AC 2011-712: DESIGN AND IMPLEMENT A COST-EFFECTIVE WIRELESS COMMUNICATION PROJECT ON A

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I immigrated to the United States from Colombia, South America in 1970, and grew up in New York City. I Graduated from Brooklyn Technical High School in 1983, enlisted in the United States Navy, and in 1984 reported to basic training in San Diego, California. I had plans of completing my four-year enlistment and separating from the navy, but things did not work out that way, and I retired from the United States Navy in 2009 after more than twenty-five years of active service, and achieving the rank of Senior Chief Petty Officer. Throughout my naval career I continued taking college courses with hopes of, one day, graduating with a bachelor's degree. On my last tour of active duty, I was assigned to Mid Atlantic Regional Center, which was a shore duty for me, and I was able to complete my educational requirements for my bachelor's degree at Old Dominion University, and in August 2009 I was awarded a Bachelor of Science Degree in Electrical Engineering Technology. While completing my studies at Old Dominion I was fortunate to have Dr. Hsiung as my professor in one of my classes, and he got me involved in microcontroller applications. I am currently employed at Norfolk Ship Support Activity as an Electrical Engineering Technician, in some way, still serving the United States Navy, and occasionally get involved with certain projects at ODU under Dr. Hsiung's direction.

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Mr. Henderson served in the United States Navy for eight years as an Electronics Technician and graduated Summa Cum Laude from Old Dominion University with a Bachelor of Science in Engineering Technologies. He currently serves as an Adjunct Professor in the Department of Electronics Engineering Technologies at Tidewater Community College and works as a Manufacturing Engineer at Measurement Specialties, Inc.

Mr. Henderson is actively involved in projects utilizing the IEEE 802.15.4 Low-Rate Wireless protocol. He is an active member of the IEEE Communications Society and the IEEE Instrumentation and Measurement Society.

Design and Implement a Cost-Effective Wireless Communication Project on a PIC Training System

Introduction

Wireless communication technology has become increasingly popular and is widely used in almost every electronic product that we may use in work, educational, and recreational activities. The radio frequency (RF) communication component plays a major role in the design and operation of wireless products. Typically, the RF application is integrated with an embedded system such as a microcontroller to implement various applications such as temperature sensing, data logging, data exchange, actuator activation, and user interaction in a wireless manner.

New rapidly changing technologies create unique teaching and training challenges for engineering technology students and faculty. A project based model can be used as an effective instructional strategy to enhance learning about complex RF concepts and technologies. This project method can lead to improved understanding and create interest by actively engaging students with hands-on experiences coupled with problem solving and critical thinking activities. This project is based on teaching and learning experiences with a previously developed low cost PIC microcontroller training system[4]. The PIC training system was coupled with a readily available RF communication module[7] that could be used in a variety of real world, hands-on applications in designing senior capstone projects for engineering and technology majors.

In 2008, Microchip Inc. introduced a 2.4 GHz RF transceiver module called the MRF24J40MA that provides several attractive benefits[6,7]. These benefits include a compact package design, low-cost, and easy to use product with a small additional parts count that includes all components less the power supply. Integrating Microchip's RF transceiver module with the PIC trainer does not require any extra hardware. Thus, the software development of SPI (Serial Peripheral Interface)[14] and protocols designs become the focus of the RF concept learning. The IEEE 802.15.4 2003 rules[5], standards, and software protocols designs with SPI interfacing are the center of the student's project. The student assessment process includes a written report, a live demonstration, and video recording of the functions using three of the RF transceiver modules with PIC trainers.

Engineering technology focuses on both "hands-on and mind-on" design work and the practice is to integrate existing technology products into real world applications. Teaching radio frequency concepts can be challenging because of complex theory and the broad array of application practices as well as related governing regulations. However, if it is implemented in a real-world project approach to teaching and learning using existing RF modules can lead to developing clear understandings and meaningful experiences in successfully applying the technologies that can make these concepts interesting and challenging to learn. Using an existing RF module such as a Microchip's transceiver can reduce many of the frustrating road blocks typically encountered. In addition, the module is integrated with a microcontroller on a PIC trainer[4] via software controls that makes the application designs flexible to fit various needs and minimizes many uncontrollable RF interferences. The project approach described here uses a Microchip RF transceiver module and PIC trainer that provides useful tools and practical experiences that make teaching and learning about complex RF subjects appealing and interesting. Additionally, the project methodology can easily be adapted to a number of other teaching and learning applications.

Review of RF Applications

There are many applications of low-power, non-licensed transmitters/receivers that operate on a variety of frequencies. Most of these low-power applications and use very little power generally are less than a milliwatt. These products and applications are “non-licensed” because the user or consumer is not required to obtain a license from the Federal Communications Commission (FCC) to use them. However, they must share these frequencies with licensed transmitters and are prohibited from causing interference to licensed transmitters[3].

The FCC has published regulations that define and establish limits as to what is referred to as harmful interference to licensed transmitters by low-power, non-licensed transmitters. The FCC’s regulations are most restrictive on products that are most likely to cause harmful interference and less restrictive on those products that are least likely to cause interference. Detailed information concerning low-power non licensed products are described in the FCC regulations themselves and can be found in Part 15 of Title 47 of the Code of Federal Regulations [3].

Part 15.23 of the Code of Federal Regulations state that hobbyist, inventors and other parties that design and build Part 15 transmitters with no intention of marketing them may construct and operate up to five such transmitters for their own personal use without having to obtain FCC equipment authorizations[3]. The manufacturers of the transmitters discussed here comply with the FCC emission regulations. The transmitters should not exceed the emission limits of the regulations. The available frequency allocations shown in FCC regulation Part 15 are identified in Table 1 of the publication and entitled “Part 15 Permitted Frequency Allocations.” Table 1 shows the frequency bands that may be used are between 38.25 MHz and 3.26 GHz and the emission limits for any type of use for a transmitter. The allowable radiated energy is stated in the list along with the actual frequencies, emission limits and their uses. Additionally, other applications such as cordless telephones, intermittent control signals, and periodic transmissions are not included in the Table 1 of Part 15.23. Some of the more common frequencies are within the bands of 385-322 MHz, 410-470 MHz, 902-928 MHz, and 2.4GHz.

Frequency Band	Type of Use	Emission Limit
38.25-40.66 MHz	Any	100 uV/m @ 3m
40.66-40.7 MHz	Any	1,000 uV/m @ 3 m
40.7-49.82 MHz	Any	100 uV/m @ 3 m
49.82-49.9 MHz	Any	10,000 uV/m @ 3 m
49.9-54 MHz	Any	100 uV/m @ 3 m
72-73 MHz	Any	100 uV/m @ 3 m
74.6-74.8 MHz	Any	100 uV/m @ 3 m
75.2-76 MHz	Any	100 uV/m @ 3 m
88-108 MHz	Any	150 uV/m @ 3 m
121.94-123 MHz	Any	150 uV/m @ 3 m
138-149.9 MHz	Any	150 uV/m @ 3 m
150.05-156.52475 MHz	Any	150 uV/m @ 3 m
156.52525-156.7 MHz	Any	150 uV/m @ 3 m
156.9-162.0125 MHz	Any	150 uV/m @ 3 m
167.17-167.72 MHz	Any	150 uV/m @ 3 m
173.2-174 MHz	Any	150 uV/m @ 3 m
216-240 MHz	Any	200 uV/m @ 3 m
285-322 MHz	Any	200 uV/m @ 3 m
335.4-399.9 MHz	Any	200 uV/m @ 3 m

410-470 MHz	Any	200 uV/m @ 3 m
806-902 MHz	Any	200 uV/m @ 3 m
902-928 MHz	Any	50,000 uV/m @ 3 m
928-960 MHz	Any	200 uV/m @ 3 m
1.24-1.3 GHz	Any	500 uV/m @ 3 m
1.427-1.435 GHz	Any	500 uV/m @ 3 m
1.6265-1.6455 GHz	Any	500 uV/m @ 3 m
1.6465-1.66 GHz	Any	500 uV/m @ 3 m
1.71-1.7188 GHz	Any	500 uV/m @ 3 m
1.7222-2.2 GHz	Any	500 uV/m @ 3 m
2.3-2.31 GHz	Any	500 uV/m @ 3 m
2.39-2.4 GHz	Any	500 uV/m @ 3 m
2.4-2.4835 GHz	Spread Spectrum Transmitters	1 Watt Output Power
2.4-2.4835 GHz	Any	50,000 uV/m @ 3 m
2.5-2.655 GHz	Any	500 uV/m @ 3 m
2.9-3.26 GHz	Any	500 uV/m @ 3 m

Table 1. Part 15 Permitted Frequency Allocation

It is apparent that there is an increasing trend in wireless communication technologies in industrial, commercial, and consumer products. Accordingly, there is an increasing concern about the security issues related to wireless products. The integrated systems of wireless communication and embedded systems technologies using smart protocol design makes the security concern easier to work with and broadens the applications in various areas. The following are examples of the more common applications of the growing list of wireless technology applications today.

- Building and Home Security
- Garage Door Opener
- Medical Monitoring
- Periodic Data Transfer
- Remote Lighting Control
- Inventory Control
- Home/ Industrial Automation
- Wireless Headsets
- Biotelemetry
- Remote Data Logger
- Cordless Phones
- Baby Monitor
- Remote Industrial Monitoring/RFID
- Remote Keyless Entry
- On-Site Paging
- Automated Utility Meter Reading
- Fire/Security Alarms
- Vending Machines
- Pagers
- Other Applications

The Comparison of the RF Modules

Samples of six companies that manufacture wireless transmitters and receivers are described in the tables that follow. Tables 2, 3, and 4 identify and provide a summary of some of the technical features and prices of these transmitter and receiver products that are compatible with the FCC Part 15 regulation. The cost, communication range, operating function complexity, and target applications objectives are the bases of selecting needed wireless communication. We selected the MRF24J40MA Microchip transceiver module for our project was based on the price, comprehensive security, and flexibilities on IEEE standards.

Part #	Freq.	Vcc	Icc	Modulation	Baud Rate	Audio	Range	Price	Maker
RCT-433-AS[10]	433.92 MHz	2-12 Vdc	5 ma@3V	ASK/OOK	4800	No	100-300 ft.	$4.90	Radiotronix
TXE-315-KH[18]	315 MHz	2.7-5.2 Vdc	3 ma		4800	No		$9.98	LINX
TXM-315-LC[18]	315 MHz	2.7-5.2 Vdc	3 ma		4800	No		$6.90	LINX

TM1V[17]	418 MHz	5 Vdc		On-Off and Pulse	4800	No	300 ft.	$16.40	GLOLAB
TWS-434[19]	433.92 MHz	2-12 Vdc	5 ma	ASK	3000	No		$8.50	Reynolds, LAIPAC Technology
TH71071[15]	315/433 MHz			FSK/FM/ASK				$11.29	Melexis

Table 2. A Summary of Low-Power and Low Cost Transmitter Products

Part #	Freq.	Vcc	Icc	Modulation	Baud Rate	Audio	Distance	Price	Maker
RCR-433-RP[9]	433.92 MHz	5 Vdc	4.5 ma	ASK/00K	4800	Yes	100-300 ft.	$5.50	Radiotronix
RCR-433-HP[9]	433.92 MHz	5 Vdc	4.5 ma	ASK/OOK	4800	No	300-800 ft.	$13.80	Radiotronix
RXM-315-LC[12]	315 MHz	2.7-4.2 Vdc	6 ma		5000	No		$13.79	LINX
RXD-315-KH[12]	315 MHz	2.7-4.2 Vdc	7 ma		4800	No		$15.93	LINX
RWS-434[8]	433.92 MHz	2.7-5.2 Vdc		CPCA	5000	No	300 ft.	$8.50	Reynolds Electronics
RM1V[12]	418 MHz	5 Vdc		On-Off and Pulse	4800	No	300 ft.	$23.75	GLOLAB
TH71101[16]	315/433 MHz	5 Vdc		FSK/FM/ASK				$15.58	Melexis

Table 3. A Summary of Low-Power and Low Cost Receiver Products

Part #	Freq.	Vcc	Icc	Modulation	Baud Rate	Audio	Applications	Price	Maker
EWM-900-FDTC-BS[2]	902-928 MHz	3 Vdc	35ma Rx 25ma Tx	FM/FSK	19.2K	Yes	Full-Duplex Data & Audio 500-1000 ft.	$69.00	Radiotronix
EWM-900-FDTC-HS[2]	902-928 MHz	3 Vdc	35ma Rx 25ma Tx	FM/FSK	19.2K	Yes	Full-Duplex Data & Audio 500-1000 ft.	$69.00	Radiotronix
MRF24J40MA[7]	2.4GHz	3.3 Vdc	19ma Rx 23ma Tx	CSMA-CA	625K	No	Full-Duplex Zigbee, MiWi, MiWi P2P 500-1000 ft.	$9.95	Microchip

Table 4. A Summary of Low-Power and Low Cost Transceiver

The MRF24J40MA Module

The MRF24J40MA module is a 2.4 GHz transceiver product manufactured by Microchip Inc. that complies with the IEEE 802.15.4 standard[5]. The price of the MRF24J40MA module is $9.95 in single quantities. It has low current consumption – at TX 23mA - RX 19mA - Sleep 2uA, Hardware CSMA-CA Mechanism, Automatic ACK Response, Hardware Security Engine (AES-128), and Automatic Packet Retransmit[7]. This module includes everything needed to perform 2.4 GHz wireless transmitter and receiver functions with a choice of 16 different channels and provides several easily implemented security features such as antenna, resonator, slave SPI interface[14], interrupt driven power saving mode, and operates on 3.3VDC power source. It is packaged in a 12-pin interface module. All the user needs to do is provide a 3.3-volt supply and address the module with SPI protocols[14]. This paper demonstrates the use of the PIC training system that has a built-in plug for the required power and SPI interface communication. The applications are directed toward the software design and IEEE 802.15.4 applications using wireless communication between one master module and two slave modules on three PIC training systems hosting three PIC16F877A PICs as the main MCUs (MicroController Units)[13].

The IEEE 802.15.4 2003 Standard

The IEEE 802.15.4 2003 standard[5] defines the protocol and interconnection of devices via radio communication in a personal area network (PAN). The purpose is to provide a standard for ultra-low complexity, ultra-low cost, ultra-low power consumption, and low data rate wireless connectivity among inexpensive devices. An LR-WPAN is a simple, low-cost communication network that allows wireless connectivity in applications with limited power and relaxed throughput requirements. The main objectives of an LR-WPAN are ease of installation, reliable data transfer, short-range operation, extremely low cost, and a reasonable battery life, while maintaining a simple and flexible protocol. An LR-WPAN device comprises a PHY (physical layer of the OSI model), which contains the radio frequency (RF) transceiver along with its low-level control mechanism, and a MAC sub-layer that provides access to the physical channel for all types of transfer.

In the star topology, the communication is established between devices and a single central controller, called the PAN coordinator. A device typically has some associated application and is either the initiation point or the termination point for network communications. A PAN coordinator may also have a specific application, but it can be used to initiate, terminate, or route communication around the network. The PAN coordinator is the primary controller of the PAN. Once the PAN identifier is chosen, the PAN coordinator can allow other devices to join its network.

The peer-to-peer topology also has a PAN coordinator. However, it differs from the star topology in that any device can communicate with any other device as long as they are in range of one another. Peer-to-peer topology allows more complex network formations to be implemented such as a mesh networking topology. Applications such as industrial control and monitoring, wireless sensor networks, asset and inventory tracking, intelligent agriculture, and security would benefit from such a network topology.

Beacons are used to synchronize the attached devices to the network to identify the PAN and describe the structure of the super frames. Any device desiring to communicate during the contention access period (CAP) between two beacons competes with other devices using a slotted CSMA-CA mechanism. All transactions shall be completed by the time of the next network beacon. In a non-beacon-enabled network, the device can transmit the data at any time.

In order to transmit data, the data has to be packaged in a specific format. The IEEE 802.15.4 2003 standard defines four types of frames:

- A Beacon Frame: used by a coordinator to transmit beacons
- A Data Frame: use for all transfers of data
- An Acknowledgement Frame: use for confirming successful frame reception
- A MAC command frame: used for handling all MAC peer entity control transfers

The physical (PHY) package and frame structure in the standard is presented in Figure 1:

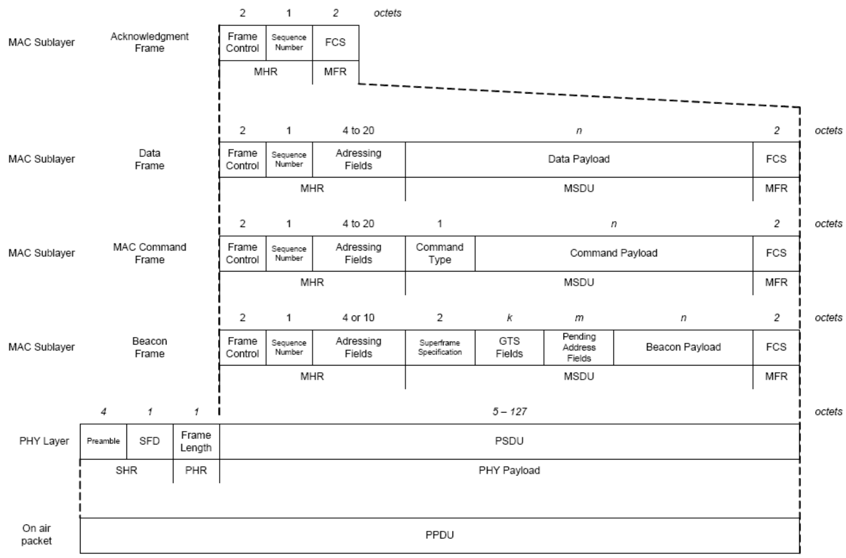


Figure 1. IEEE 802.15.4 Data Frame

The data frame which used in this wireless communication project is composed of the header length, the frame length, the header, and the data payload. The payload is comprised of the data that the user desires to be transmitted. The MHR is composed of several elements: frame control, sequence number, address information, and security related information. The frame control field is 16 bits in length and contains information defining the frame type, addressing fields, and other control flags. All the devices in the network are required to have a unique 64 bits address.

The Implementation of the MRF24J40MA Module

This paper provides an overview of a capstone demonstration project that is a required senior design project and is an integral part of EET curriculum at Old Dominion University. Students may choose to participate in the microprocessor capstone project with faculty mentors as part of a university research activity or they may elect to prepare and submit a proposal for an alternative project funded by the student under faculty direction. This demonstration project is one of the components of an on-going undergraduate research project in the Electrical Engineering Technology department.

Student team members in this demonstration project were given all of the necessary hardware and software resources to complete the project. Additionally, a list of the anticipated outcome objectives was provided. The hardware for the demonstration project teams included the following:

- Three PIC training system boards with PIC16F877A MCUs (fully assembled and tested),
- Three MRF24J40MA transceivers,
- Three LCD display modules, and
- One 3*4 matrix keypad.

The outcomes of the objectives are well defined and straightforward. Accordingly, the teams are expected to:

- Design and construct a master system provides user interaction interface via a keypad and LCD module to transmit and receive the information wirelessly.
- Design and construct two slave systems that are responsible to receive a message (6 bytes of data), display the message on the LCD modules, and wirelessly echo back to the master to signal completion of the message.

This 2.4 GHz wireless project uses the data frame for communication and is based on a peer-to-peer topology. The master unit is the PAN coordinator. The acknowledgment frame is handled automatically by the hardware of the MRF24J40MA module. This implementation operates in a non-beacon enabled mode that means any device may to transmit any time, so the coordination relies on the software design based on the module's INT signal. The IEEE standard requires that all devices on a network have a unique 64 bits address (a total of 8 bytes of PANIDs and addresses). This data packet contains one byte that defines the length of the total packet, 2 frame control bytes, one sequence byte, 64 bits/8 bytes address are: 2 bytes for the destination PANID, 2 bytes for destination short address, 2 bytes for source PANID, 2 bytes for source short address, and 6 bytes for the data for this particular application. They are formulated as:

1. Length
2. Frame Control 1
3. Frame Control 2
4. Sequence
5. Destination PANID Low Byte
6. Destination PANID High Byte
7. Destination Short Address Low Byte
8. Destination Short Address High Byte
9. Source PANID Low Byte
10. Source PANID High Byte
11. Source Short Address Low Byte
12. Source Short Address High Byte
13. Data Byte 1
14. Data Byte 2
15. Data Byte 3
16. ----------
17. Data Byte N (6 in this project)

A data packet includes a security field, two frame fields, a sequence field, and then the destination PAN ID, destination short address, source PAN ID, and source short address. This is followed by the data itself is written to address 0X000 to 0X012 at TX Normal FIFO (First In First Out) buffer control memory in MRD24J40MA module and a transmission command (0X01) is sent to the TXNCON (short address at 0X1B) the packet is transmitted.

On the receiving end, when a data package is received and the falling edge of the INT signal will be generated by the receiving module and the data is stored at addresses 0X300 to 0X311 at RX FIFO buffer memory available for the receiver microcontroller to display the received information. The data transfer frame specific requirements for each transmitted data packet that must include the security field, frame fields, sequence number, destination and source addressing and the data payload. This data packet for TX and RX are presented in the RAM memory map in the MRF24J40MA module as in Figure 2:

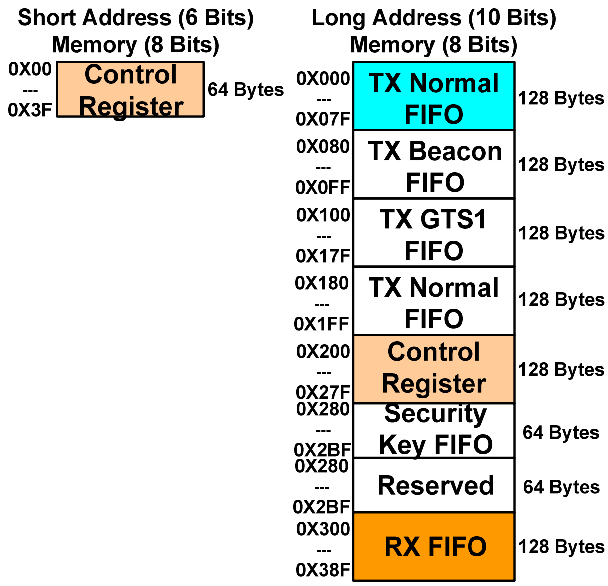


Figure 2. An Overview of the MRF24J40MA RAM Memory Map

The IEEE standard also requires one of the RF chips to be configured as the PAN coordinator, in our network either one could have been the coordinator, so the master and slave units will be designated as the coordinator. Designating the chip as a PAN designator required writing to the Receive Mac Control Register (RXMCR) at short address 0X00. This same register is also accessed to set the reception modes, such as Normal, Error, or Promiscuous modes. In Normal mode the screening process for received data is the most stringent, where the transmitted package must meet all the requirements of the IEEE 802.15.4 Specification. In an Error mode, all packets with a good or bad cyclic redundancy check (CRC)[1] are accepted, and in Promiscuous mode, all packets with a good CRC are accepted. This project used Normal mode that means a package will only be accepted with good CRC and reject mismatch MAC address or illegal frame type. With one byte of data sent to this register, the particular module was set as the PAN coordinator, disabled automatic acknowledgement response and set the reception mode. Transmission will happened automatically when data package is filled in the TX normal FIFO in the transmitting module RAM following by a transmit trigger command in the TXCON register. The receiving unit will automatically make the data package available in the RX FIFO RAM in the receiving module following by a falling signal on INT pin 4[7]. The packet format used here is IAW the IEEE 802.15.4 standard and consists of a security field, two frame fields, a sequence field, and then the destination PANID, destination short address, source PANID, source short address followed by the data payload.

The package transmission and its TX Normal FIFO format are shown in Figure 3:

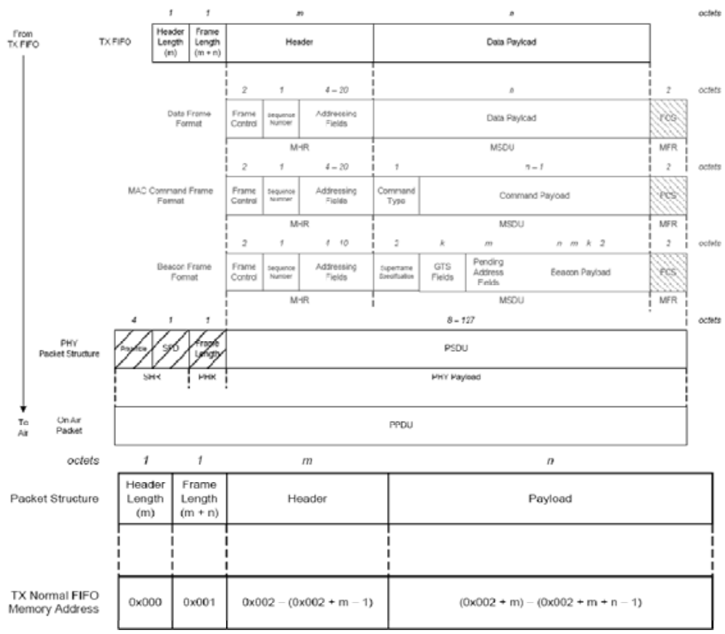


Figure 3. TX Normal FIFO Package Format

The package reception and its RX FIFO format are presented in Figure 4:

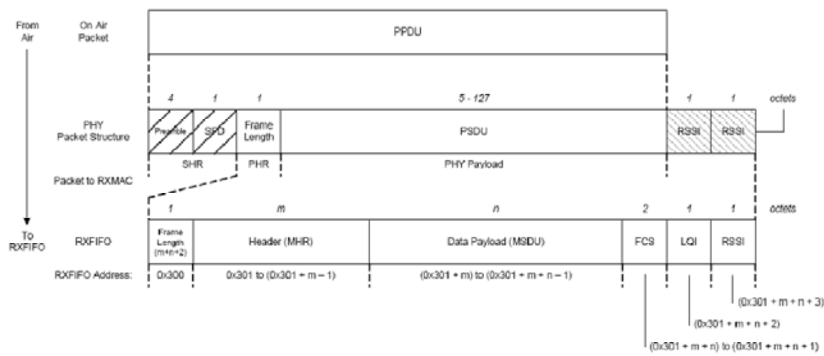


Figure 4. RX FIFO Package Format

The Software Design of MRF24J40MA Applications

The serial peripheral interface (SPI) and control interface between the MCU (PIC16F877A) and MRF24J40MA module is demonstrated in Figure 5:

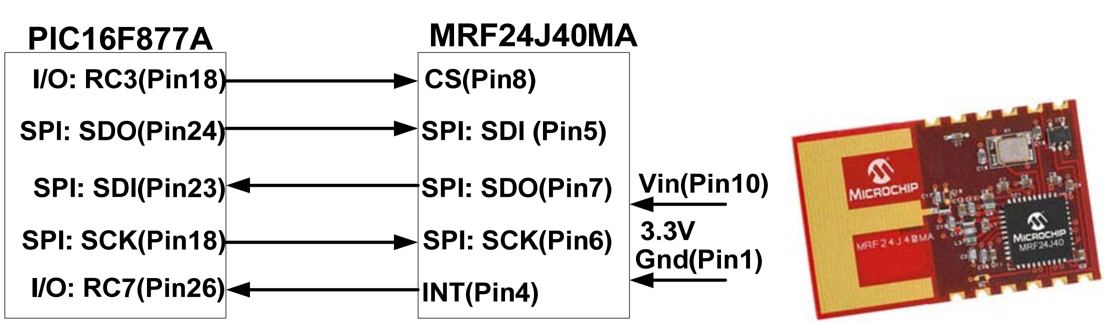


Figure 5. MRF24J40MA Module and Hardware Interface

There are short and long addresses in the static RAM memory organization in the MRF24J40MA module that is accessible via the SPI interface protocol. The diagram shown in Figure 6 illustrates required communication formats.

MRF24J40MA Short Address Read

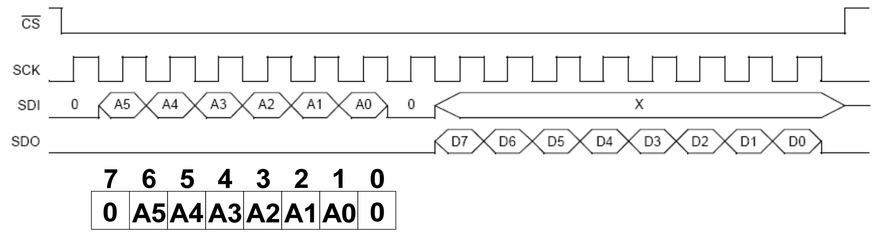


Figure 6. Short Address Read SPI Protocol

MRF24J40MA Short Address Write

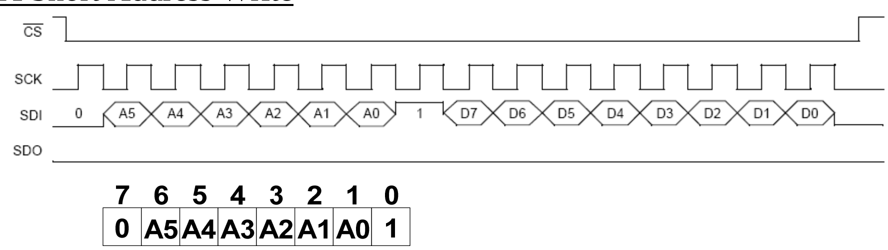


Figure 7. Short Address Write SPI Protocol

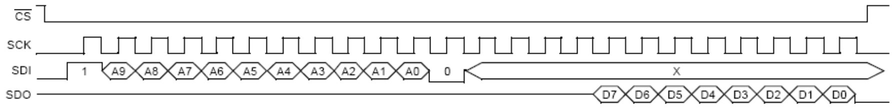
The specifications state that there are only 6 bits needed in short address for either read or write to the memory in the MRF24J40MA. It is important to note that the communication with SPI protocols on the short address memory is not lined up. This requires a simple conversion by shifting the bits and package by *zero* or *one* must be done before the address can be sent via SPI. A software design such as shown in Program Listing 1 can simplify the process and make the controls of MRF24J40MA more easily understood.

```
ST_ADDR_W                           ;Short Address Write Routine
        MOVWF       ST_ADDR
        RLF         ST_ADDR,F       ;Rotate left on address thru C flag
        BSF         ST_ADDR,0       ;Insert Hi  on bit 0 in short address for Write
        MOVF        ST_ADDR,W
        CALL        SUB_SPI
        RETURN

ST_ADDR_R                           ;Short Address Read Routine
        MOVWF       ST_ADDR
        RLF         ST_ADDR,F       ;Rotate left on address thru C flag
        BCF         ST_ADDR,0       ;Insert Lo on bit 0 in short address for Read
        MOVF        ST_ADDR,W
        CALL        SUB_SPI
        MOVLW       0XFF
        CALL        SUB_SPI
        RETURN
```

Program Listing 1. An illustration of a program listing that performs a simple conversion by shifting the bits and package by *zero* or *one* short addressing scheme. This process is completed before sending an address via serial peripheral interface (SPI).

MRF24J40MA Long Address Read

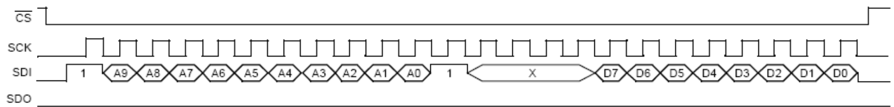


15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	A9	A8	A7	A6	A5	A4	A3	A2	A1	A0	0	0	0	0	0

Address High Byte   Address Low Byte

Figure 8. Long Address Read SPI Protocol

MRF24J40MA Long Address Write



15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	A9	A8	A7	A6	A5	A4	A3	A2	A1	A0	1	0	0	0	0

Address High Byte   Address Low Byte

Figure 9. Short Address Read SPI Protocol

There are 10-bit long addresses needed to access the MRD24JMA memory shown in Figures 8 and 9 and yet again they are not aligned and must be divided into high and low byte addresses for the 8-bit SPI communication. Therefore, it is important to note that the repackaging of the bytes must be done before being sent via SPI. Much the same as in working with the short addresses a similar software design in packaging the bits will make the control much easier. As presented in Program Listing 2 are the conversion routines.

```
LN_ADDR_R                                ;Long Address READ routine
          BCF       STATUS,C             ; Clear C flag
          RLF       LN_ADDR_LO,F         ; Rotate left on Lo byte address thru C flag
          RLF       LN_ADDR_HI,F         ; Rotate left on Hi byte address thru C flag
          RLF       LN_ADDR_LO,F
          RLF       LN_ADDR_HI,F
          RLF       LN_ADDR_LO,F
          RLF       LN_ADDR_HI,F
          RLF       LN_ADDR_LO,F
          RLF       LN_ADDR_HI,F
          RLF       LN_ADDR_LO,F
          RLF       LN_ADDR_HI,F
          BSF       LN_ADDR_HI,7         ; Insert Hi on MSB bit in long address
          CALL      WR_LN_ADDR
          MOVLW     0XFF
          CALL      SUB_SPI
          RETURN

LN_ADDR_W                                ;Long Address Write Routine
          BCF       STATUS,C             ; Clear C flag
          RLF       LN_ADDR_LO,F         ; Rotate left on Lo byte address thru C flag
          RLF       LN_ADDR_HI,F         ; Rotate left on Hi byte address thru C flag
          RLF       LN_ADDR_LO,F
          RLF       LN_ADDR_HI,F
          RLF       LN_ADDR_LO,F
          RLF       LN_ADDR_HI,F
          RLF       LN_ADDR_LO,F
          RLF       LN_ADDR_HI,F
```

```
            RLF         LN_ADDR_LO,F
            RLF         LN_ADDR_HI,F
            BSF         LN_ADDR_HI,7    ; Insert Hi on MSB bit in long address
            BSF         LN_ADDR_LO,4    ; Insert Hi on Bit 4 in long address for Write
            CALL        WR_LN_ADDR
            RETURN

WR_LN_ADDR
            MOVF        LN_ADDR_HI,W
            CALL        SUB_SPI
            MOVF        LN_ADDR_LO,W
            CALL        SUB_SPI
            RETURN

SUB_SPI
            MOVWF       SSPBUF          ;Send data out via SPI
            BSF         STATUS,RP0      ;Bank 1
WAIT        BTFSS       SSPSTAT,BF      ;Poll for BF bit for SPI communication
            GOTO        WAIT
            BCF         STATUS,RP0      ;Bank  0
            MOVF        SSPBUF,W        ;Clear BF bit and read SPI buffer
            RETURN
```

Program Listing 2. An illustration of a program listing that performs a simple conversion by shifting the bits and package by *zero* or *one* for the long addressing scheme. This process is completed before sending an address via serial peripheral interface (SPI).

The transmitter and receiver must be initialized before they can transmit or receive data[7]. After the transmitter and receiver are initialized the transmission data package/frame or receiving data package/frame must be established. The receiver will also poll on the INT line until it becomes *low* on the module to gain access of the received data.

The initialization steps of the MRF24J40MA that are required by the Microchip's data specifications [7] can be accomplished with short and long addresses *writes* as shown below:

1. Write 0X07 to SOFTRST at short address 0X2A to perform software reset
2. Write 0X98 to PACON2 at short address 0X18 to set FIFO and transmission enable
3. Write 0X95 to TXSTBL at short address 0X2E to set VCO stabilization period
4. Write 0X01 to RFCON1 at long address 0X201 to set VCO optimize control
5. Write 0X80 to RFCON2 at long address 0X202 to enable PLL
6. Write 0X90 to RFCON6 at long address 0X206 to enable TX filter and recover from sleep for 1ms
7. Write 0X80 to RFCON7 at long address 0X207 to choose 100KHz internal oscillator
8. Write 0X10 to RFCON8 at long address 0X208 to enable RFVCO bit
9. Write 0X21 to SLPCON1 at long address 0X220 to disable clock out and clock divisor to minimum
10. Write 0X78 to BBREG2 at short address 0X3A to set CCA recommended value
11. Write 0X60 to RSSITHCCA at short address 0X3F to set CCA ED threshold
12. Write 0X40 to BBREG6 at short address 0X3E to set calculate RSSI for each package
13. Write 0XF6 to INTCON at short address 0X32 to enable RX and TX FIFO interrupts
14. Write 0X02 to RFCON0 at long address 0X200 to choose 2.405 GHz communication

15. Write 0X98 to PANIDL at short address 0X01 to set PANID Low byte=0X98
16. Write 0X76 to PANIDH at short address 0X02 to set PANID High byte=0X76
17. Write 0X14 to ADDRL at short address 0X03 to set address Low byte=0X14
18. Write 0X58 to ADDRH at short address 0X04 to set address High byte=0X58
19. Write 0X68 to EADDR0 at short address 0X05 to set extended address 0=0X68
20. Write 0X19 to EADDR1 at short address 0X06 to set extended address 1=0X19
21. Write 0X27 to EADDR2 at short address 0X07 to set extended address 2=0X27
22. Write 0X11 to EADDR3 at short address 0X08 to set extended address 3=0X11
23. Write 0X65 to EADDR4 at short address 0X09 to set extended address 4=0X65
24. Write 0X19 to EADDR5 at short address 0X0A to set extended address 5=0X19
25. Write 0X29 to EADDR6 at short address 0X0B to set extended address 6=0X29
26. Write 0X03 to EADDR7 at short address 0X09 to set extended address 7=0X03
27. Write 0X00 to RFCON3 at long address 0X203 to choose max power
28. Write 0X01 to RXFLUSH at short address 0X0D to set reset RXFIFO pointer
29. Write 0X04 to RFCTL at short address 0X36 to reset RF state machine
30. Write 0X00 to RFCTL at short address 0X36 to reset RF state machine
31. Delay for 192 µsec

This initialization setup relies on default setting of cyclic redundancy check (CRC)[1], with no security and in a non-beacon mode. Accordingly, the communication package/data frame will be accepted only with a good CRC and does not enforce encrypted security and communication with no beacon and normal FIFO buffer.

The transmitter package (data frame) should be formulated as:

1. Write package length to TX normal FIFO at long address 0X000
2. Write frame control 1 to TX normal FIFO at long address 0X001
3. Write frame control 2 to TX normal FIFO at long address 0X002
4. Write sequence to TX normal FIFO at long address 0X003
5. Write destination PANID LSB to TX normal FIFO at long address 0X004
6. Write destination PANID MSB to TX normal FIFO at long address 0X005
7. Write destination short address LSB to TX normal FIFO at long address 0X006
8. Write destination short address MSB to TX normal FIFO at long address 0X007
9. Write source PANID LSB to TX normal FIFO at long address 0X008
10. Write source PANID MSB to TX normal FIFO at long address 0X009
11. Write source short address LSB to TX normal FIFO at long address 0X00A
12. Write source short address MSB to TX normal FIFO at long address 0X00B
13. Write transmission data to TX normal FIFO at long address 0X00C
14. Write transmission data to TX normal FIFO at long address 0X00D
15. -------------
16. Write transmission data to TX normal FIFO at long address 0X012
17. The data write continues depends on its desired length
18. -------------

Set transmit the frame in the TX normal FIFO bit in TXNCON at short address 0X1B to start the transmission. The module hardware will automatically transmit the data frame to the designated slave receiving module. The TX normal will generate an interrupt to the MCU when it has completed the transmission. A *read* of the INTSTAT is necessary to clear the INT flag (a read action to clear the flag that is required by the module hardware) and use it as a signal to precede next action on the master control unit.

The receiver package (data frame) is available after the INT line (pin 4) on the module goes *low*. The receiver should constantly poll until the INT bit on MRF24J40MA pin 4 goes *low* on the module and causes it to wait for the received data frame ready then the package information is available as:

1. Read package length from RX FIFO at long address 0X300
2. Read frame control 1 from RX FIFO at long address 0X301
3. Read frame control 2 from RX FIFO at long address 0X302
4. Read sequence from RX FIFO at long address 0X303
5. Read destination PANID LSB from RX FIFO at long address 0X304
6. Read destination PANID MSB from RX FIFO at long address 0X305
7. Read destination short address LSB from RX FIFO at long address 0X306
8. Read destination short address MSB from RX FIFO at long address 0X307
9. Read source PANID LSB from RX FIFO at long address 0X308
10. Read source PANID MSB from RX FIFO at long address 0X309
11. Read source short address LSB from RX FIFO at long address 0X30A
12. Read source short address MSB from RX FIFO at long address 0X30B
13. Read transmission data from RX FIFO at long address 0X30C
14. Read transmission data from RX FIFO at long address 0X30D
15. -------------
16. Read transmission data from RX FIFO at long address 0X311
17. The data read continues depends on its desired length
18. -------------

The very last action on the receiving side is to do a *read* on the INTSTAT register (short address at 0X31) to clear the INT flag(s) and it will automatically stop the INT action from the module to the MCU.

The actual set up of the hardware of the master control unit is shown in photo 1: A microcontroller trainer configured as a master (a PIC16F877A MCU) control unit in association with a MRF24J40MA transceiver module, power supply and miscellaneous passive components are assembled and configured on the PIC trainer. You will note that MRF24J40MA module is plugged into its mating connector in the upper left corner of the trainer. Also the PIC16F877A is plugged into an on-board ZIF® socket. An LCD display is also included for displaying data and the keypad is used between the system and user interactions of the transmitted data. Interconnections are achieved by using 26 GA wire as patch cables. The breadboard experimenter socket is used as a patch panel and for designing and constructing circuits. While our demonstration included microcontroller trainers that were design and manufactured for our classes at Old Dominion University, the communication system and related instruction strategies may easily be reproduced using experimenter breadboard sockets, PIC16F877A, MRF24J40MA transceiver module, power supply and miscellaneous passive components.

Photo 1. Master System Board

Two additional trainers are used as slave units to communicate with the master control unit. Each of the slave trainers is identically wired the only difference is the PANID and addresses that is manipulated with software. Photo 2 shows two slave units are constructed identically with the same hardware. The LCD is used to indicate the received data that master transmitted. There is no need for a keypad on the slave modules because no user input is required. However, the master module needs a keypad for user interaction.

Photo 2. A Pair of Slaves System Boards

Conclusion and Recommendations

The focus of this wireless communication demonstration project was to provide a hands-on-minds-on learning experience for capstone project classes. The project and instructional strategies were built around a 2.4GHz RF module (Microchip: MRF24J40MA) and a PIC trainer. This Microchip transceiver has all the required hardware except the 3.3VDC power source and several recommended passive capacitors. The PIC training system has a plug-in connector for the transceiver and everything to support the operation of the module. The MRF24J40MA transceiver is easily addressed using only *five* interface lines with the MCU. The design efforts are thus directed toward the software development and make it easy to modify as well as flexible to explore and develop in different applications. The current application revolves around a master control unit and two slave units. The flexibility of the systems provides an easy path toward adding more slave units to expand the system if needed by a particular application. Additionally, the project design has potential for expansion into control areas such as robot arms, remote data logging, wireless sensing, intelligent sensor networks, smart appliances, and home automation network[6]. Since the successful completion of this RF demonstration project, it has become apparent by faculty and students that it is a building block for expanding the hands-on microprocessor learning experiences. Subsequently, video materials created during the demonstration project are used in other courses to highlight learning experiences and benefits.

Wireless communication technologies are very pervasive and found in nearly every area that you can imagine! Wireless technologies have been widely used for decades in business, industry, and in consumer product development. The recent advancements in miniaturization and communication technology have made wireless applications even more attractive and made our daily life heavily dependent on these technologies. Technological advancements have made it possible to design and fabricate complex circuits and place them onto a single integrated circuit. Embedded systems typically use microcontrollers and are designed with minimum external components that reduce parts count and costs while still support various product development needs. A close look at the new products available in the market today reveals the growing trend in the integration of the embedded systems. Engineers as well as consumers are concerned about security issues with so many wireless devices that are now available. The security issues associated with wireless communication can be addressed with embedded controllers using intelligent software protocols. The merging of RF devices and embedded systems is a major focus in newly developed industry products. The reflection of the current developments in technology, with regard to computer and electronic technology curricula and project implementations, is crucial to the success of the academic programs and the enrolled students.

Definition of Terms

1. OOK (On-Off Keying): In this type of transmitter, the main oscillator is turned off when a zero is being transmitted and it is turned on when a one is being transmitted. The benefits of an OOK transmitter are that the current consumption becomes a function of the ratio between 1's and 0's in the data stream and it achieves better modulation depth than Amplitude Shift Keying transmission. The OOK data rate is limited by the start-up time of the oscillator. The start-up time of the oscillator determines the maximum data rate that the transmitter can send.

2. ASK (Amplitude Shift Keying): In this type of transmitter, the output amplifier's gain is varied; a lower gain for a 0 and a higher gain of a 1. Thus, a 1 causes a higher output power. The difference between OOK and ASK is that the oscillator is always on in an ASK system because the oscillator does not have to restart each time the data input pin transitions from a 0 to a 1, the ASK transmitter can send much higher data rates. However, ASK transmitters are more expensive to build, use more current, and are less sensitive to noise than OOK transmitters.

3. FM (Frequency Modulation): Modulation in which the instantaneous frequency of a sine wave carrier is caused to deviate from the center frequency by an amount proportional to the

instantaneous value of the modulating signal. In FM transmission, the carrier frequency is called the center frequency.

4. FSK (Frequency-Shift Keying): Frequency modulation where the modulating signal shifts the output frequency between predetermined values. Usually, the instantaneous frequency is shifted between two discrete values termed the “mark” and “space” frequencies. A “mark” corresponding to a logic 1 and a “space” corresponding to a logic 0.

5. LR-WPAN (Low-Rate Wireless Personal Area Network): Methods for controlling keying material throughout the life cycle of the low-rate wireless personal area network including creation, distribution, and destruction.

6. MAC (Media Access Control): The exchange of related, consecutive frames between two peer media access control entities, required for a successful transmission of a MAC command or data frame.

7. MHR: Media Access Control (MAC) Header

8. PAN (alternate personal area network coordinator): A coordinator that is capable of replacing the personal area network (PAN) coordinator, should it leave the network for any reason. A PAN can have zero or more alternate PAN coordinators.

9. RFID (Radio Frequency Identification): A basic RFID system consists of an antenna or coil, a transceiver (with decoder), and a transponder (RF tag) electronically programmed with unique information.

10. NRZ (Non-Return To Zero): Non-Return to zero encoding is commonly used in slow speed communications interfaces for both synchronous and asynchronous transmission. Using NRZ, a logic 1 bit is sent as a high value and a logic 0 bit is sent as a low value. A problem arises when using NRZ to encode a synchronous link, which may have long runs of consecutive bits with the same value. For example, during long “runs” of 0’s there are no observable bit boundaries making it difficult for the receiver to distinguish one *zero* from another.

11. SAW (Surface Acoustic Wave): A fundamental frequency device that resonates at frequencies much higher than crystals

12. CPCA: Carrier-Present, Carrier Absent

13. VSWR (Voltage Standing Wave Ratio): The ratio of the maximum to minimum voltage in standing wave pattern. It varies from 1 to (plus) infinite.

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