Writer is described in the following paragraphs. The protocol provides a robust, easily managed interface that supports debugging on a simple ASCII terminal, in addition to providing a checksum for message validation.

The general message format is as follows:

EXAMPLE 1: General Message Format

| | | | | |
|-----------|---------|------|----------|-------|
| Sync Char | Command | Data | Checksum | CR LF |
|-----------|---------|------|----------|-------|

TABLE 1: GENERAL MESSAGE DETAIL

| | |
|-----------|---|
| Sync Char | Single byte character '@', denoting the beginning of a message. |
| Command | Single byte character defining the command this message represents. See Table 2 for a list of commands. |
| Data | A variable length field containing additional information support for the command. |
| Checksum | The two-byte checksum used for the message includes the Sync Char through the end of the Data field. See the following paragraph for more information on the checksum used. |
| CR LF | This two-byte field is the standard ASCII carriage return '0x0D' and the line feed '0x0A'. |

TABLE 2: COMMAND OVERVIEW

| Command Char | From | To | Description |
|--------------|------|-----|---|
| '2' | R/W | PC | Data field contains MCRF355 data (14 bytes) |
| '3' | R/W | PC | Data field contains MCRF355 data (18 bytes) |
| '4' | R/W | PC | Data field contains MCRF4XX data blocks (Read) |
| '5' | R/W | PC | Data field contains MCRF4XX data blocks (Write) |
| '6' | R/W | PC | Data field contains MCRF4XX FRB response data |
| '7' | R/W | PC | Data field contains MCRF4XX FRR response data |
| 'F' | R/W | PC | Firmware version |
| 'R' | R/W | PC | Response message |
| 'R' | PC | R/W | Reset request command |
| 'M' | PC | R/W | Mode select command |
| 'N' | PC | R/W | No operation |
| 'V' | PC | R/W | Verbose read command |
| 'W' | PC | R/W | Write command |
| 'C' | PC | R/W | Configuration message |
| 'L' | PC | R/W | Load command |

CHECKSUM

The checksum is a two-character field. Adding the fields Sync Char through Data into an unsigned byte type, and ignoring any overflow generated, determines this value. The resultant value is then negated to provide a two's complement checksum value. This 8-bit result is then converted to two hex characters to represent the checksum in the message (e.g. checksum byte value 00101100 results in a checksum of two ASCII bytes '2C', represented in the message).

Message Formats

The following paragraphs detail the individual commands and messages.

LOAD MESSAGE

The load command provides a method to update the PIC16F876 firmware in the field via the RS232 interface. The Data Field length is zero. When the load command is received, the RFID Reader/Writer will transition to a 'loader', which will then accept hex record lines to be written to program memory. The format of the hex record should be the format generated by the Microchip assembler/linker. Each hex record line is validated before writing to program memory. The RFID Reader/Writer will either respond with a 'Ready' response message upon successful write or an error message, if unsuccessful. Once the final line of the .HEX file is sent, the newly loaded program is entered using the POR vector at address 0000. See Response Message paragraphs for more information on this.

EXAMPLE 2: Load Message Format

| | | | | |
|------|-----|------|----------|-------|
| 0x40 | 'L' | Data | Checksum | CR LF |
|------|-----|------|----------|-------|

RESPONSE MESSAGE

The response message is used to provide an acknowledge and status response from the R/W to the external PC. The data field contains the specific response encoded as a 2-digit hexadecimal number. The responses supported are listed in Table 3.

EXAMPLE 3: Response Message Format

| | | | | |
|------|-----|-----------------|----------|-------|
| 0x40 | 'R' | Response Number | Checksum | CR LF |
|------|-----|-----------------|----------|-------|

TABLE 3: RESPONSE MESSAGES

| Response Number | Equivalent Text | Description |
|-----------------|----------------------------|--|
| 00 | "Ready" | Ready for the next message. |
| 01 | "EEPROM Burn Failed" | Previous write was read back and validated unsuccessfully. |
| 02 | "No Entry Point Specified" | No processor instructions were given for ROM locations 0-3. |
| 03 | "Invalid Address" | A write to Program ROM was outside valid range. |
| 04 | "Invalid Hex Data" | The characters representing hex data were not in the range 0-9 or A-F. |
| 05 | "RS232 Error" | Characters were lost or garbled. Message should be resent. |
| 06 | "Invalid Checksum" | Checksum did not verify. |
| 07 | "Undefined Command" | Command byte sent is not a known command. |
| 08 | "Invalid Parameter" | Contents of a command string are invalid. |
| 09 | "Bad Processor" | The slave processor failed to communicate. |

RESET MESSAGE

The reset message is sent from the external PC to the Reader/Writer. It instructs the R/W to reset itself and return to the just-powered-up state. In this state, the carrier is off and the R/W is sending 'A' characters over the RS232 line at a 50 Hz rate, looking for a PC-based application to communicate with. See the paragraph on "Auto Detect Support" for a more complete description. The data field length is zero.

EXAMPLE 4: Reset Message Format

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | 'R' | Data Field | Checksum | CR LF |
|------|-----|------------|----------|-------|

NOP MESSAGE

The NOP message is a non-operation message. It can be used as a 'heartbeat' message to maintain communication, if needed. The Data Field length is zero. This command returns the "Ready" Response Message ('R'). Note that this, and every, command causes the Reader/Writer to stop its current operations to process the new command. After this command, the Reader/Writer remains in the idle loop, waiting for the next command.

EXAMPLE 5: NOP Message Format

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | 'N' | Data Field | Checksum | CR LF |
|------|-----|------------|----------|-------|

AN759

MODE SELECT MESSAGE

The mode select message is used to put the RFID Reader/Writer in a specific read mode, as defined below.

EXAMPLE 6: Mode Select Message Format

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | 'M' | Data Field | Checksum | CR LF |
|------|-----|------------|----------|-------|

The mode field contains a one-byte character that defines the specific mode to place the reader into. This byte is defined below.

TABLE 4: MODE SELECT CHARACTERS

| Mode Char | Description |
|-----------|--|
| '0' | Read MCRF355/360 tags, returning the data in Microchip format. No anti-collision – all tag reads are reported. |
| '1' | Read MCRF355/360 tags, returning raw tag data. No anti-collision – all tag reads are reported. |
| '2' | Read MCRF355/360 tags, returning the data in Microchip format. Anti-collision enabled – subsequent reads of the same tag are ignored. |
| '3' | Read MCRF355/360 tags, returning raw tag data. Anti-collision enabled – subsequent reads of the same tag are ignored. |
| 'I' | Inventory read mode (FRR & FRB: tags are put to sleep after being identified). |
| 'C' | Continuous read mode (FRR & FRB). |
| 'A' | Alarm mode (FRR only). |
| 'S' | Stop reading mode (Leave carrier on). |
| 'F' | Reader/writer off (Turn carrier off). |

MCRF355 DATA BLOCKS MESSAGE – MICROCHIP FORMAT

This message contains the entire data block from the MCRF355/360 represented in ASCII hex format. It assumes the tag was written in Microchip format, which is: 10-bit header (9 ones and 1 zero), followed by 14 8-bit bytes and a 2-byte checksum, with each byte separated by a zero bit, and written MSB first. The checksum of the block is verified before transmission.

EXAMPLE 7: MCRF355/360 Data Blocks Message

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | '2' | Data Block | Checksum | CR LF |
|------|-----|------------|----------|-------|

The format of the data block is as follows:

Data Block Format

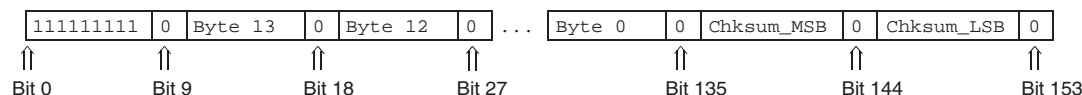
| |
|-----------------------|
| T<time stamp>, <data> |
|-----------------------|

Where:

TABLE 5: MCRF355/360 DATA BLOCKS MESSAGE DETAIL

| Field name | Description |
|------------|--|
| Time stamp | The time stamp that indicates when the device was read. This value consists of 2 bytes (4 ASCII hex characters), with the LSB = 819.2 μS. The clock is a free-running counter, with a rollover period of 53.7 seconds. The bytes are sent MSB first. |
| Data | The 14 data bytes represented in ASCII hex characters. Byte 13 is first; byte 0 is last. The checksum bytes are not transferred. |

"Microchip Format" is defined by the MCRF355/360 Contact Programmer and is shown graphically below. Of the 154 bits in the tag, the first 9 are the preamble, and fixed as '1' bits. Following the preamble, and separating each byte, are spacer bits (zeros). All bytes are Most Significant Bit (MSB) first. This format allows 14 data bytes followed by a 16-bit checksum (simple summation of all 14 bytes).



AN759

MCRF355 DATA BLOCKS MESSAGE – RAW FORMAT

This message contains the data block from the MCRF355/360 represented in ASCII hex format. It assumes the tag was written in Microchip format, however, the spacer bits which exist between every byte are not removed. Internally, the data is converted to Microchip format so that the block checksum can be calculated and verified before transmission.

EXAMPLE 8: MCRF355/360 Data Blocks Message Format

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | '3' | Data Block | Checksum | CR LF |
|------|-----|------------|----------|-------|

The format of the Data Block is as follows:

Data Block Format

| |
|-----------------------|
| T<time stamp>, <data> |
|-----------------------|

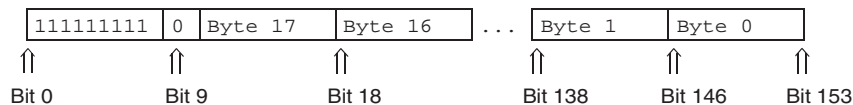
Where:

TABLE 6: MCRF355/360 DATA BLOCKS MESSAGE DETAIL

| Field name | Description |
|------------|--|
| Time stamp | The time stamp that indicates when the device was read. This value consists of 2 bytes (4 ASCII hex characters), with the LSB = 819.2 μ S. The clock is a free-running counter with a rollover period of 53.7 seconds. The bytes are sent MSB first. |
| Data | The 18 data bytes represented in ASCII hex characters. Byte 17 is sent first. |

For purposes of displaying it in 'Raw Format', the tag data is assumed to be as shown graphically below. It is similar to the Microchip Format in that all bytes are Most Significant Bit (MSB) first, and the first 10 bits are the fixed preamble (9 one-bits followed by a zero bit). The remaining 143 bits make up the 18 8-bit bytes.

Note: The last byte has one missing bit. Its Least Significant Bit (LSB) is fixed at zero.



MCRF4XX DATA BLOCKS MESSAGE

EXAMPLE 9: MCRF4XX Data Blocks Message Format

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | '4' | Data Block | Checksum | CR LF |
|------|-----|------------|----------|-------|

This message contains the data blocks returned from the MCRF4XX in response to a Verbose Read command. All 32 blocks of the MCRF4XX tag are included. The message elements are defined below. The format of the Data Block is:

Data Block Format

| |
|---|
| I<id>, <block>:<data>, <block>:<data>, ... <block>:<data> |
|---|

Where:

TABLE 7: MCRF4XX DATA BLOCKS MESSAGE DETAIL

| Field name | Description |
|------------|---|
| I<id> | The ASCII hex representation of the 4-byte tag ID. LSB first. |
| Block | Block number, represented by 2 ASCII hex characters. Its value ranges from 00 to 1F (31 decimal). Block numbers are followed by a colon. |
| Data | One data block (4 bytes) from the tag, represented in ASCII hex characters. Data blocks are separated by commas. A block that is unreadable (invalid CRC) will return "XXXX" for the data. In this case, it will be 4 characters instead of 8. The data is LSB first. |

MCRF4XX DATA BLOCKS WRITTEN MESSAGE

EXAMPLE 10: MCRF4XX Data Blocks Message Format

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | '5' | Data Block | Checksum | CR LF |
|------|-----|------------|----------|-------|

This message contains the data blocks returned from the MCRF4XX in response to a Verbose Write command. One message is returned per tag written. The message elements are defined below. The format of the Data Block is:

Where:

TABLE 8: MCRF4XX DATA BLOCKS MESSAGE DETAIL

| Field name | Description |
|------------|--|
| I<id> | The ASCII hex representation of the 4-byte tag ID. LSB first. |
| Block | Block number, represented by 2 ASCII hex characters. Its value ranges from 00 to 1F (31 decimals). Block numbers are followed by a colon. |
| Data | One data block (4 bytes) from the tag, represented in ASCII hex characters. This data is what the tag returns following the write to this block. A block which is write-protected will return to "RO" for the data. In this case, it will be 2 characters instead of 8. A block that is unreadable (invalid CRC) will return "XXXX" for the data. The data is LSB first. |

AN759

MCRF4XX FRB RESPONSE MESSAGE

EXAMPLE 9: MCRF4XX FRB Response Message Format

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | '6' | Data Block | Checksum | CR LF |
|------|-----|------------|----------|-------|

This message contains the data returned from the MCRF4XX in response to an FRB command. The message elements are defined below. The format of the Data Block is:

Data Block Format

| |
|-------------------------------------|
| T<time stamp>, <TC/TP>, <ID>, <FRF> |
|-------------------------------------|

Where:

TABLE 9: MCRF4XX FRB RESPONSE MESSAGE DETAIL

| Field name | Description |
|------------|---|
| Time stamp | The time stamp which indicates when the device was read. This value consists of 2 bytes (4 ASCII hex characters), with the LSB = 819.2 μ S. The clock is a free-running counter with a rollover period of 53.7 seconds. The bytes are sent MSB first. |
| ID | One data block (4 bytes) represented in ASCII hex characters. The data is from Block #1, the tag's ID. The data is sent LSB first. |

MCRF4XX FRR RESPONSE MESSAGE

EXAMPLE 6: MCRF4XX FRR Response Message

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | '7' | Data Block | Checksum | CR LF |
|------|-----|------------|----------|-------|

This message contains the data returned from the MCRF4XX in response to an FRR command. The message elements are defined below. The format of the Data Block is:

Data Block Format

| |
|--|
| T<time stamp> , <TC/TP> , <ID> , <FRF> |
|--|

Where:

TABLE 10: MCRF4XX FRR RESPONSE MESSAGE DETAIL

| Field name | Description |
|------------|---|
| Time stamp | The time stamp indicates when the device was read. This value consists of 2 bytes (4 ASCII hex characters), with the LSB = 819.2 μ S. The clock is a free-running counter with a rollover period of 53.7 seconds. The bytes are sent MSB first. |
| TC/TP | One byte containing the TC and TP values from the tag, represented in ASCII hex characters. Bits 0-2 are the TC value; bits 3-7 are the TP (tag parameters) value. See the MCRF4XX Data Sheet on the format of the TP field. |
| ID | One data block (4 bytes) represented in ASCII hex characters. The data is from Block #1, the tag's ID. The data is sent LSB first. |
| FRF | The Fast Read Field, represented in ASCII hex characters. The data is from Blocks #3 through 5. The exact number of bytes in the FRF depends upon the 2 DF bits within the TP field and can be 4, 6, 8 or 12. The LSB is sent first. |

FIRMWARE VERSION RESPONSE MESSAGE

EXAMPLE 7: Firmware Version Response Message Format

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | 'F' | Data Block | Checksum | CR LF |
|------|-----|------------|----------|-------|

This message is sent once, immediately following connection establishment. The format of the Data Block is 2 ASCII digits, indicating the major and minor revision numbers. The range of revision numbers supported is 1.0 through 9.9.

AN759

VERBOSE READ MESSAGE

This message will terminate continuous read mode and initiate a read of a specific ID tag in the field. Use the second form of the message to read any tag which comes into the field. The response to this message will be a MCRF4XX Data Block message ('4').

EXAMPLE 8: Verbose Read Message Format

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | 'V' | Data Block | Checksum | CR LF |
|------|-----|------------|----------|-------|

The Data Block has the following format when reading from one selected tag. All characters not between braces ('<' '>') are necessary for a valid message. The <start> and <end> values range from 00 to 1F, covering the 32 Blocks of the tag.

Data Block Format

| |
|-----------------------|
| I<id>, <start>, <end> |
|-----------------------|

Where:

TABLE 11: VERBOSE READ MESSAGE DETAIL

| | |
|---------------|--|
| I<id> | The ASCII hex representation of the 4-byte tag ID (LSB first). |
| <start block> | The beginning block number to read, represented in ASCII hex. |
| <end block> | The final block number to read, in ASCII hex representation. |

The Data Block has the following format to read data blocks from all devices in the R/W field.

Data Block Format

| |
|-----------------------|
| I<id>, <start>, <end> |
|-----------------------|

Where

TABLE 12: VERBOSE READ MESSAGE DETAIL

| | |
|---------------|---|
| * | Replacing the I<id> field with a star character denotes all tags. |
| <start block> | The beginning block number to read, represented in ASCII hex |
| <end block> | The final block number to read, in ASCII hex representation |

WRITE MESSAGE

The write message provides the capability to program one, or all, MCRF4XX devices with 1 to 16 blocks of data. If 'write-all-tags' is selected, the Reader/Writer will look for all FRR and FRB parts in the field, writing them as soon as they are found, until the user places the Reader/Writer into another mode (or idle state). If 'one-tag-write' is selected, the carrier is turned off once the selected tag is found and written. The response to this message will be one or more MCRF4XX Data Blocks Written message ('5') - one per tag.

Block 1 (the tag ID) should not be written.

If the starting block number is 0 or 2, the number of data blocks to be written is limited to 1 block.

In order to prevent an FRR part from becoming inaccessible in the case of a failed write to blocks 0, 3, 4 or 5, the Reader/Writer will turn an FRR part into an FRB part prior to writing these blocks. Only if all blocks were written correctly will it turn back into an FRR part. When writing to block 0, Bit 31 should be kept clear to keep from flagging a special case.

Two special cases of the Write Command exist: converting FRR tags into FRBs, and converting FRB tags into FRRs.

To turn devices into FRR parts, issue the Write Message for data block 0, with the two most significant bits of the data (Fast Read and Talk First bits) set to '1'. The remaining 30 data bits are 'don't cares'. When the Reader/Writer sees this situation, it will calculate the correct FRR response CRC for the tag and write it to the lower 16 bits of block 0. Upon a successful write, it then sets the FR bit. A MCRF4XX Data Blocks Written message ('5') is returned for each tag that is changed from an FRB part to an FRR part.

To turn devices into FRB parts, issue the Write Message for data block 0, with Bit 31 of the data (Fast Read) set to '1', and bit 30 (Talk First) set to '0'. The remaining 30 data bits are 'don't cares'. The Reader/Writer will clear the FR bit (Bit 31 of block 0) without affecting any other tag memory bits. A MCRF4XX Data Blocks Written message ('5') is returned for each tag that is changed from an FRR part to an FRB part.

The format of the message is as follows.

EXAMPLE 9: Write Message Format

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | 'W' | Data Block | Checksum | CR LF |
|------|-----|------------|----------|-------|

The Data Block has the following format when writing to one selected tag. All characters not between braces ('<' '>') are necessary for a valid message. The total number of <data> fields must be 16 or less.

Data Block Format

| |
|---|
| I<id>, <block number>, <data>, . . . , <data> |
|---|

Where:

TABLE 1: WRITE MESSAGE DETAIL

| Field Name | Description |
|----------------|---|
| I<id> | The ASCII hex representation of the 4-byte tag ID (LSB first). |
| <block number> | The beginning block number to write, represented in ASCII hex. |
| <data> | A 4-byte block of data, LSB first, in ASCII hex representation. |

The Data Block has the following format to write to all devices in the R/W field. The total number of <data> fields must be 16 or less.

Data Block Format

| |
|--|
| *, <block number>, <data>, <data>,, <data> |
|--|

Where:

TABLE 13: WRITE MESSAGE DETAIL

| Field name | Description |
|----------------|---|
| * | Replacing the I<id> field with a star character denotes all tags. |
| <block number> | The beginning block number to write, represented in ASCII hex. |
| <data> | A 4-byte block of data, LSB first, in ASCII hex representation. |

AN759

CONFIGURATION MESSAGE

The configuration message provides a method to set specific attributes within the RFID Reader/Writer firmware. The format of the message is as follows:

EXAMPLE 10: Configuration Message

| | | | | |
|------|-----|------------|----------|-------|
| 0x40 | 'C' | Data Block | Checksum | CR LF |
|------|-----|------------|----------|-------|

The Data Block consists of up to 7 parameters that can be set. The parameters are separated by commas and begin with an identifying character. Any parameter not included in the command retains the value it had before the Configuration Message. The order of the parameters is not important.

Data Block Format

| |
|---|
| T<ts>,M<tcmax>,S<speed>,P<ppm timing>,G<gap timing>,V<vpp>,I<audio> |
|---|

Where:

TABLE 14: CONFIGURATION MESSAGE DETAIL

| Field | POR Value | Description |
|---------------|-----------|---|
| T<ts> | 16 | The ASCII hex representation of 1 byte. The number of Time Slots used in the tag's FRR command. Valid values are: 1, 16, 64. |
| M<tcmax> | 1 | The ASCII hex representation of 1 byte. The TC MAX value to use in the tag's FRR command. Valid values are: 1, 2, 4. If TS = 64, then TC MAX must be 1. |
| S<speed> | 0 | The ASCII hex representation of 1 byte. Whether to modulate the carrier at Normal Speed or Fast Speed for the PPM symbols. A value of 0 sets Normal Speed while a value of 1 sets Fast Speed. |
| P<ppm timing> | 0 | The ASCII hex representation of an 8-bit signed integer. The relative timing to use for gap periods. Valid range is -6 to +6, with 0 being nominal (175 μ S Normal Speed/10 μ S Fast Speed). -6 corresponds to 20% reduction in time, and +6 corresponds to 20% increase in time. +/- 3 corresponds to +/-10%, etc. |
| G<gap timing> | 0 | The ASCII hex representation of an 8-bit signed integer. The relative timing to use for gap widths. Valid range is -6 to +6, with 0 being nominal (100 μ S Normal Speed/6 μ S Fast Speed). -6 corresponds to 20% reduction in time, and +6 corresponds to 20% increase in time. +/- 3 corresponds to +/-10%, etc. |
| V<vpp> | FFh | The ASCII hex representation of 1 byte: The relative strength of the carrier signal. A value of 0 sets no carrier while a value of FFh sets maximum carrier field strength. |
| I<audio> | 1 | The ASCII hex representation of 1 byte: A value of 1 enables beeps when each tag is detected. A value of 0 disables audible indication. |

AUTO DETECT SUPPORT

At power-up of the RFID Reader/Writer, the character 'A' will be continuously transmitted at a 50 Hz rate over the serial port. This provides a serial stream to support auto-detection of the device by a PC. When the Reader/Writer receives a 'B' character from the PC, it will cease transmission of the 'A' characters, and return a type 'F' Response Message (Firmware Version), thus establishing a positive confirmation of communication. The RS232 parameters are: 19.2 Kbaud, 8 bits, no parity and 1 stop bit.

REFERENCED DOCUMENTS

The following references are used for this document:

1. EIA Standard RS232-C
2. RS232A Specification

REVISION HISTORY

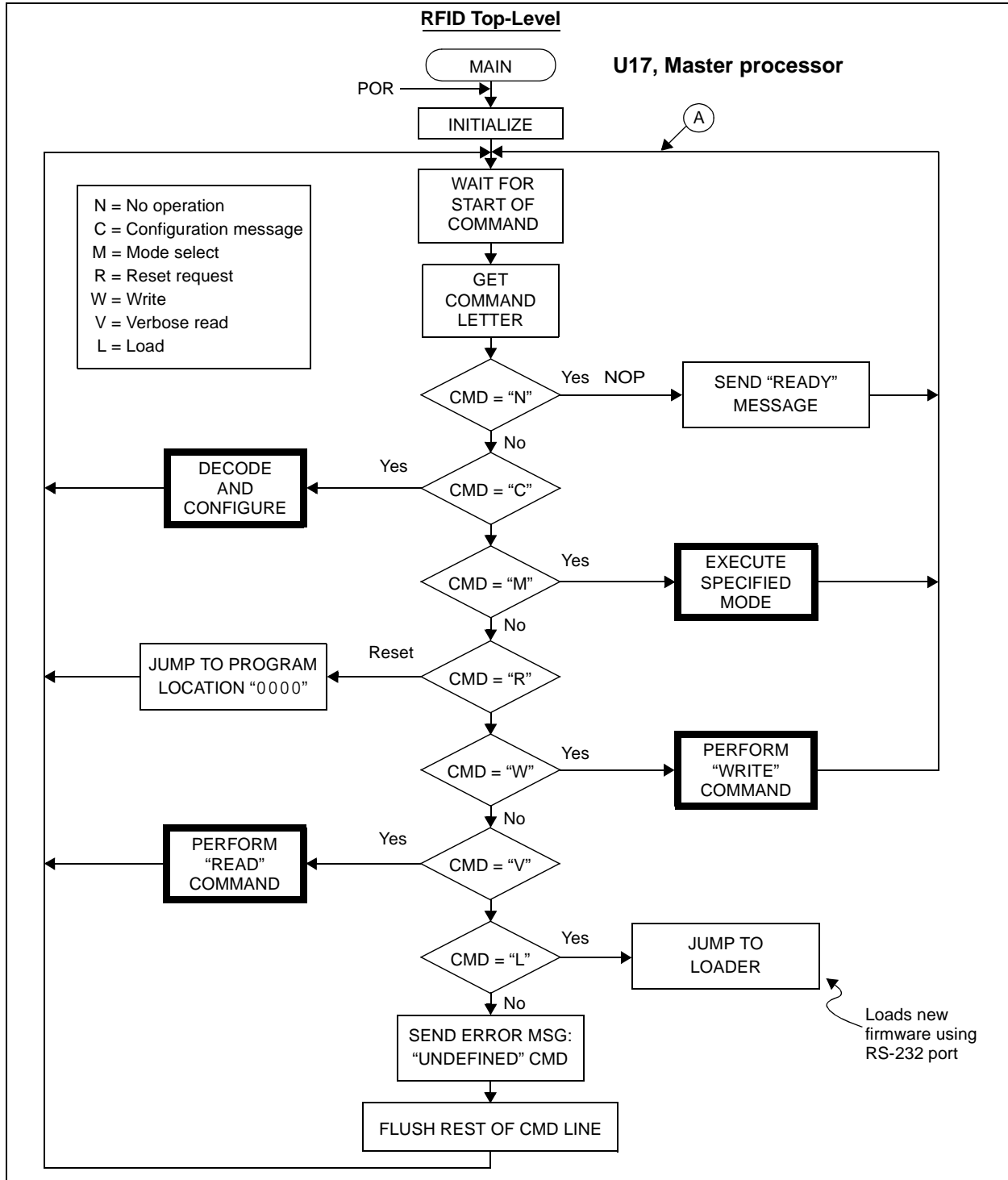
7/10/02 - Changed 'V' message to reflect:

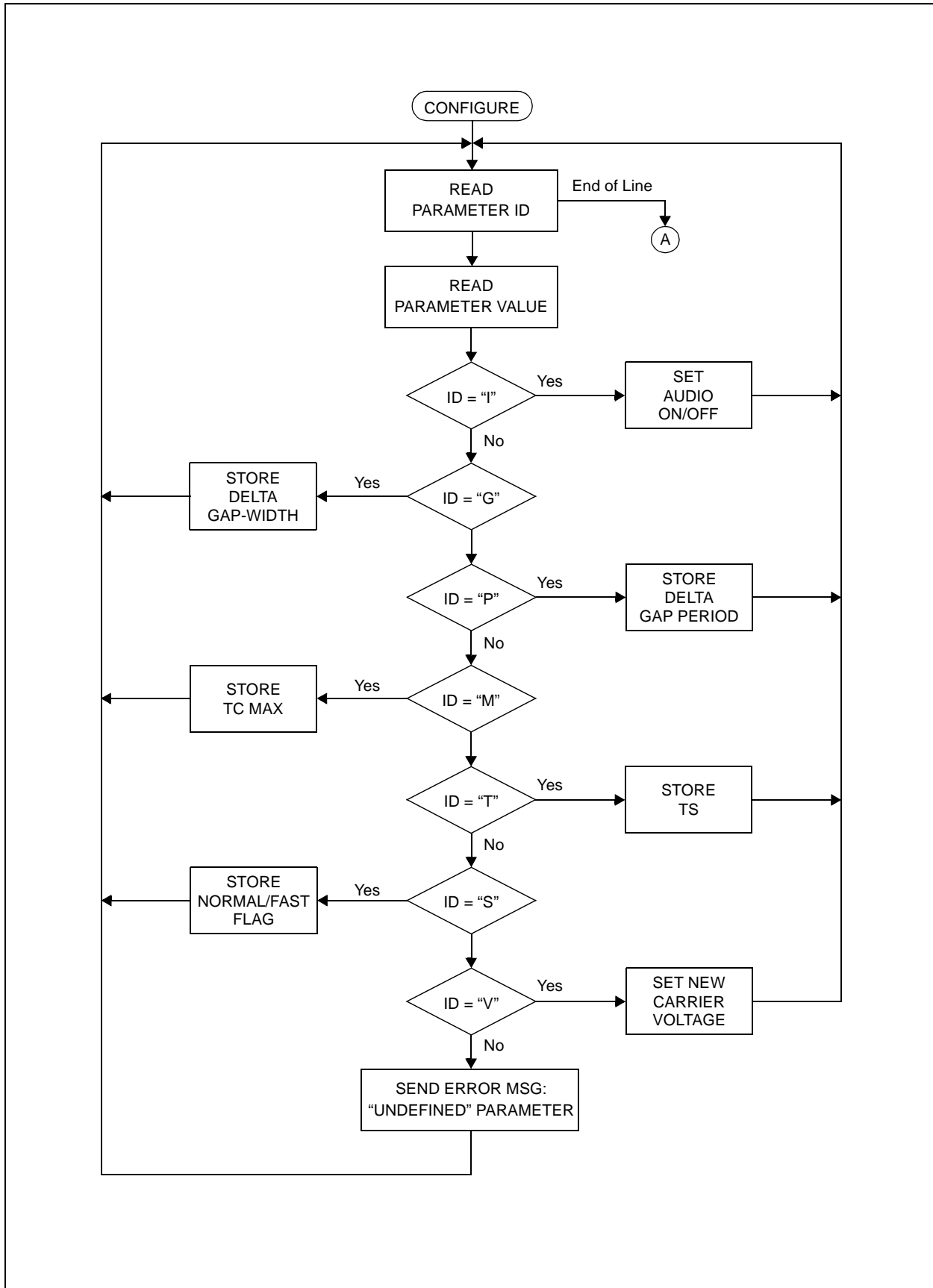
- a) all tags
- b) range of blocks

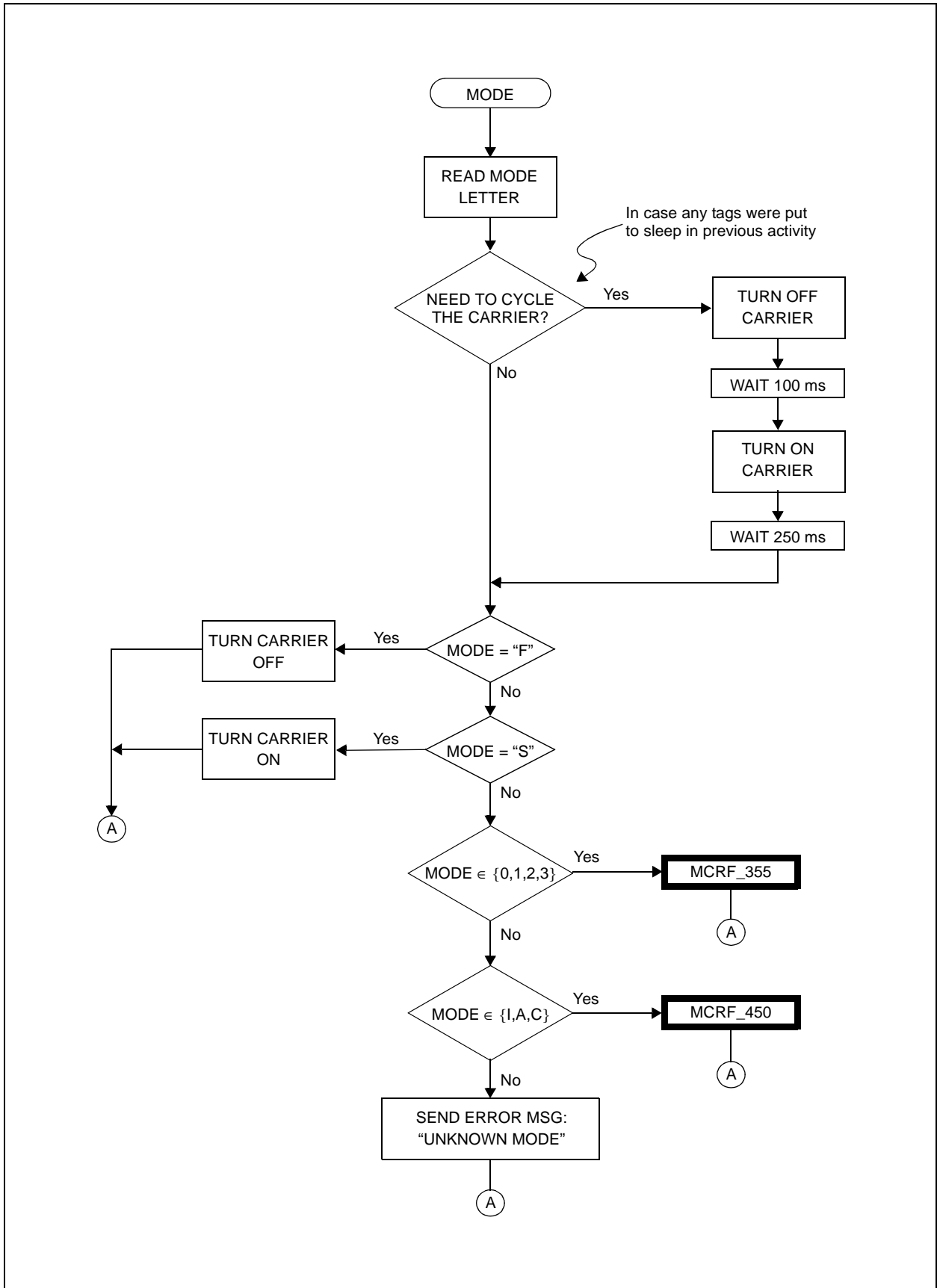
AN759

NOTES:

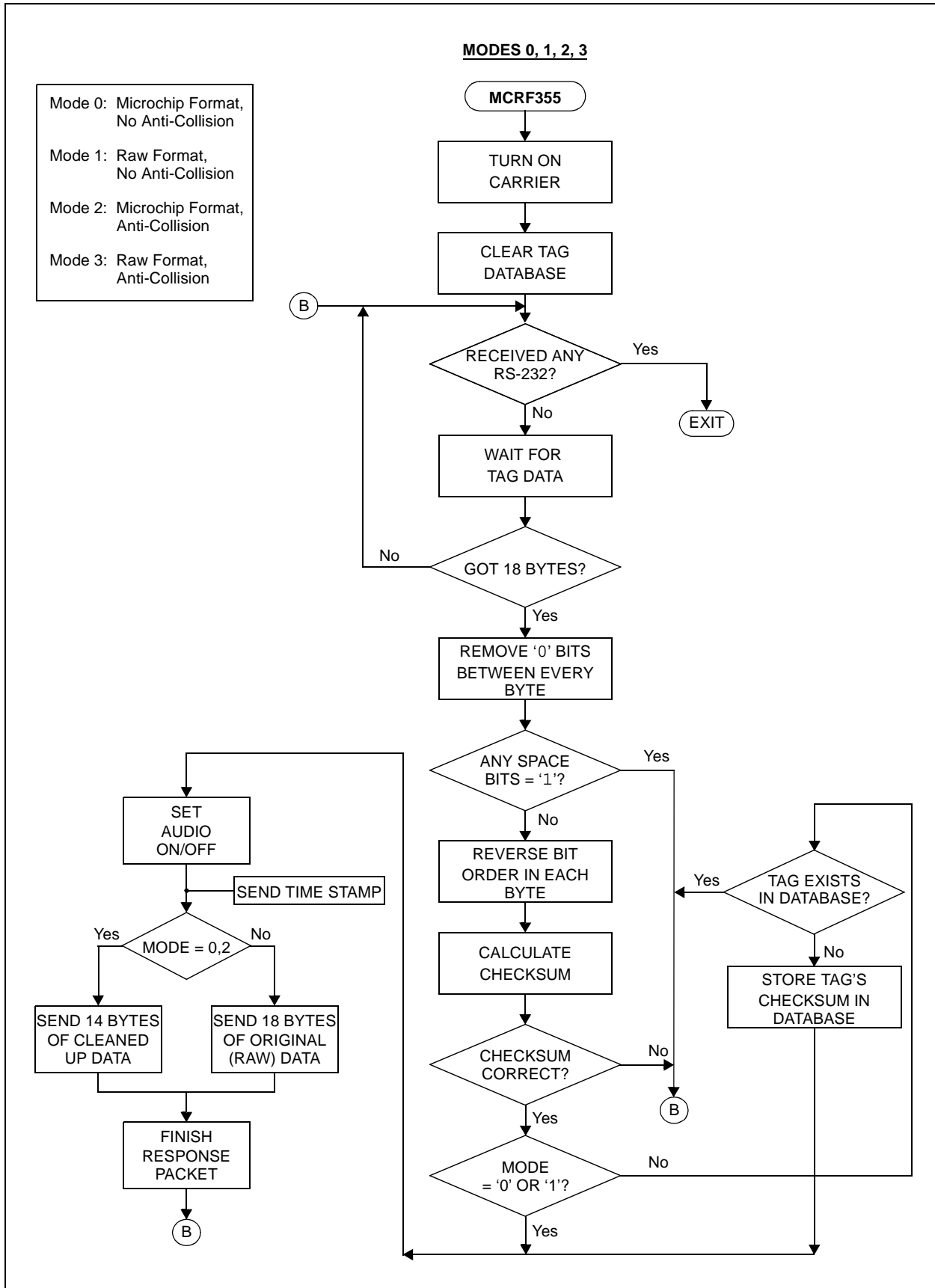
**PICmicro[®] Microcontroller Firmware Flowchart
of DV103006 Demo Reader for MCRF3XX and MCRF4XX Devices**

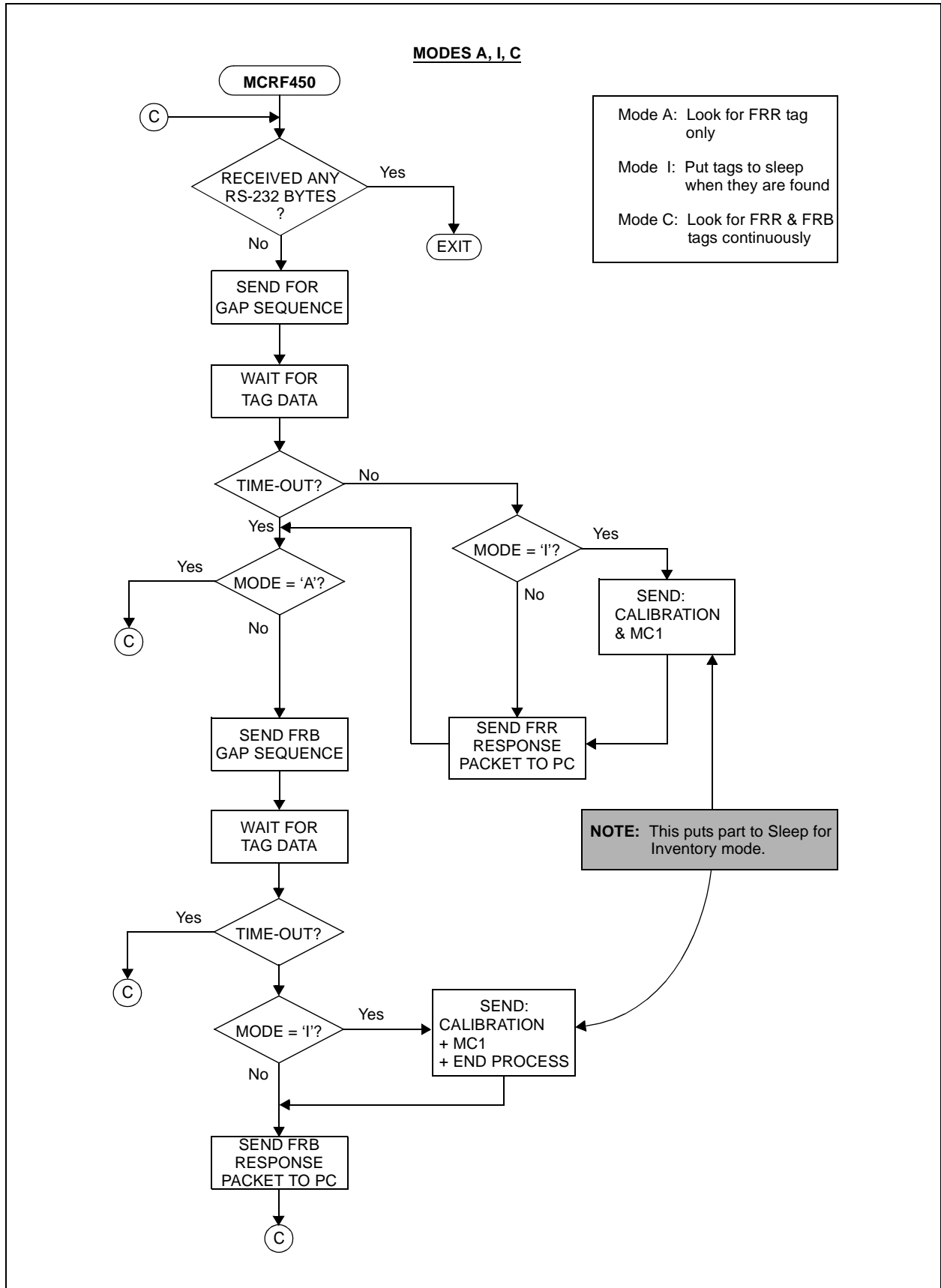


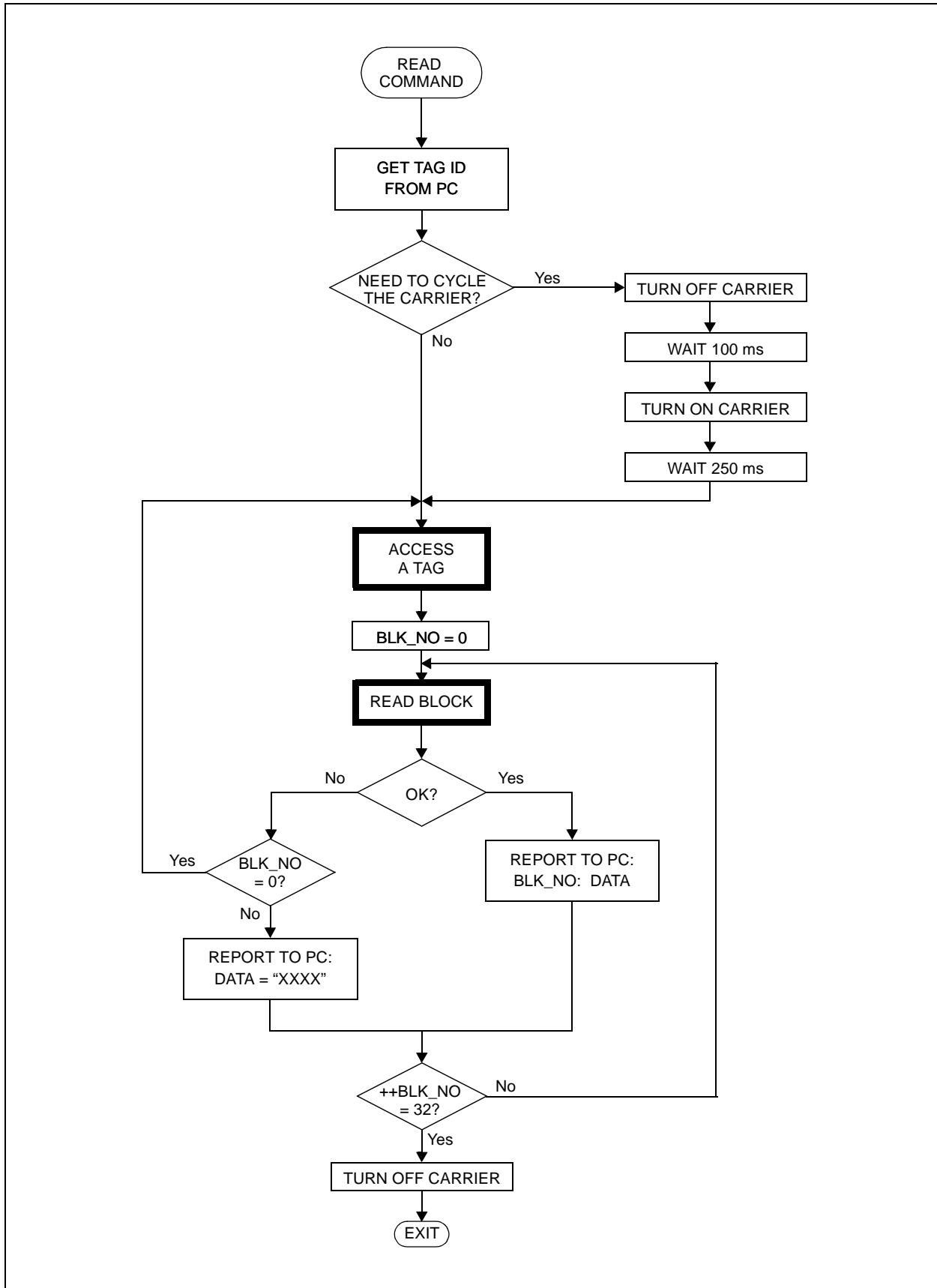


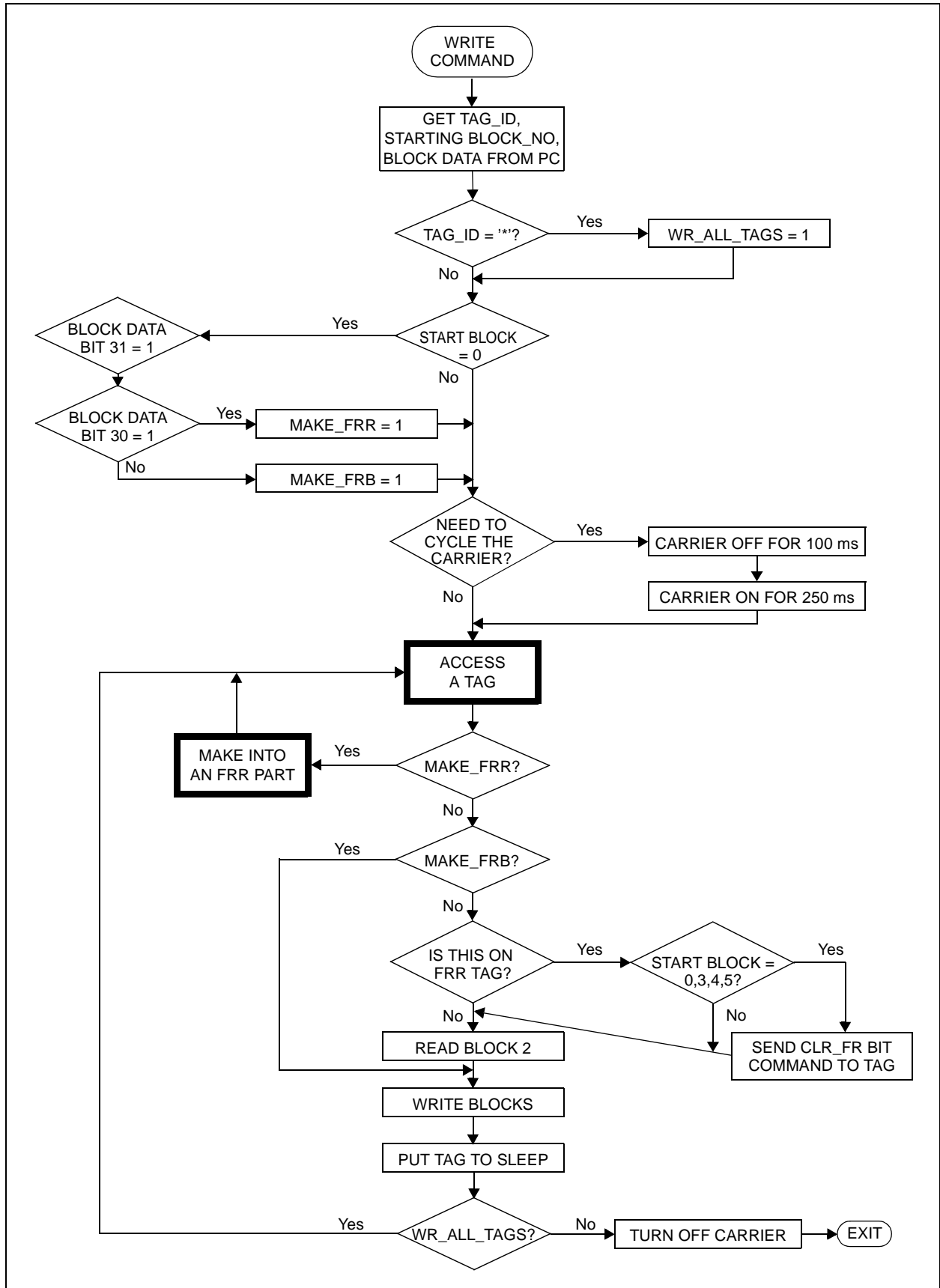


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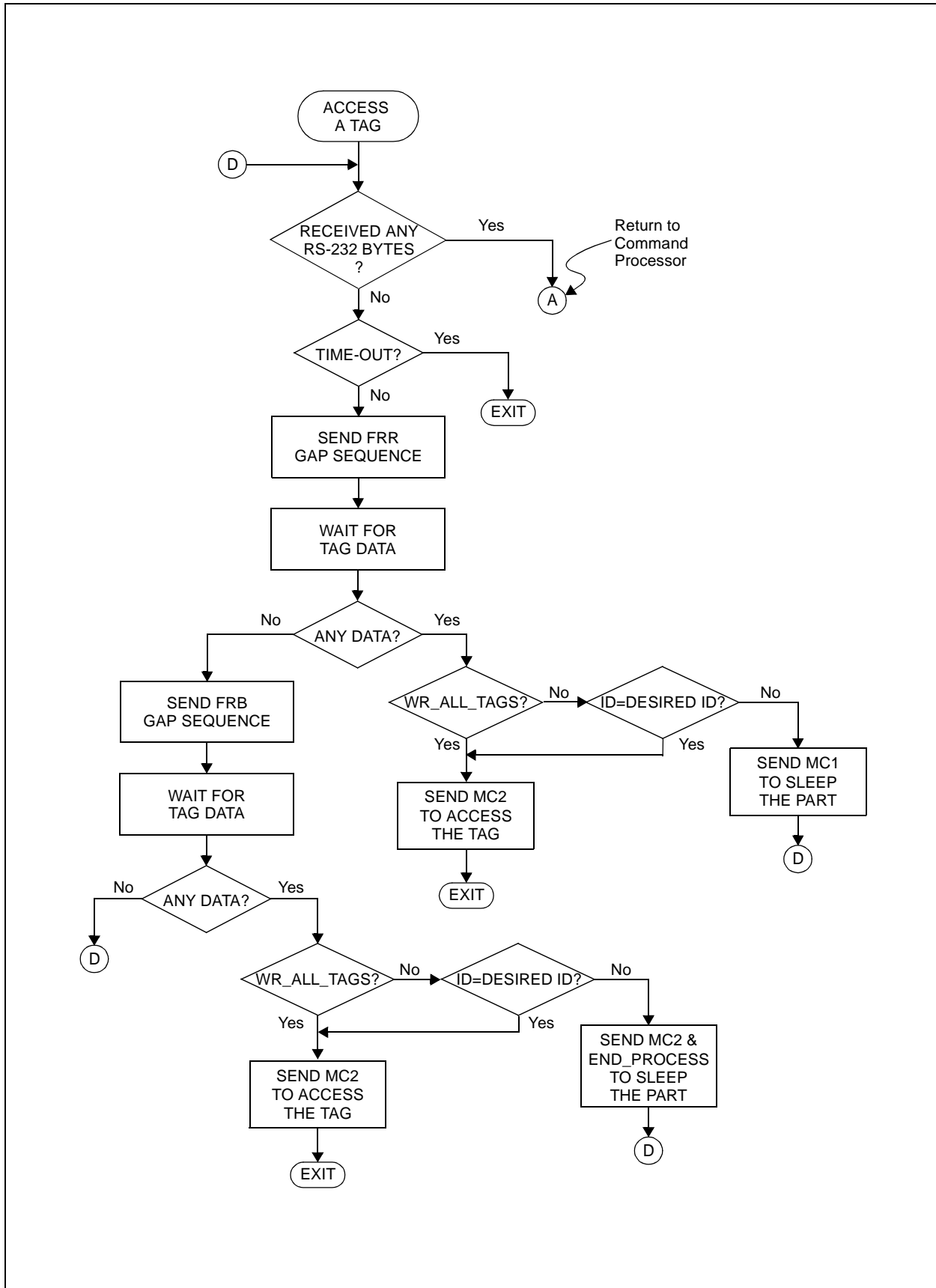


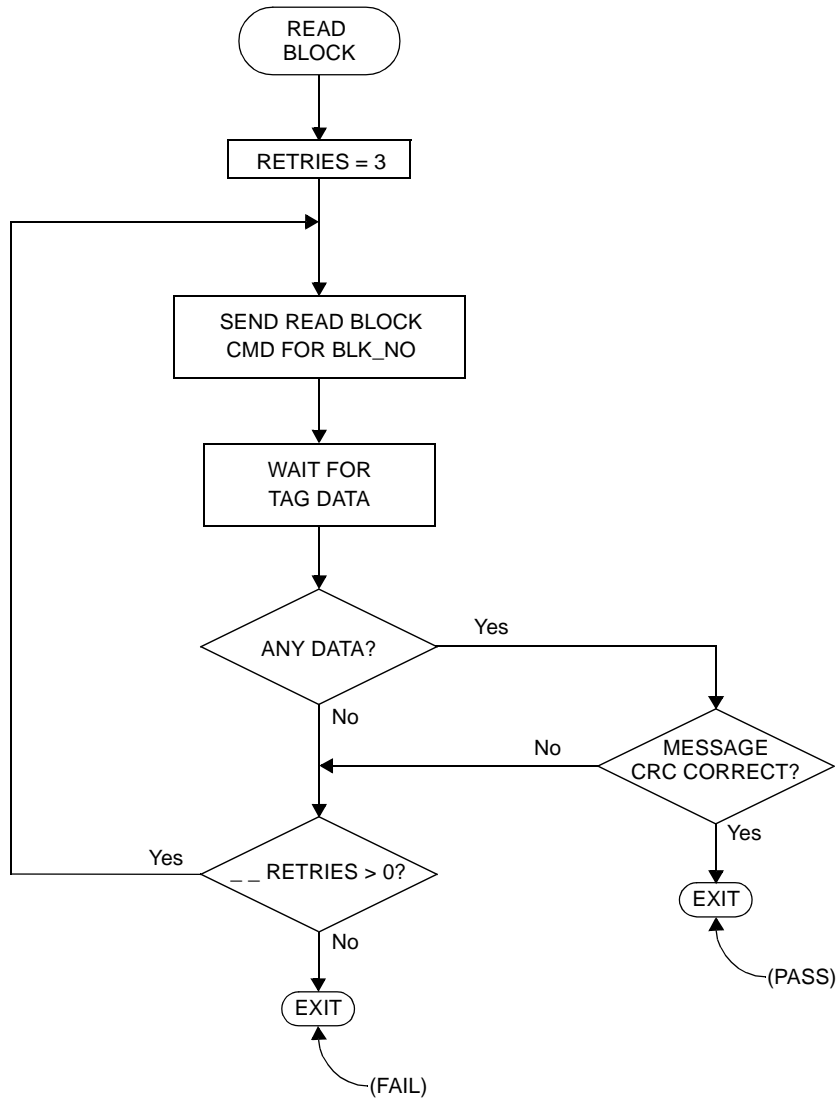




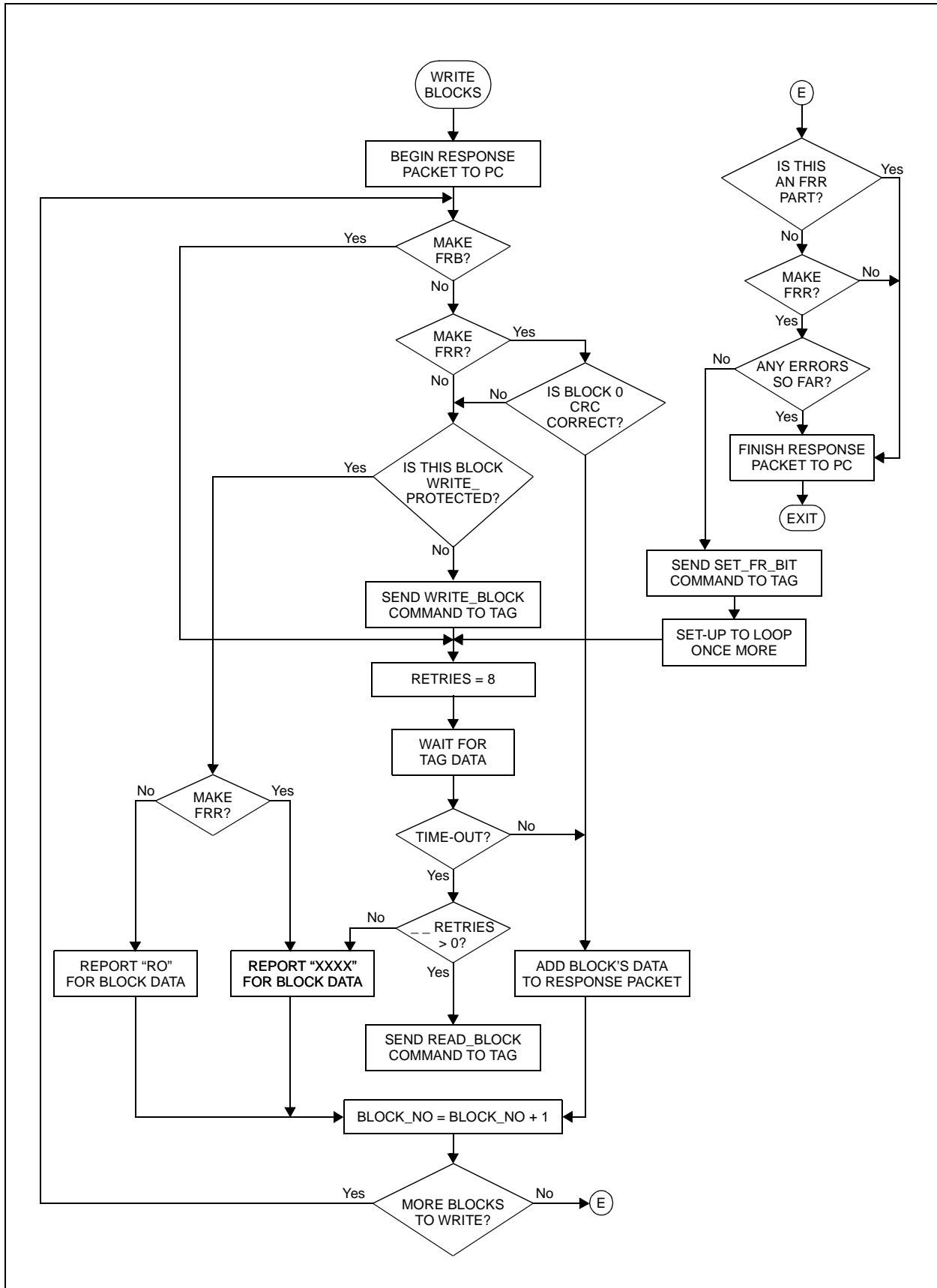


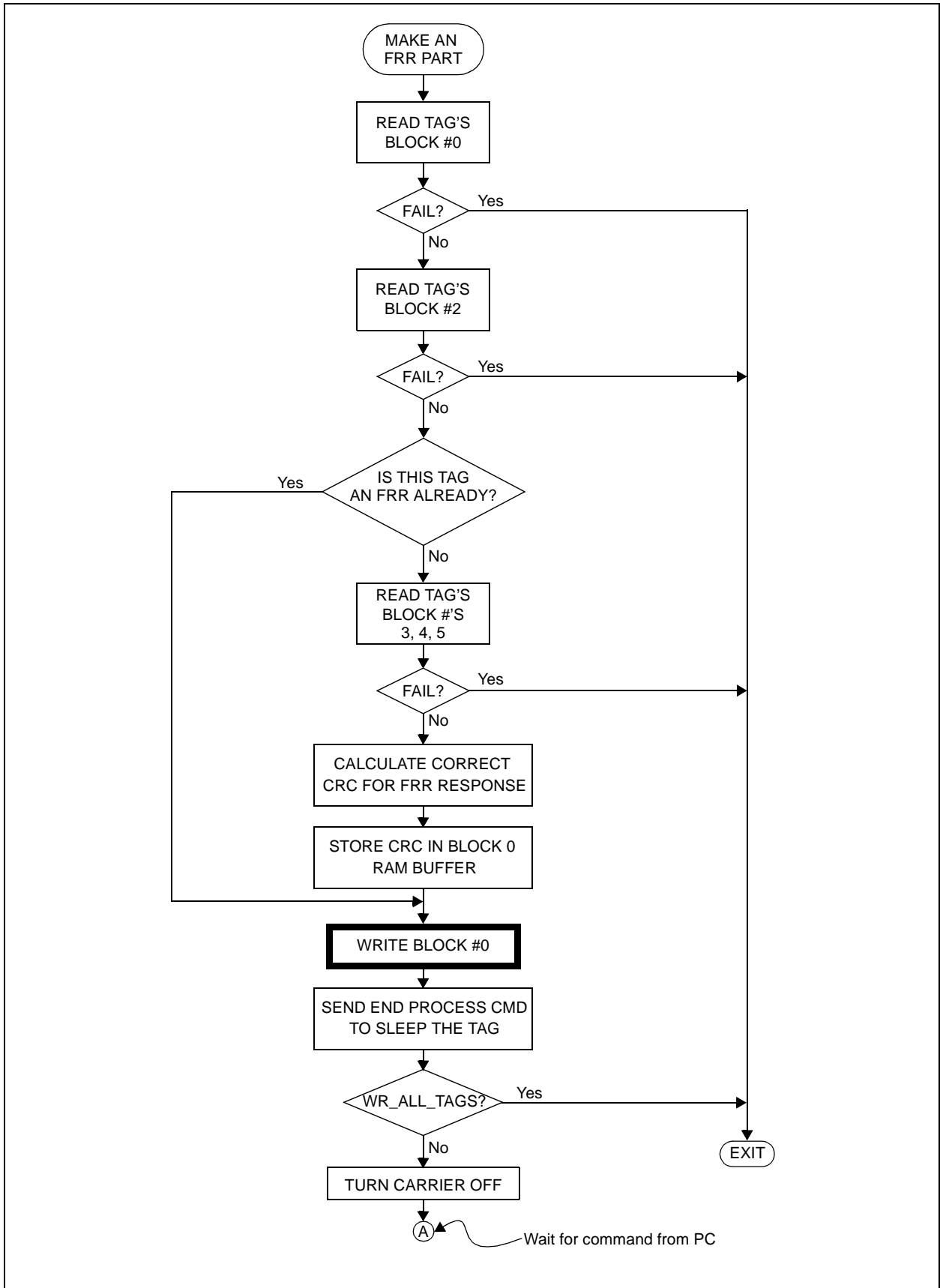
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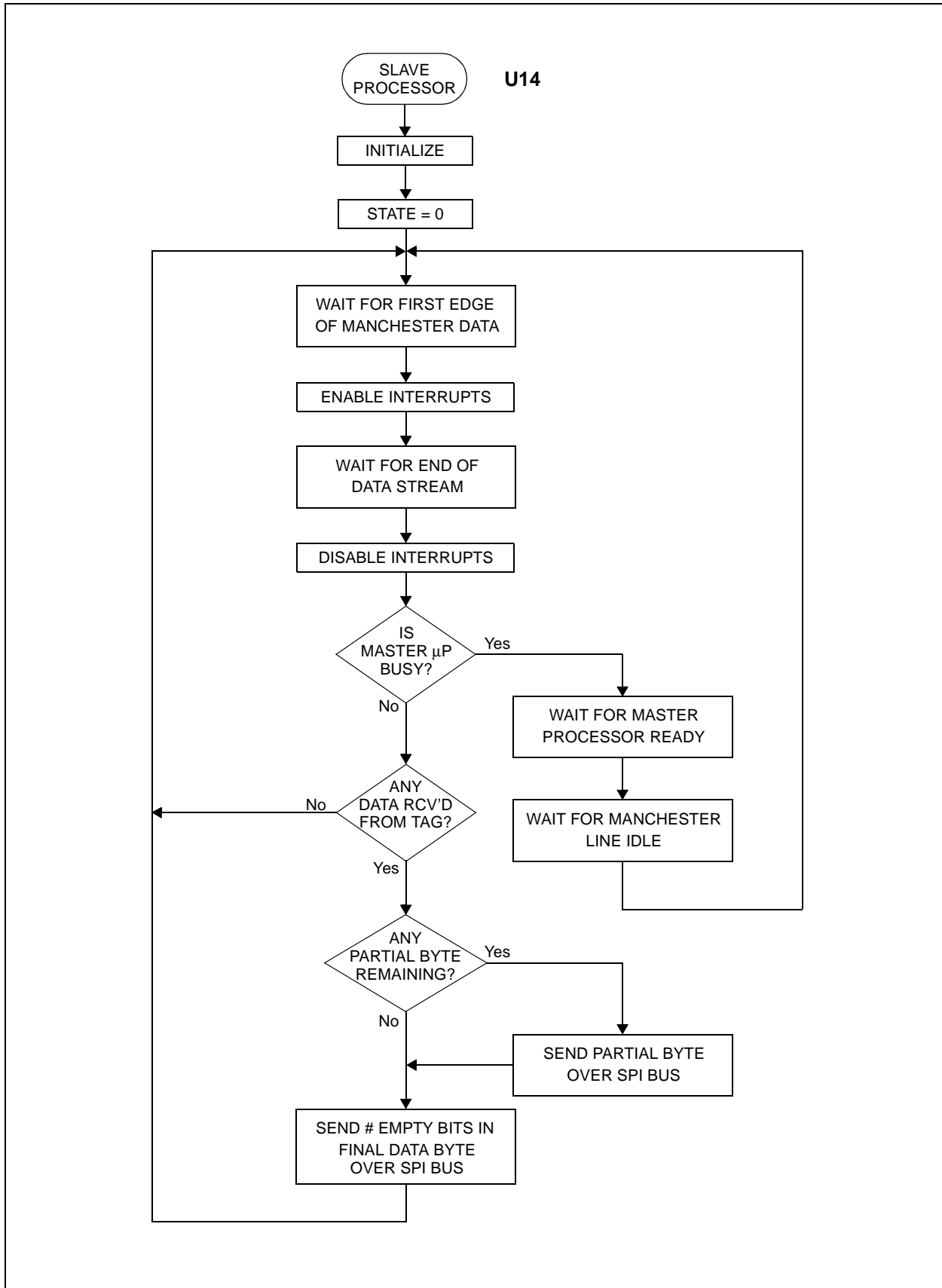


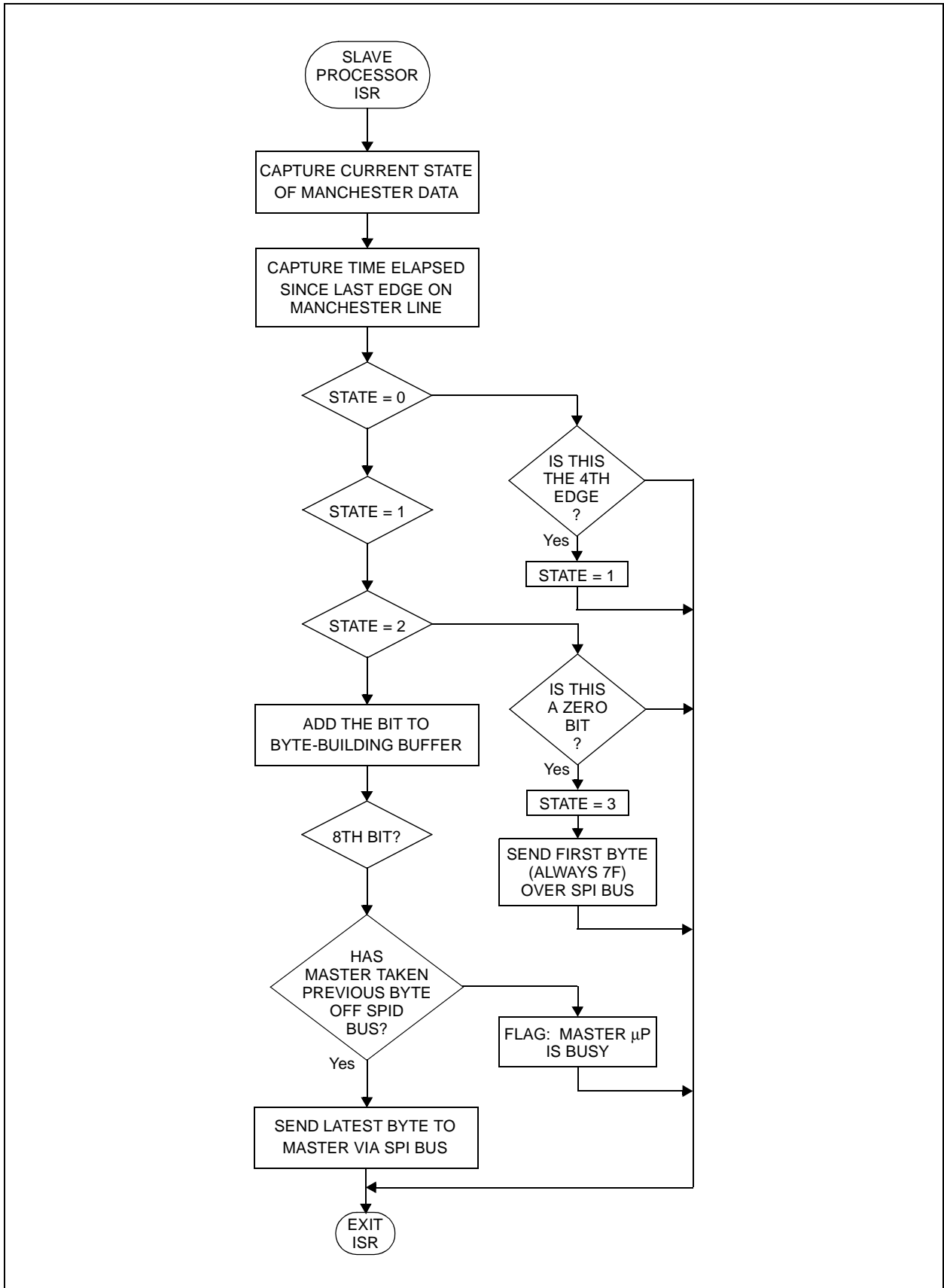


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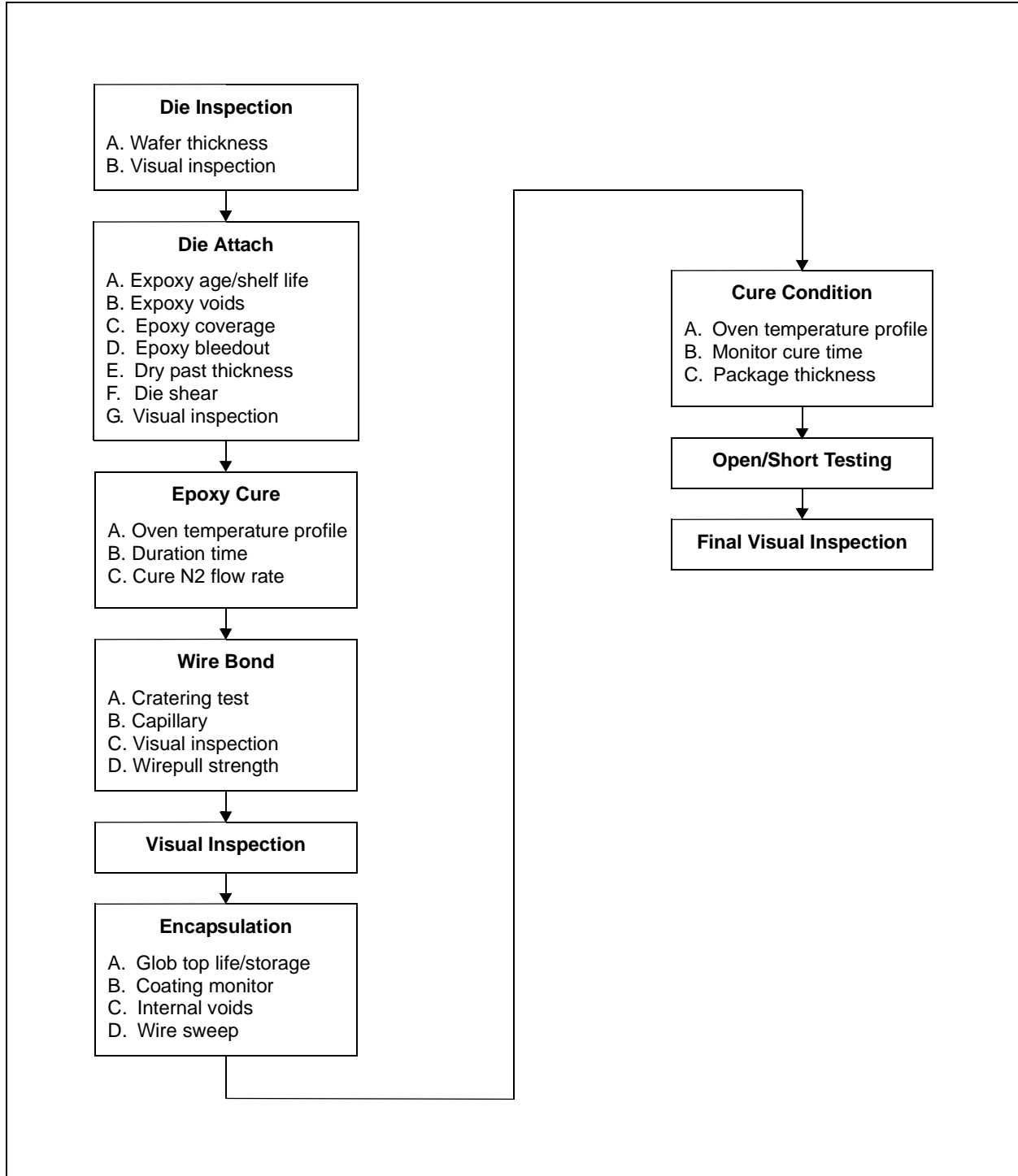
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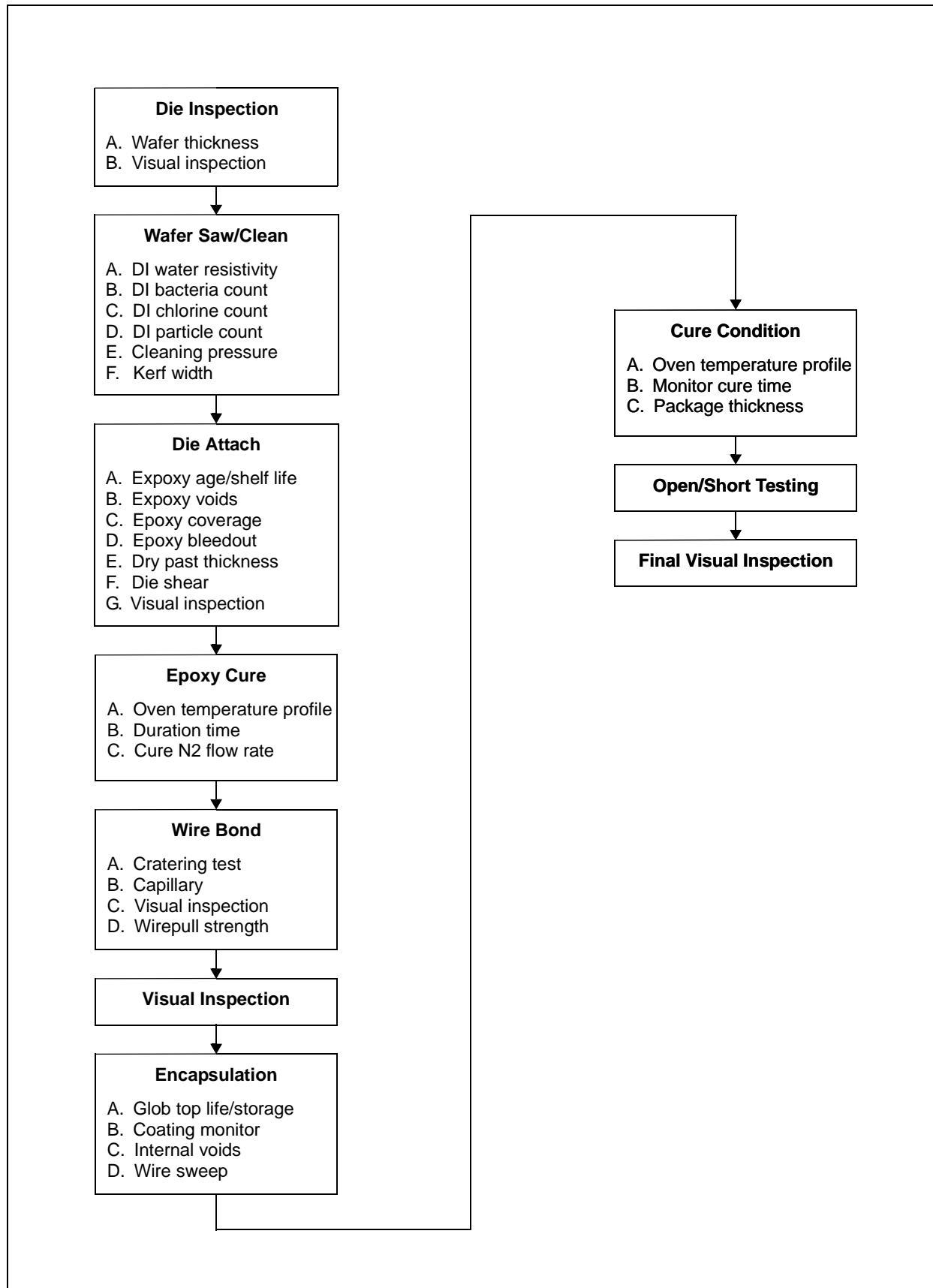
Recommended Assembly Flows

1.0 WAFER ON FRAME ASSEMBLY FLOW



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2.0 WAFER ASSEMBLY FLOW



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