AN1629

Simple Link Budget Estimation and Performance Measurements of Microchip 2.4 GHz Radio Modules

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INTRODUCTION

The increased popularity of short range wireless in home, building and industrial applications with 2.4 GHz band requires the system designers to understand the methods, estimation, cost and trade-off in short range wireless communication. Apart from considering the range estimation formula, it is good to understand the wireless channel and propagation environment involved with 2.4 GHz. Generally, RF/wireless engineers perform a link budget while starting an RF design. The link budget considers range, transmit power, receiver sensitivity, antenna gains, frequency, reliability, propagation medium (which includes the principles of physics linked to reflection, diffraction and scattering of electromagnetic waves), and environment factors to accurately calculate the performance of a 2.4 GHz RF radio link.

Usually, 2.4 GHz channels are part of unlicensed Industrial Scientific Medical (ISM) frequency bands. Many protocols such as ZigBee® (IEEE 802.15.4), Bluetooth® (IEEE 802.15.1), Wi-Fi® (IEEE 802.11 b/g/n), Wireless Universal Serial Bus (WUSB), proprietary protocols (MiWi™) and few cordless phones occupy this space. However, operation in the 2.4 GHz ISM band induces the radios to interfere with other protocols utilizing the same spectrum.

This application note describes a simple link budget analysis, measurement and techniques to evaluate the range and performance of wireless transmission with results and uses developed models to estimate the path loss for short range Microchip MRF24J40 2.4 GHz modules both for indoor and outdoor environment. Hence, an attempt is made to provide designers with an initial estimate on wireless communication system's performance. The performance parameters include range, path loss, receiver sensitivity and Bit Error Rate (BER)/Packet Error Rate (PER) parameters which are critical in any communication.

Microchip's MRF24J40MA, MRF24J40MB and MRF24J40MC are the three modules which have varied specifications relating to power and type of antenna. These modules are considered for measurement purpose in this application note.

LINK BUDGET

Link budget is the accounting of all gains and losses from the transmitter (TX) through the medium (free space) to the receiver (RX) in a wireless communication system. Link budget considers the parameters that decide the signal strength reaching the receiver. The factors such as antenna gain levels, radio TX power levels and receiver sensitivity figures must be determined to analyze and estimate the link budget.

The following parameters are considered to perform the basic link budget:

- Transmitter power
- Antenna gains (related to TX and RX)
- Antenna feed losses (related to TX and RX)
- Antenna type and sizes
- Path losses

Several secondary factors which are directly or indirectly responsible for link budget are as follows:

- Receiver sensitivity (this is not part of the actual link budget, but this threshold is necessary to decide the received signal capability)
- Required range
- Available bandwidth
- Data rates
- Protocols
- Interference and Interoperability

The link budget calculation is shown in Equation 1.

EQUATION 1: SIMPLE LINK BUDGET EQUATION

$$Received\ Power(dBm) = Transmitted\ Power(dBm) + Gains(dB) - Losses(dB)$$

Equation 1 considers all the different gains and losses between TX and RX. By assessing the link budget, it is possible to design the system to meet its requirements and functionality within the desired cost. Some losses may vary with time. For example, periods of increased BER for digital systems or degraded signal to noise ratio (SNR) for analog systems. In this application note, the link budget estimations and approximations are done by measuring the performance parameters and then optimizing the range or power based on the link budget models as discussed in Link Budget Model Approach: Estimation and Evaluation.

RANGE TESTING OVERVIEW

In wireless communication, a good range is usually obtained from the Free Space Path Loss (FSPL). FSPL is the loss in signal strength of an electromagnetic wave due to the Line of Sight (LOS) path through the free space with no obstacles near the source of the signal to cause reflection or diffraction. Path loss (or path attenuation) is the reduction in power density (attenuation) of an electromagnetic wave as it propagates through free space.

Path loss is caused by free space loss, refraction, diffraction, reflection and absorption, or all of these. It is also influenced by the terrain types, environment (urban or rural, vegetation and flora), propagation medium (moist or dry air), distance between the TX and RX, and antenna height and location. Path loss is unaffected by the factors such as antenna gains of TX and RX, and the loss associated with hardware imperfections. The FSPL is dominant in an outdoor LOS environment, where the antenna is placed far from the ground and with no obstructions.

The path loss formula calculates the FSPL, and these calculations are compared to actual measurements specified in Range Measurement Conditions and Results. When the antennas are assumed to have unity gain, the path loss formula reduces to Equation 2. The free space model is only valid for distances that are in the far field region of the transmitting antenna.

EQUATION 2: PATH LOSS EQUATION

$$PathLoss\ (dB) = 20 \times \log(f) + 20 \times \log(d) + 32.44\, dB$$

Where,

f = Frequency (MHz)

d = Distance (km)

Note: For all the log functions used in this application note, $log(f) = log_{10}(f)$.

For Equation 2 in free space (ideal transmission channel), the path loss is calculated when loss coefficient is 2. When the transmission channel is non-ideal, the typical path loss coefficient values are 2.05 to 2.5 for LOS and 3.0 to 4.0 for indoor/non-LOS environments. The non-ideal characteristics of the transmission channel result in the transmitting wave producing reflection, diffraction, absorption and scattering.

In an indoor environment, many obstructions may add constructively or destructively for the radio wave propagations. For example, part of the wave energy is transmitted or absorbed into the obstruction, and the remaining wave energy is reflected off the medium's surface.

Also, the RF wave energy is a function of the geometry and material properties of the obstruction, phase, amplitude and polarization of the incident wave. Reflection occurs when electromagnetic (RF) wave strikes upon an obstruction with very large dimension compared to the wavelength of the radio wave during propagation. Reflections from the surface of the earth and from buildings produce reflected waves that may interfere constructively or destructively at the receiver point. Diffraction occurs when the radio transmission path between the TX and RX is obstructed by sharp edges. Based on Huygen’s principle, secondary waves are formed behind the obstructing body even though it is not LOS between the TX and RX. RF waves travelling in urban and rural area (non-LOS) are due to Diffraction. This phenomenon is also called Shadowing, because the diffracted field can reach a receiver even when it is shadowed by thick obstruction.

Similar to reflection, diffraction is affected by the physical properties of the obstruction and the incident wave characteristics. When the receiver is heavily obstructed, the diffracted waves may have sufficient strength to produce a useful signal. Scattering occurs when the radio channel contains objects with dimensions that are in the order of the wavelength or less of the propagating wave. Scattering almost follows the same physical principles as diffraction and causes energy from a TX to be radiated again in different directions. Scattering also occurs when the transmitted wave encounters a large quantity of small dimension objects such as lamp posts, bushes and trees. The reflected energy in a scattering situation is spread in all directions. Analyzing and predicting the scattered waves is the most difficult of the three propagation mechanisms in wireless communication.

Generally, the obstructed path loss is more difficult to analyze, especially for different indoor scenarios and materials. Hence, different path loss models exist to describe unique and dominant indoor characteristics, such as multi-level buildings with windows and single level buildings without windows. The attenuation decreases floor wise with the increase in the number of floors. This phenomenon is caused by diffraction of the radio waves along the side of a building as the radio waves penetrate the building's windows. However, this is apart from the average signal loss for radio path obstruction by different materials and Floor Attenuation Factor (FAF) for signal penetration across multiple floors. Also, different indoor configurations can be categorized for buildings with enclosed offices or office spaces consisting of a mix of cubicles and enclosed rooms.

Table 1 provides examples of 2.4 GHz signal attenuation through obstacles for various materials.

TABLE 1: ATTENUATION THROUGH DIFFERENT MATERIALS

Material Type	Attenuation (dB)
Window brick wall	2
Metal frame glass wall into building	6
Office wall	6
Cinder block wall	4
Metal door in office wall	12
Brick wall next to metal door	3

When transmitted, radio wave transforms in the indoor environment and it reaches the receiving antenna through many routes giving rise to multi-path noise. Multi-path introduces random variation in the received signal amplitude. Multi-path effect varies based on the location and antenna type used. These variations as much as 40 dB occur due to multi-path fading (because of the radio waves combining constructively or destructively). Fading can be rapid or slow depending on the moving source and the propagation effects manifested at the receiver antenna. Rapid variations over short distances are defined as small scale fading. In indoor testing, fading effects are caused by human activities and these generally exhibit both slow and fast variations. For example, even rotating metal blade of fans causes rapid fading effects.

The Low-Rate Wireless Local Area Network (LR-WLAN) applications for indoors can either be fixed or mobile. Therefore, small scale fading effects are described using multi-path time delay spreading. The signals experience different arrival times because the signals can take many paths before reaching the receiver antenna. Hence, a spreading in time (frequency) can occur. Different arrival times ultimately create further degeneration of the signal. Increase in the number of different LR-WLAN products leads to an increased demand for more indoor radio range metrics and benchmarks, specifically in comparison of Frequency Hopping (FH) and Direct Sequence (DS) radio systems. In addition, the usage of LR-WLAN radio dictates the performance of the radio in network applications. Therefore, the indoor range of a user may vary from the results due to the differences in indoor environments.

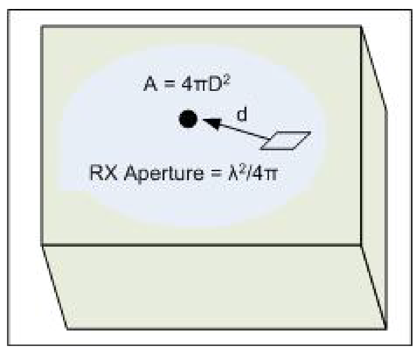
The directional properties of an antenna can be modified by the ground because the earth acts as a reflector. For example, if a dipole antenna is placed horizontally to the ground, most of the downward radiated energy is reflected upward from the dipole. The reflected waves combine with the direct waves (those radiated at angles above the horizontal) in different ways, depending on the antenna height, frequency and electrical characteristics.

However, indoor environments, different antenna heights are used not because of the ground effect but due to obstructions in the indoor office environment.

At some vertical angles above the horizon, the direct and reflected waves may be exactly in phase where the maximum signal or field strengths of both waves are arrived simultaneously at some distant point. In this case, the resultant field strength is equal to the sum of the two components. At other vertical angles, the two waves may be completely out of phase at some distant point (i.e., the fields are maximized at the same instant but the phase directions are opposite). The resultant field strength in this case is the difference between the two waves. At some other angles, the resultant field have intermediate values. Therefore, the effect from ground is to increase the radiation intensity at some vertical angles and to decrease it at other angles. The occurence of maxima and minima for elevation angles primarily depends on the antenna height above the ground (electrical characteristics of the ground also have some effect).

The FSPL formula is applicable to situations where only the electromagnetic wave exists (for far field situations). It does not hold true for near field situations. The spherical wavefront in open space with isotropic antenna is considered for reference, where power is radiated in all the directions. Figure 1 illustrates the geometric interpretation of spherical wavefront using an isotropic antenna.

FIGURE 1: GEOMETRIC INTERPRETATION OF SPHERICAL WAVEFRONT



All antennas have a gain factor expressed in dB which is relative to an isotropic radiator. An isotropic radiator radiates uniformly in all directions like a point source of light. All the power that the TX produces ideally is radiated by the antenna. However, this is not generally true in practice as there are losses in both the antenna and its associated feed line. Also, antenna gain does not increase power, it only concentrates on the effective radiation pattern.

RANGE AND PERFORMANCE MEASUREMENTS OF MRF24J40 MODULES

Performance Measurement Parameters

The following are some general concerns in wireless communication systems:

- The radio distance acceptable between the TX and RX for communication
- The parameter changes required to enhance the range and gain for optimum performance

To resolve the above concerns, FSPL model is used in determining the transceiver separation, and changing (increase) the TX power to increase the separation distance. While these two assumptions work under restricted conditions, in general they are very useful for most situations. Apart from these two changes related to link budget, some emphasis on the data rate and protocol which cannot be undermined must be provided as these parameters are related to the frequency and modulation technique which is dependent on the operational band.

It is possible to improve the receive sensitivity and range by reducing data rates over air. Receive sensitivity is a function of the transmission baud rate. Receive sensitivity goes up as baud rate goes down. To maximize the range, many radios provide the user the ability to reduce the baud rate through its register configurations. Moreover, a better understanding of the wireless changes that needs to be done in the system can improve the transmission distance. In this application note, the measured field and data is presented that approximately supports the realistic math models.

This section provides details on various test factors that measure the performance of Microchip 2.4 GHz radio modules.

The following are the test factors:

- Transmitting power
- Receive power
- Path loss and sensitivity performance
- PER/BER
- Range environment models
- Radiation pattern
- Impedance measurements
- Received Signal Strength Indicator (RSSI)

However, the following performance parameters including the range are measured in this application note:

- Range
- PER/BER
- Sensitivity Performance
- RSSI

Measurement Test Requirements and Setup

For measurements to be done, related hardware and software/utility setup are necessary. This section provides details of the hardware test setup and software/utilities used.

The Microchip MRF24J40 transceiver 2.4 GHz IEEE 802.15.4 based modules are used for measurements. These FCC/ETSI/IC certified modules differ from other embedded 2.4 GHz modules by offering a variety of regulatory and modularly certified Printed Circuit Board (PCB) antennas (inverted E/inverted F type) along with external (Whip type) antenna, usually mounted on development boards or daughter cards.

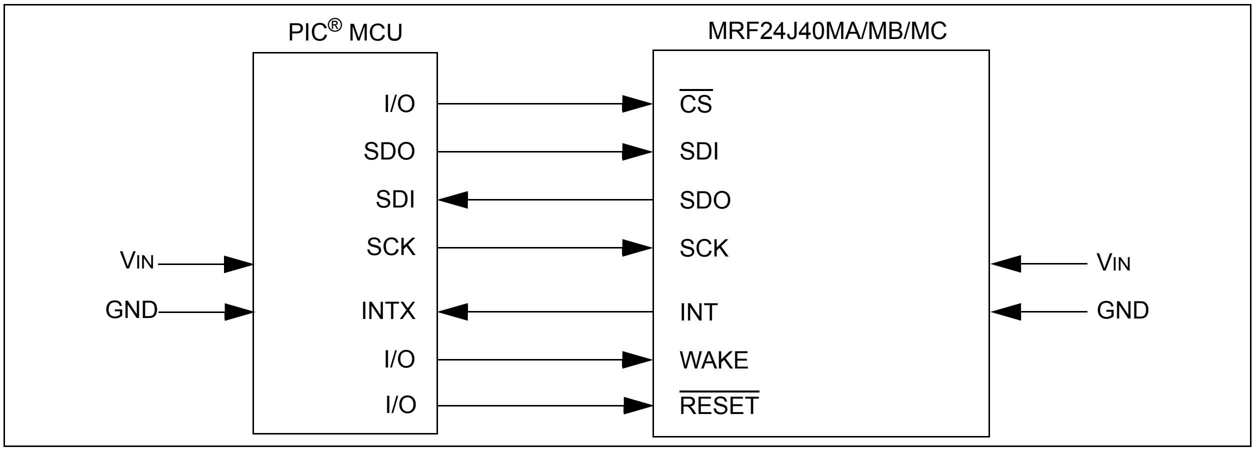
HARDWARE USED FOR TEST SETUP

The following hardware are used for the range and performance parameter tests with the MRF24J40 transceiver modules:

- Two MRF24J40MA/MB/MC PICtail™/PICtail Plus Daughter Boards
- Portable 2 dBi/5 dBi Aristotle P/N RFA-02-5-F7H1-70B-15 with type whip/dipole, if the MRF24J40MC module is used
- Any of the following Microchip hardware development platforms:
  - Two Explorer 16 Development Boards (Part number: DM240001)
  - Two PIC 18 Explorer Development Boards (Part number: DM183032)
  - Two 8-bit Wireless Development Boards (Part number: DM182015)
  - Any two custom developed boards which has the provision to mount the MRF24J40MA/MB/MC modules or related PICtail daughter boards
- One of the following Microchip development tools for programming/debugging:
  - MPLAB® REAL ICE™/MPLAB® ICD/PICkit™ 3
  - ZENA™ Wireless Adapter - 2.4 GHz (AC182015-1)
- Power supply: 9V/0.75A or equivalent battery pack

The hardware interface of the MRF24J40 transceiver module with any of the PIC® MCU, generally known as Wireless Node, is illustrated in Figure 2. The same wireless nodes can be realized using a combination of the PIC MCU development board and PICtail daughter board.

FIGURE 2: MICROCONTROLLER TO MODULE INTERFACE – WIRELESS/RF NODE DIAGRAM



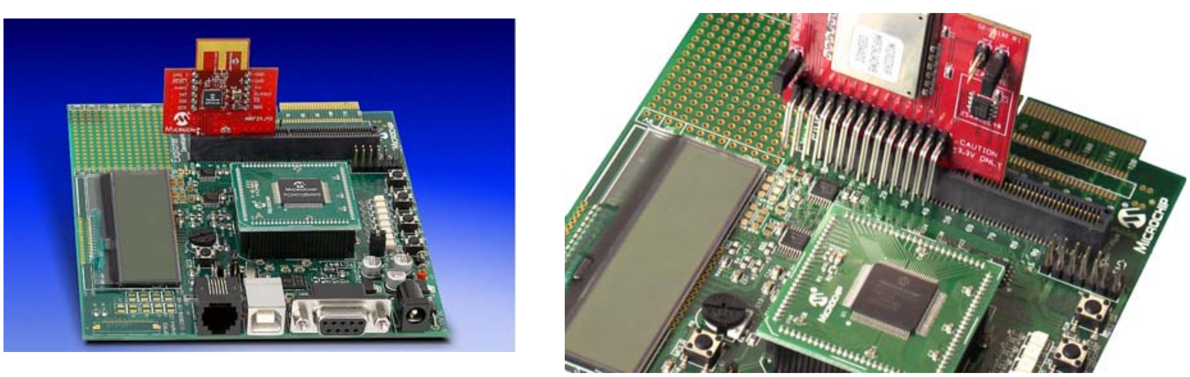
HARDWARE TEST SETUP

The range and performance experiments require at least two wireless nodes for testing. The measurement setup is done using any of the two development boards with identical MRF24J40 modules on each of them (for simplicity purpose). Otherwise, a combination of these modules can also be used for measurements and analysis, based on the user application requirement. In this application note, the measurements are done using identical RF nodes. For more information on the MRF24J40 modules, refer to **Appendix A: "Microchip MRF24J40 Based Modules Used for Measurements"**.

Explorer 16 Development Board and MRF24J40 Module Connections

The MRF24J40 RF transceiver daughter card's 30-pin PCB-edge connector (J3) is used to connect the Explorer 16 Development Board's PICtail plus connector. This connection supplies 3.3V power, four wire Serial Peripheral Interface (SPI), reset, wake and interrupt connections to the MRF24J40 RF transceiver. Figure 3 illustrates the plugging arrangement between the Explorer 16 Development Board and MRF24J40 modules. For more information on the use and programming of the development board with 2.4 GHz modules, refer to the *"MRF24J40MA/MB PICtail™/ PICtail Plus Daughter Board User's Guide"* (DS51867).

FIGURE 3: MRF24J40 MODULE ON EXPLORER 16 DEVELOPMENT BOARD



MRF24J40MA Module

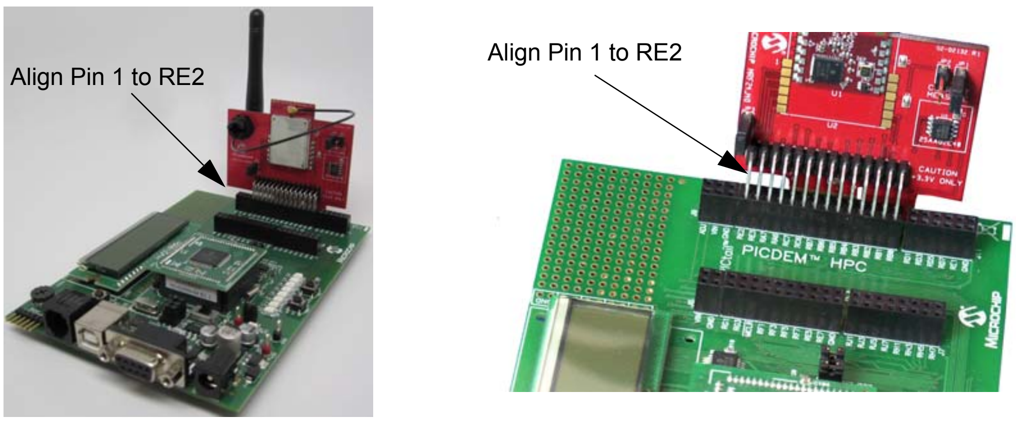
MRF24J40MB Module

PIC 18 Explorer Development Board and MRF24J40 Module Connections

The MRF24J40 module PICtail board's 28-pin PCB-edge connector (P2) is used to connect the PIC18 Explorer Development Board on PICtail connector (Explorer 2) slot. This connection supplies 3.3V power, four wire SPI, reset, wake and interrupt connections to the MRF24J40 RF transceiver.

Figure 4 illustrates the MRF24J40 module connections with the PIC18 Explorer Development Board. For more information on the PIC18 Explorer Development Board usage and programming, refer to the *"MRF24J40MA/MB PICtail™/PICtail Plus Daughter Board User's Guide"* (DS51867).

FIGURE 4: MRF24J40 MODULE ON PIC18 EXPLORER DEVELOPMENT BOARD



MRF24J40MC Module

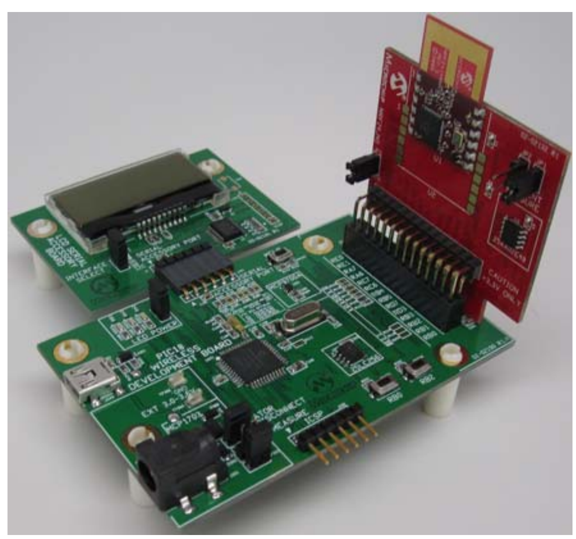
MRF24J40MA Module

8-Bit Wireless Development Board and MRF24J40 Module Connections

The MRF24J40 module PICtail board's 28-pin PCB-edge connector (P2) is used to connect the 8-bit Wireless Development Board on PICtail connector slot. This connection supplies 3.3V power, four wire SPI, reset, wake and interrupt connections to the MRF24J40 RF transceiver.

Figure 5 illustrates the MRF24J40 module connections with the 8-bit Wireless Development Board. For information on the 8-bit Wireless Development Board usage and programming, visit the Microchip web site (www.microchip.com/WDK).

FIGURE 5: MRF24J40 MODULE ON 8-BIT WIRELESS DEVELOPMENT BOARD



SOFTWARE/UTILITY SETUP REQUIREMENTS

The basic utility driver firmware or demo application based on the Microchip MiWi™ P2P protocol is used for measurements and verifying the range and performance functionality of the MRF24J40 modules. The driver utility and MiWi based application demo runs on any of the Microchip development board, as discussed in Hardware Test Setup.

Refer to the Microchip web site (www.microchip.com) for the following application/software download:

- For information on driver utility or Ping-Pong code, refer to the *"MRF24J40 Radio Utility Driver Program"* (AN1192).
- For information on the application demo, refer to the *"Microchip MiWi™ P2P Wireless Protocol"* (AN1204).

Wireless Development Studio (WDS), ZENA Wireless Adapter and Windows terminal emulator program (for example, HyperTerminal or Teraterm) PC tools are also conveniently used for control and monitoring. For information on WDS Help and Software, visit the Microchip web site (www.microchip.com\wds). For information on ZENA Network Analyzer, visit the Microchip web site (www.microchip.com/zena).

The code available is modified and compiled using the MPLAB® IDE and C18/C30/XC compilers. The basic driver demo or MiWi application requires commands from the terminal emulator program and output the results on the terminal emulator program. The demo board used for measurements is connected to the terminal emulator program of the PC through serial port with Baud-19200, Data bits-8, Parity-None, Stop bits-1 and Flow control-None as settings.

Summary of Tools Used for Range/ Performance Measurements

The following must be ensured during indoor and outdoor tests:

- Explorer 16 Development Boards/PIC18 Development Boards/8-bit Wireless Development Board are used with a provision for mounting and plugging the battery pack in the general purpose PCB area.
- Versions of the module boards have some variations in the RF power output.
- PCB antenna must be protruded outside the development board to minimize the interference and enhance the lobe power.
- MiWi P2P Simple Demo Code is used for testing with slight code modifications. However, Ping-Pong related code and MRF24J40 Driver Software can also be used.
- Configure for MRF24J40MA or MB or MC is done through software while the hardware for all of these modules remain the same.
- Terminal emulator program on PC/ZENA Wireless Adapter/LCD can be used as display units. However, for open field environment on-board LCD consumes less power from its battery source.

Table 2 provides a detailed list of the hardware and software tools used for measurements in this application note. As discussed in Hardware Test Setup and Software/Utility Setup Requirements, the test setup requires two sets of hardware for transmission and reception at any time, and the process is repeated vice-versa.

TABLE 2: TOOLS FOR RANGE/PERFORMANCE MEASUREMENTS

Mother Board/Base Board	Daughter Card Name with Module/ Rev.	Daughter Card Part Number	Daughter Card Details	Cards Used	Maximum Power (dB)	Antenna Type	Antenna Direction	Antenna Length (cm)	Demonstration Program	Monitoring/ Display
Explorer 16/ PIC18 Explorer/8-bit Wireless Development Board	MRF24J40MA (Rev.3) PICtail/PICtail Plus Daughter Board	AC164134-1	Rev. R1	2	0	PCB	Vertical	NA	MiWi P2P Simple Demo/Simple P2P Ping-Pong/ MRF24J40 Driver Software (PER, RSSI, and so on)	Terminal emulator program on PC/ZENA Wireless Adapter on PC/LCD
Explorer 16/ PIC18 Explorer/8-bit Wireless Development Board	MRF24J40MB (Rev.8) PICtail/PICtail Plus Daughter Board	AC164134-2	Rev. R1	2	+20	PCB	Vertical	NA	MiWi P2P Simple Demo/Simple P2P Ping-Pong/ MRF24J40 Driver Software (PER, RSSI, and so on)	Terminal emulator program on PC/ZENA Wireless Adapter on PC/LCD
Explorer 16/ PIC18 Explorer/8-bit Wireless Development Board	MRF24J40MC (Rev.3) PICtail/PICtail Plus Daughter Board	AC16414	Rev. R1	2	+ 20	Ext. +2/5 dBi	Vertical	$\lambda/4$	MiWi P2P Simple Demo/Simple P2P Ping-Pong/ MRF24J40 Driver Software (PER, RSSI, and so on)	Terminal emulator program on PC/ZENA Wireless Adapter on PC/LCD

Note: Any of the custom application code (simple user application specific code) can also be used for measurements.

MEASUREMENT AND PERFORMANCE TEST

Range Measurement Environments

Operating terrains (environments) highly impact the wave propagation. Range tests are conducted in a variety of indoor and outdoor environments to provide a basic understanding of the range performance that the MRF24J40 modules are capable of. The chosen environments include Line of Sight (LOS) on level and uneven terrain, and obstructed paths on level and uneven terrain.

The measurements are also based on the following factors:

- PCB antenna orientation (vertical or horizontal)
- Output power of the MRF24J40 modules (maximum or default)
- Power Amplifier (PA)/Low Noise Amplifier (LNA) (enabled or disabled value)
- Type of antenna PCB/Wire/Standard dipole
- Antenna (inverted F, inverted E or whip/dipole)

The factors affecting indoor measurements:

- Office equipments
  - Wi-Fi/Bluetooth/Microwave in the vicinity
  - Concrete structures/walls/glass nearby/ wood/metal, and so on

The purpose of actual measurements for outdoor and indoor, and understanding the operating scenes is to gain confidence in the operating environment. Ideally, the wireless networks commissioned are not operated in a conducive environment.

Figure 6 illustrates the ideal test setup for any lab measurements including the mounting and arrangement. However, the field test setup does not involve any complexities such as anechoic chamber or ideal LOS environments.

FIGURE 6: MRF24J40 MODULE/RF NODE-LAB MOUNTING

MRF24J40MA Module

Typical environments that are considered in this application note for range testing are as follows:

- Outdoor – open plane field (with even surface)
- Outdoor – open plane field (with irregular surface)
- Outdoor – vicinity of buildings
- Indoor – office/home environment
- Indoor - inter floor test (indoor)
- Indoor/Outdoor: PER test in open plane field and office environment

For range tests, the main differentiating factors are the module mounting, antenna orientation and the constant battery power source (not allowing the source voltage to drop below supply voltage requirements).

Figure 7 illustrates the vertical (with elevation lobe/ plane) and horizontal (with azimuth lobe/plane) mounting of antenna on the base board. The antenna is mounted either vertically or horizontally based on the effective output power achieved, application space requirements and constraints (i.e., having a strong primary lobe based on the center fundamental frequency and secondary lobes based on its third harmonic frequency).

FIGURE 7: ANTENNA MOUNTING AND ORIENTATION

Vertical Mounting

Horizontal Mounting

Range Measurement Procedure

The following is the procedure on how to conduct simple range test or measurements:

1. Program the two RF/wireless MRF24J40 based transceiver nodes with MiWi P2P demo code.
2. Place any one RF node on a stand (5 ft-6 ft pole) as illustrated in Figure 6 after configuring a specific operating channel. By default, the wireless node is in receiving mode.
3. Place a similar RF node on a second stand (5 ft-6 ft pole) and set for the same working channel.
4. Make one of the nodes stationary and the other node mobile.
5. Setup nodes and ensure the two nodes are connected to each other.
6. Move the mobile node and test for transmission and reception. Measure for every 5 ft-10 ft.
7. Once the critical point is attained, measure the actual/radial distance from the TX to the RX.

Note:	Critical distance is a point where the TX and RX communication becomes intermittent.

8. Return 5 ft from the critical point and check for reliable communication.
9. On a conservative note, subtract 5 ft-10 ft from the critical distance to get the actual range.

Note:	Range is the least radius or linear radio distance measured between two antennas.

Figure 8 illustrates the distance measurement method, and it also shows that the increase in range value is a function of variables with the TX module height being most sensitive.

FIGURE 8: DISTANCE MEASUREMENT METHOD

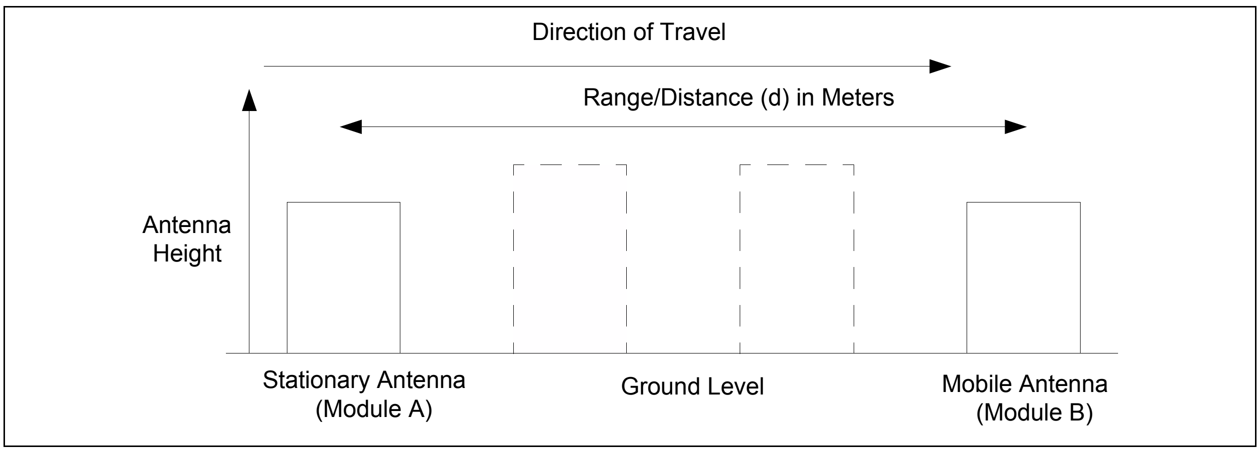


Figure 9 illustrates the outdoor measurement test setup for open field/PER/BER test.

FIGURE 9: OUTDOOR MEASUREMENTS TEST SETUP: OPEN FIELD/PER/BER TEST

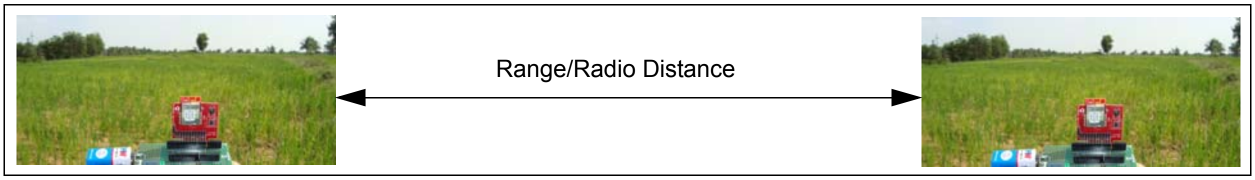


Figure 10 illustrates the outdoor measurement test setup for vicinity of buildings.

FIGURE 10: OUTDOOR MEASUREMENTS TEST SETUP: VICINITY OF BUILDINGS

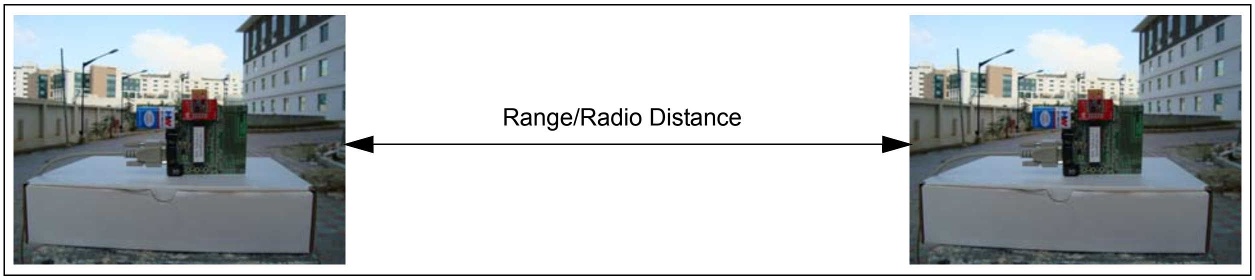


Figure 11 illustrates the outdoor measurement test setup for buildings in between antennas.

FIGURE 11: OUTDOOR MEASUREMENTS TEST SETUP: BUILDINGS IN BETWEEN ANTENNAS

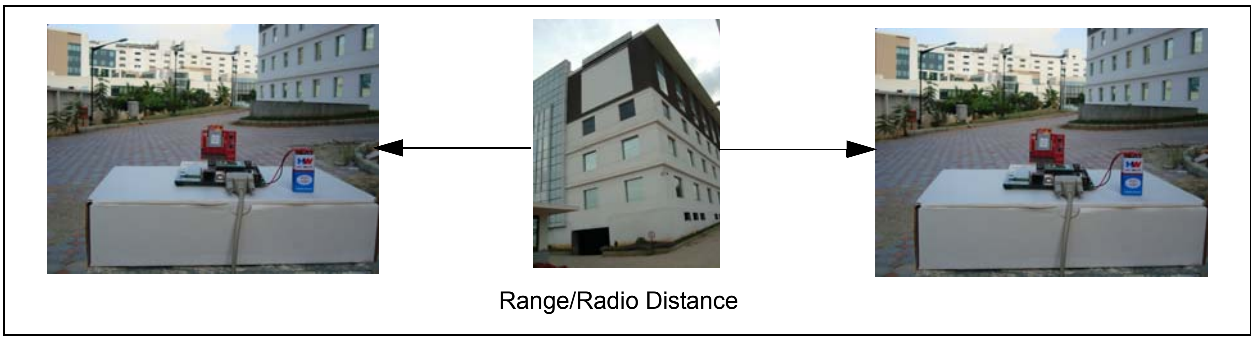


Figure 12 illustrates the indoor measurement test setup for office/PER/BER test.

FIGURE 12: INDOOR MEASUREMENTS TEST SETUP: OFFICE/PER/BER TEST

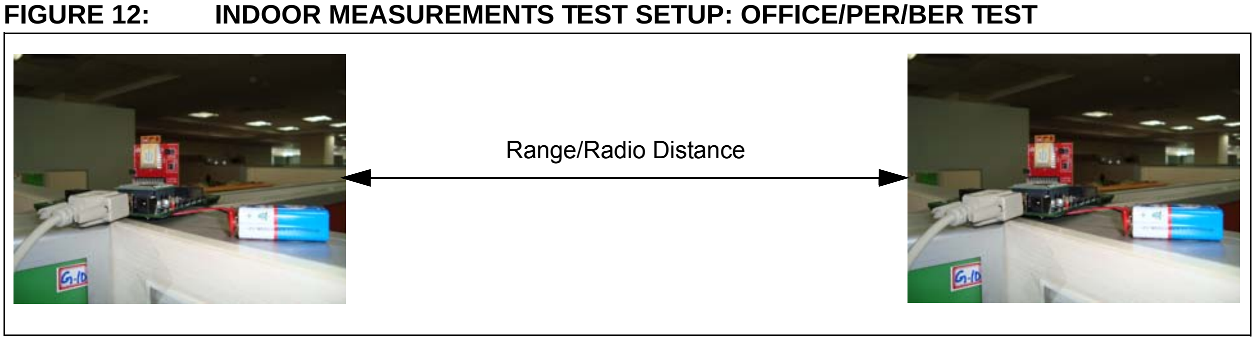
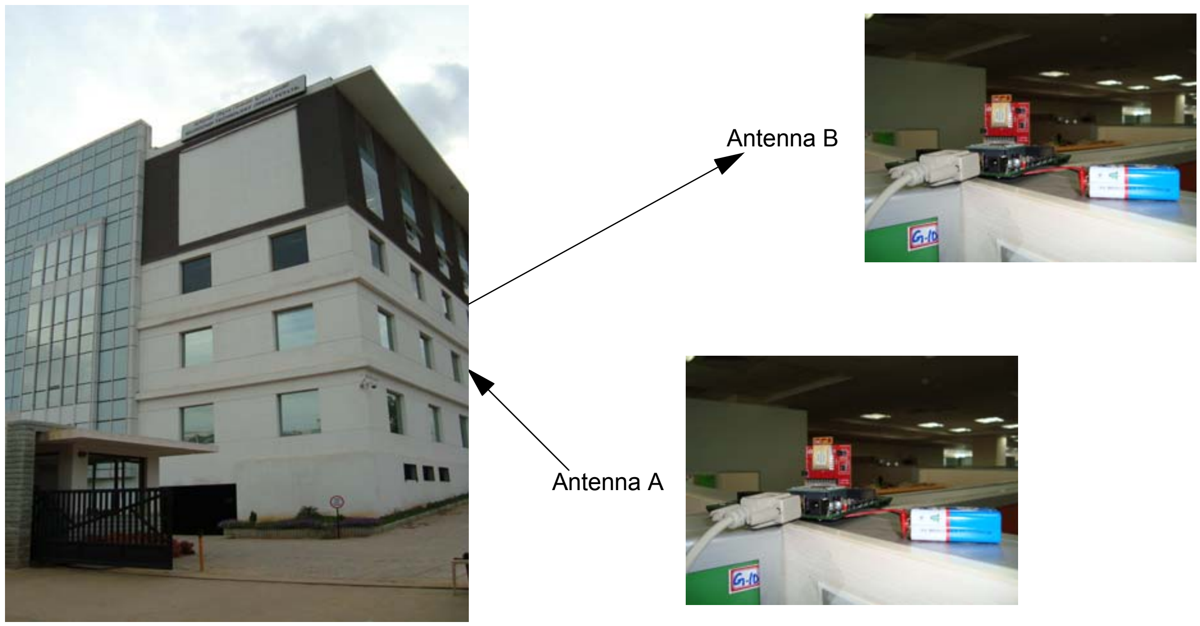


Figure 13 illustrates the indoor measurement test setup for inter floor.

FIGURE 13: INDOOR MEASUREMENTS TEST SETUP: INTER FLOOR



MEASUREMENT ENVIRONMENT AND RESULTS

This section provides different type of environments and conditions used for performing range tests. The basic idea adopted is to conduct outdoor (nearly LOS) and indoor tests (with obstacles) to measure nature and characteristics that each of the modules contribute for performance in different environments.

The following different types of environments (indicated in abbreviations) are considered for range/other performance measurements:

- Outdoor measurement setup
  - Open field: Even surface (OP(E))
  - Open field: Uneven surface (OP(U))
  - Vicinity of buildings: Even surface (VOB(E))
  - Vicinity of buildings: Uneven surface (VOB(U))
  - Building/s in-between TX and RX antenna: Even surface (BIA(E))
- Indoor measurement setup
  - Indoor: Office

Outdoor Measurement Environments

ENVIRONMENT: OPEN FIELD

- Test: Range/PER/BER
- Land characteristics: Even
- Reference level: Ground
- Mounting: 5 ft above ground
- Antenna orientation: Vertical
- Operating frequency: 2.480 GHz
- Operating channel: 26

Figure 14 illustrates the outdoor measurement done in an open field with even surface.

FIGURE 14: OPEN FIELD - EVEN SURFACE

ENVIRONMENT: OPEN FIELD

- Test: Range
- Land characteristics: Uneven
- Reference level: Ground
- Mounting: 5 ft above ground
- Antenna orientation: Vertical
- Operating frequency: 2.480 GHz
- Operating channel: 26

Figure 15 illustrates the outdoor measurement done in an open field with uneven surface.

FIGURE 15: OPEN FIELD - UNEVEN SURFACE

ENVIRONMENT: VICINITY OF BUILDINGS

- Test: Range
- Land characteristics: Even/Uneven
- Reference level: Ground
- Mounting: 5 ft above ground
- Antenna orientation: Vertical
- Operating frequency: 2.480 GHz
- Operating channel: 26

Figure 16 illustrates the outdoor measurement done near vicinity of buildings.

FIGURE 16: OUTDOOR: VICINITY OF BUILDINGS

ENVIRONMENT: BUILDING IN BETWEEN

- Test: Range
- Land characteristics: Even/uneven
- Reference level: Ground
- Mounting: 5 ft above ground
- Antenna orientation: Vertical
- Operating frequency: 2.480 GHz
- Operating channel: 26

Figure 17 illustrates the outdoor measurement done in between buildings.

FIGURE 17: OUTDOOR: BUILDINGS IN BETWEEN

Indoor Measurement Environments

ENVIRONMENT: OFFICE

- Test: Range/PER/BER
- Land characteristics: Level
- Reference level: Same floor
- Mounting: 5 ft above ground, cubical top
- Antenna orientation: Vertical
- Operating frequency: 2.480 GHz
- Operating channel: 26

Figure illustrates the indoor measurements done inside the office (same floor).

FIGURE 18: INDOOR: OFFICE

ENVIRONMENT: OFFICE

- Test: Range
- Land characteristics: Level
- Reference level: Inter floor
- Mounting: 3 ft above ground, on table
- Antenna orientation: Vertical
- Operating frequency: 2.480 GHz
- Operating channel: 26
- Inter floor distance: 13 ft

Figure 19 illustrates the indoor measurement done in the office (inter floor).

FIGURE 19: INDOOR: OFFICE (INTER FLOOR)

Range Measurement Conditions and Results

The 2.4 GHz PHY (high-band) uses Offset Quadrature Phase Shift Keying (OQPSK) modulation. The modulation modes offer extremely good BER performance at low signal to noise ratios. The IEEE 802.15.4 physical layer offers a total of 27 channels, one channel in the 868 MHz band, ten channels in the 915 MHz band, and, 16 channels in the 2.4 GHz band. The raw bit rates on these three frequency bands are 20 kbps, 40 kbps, and 250 kbps, respectively.

The following settings must be ensured to accomplish the range measurements:

- Less noisy channel is assigned as the operating channel for all the measurements. Operating channel 26 is assigned by using the RFCON0 register from the MRF24J40 device.
- Transmit power controlled by the RFCON3 register is assigned as 0x0000. Refer to the specific module data sheet for more information on the PA/LNA settings for the MRF24J40MA/MB/MC modules.
- Data rate is set as 250 kbps (standard/default)
- Baud rate is set as 19200 for communication between terminal emulator program and base board when the serial port is used for monitoring and debug purpose.

With and Without ACK suggests the following during range measurements:

- With ACK: Are unicast messages that have acknowledgments (ACK) for transmitted packets.
- Without ACK: Are broadcast messages that have no acknowledgments (ACK) for transmitted packets.

As there are some significant differences in the measurement values of With and Without ACK, the same are tabulated in Table 3.

Table 3 provides the measured range details of the MRF24J40MA/MB/MC modules. The environment and other conditions are also specified in this table.

The range measurement test conditions are as follows:

- Transceiver: MRF24J40
- Environment: Specified in Table 3
- Land characteristics: Specified in Table 3
- Level: Ground
- Antenna orientation: Vertical
- Operating frequency: 2.480 GHz
- Operating channel: 26
- Data rate: 250 kbps
- Baud rate: 19200
- Data packets transmitted: Variable string packet
- TX Power: 0/20/22-25 dBm
- LNA Gain : +5 dBm (high gain)
- Receiver Sensitivity: -95 dBm
- RSSI Threshold: -69 dB

Apart from above test above conditions, the radiated power from each module can be estimated to the sum of Tx power present at antenna feeding point and average antenna gain.

On average, the radiated power estimations are as follows:

- MRF24J40MA: -0.5 dBm + 1.5 dB = 1 dBm
- MRF24J40MB: 18 dBm + 1.5 dB = 19.5 dBm
- MRF24J40MC with 2 dBi external whip antenna: 18.5 dBm + 2 dB = 20.5 dBm
- MRF24J40MC with 5 dBi external whip antenna: 18.5 dBm + 5 dB = 23.5 dB

TABLE 3: RANGE MEASUREMENT RESULTS OF MRF24J40 MODULES

Module Type	Antenna Type and Position	Frequency (GHz)	Power Setting (dB)	Environment /View	Terrain	Range (in M) With ACK	Range (in M) Without ACK	Inter-Floor Communication
MRF24J40MA	PCB inverted E mounted vertically	2.480	0	Office	—	40-45	50-55	Office environment, one floor
				Outside office	—	50-55	60-65	
				Vicinity of buildings	—	75-80	80-85	
				Open field	Uneven surface	120-125	125-130	
				Open field	Even surface	135-140	140-150	
MRF24J40MB	PCB inverted F mounted vertically	2.480	20	Office	—	120-125	135-140	Office environment, four floors
				Outside office	—	170-180	220-230	
				Vicinity of buildings	—	190-200	220-230	
				Open field	Uneven surface	430-440	450-460	
				Open field	Even surface	675-700	750-775	
MRF24J40MC	External Whip antenna (2 dBi) mounted vertically	2.480	20 + 2 dBi	Office	—	135-140	150-160	Office environment, four floors
				Outside office	—	195-205	240-250	
				Vicinity of buildings	—	210-220	240-250	
				Open field	Uneven surface	450-460	465-475	
				Open field	Even surface	750-775	775-800	
MRF24J40MC	External Whip antenna (5 dBi) mounted vertically	2.480	20 + 5 dBi	Office	—	140-150	155-165	Office environment, four floors
				Outside office	—	205-215	250-260	
				Vicinity of buildings	—	220-230	250-260	
				Open field	Uneven surface	460-470	475-490	
				Open field	Even surface	775-800	800-825	

Note 1: All the range measurement results specified in Table 3 are conservative and may vary based on the environment and test conditions. However, better results may be achieved by further refining the tests conducted.

2: For more information on variable power configuration, refer to the MRF24J40 device data sheet and specific MRF24J40MA/MB/MC module data sheet.

3: The frequency band, center frequency, bandwidth and the data rate values on both transceivers (sender and receiver units) must be the same for successful reception of the transmitted content.

4: The power measurements are not part of the table as to suppress the ambiguity of environment variables.

Packet Error Rate (PER) Test

PER TEST BETWEEN TWO DEVICES

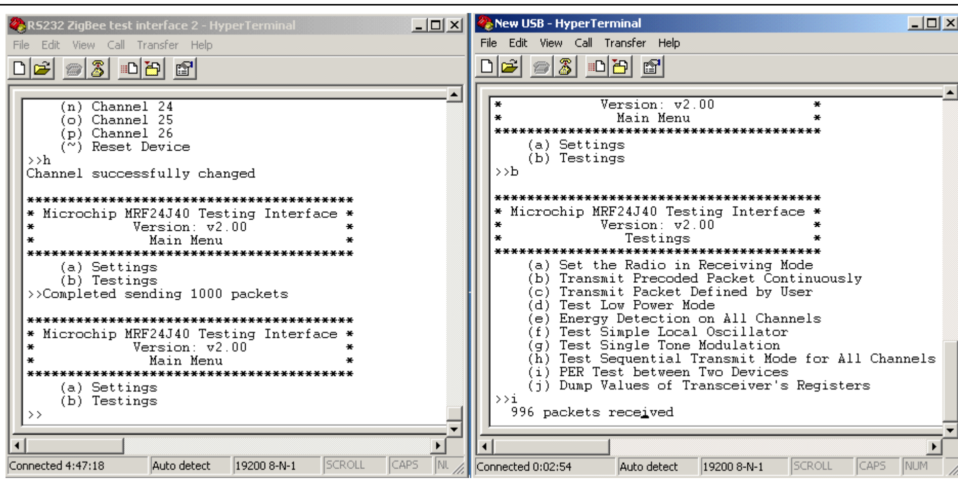
The PER test analyses the indoor and outdoor valid data coverage between two wireless nodes. This section explains a simple PER test setup and its procedure. The PER test setup is similar to the open field test setup.

The PER test between two modules is done in a single iteration with predetermined number of data packets. The ISM/IEEE 802.15.4 specification defines a reliable link as having PER below or equal to 1% for the 1000 data packets transmitted/received. PER measures the capability of a device to receive a signal without degradation due to undesirable signals at other frequencies. The desired signal's degradation of its PER must be less than 1% or the BER must be less than 0.1%. PER test is conducted by adding the delay between packets, if required. For more information, refer to the *"MRF24J40 Radio Utility Driver Program"* (AN1192).

The following is the procedure to conduct simple PER test measurements:

1. Program the two MRF24J40 based transceiver wireless nodes with Utility Driver firmware for PER test.
2. Place any one RF node on a stand (5 ft-6 ft pole) as illustrated in Figure 6 after configuring a specific operating channel. By default, the wireless node is in receiving mode.
3. Place a similar RF node on a second stand (5 ft-6 ft pole) and set for the same working channel.
4. Make one of the nodes stationary and the other node mobile.
5. Setup nodes and ensure the two nodes are connected to each other.
6. Trigger the following sequence for the second RF node, as illustrated in Figure 20.
7. The RF node sends a message/request to the first module to start sending 100/1000 data packets, and immediately the RF node enters the Receive mode to handle all of these 100/1000 incoming data packets.
8. Move the mobile node and test for transmission and reception for every 5 ft-10 ft, and record the reading.

FIGURE 20: TRANSMITTER-RECEIVER SCREENS DURING PER TEST



PER TEST CONDITIONS AND RESULTS

Additional parameters such as baud rate (19200) and transmitted data packets (100/1000) are included as part of the test conditions specified in Outdoor Measurement Environments and Indoor Measurement Environments for PER/BER. Table 4 provides the PER test details and results in outdoor environment. The table cells show the number of data packets received for every 1000 data packets transmitted/sent over the measured distance (in meters).

TABLE 4: OUTDOOR (OPEN FIELD) PER TEST RESULTS

Module Type	Power (dB)	Maximum Measured Range (M)	10 (m)	20 (m)	40 (m)	80 (m)	100 (m)	125 (m)	150 (m)	175 (m)	200 (m)	250 (m)	300 (m)	500 (m)	750 (m)	1000 (m)	1500 (m)
MRF24J40MA	0	140	1000	1000	1000	1000	900	800	500	0	0	0	0	0	0	0	0
MRF24J40MB	20	700	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	950	550	0	0
MRF24J40MC	20 + 2 dBi	800	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	900	650	0	0
MRF24J40MC	20 + 5 dBi	825	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	750	0	0

Table 5 provides the PER test details and results in the indoor environment. The table cells show the number of data packets received for every 1000 data packets transmitted/sent over the measured distance (in meters).

TABLE 5: INDOOR (OFFICE) PER TEST RESULTS

Module Type	Power (dB)	Maximum Measured Range (M)	10 (m)	20 (m)	40 (m)	80 (m)	100 (m)	125 (m)	150 (m)	175 (m)	200 (m)	250 (m)	300 (m)	500 (m)	750 (m)	1000 (m)	1500 (m)
MRF24J40MA	0	55	1000	1000	1000	0	0	0	0	0	0	0	0	0	0	0	0
MRF24J40MB	20	140	1000	1000	1000	1000	1000	500	0	0	0	0	0	0	0	0	0
MRF24J40MC	20 + 2 dBi	160	1000	1000	1000	1000	1000	900	700	0	0	0	0	0	0	0	0
MRF24J40MC	20 + 5 dBi	170	1000	1000	1000	1000	1000	1000	750	0	0	0	0	0	0	0	0

Note: Better results may be achieved by further refining the PER tests conducted.

Bit Error Rate (BER) Test

The BER measurement is done by sending the stream of data through the wireless nodes and comparing output to the input. Over an infinitely long period of time, the general assumption is that the data transmission is a random process. Therefore, a pseudo-random data sequence is used for the BER test. It is “pseudo” random because, a truly random signal cannot be created using deterministic (mathematical) methods. But, few approximations of random behavior are available to perform accurate BER measurements.

However, no simple test methods exist that enables for direct BER measurements. An acceptable simple method is to calculate BER from PER. The setup for measurement of the PER/BER is similar to the range measurement.

BER TEST CONDITIONS AND RESULTS

Additional parameters such as baud rate (19200) and transmitted data packets (100/1000) are included as part of the test conditions specified in Outdoor Measurement Environments and Indoor Measurement Environments for BER. Table 6 provides the PER/BER test details and results in outdoor environment. The table cells show the number of data packets received for every 1000 data packets transmitted/sent over the measured distance (in meters).

TABLE 6: OUTDOOR (OPEN FIELD) BER TEST RESULTS

Module Type	Power (dB)	Maximum Measured Range (M)	10 (m)	20 (m)	40 (m)	80 (m)	100 (m)	125 (m)	150 (m)	175 (m)	200 (m)	250 (m)	300 (m)	500 (m)	750 (m)	1000 (m)	1500 (m)
MRF24J40MA	0	140	1000	1000	1000	1000	900	800	500	0	0	0	0	0	0	0	0
MRF24J40MB	20	700	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	950	550	0	0
MRF24J40MC	20 + 2 dBi	750	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	900	650	0	0
MRF24J40MC	20 + 5 dBi	825	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	750	0	0

Table 7 provides the BER test details and results in indoor environment. The table cells show the number of data packets received for every 1000 data packets transmitted/sent over the measured distance (in meters).

TABLE 7: INDOOR (OFFICE) BER TEST RESULTS

Module Type	Power (dB)	Maximum Measured Range (M)	10 (m)	20 (m)	40 (m)	80 (m)	100 (m)	125 (m)	150 (m)	175 (m)	200 (m)	250 (m)	300 (m)	500 (m)	750 (m)	1000 (m)	1500 (m)
MRF24J40MA	0	55	1000	1000	1000	0	0	0	0	0	0	0	0	0	0	0	0
MRF24J40MB	20	140	1000	1000	1000	1000	1000	500	0	0	0	0	0	0	0	0	0
MRF24J40MC	20 + 2 dBi	160	1000	1000	1000	1000	1000	900	700	0	0	0	0	0	0	0	0
MRF24J40MC	20 + 5 dBi	170	1000	1000	1000	1000	1000	1000	750	0	0	0	0	0	0	0	0

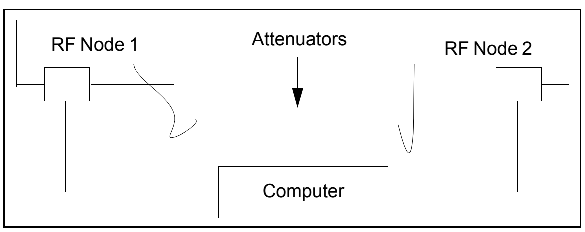
Note: Better results may be achieved by further refining the BER tests conducted.

Sensitivity Test Setup

Sensitivity test setup is used to get an indication of the sensitivity limit. This section describes the measured sensitivity of the MRF24J40MA module, which is considered as a case study in this application note. The input power level to the receiver is lowered through attenuators until the PER < 1%, and is no longer measured at the receiver. The test setup consists of two MRF24J40MA modules, see Figure 22. The transmitting MRF24J40MA is connected through an electronic attenuator to the receiving MRF24J40MA. Both of the MRF24J40MAs are connected to a PC/ laptop with a USB cable/Serial Ports (RS232). The PC executes the test tool with PER test scripts using the Driver Utility software. All the PER tests are performed without retransmission.

PER test for sensitivity provides the user with the freedom to increase the distance between the two nodes and check how far the communication can keep PER below 1% with the compensations across channels. Figure 21 illustrates a similar arrangement for sensitivity.

FIGURE 21: TEST SETUP FOR SENSITIVITY



Note:	Increasing distance and keeping PER below 1%.

A simple method for the sensitivity setup is as follows:

1. Use two RF nodes and a variable attenuator between the RX and TX board (with small mounting antenna (SMA) connector for whip type antenna, and so on).
2. Increase the attenuation until the data packets are lost (% depends on the payload size). It is recommended to place either the TX node or the RX node in a shielded box. The total attenuation from the attenuator along with the cable attenuation must now be close to the sensitivity limit since the output power is 0 dBm.
3. It is good to place the RX node in a shielded box, because possible collisions from the environmental ISM band might affect the accuracy of received data packets. In the current measurement test setup, the node is open and is not shielded, and hence the module will have traces exposed to environment.
4. The coaxial chokes are usually inserted along the coaxial cable. The chokes stops RF surface currents to travel along the coaxial cable and dramatically affect the measurements.
5. Measure the PER by finding the ratio between the TX and RX data packets (for example, transmit 1000 data packets and check how many data packets are received). The sensitivity test must be performed in standard Data Burst mode (i.e., not using ACK/retransmission enabled).

The sensitivity measurement results are provided in Table 8. The readings obtained are relative to the environment. The channel relative results provide details of the MRF24J40MA module behavior in the indoor environment in terms of PER and varied received power in dBm. Similar tests are conducted using the MRF24J40MB/MC modules.

TABLE 8: SENSITIVITY TABLE

Power Level (dBm)	TX Packets	Valid RX Packets	Error Packets	Lost Packets	PER at Receiver (%)
Channel 11					
-92	1000	1000	0	0	0
-93	1000	1000	0	0	0
-94	1000	1000	0	0	0
-95	1000	1000	0	0	0
-96	1000	982	17	1	1.8
-97	1000	873	107	20	12.7
Channel 12					
-92	1000	1000	0	0	0
-93	1000	1000	0	0	0
-94	1000	1000	0	0	0
-95	1000	998	2	0	0.2
-96	1000	982	17	1	1.8
-97	1000	873	106	19	12.5
Channel 15					
-92	1000	1000	0	0	0
-93	1000	1000	0	0	0
-94	1000	1000	0	0	0
-95	1000	999	1	0	0.1
-96	1000	980	19	1	2
-97	1000	865	123	12	13.5
Channel 16					
-92	1000	1000	0	0	0
-93	1000	1000	0	0	0
-94	1000	1000	0	0	0
-95	1000	998	2	0	0.2
-96	1000	983	16	1	1.7
-97	1000	856	128	16	14.4
Channel 19					
-92	1000	1000	0	0	0
-93	1000	1000	0	0	0
-94	1000	1000	0	0	0
-95	1000	999	1	0	0.1
-96	1000	973	26	1	2.7
-97	1000	866	113	21	13.4
Channel 20					
-92	1000	1000	0	0	0
-93	1000	1000	0	0	0
-94	1000	1000	0	0	0
-95	1000	999	1	0	0.1
-96	1000	980	19	1	2
-97	1000	828	149	23	17.2

Note: Sensitivity table is based on PER ≤ 1%.

TABLE 8: SENSITIVITY TABLE (CONTINUED)

Power Level (dBm)	TX Packets	Valid RX Packets	Error Packets	Lost Packets	PER at Receiver (%)
Channel 24					
-92	1000	1000	0	0	0
-93	1000	1000	0	0	0
-94	1000	1000	0	0	0
-95	1000	994	6	0	0.6
-96	1000	974	26	0	2.6
-97	1000	819	159	22	18.1
Channel 25					
-92	1000	1000	0	0	0
-93	1000	1000	0	0	0
-94	1000	1000	0	0	0
-95	1000	996	4	0	0.4
-96	1000	977	22	1	2.3
-97	1000	825	149	26	17.5
Channel 26					
-92	1000	999	1	0	0.1
-93	1000	1000	0	0	0
-94	1000	998	2	0	0.2
-95	1000	989	11	0	1.1
-96	1000	982	17	1	1.8
-97	1000	0	0	1000	100
Note: Sensitivity table is based on PER ≤ 1%.					

Note: Better results may be achieved by further refining the Sensitivity tests conducted.

SENSITIVITY MEASUREMENT RESULTS

Figure 22 illustrates the PER for MRF24J40MA (0 dBm module), and is an indicative/reference figure only. The sensitivity measurement reference chart is based on PER ≤1%.

FIGURE 22: PER (WITHOUT PA/LNA)

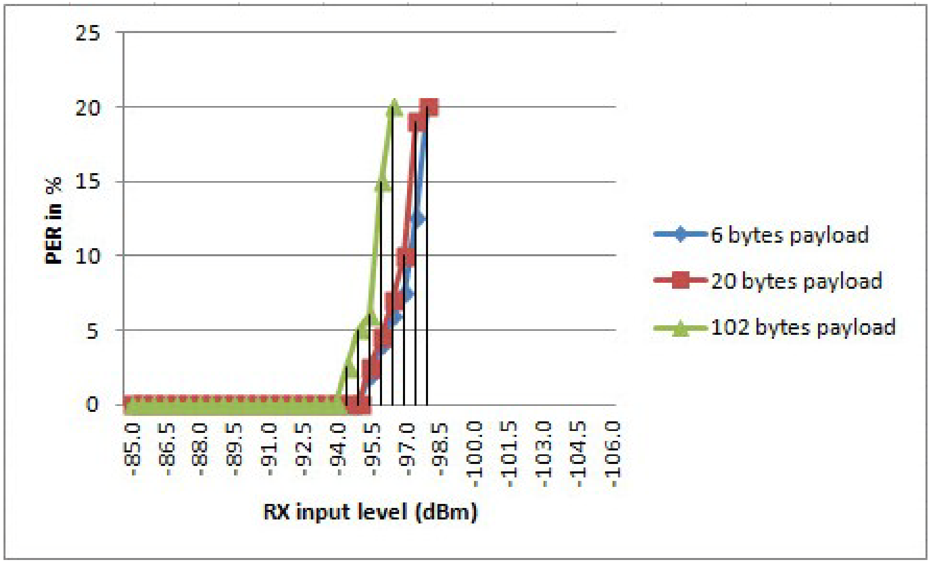
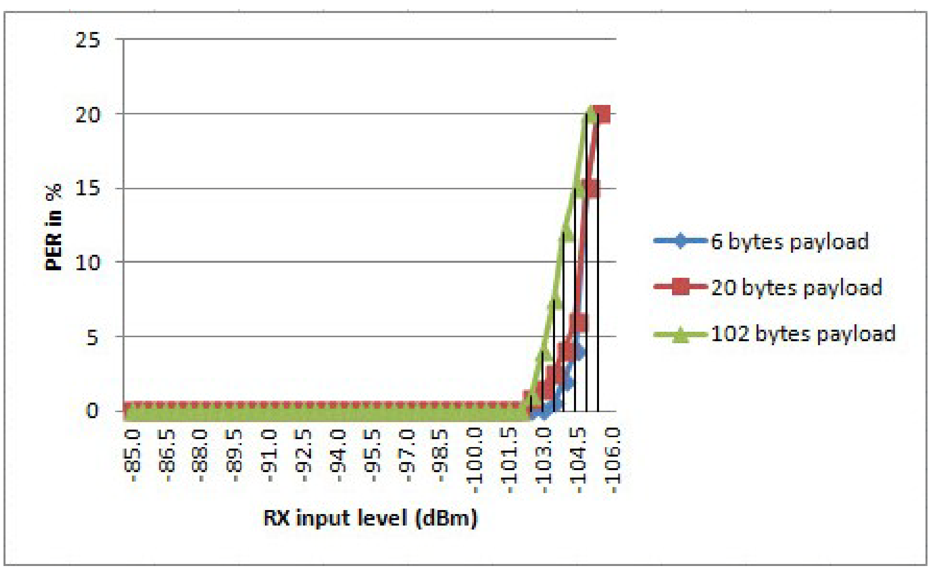


Figure 23 illustrates the PER for MRF24J40MB (+20 dBm module), and is an indicative/reference figure only. The sensitivity measurement reference chart is based on PER ≤1%.

FIGURE 23: PER (WITH PA/LNA)

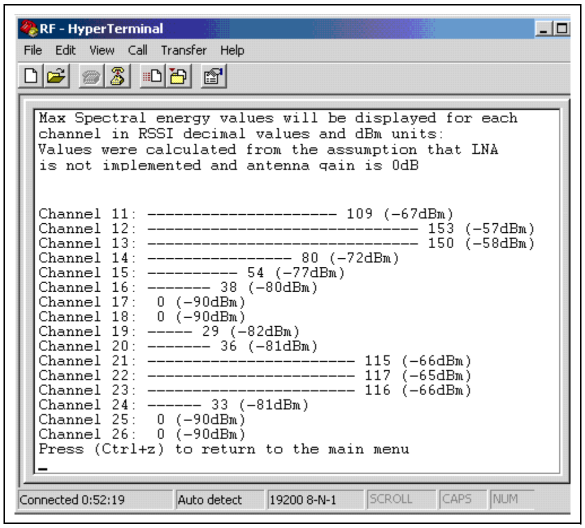


The PER charts results provide details of the MRF24J40MA and MRF24J40MB modules behavior in the indoor environment in terms of PER and varied received power in dBm with varying. However, better results may be achieved by further refining the tests conducted if required. Similar test can also be conducted for MRF24J40MC modules.

RSSI Test

The menu option from the driver/utility software illustrated in Figure 24 scans the energy levels on all the 16 channels of 2.4 GHz band complaint to the ISM/ IEEE 802.15.4 specification. The RSSI reading from the MRF24J40 transceiver is averaged over 200 samples for better accuracy.

FIGURE 24: RSSI VALUES FROM UTILITY DRIVER MENU



The RSSI values are used for selecting the operating channel by looking out for the least occupied channel or less noisy channel. PER is also done on the less noisy channel. RSSI test is comparable with the test done by a spectrum analyzer as shown in Figure 25, and the same correlates with the values from Figure 24.

Few requirements for the RSSI test are as follows:

- Equivalent antennas must be used and the comparison must incorporate cable loss. For Figure 25, the whip antenna has 1 dBi gain and 0.3 dB cable loss.
- Sweeping time of ISM bands must be the same.
- Spectrum analyzer must have appropriate resolution bandwidth.
- If the RF node has a high-gain LNA, the RSSI values in Figure 24 must be adjusted accordingly. The same RSSI values can be seen by the ZENA Network analyzer, as illustrated in Figure 25.

In this section, only an indicative RSSI test setup and procedure is explained. The measurement results are relative to the environment and hence have not been drafted. Similar test is conducted using the MRF24J40MB/MC modules. For more information on the RSSI values, refer to the *"MRF24J40 Data Sheet"* (DS39776).

FIGURE 25: ENERGY DETECTION FROM SPECTRUM ANALYZER

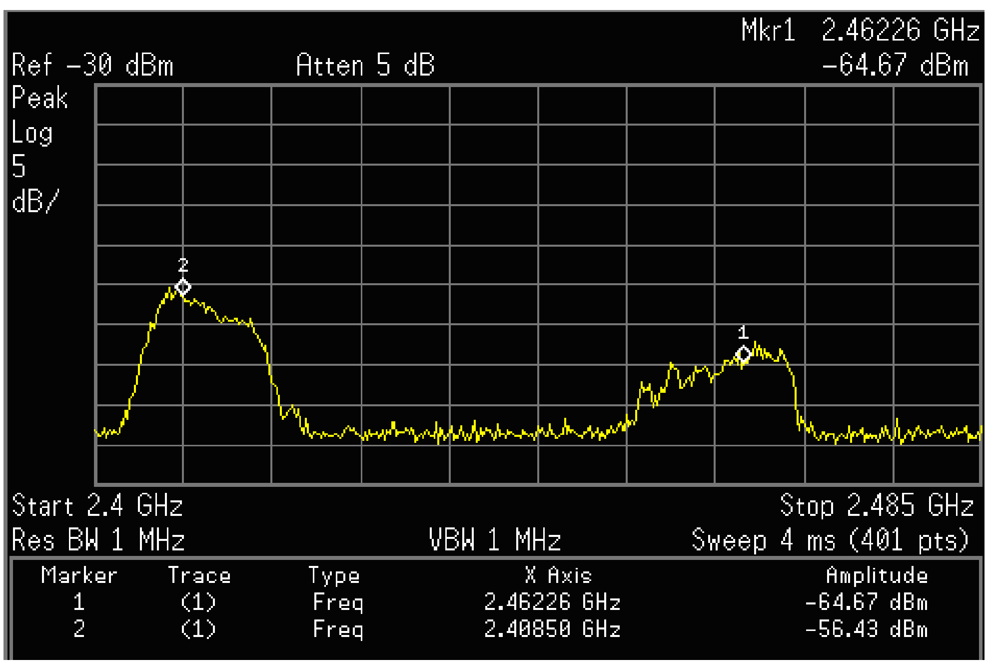
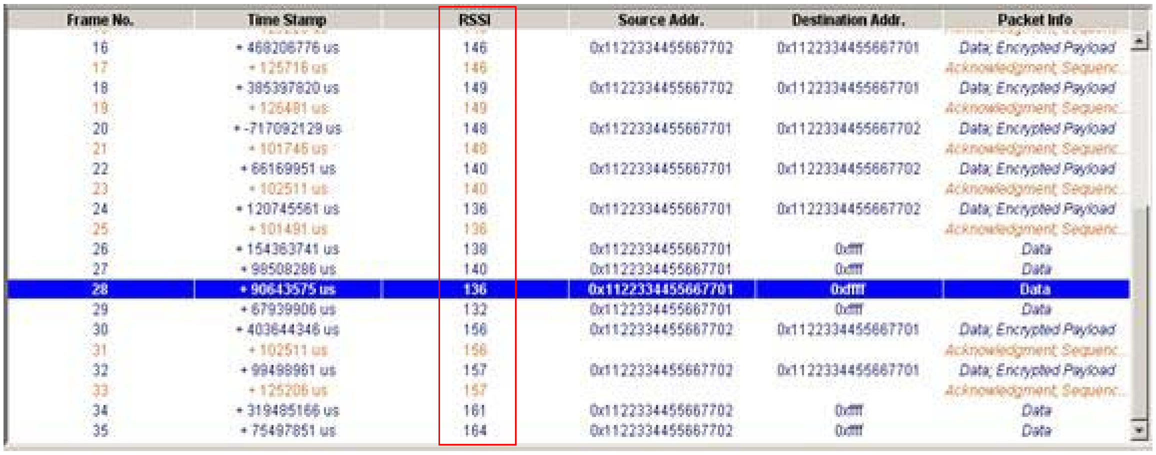


Figure 26 illustrates the RSSI values from the ZENA on WDS.

FIGURE 26: RSSI VALUES FROM ZENA ON WDS



Frame No.	Time Stamp	RSSI	Source Addr.	Destination Addr.	Packet Info
16	+ 468206776 us	146	0x1122334455667702	0x1122334455667701	Data; Encrypted Payload
17	+ 125716 us	146			Acknowledgment; Sequenc...
18	+ 385397820 us	149	0x1122334455667702	0x1122334455667701	Data; Encrypted Payload
19	+ 126481 us	149			Acknowledgment; Sequenc...
20	+ -717092129 us	148	0x1122334455667701	0x1122334455667702	Data; Encrypted Payload
21	+ 101746 us	140			Acknowledgment; Sequenc...
22	+ 66169951 us	140	0x1122334455667701	0x1122334455667702	Data; Encrypted Payload
23	+ 102511 us	140			Acknowledgment; Sequenc...
24	+ 120745561 us	136	0x1122334455667701	0x1122334455667702	Data; Encrypted Payload
25	+ 101491 us	136			Acknowledgment; Sequenc...
26	+ 154363741 us	138	0x1122334455667701	0xffff	Data
27	+ 98508286 us	140	0x1122334455667701	0xffff	Data
28	+ 90643575 us	136	0x1122334455667701	0xffff	Data
29	+ 67939906 us	132	0x1122334455667701	0xffff	Data
30	+ 403644346 us	156	0x1122334455667702	0x1122334455667701	Data; Encrypted Payload
31	+ 102511 us	156			Acknowledgment; Sequenc...
32	+ 99498961 us	157	0x1122334455667702	0x1122334455667701	Data; Encrypted Payload
33	+ 125206 us	157			Acknowledgment; Sequenc...
34	+ 319485166 us	161	0x1122334455667702	0xffff	Data
35	+ 75497851 us	164	0x1122334455667702	0xffff	Data

LINK BUDGET MODEL APPROACH: ESTIMATION AND EVALUATION

Short Distance Path Loss Model

Large scale models predict behavior averaged over distances >>1. The large scale model is a function of distance and significant environmental features roughly frequency independent. This model exorbitantly breaks down as the distance decreases but is useful for modeling the range of a radio system and rough capacity planning. Small scale (fading) models describe signal variability on a scale of 1. It has dominating multi-path effects (phase cancellation). The path attenuation is considered constant but is mostly dependent on the frequency and bandwidth.

However, usually the initial focus is on small scale modeling with rapid change in the signal over a short distance or length of time. If the estimated received power is sufficiently large (typically relative to the receiver sensitivity) which may be dependent on the communications protocol in use, the link becomes useful for sending data. The amount by which the received power exceeds receiver sensitivity is called the Link Margin.

The Link/Fade margin is defined as the power (margin) required above the receiver sensitivity level, to ensure reliable radio link between the TX and RX. In favorable conditions (antennas are perfectly aligned, no multi-path or reflections exist, and there are no losses), the necessary link margin would be 0 dB. The exact Fade margin required depends on the desired reliability of the link, but a good rule of thumb is to maintain 22 dB to 28 dB of Fade margin at any time. Having a Fade margin of not less than 15 dB in good weather conditions provides a high degree of assurance that the RF system continues to operate effectively in harsh conditions due to weather, solar, and RF interference.

Link Budget: Equations and Estimations

The link budget equation includes all the parameters shown in Equation 3 that are expressed logarithmically.

EQUATION 3: LINK BUDGET EQUATION

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX}$$

Where,

P_{RX} = Received power (dBm)

P_{TX} = Transmitter output power (dBm)

G_{TX} = Transmitter antenna gain (dBi)

G_{RX} = Receiver antenna gain (dBi)

L_{TX} = Transmit losses (coax connectors, and so on) (dB)

L_{FS} = Free space loss or path loss (dB)

L_M = Miscellaneous losses (fading margin, body loss, polarization mismatch and other losses) (dB)

L_{RX} = Receiver losses (coax, connectors, and so on)

The path loss due to propagation between the reception and transmission antennas is written in dimensionless form by normalizing the distance to the wavelength. When parameter values are substituted in Equation 3, the result is the logarithmic form of the Friis Transmission equation as shown in Equation 4.

EQUATION 4: FRIIS EQUATION FOR PATH LOSS

$$L_{FS} = 20 \times \log\left(\frac{4\pi d}{\lambda}\right)$$

Where,

L_{FS} = FSPL (dB)

λ = Wavelength (m)

d = TX-RX distance (m)

In some cases, it is convenient to consider the loss due to distance and wavelength separately. In this case, it is important to track the units being used, since each choice involves a differing constant offset. Some examples are provided in Example for Link Budget Calculation and LOS CALCULATIONS. Equation 5 shows the FSPL in dB which is obtained by simplifying Equation 4.

EQUATION 5: FSPL IN DB

$$FSPL\ (dB) = 20 \times \log(d) + 20 \times \log(f) + K$$

Where,

d = Distance (m)

f = Frequency (MHz)

K = Constant has a value of -147.55 for the units used for d and f

Table 9 shows FSPL (dB) for different distances at a frequency of 2.4 GHz. It implies that the variation of FSPL (dB) is almost linear for the distance specified, and the values can be interpolated or extrapolated based on the distance <1 km or >50 km.

TABLE 9: DISTANCE-FSPL CHART

Distance (km)	FSPL (dB)
1	100.05
2	106.07
3	109.60
4	112.10
5	114.03
10	120.05
20	126.07
30	129.60
40	132.10
50	134.03

EXAMPLE FOR LINK BUDGET CALCULATION

As an example, it is good to estimate the feasibility of a 1 km link (range) with RF node 1 and RF node 2 with MRF24J40MB modules with 20 dBm output power. Node 1 is connected to an omni-directional PCB antenna with 1 dBi gain, while node 2 is also connected to a similar PCB antenna with 1 dBi gain. The transmitting power of node 1 is 100 mW (or 20 dBm) and its sensitivity is -102 dBm. The transmitting power of node 2 is 100 mW (or 20 dBm) with a similar sensitivity as node 1, its sensitivity is -102 dBm. The cables are short and are approximated with a loss of 1 dB on each side.

Substituting the power gain, losses values in Equation 3 gives Equation 6. Equation 6 shows adding all the gains and subtracting all the losses from node 1 to node 2 link considering only the free space loss for a path loss of 1 km link.

EQUATION 6: GAIN AND PATH LOSS - NODE 1 TO NODE 2 USING MRF24J40MB

$$20\,dBm(TXPowerRadio1) + 1\,dBi(AntennaGainRadio1) - 1\,dB(CableLossRadio1)$$
$$+1\,dBi(1\,dBiAntennaGainRadio2) - 1\,dB(CableLossRadio2)$$
$$TotalGain = 20\,dB$$
$$PathLoss = 20 + 20 \times \log(1000) = 80\,dB$$

Subtracting path loss from the total gain,

$$20\,dB - 80\,dB = -60\,dB$$

Since -60 dB is greater than the minimum receive sensitivity of node 2 (-102 dBm), the signal level is just enough for node 2 to communicate with node 1. From Equation 6, there is 42 dB margin (102 dB - 60 dB) which is suitable for good transmission under good weather conditions, but may not be enough to protect against harsh weather conditions. Equation 7 calculates the link from node 2 back to node 1.

EQUATION 7: GAIN AND PATH LOSS - NODE 2 TO NODE 1 USING MRF24J40MB

$$20\,dBm(TXPowerRadio2) + 1\,dBi(AntennaGainRadio2) - 1\,dB(CableLossRadio2) + 1\,dB(AntennaGainRadio1)$$
$$-1\,dB(CableLossRadio1)$$
$$TotalGain = 20\,dB$$
$$PathLoss = 20 + 20 \times \log(1000) = 80\,dB$$

Subtracting path loss from the total gain,

$$20\,dB - 80\,dB = -60\,dB$$

The path loss is same on the return path. Therefore, the received signal level on node 1 side is -60 dB. Since the receive sensitivity of node 1 is -102 dBm, this leaves a Fade margin of 42 dB (102 dB - 60 dB). Additionally, there are losses due to environment (fading) even at LOS and could further reduce by 20 dB which is within the requirement for communication without any additional gain.

However, if node 2 is an MRF24J40MA module with 0 dB gain (output power), calculating the link from node 2 back to node 1 is shown in Equation 8. Subtracting the path loss from total gain (path loss is same on the return path), the received signal level on node 1 side.

EQUATION 8: GAIN AND PATH LOSS - NODE 1 TO NODE 2 USING MRF24J40MA

$$0\,dBm\,(TXPowerRadio2) + 1\,dBi\,(AntennaGainRadio2) - 1\,dB(CableLossRadio2) + 1\,dBi(AntennaGainRadio1) - 1\,dB(CableLossRadio1)$$

$$TotalGain = 0\,dB$$

The path loss for a kilometer link considering only the free space loss is:

$$PathLoss = 0 + 20 \times \log(1000) = 60\,dB$$

Equation 9 provides the total gain and path loss calculation from node 2 to node 1 for MRF24J40MA module.

EQUATION 9: GAIN AND PATH LOSS - NODE 2 TO NODE 1 USING MRF24J40MA

$$LinkMargin = ReceivedPower - ReceiveSensitivity$$

$$0\,dBm - 60\,dB = -60\,dBm$$

Since the receive sensitivity of node 1 is -95 dBm, this leaves a fade margin of 25 dBm (95 dB - 60 dB). Additionally, there are losses due to environment (fading) even at LOS and can further reduce by 20 dB which communicates only with some additional gain of 15 dB to 20 dB.

LOS CALCULATIONS

FSPL depends on two parameters; frequency of radio signals and wireless transmission distance as shown in Equation 10.

EQUATION 10: FSPL EQUATION

$$L_{FS}(dB) = 20 \times \log(f) + 20 \times \log(d) - 147.55$$

Where,

f = Frequency is in MHz

d = Distance is in meters

For example, using Equation 10 for distance = 150m for MRF24J40MA module (1 mW, 0 dBm) operating on channel 26 with a frequency of 2.480 GHz, the calculation is shown in Equation 11.

EQUATION 11: FSPL CALCULATION

$$FSPL(dB) = 20 \times \log(f) + 20 \times \log(d) - 147.55$$

$$= 20 \times \log(2.480 \times 10^3) + 20 \times \log(150) - 147.55$$

$$= (67.60 + 43.52 - 147.55) = -36.43\,dBm$$

From the fade margin equation, FSPL can also be computed as shown in Equation 12.

EQUATION 12: FADE MARGIN CALCULATION FROM FSPL

$$FSPL(dB) = TxPower - TxCableLoss + TxAntennaGain + RxAntennaGain - RxCableLoss - RxSensitivity - FadeMargin$$

$$(0\,dBm - 1\,dB + 1\,dBi + 1\,dBi - 1\,dB - 95 - 203.84) = -298.84\,dBm$$

With the FSPL equations shown in Equation 11 and Equation 12, the distance (m) can be calculated as shown in Equation 13.

EQUATION 13: DISTANCE CALCULATION FROM FSPL

$$L_{FS}(dB) = 20 \times \log(frequency) + 20 \times \log(distance) - 147.55$$

$$20 \times \log(distance) = -20 \times \log(frequency) + L_{FS}(dB) + 147.55$$

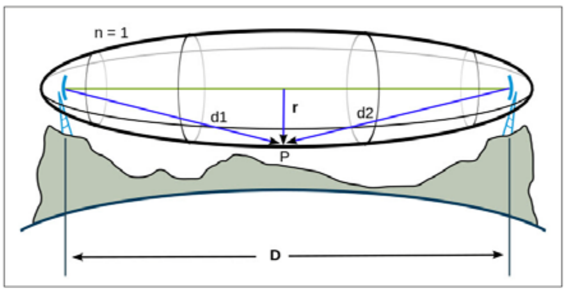
Where, $frequency$ is in MHz and $Distance$ is in meters.

Substituting f = 2.480 GHz, K = -147.55 and $L_{FS}\ (dB)$ = 36.43, gives d = 149.96m from Equation 10. Hence, assuming $Lfs\ (dB)$ is in between 25 dB-35dB provides good radio range.

Note: Some parameters such as Fade Margin in the calculations are calculated/deduced using the link budget calculator.

Fresnel Zone is the area around the visual LOS that radio waves spread out after they leave the antenna as shown in Figure 27. It is good have the LOS to maintain strength, specially for 2.4 GHz wireless systems. This is because the 2.4 GHz waves are absorbed by water. The rule of thumb is that 60% of Fresnel Zone must be clear of obstacles. Typically, 20% Fresnel Zone blockage introduces little signal loss to the link, and beyond 40% blockage the signal loss becomes significant.

FIGURE 27: FRESNEL ZONE



Equation 14 shows the formula to calculate the first Fresnel Zone block radius.

EQUATION 14: FRESNEL ZONE EQUATION

$$r(FSPL) = 17.32 \times \sqrt{\frac{d}{4f}}$$

Where,

d = Distance (km)

f = Frequency (GHz)

r = Radius (m)

Substituting f = 2.480 GHz and $L_{FS}\ (dB)$ = 36.43 from Equation 11, gives d = 43.88m for Equation 14. Hence, assuming $Lfs\ (dB)$ is in between 25 dB-35 dB provides good radio range for indoor environments.

For Fresnel Zone, it is important to enumerate the extent to which it can be blocked. Typically, 20% to 40% Fresnel Zone obstruction introduces little to no interference into the communication link. It is better to have an inaccuracy up to more than 20% blockage of the Fresnel Zone.

NON-LOS CALCULATIONS

The propagation losses for indoors can be significantly higher in building obstructions such as walls and ceilings. This occurs because of a combination of attenuation by walls and ceilings, and blockage due to equipment, furniture and human intervention:

- Trees attenuate around 8 dB to 18 dB of loss per tree in the direct path. This attenuation depends on the size, shape and type of tree.
- A 2x4 dry wood wall on both sides results in about 6 dB loss per wall.
- Comparatively older buildings may have greater internal losses than new buildings due to materials and LOS issues.
- Concrete walls account to 10 dB to 15 dB depending upon the size and shape of the construction.
- Floors in building accounts for 12 dB to 27 dB of loss. The concrete and steel floors attenuate more compared to the wooden floors.
- Mirrored walls have very high loss because the reflective coating is conductive.

The Fresnel Zone is sometimes a good indication of an indoor environment range measurement. Generally, the LOS propagation is valid only for about first 3m. Beyond 3m, the indoor propagation losses can go up to 30 dB per 30m in dense office environments. Conservatively, it overstates the path loss in most cases. Actual propagation losses may vary significantly depending on the building construction, structure and layout.

Some of the possible reasons for propagation losses through the Fresnel zone are:

- Collisions with other transmitters
- Weak Error Vector Magnitude (EVM) from transmitter generally in the range of 20% to 24% rms
- Reflections from every object (for example, moving objects or people).

Long Distance Path Loss Model

Long distance path loss can be characterized by the path loss exponent (n), whose value is normally in the range of 2 to 4 (where, 2 is for propagation in free space and 4 is for relatively much lossy environments). In environments such as buildings, auditoriums, stadiums and other indoor environments, the path loss exponent can reach values in the range of 4 to 6. However, a passageway may act as a wave guide resulting in a path loss exponent <2.

PATH LOSS AND DISTANCE CALCULATIONS

Path loss is expressed in dB and is calculated as shown in Equation 15.

EQUATION 15: LONG DISTANCE PATH LOSS MODEL EQUATION

$$L = 10 \times n \times \log(d) + C$$

Where,

L = Path loss (dB) is the path loss exponent

d = Distance (m) between TX and RX

C = Constant which accounts for system losses

n = Path loss/scattering exponent

Radio and antenna engineers use Equation 4 for the calculation of path loss (dB) between two isotropic antennas in free space. From Long Distance Path Loss model, the calculated range values are approximated to the measured range values. The results obtained for ranges at 2.480 GHz (26th channel) are in-line with the measured values. The Long Distance Path Loss model for simple point to point communication perfectly suits the LOS and obstructed ranges with approximations. However, the model is also used for multipoint obstructions.

Measured data from LOS calculations offers a mode to understand Path Loss model used for calculating the transmission distance. The calculated versus measured results demonstrate the limitations of the free space model. Results from even terrains versus level surfaces are better modeled with a path loss coefficient of 2.1 and 2.2, respectively. Better predictions of range performance are possible with the range models specified in Range Measurement Environments.

Range results and path loss calculations are useful in determining the link budgets. For example, MRF24J40MA demonstrates the capability to reach 50m (non-LOS) to 150m (LOS) without the use of on-board PA/LNA. The accommodative range with exceptional coverage is predicted to be in the order of 100m to 200m when applying the FSPL and fade margin equations. Similarly, MRF24J40MB touches a range of 120m (non-LOS) to 650m (LOS) with the use of on-board PA/LNA. The accommodative range with exceptional coverage is predicted to be in the order of 160m to a kilometer when applying the FSPL and fade margin equations for longer ranges.

RANGE PERFORMANCE SUMMARY

This section summarizes the measured range and other performance parameters with the estimations done through a range/link budget model.

A common rule of thumb used in the RF design is 6 dB increase in the link budget results when doubling the transmission distance. This rule holds true for the FSPL model, but is more optimistic and does not hold true for more realistic models. In few cases, it may take in excess of 15 dB increase in the link budget to double the transmission distance. Most antennas broadcast in a horizontal pattern, so vertical separation is more meaningful than the horizontal separation. The measured antenna radiation patterns are useful when applying the range models.

The range measurements also show that the terrain profiles have a significant effect on range performance. In Table 3, it shows the differences in measurements between the two selected terrains. All of these factors randomly combine to create extremely complex scenarios. Various outdoor and indoor propagation models have been created to deal with the apprehension. The outdoor radio channel differs from the indoor channel because the indoor channel has shorter distances to cover, higher path loss variability and greater variance in the received signal power. However, variability in the received signal power is insignificant for immobile wireles devices. Building layout, type, shape and construction materials strongly affect the indoor propagation.

The following variables must be known when applying the range models for the path loss formula:

- Gains of the TX and RX antennas
- Power delivered by the TX into the antenna
- Power received at the RX input

The other factors that may affect range performance in addition to the antenna radiation patterns of the TX and RX are as follows:

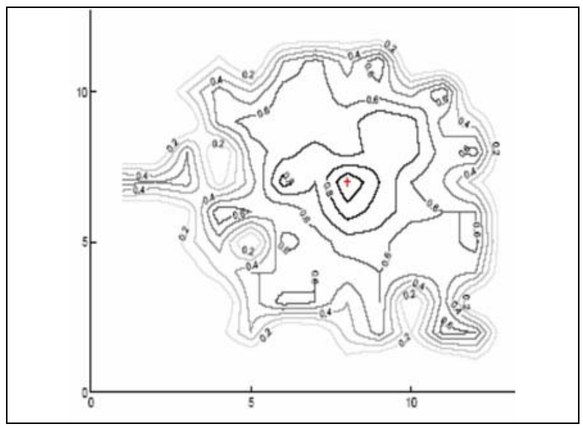
- Antenna losses (due to matching network design)
- Multi-path fading
- Interference of other propagating signals
- Background noise

The range measurements detailed in Range Measurement Conditions and Results quantify the improvements made by the following factors:

- Setting the maximum internal PA output power to maximum
- Using an LNA (match its input for the minimum noise required impedance and not for minimum insertion loss)
- Configuring for the highest value of receiver sensitivity
- Orienting the antenna in the upright position
- Designing the application board can be with any type of antennas which include inverted E, inverted F or whip antenna
- Setting the transmitter in the LOS of the receiver for open field tests

The increase in gain is required to double the distance for various path loss models and system variables as shown in Example for Link Budget Calculation. Hence, the values are calculated for two different TX antenna modules respectively, MRF24J40MA and MRF24J40MB. Empirically, the path loss is identified as the irregular signal strength contours relative to the TX as illustrated by the small red cross in Figure 28. This figure also illustrates the numerous physical environment parameters used to a certain degree by the models discussed and Example for Link Budget Calculation.

FIGURE 28: IRREGULAR SIGNAL STRENGTH DUE TO OBSTRUCTIONS



Similar signal strength measurements done with MRF24J40MB modules are shown in Figure 29 and Figure 30. The settings with TX (node 1) stationed on the ground/same floor and the RX (node 2) was made mobile. The measurements at various known points in the open field and in areas surrounding the building were noted. In support, these figures shows measurements with different signal strength contours made using GPS which are both near LOS (for example, paddy field) and harsh/extreme non-LOS (for example, industrial environment). The different points shown by the rings are averaged measurement points.

FIGURE 29: LOCATION AND DISTANCE FOR LOS ENVIRONMENT

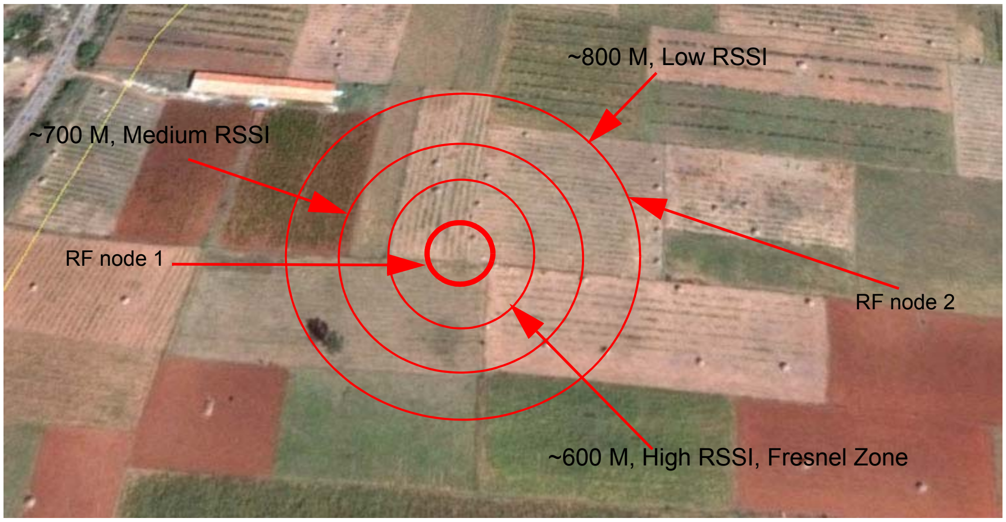
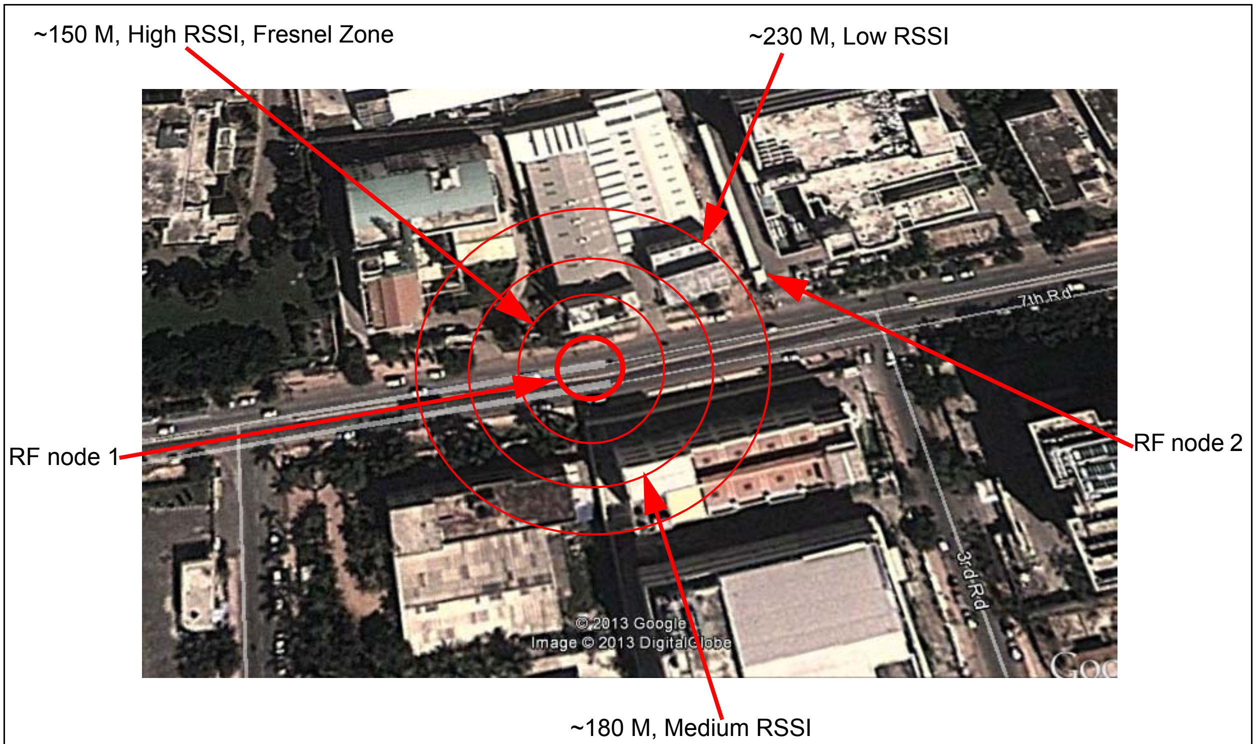


FIGURE 30: LOCATION AND DISTANCE FOR URBAN ENVIRONMENT



Note: As distance increases, RSSI reduces, and vice versa.

Range Measurement Results in Graphical Format

In continuation with analysis from Range Performance Summary considering the location/environment and distance as criteria, this section provides the graphical representation for Table 3.

Figure 31 illustrates the range comparison for different environments for the MRF24J40MA without ACK.

FIGURE 31: RANGE COMPARISON IN DIFFERENT ENVIRONMENT FOR MRF24J40MA WITHOUT ACK

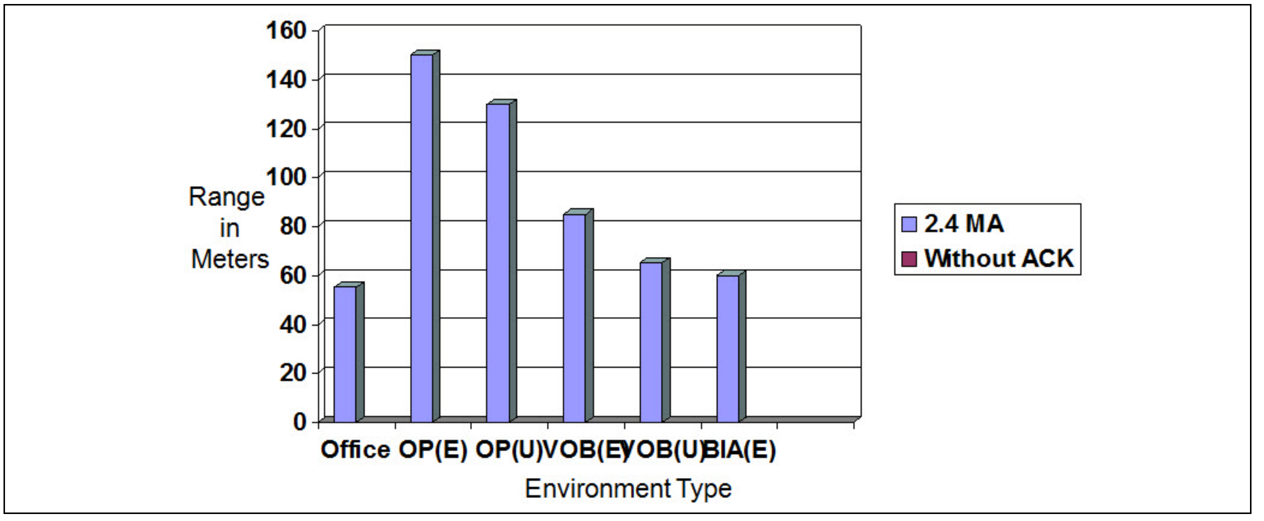


Figure 32 illustrates the range comparison for different environments for the MRF24J40MA with ACK.

FIGURE 32: RANGE COMPARISON IN DIFFERENT ENVIRONMENTS FOR MRF24J40MA WITH ACK

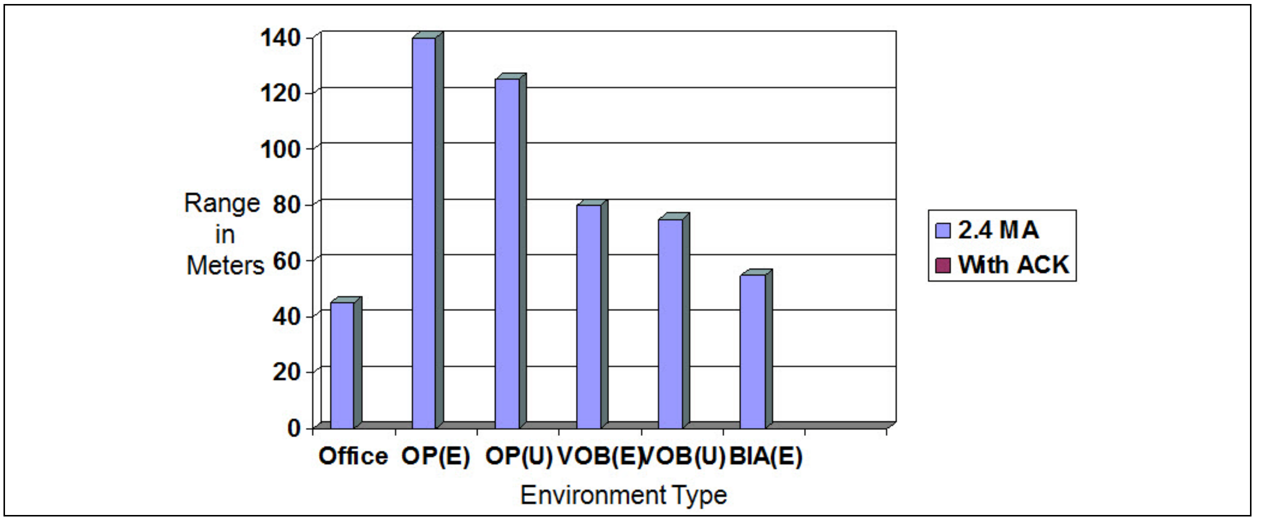


Figure 33 illustrates the range comparison for different environments for the MRF24J40MB without ACK.

FIGURE 33: RANGE COMPARISON IN DIFFERENT ENVIRONMENTS FOR MRF24J40MB WITHOUT ACK

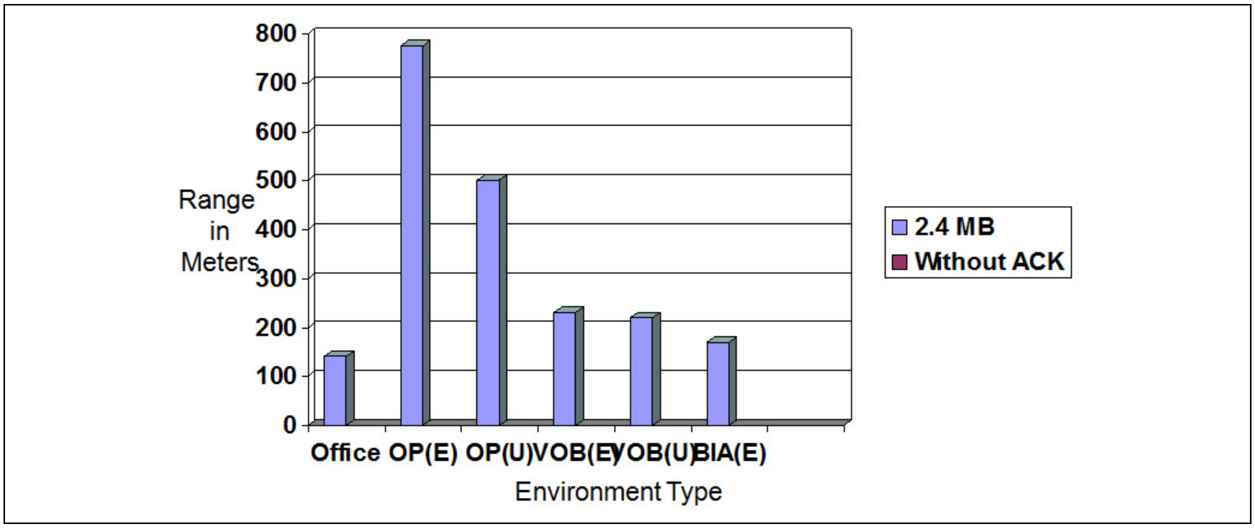


Figure 34 illustrates the range comparison for different environments for the MRF24J40MB with ACK.

FIGURE 34: RANGE COMPARISON IN DIFFERENT ENVIRONMENTS FOR MRF24J40MB WITH ACK

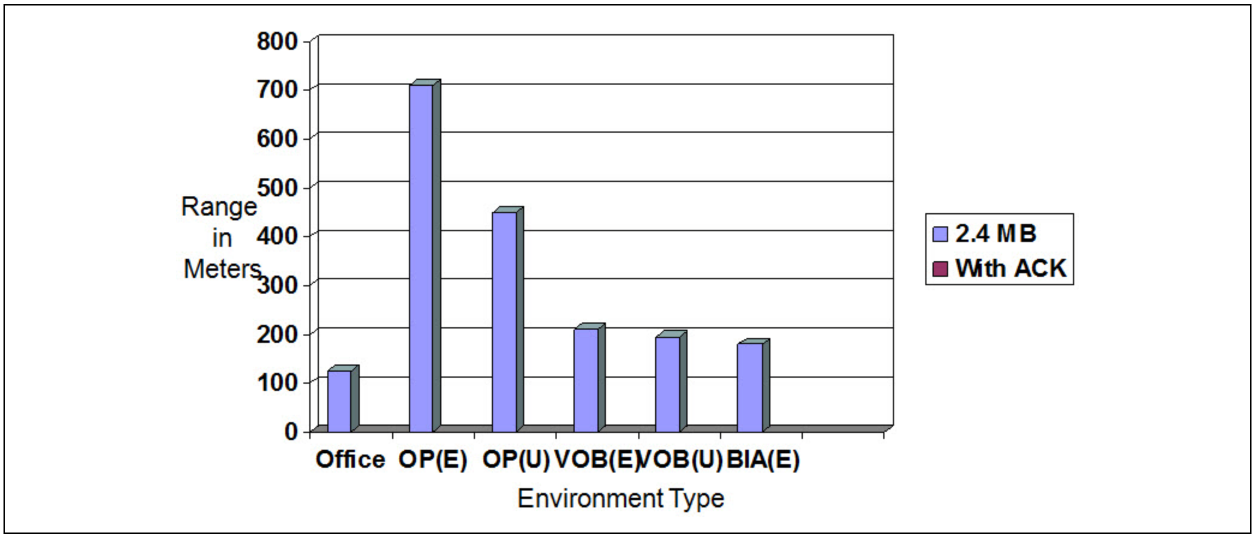


Figure 35 illustrates the range comparison for different environments for MRF24J40MC (with 2 dBi external antenna) without ACK.

FIGURE 35: RANGE COMPARISON IN DIFFERENT ENVIRONMENTS FOR MRF24J40MC (2 dBi) WITHOUT ACK

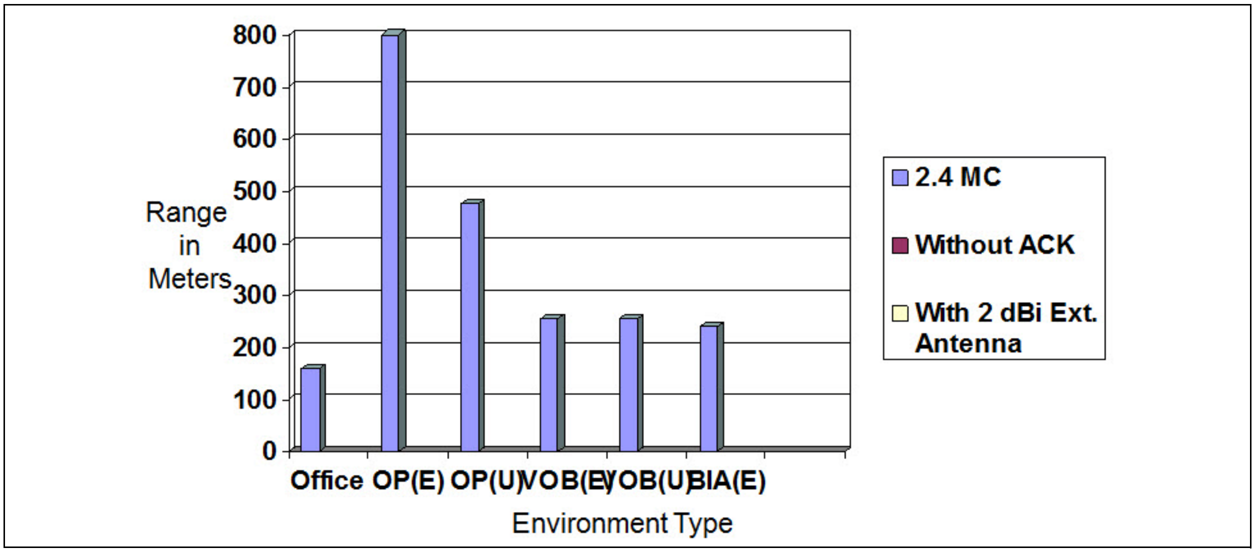


Figure 36 illustrates the range comparison for different environments for the MRF24J40MC (with 2 dBi external antenna) with ACK.

FIGURE 36: RANGE COMPARISON IN DIFFERENT ENVIRONMENTS FOR MRF24J40MC (2 dBi) WITH ACK

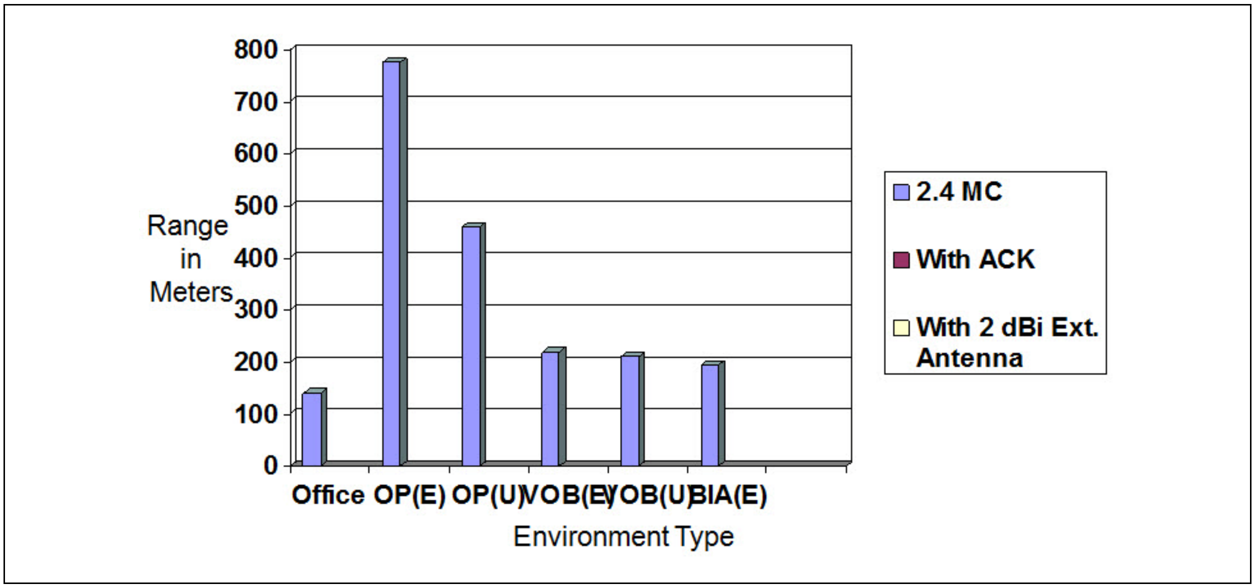


Figure 37 illustrates the range comparison for different environments for the MRF24J40MC (**w**ith 5 dBi external antenna) without ACK.

FIGURE 37: RANGE COMPARISON IN DIFFERENT ENVIRONMENTS FOR MRF24J40MC (5 dBi) WITHOUT ACK

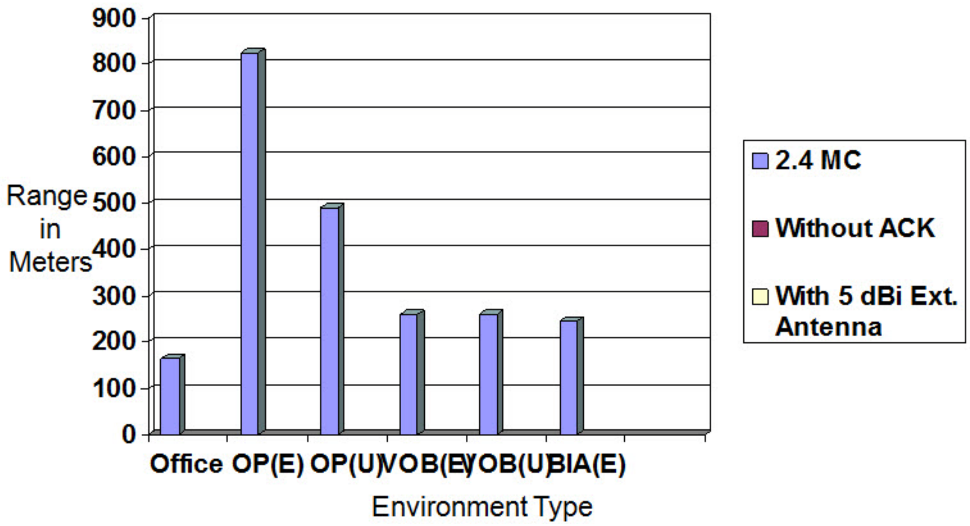
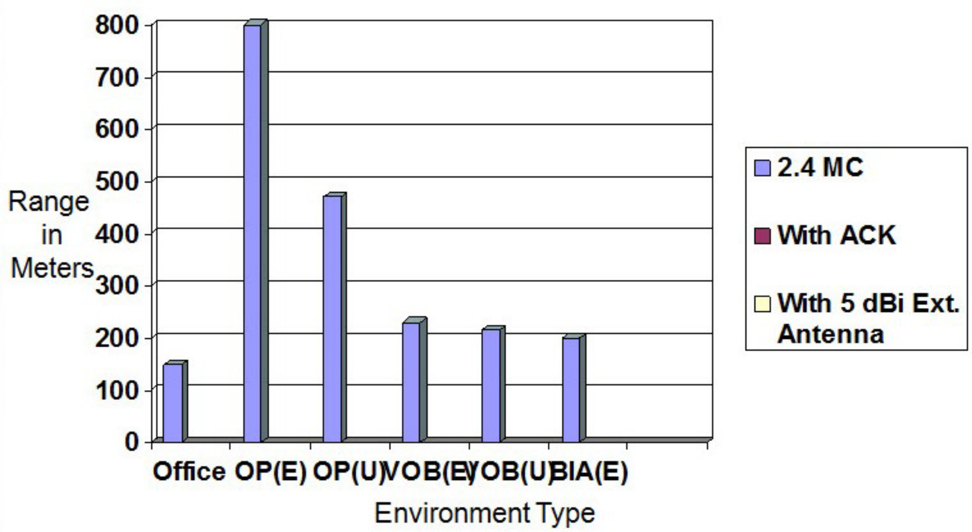


Figure 38 illustrates the range comparison for different environments for the MRF24J40MC (with 5 dBi external antenna) with ACK.

FIGURE 38: RANGE COMPARISON IN DIFFERENT ENVIRONMENTS FOR MRF24J40MC (5 dBi) WITH ACK



CONCLUSION

Care must be ensured when choosing the Path Loss model for predicting the RF system performance. Serious errors can occur by using the Free Space Path Loss (FSPL) model for most cases except few restricted cases. A more realistic model to use for urban environments is the ITU Indoor Propagation which is out of scope in this application note.

For urban environments, the use of 10-12 dB is a good rule of thumb for predicting the required increase in the link budget to double the transmission distance. Receiver sensitivity is the first variable in a system that must be taken care of and optimized to increase the transmission distance. Other variables in any wireless system also affect distance but must be changed by a greater percentage to equal the effects presented by changing the receiver sensitivity.

Fading due to multi-path can result in a signal attenuation of more than 30 dB to 40 dB, and it is highly recommended that sufficient link margin is factored into the link budget to overcome this loss while designing a wireless system.

There are a number of methods to estimate the fade margin of a system without complex calculations. Choose one or more of the following to ensure robust installation:

- Many radios have programmable output power. Reduce the power until the performance downgrades and then raise the power backup to a minimum of 10 dB. Note that doubling the output power yields 3 dB and an increase of 10 dB requires a ten times increase in the TX power.
- Consider using a small 10 dB attenuator (choose appropriately based on radio frequency). In cases of unreliable communication or data loss indicating not enough Fade margin, install an attenuator in-line with one of the antennas.
- Antenna cable is lossy at higher frequencies. Specifications vary by type and manufacturer and must be checked. At 2.4 GHz, a cable length of 20 ft to 40 ft (6m to 12m) yields 10 dB, and for omni-directional PCB antennas, it yields around 5 dB. If the system still operates reliably with the test length designed PCB antenna with losses, there is at least 10 dB of fade margin.

Therefore, the performance and range results ensure that the transceiver, modules, type and specifications of antenna tuning and so on are adequate for the recorded distances and adhere to some of the model estimates which when tuned further can provide better results.

The maximum distances that are obtained in LOS with obstructions with other performances are as follows:

- MRF24J40MA: 140m to 150m LOS and 50m to 60m non-LOS
- MRF24J40MB: 650m to 700m LOS and 120m to 130m non-LOS
- MRF24J40MC along with external whip antenna (+2 dBi): 750m to 800m LOS and 140m to 150m non-LOS
- MRF24J40MC along with external whip antenna (+5 dBi): 775m to 825m LOS and 150m to 160m non-LOS

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- (http://www.bb-elec.com/Learning-Center/All-White-Papers/Wireless-Cellular/10-Commandments-of-Wireless-Communications.aspx)

APPENDIX A: MICROCHIP MRF24J40 BASED MODULES USED FOR MEASUREMENTS

The Microchip MRF24J40 transceiver 2.4 GHz IEEE 802.15.4 based modules are used for measurements. Microchip's modules differ from other embedded 2.4 GHz modules by offering a variety of regulatory and modularly certified on-board PCB (inverted E and inverted F type) and external antennas versions. For more information on MRF24J40 and related modules, visit www.microchip.com/mrf24j40.

A.1 MRF24J40MA (Without PA/LNA)

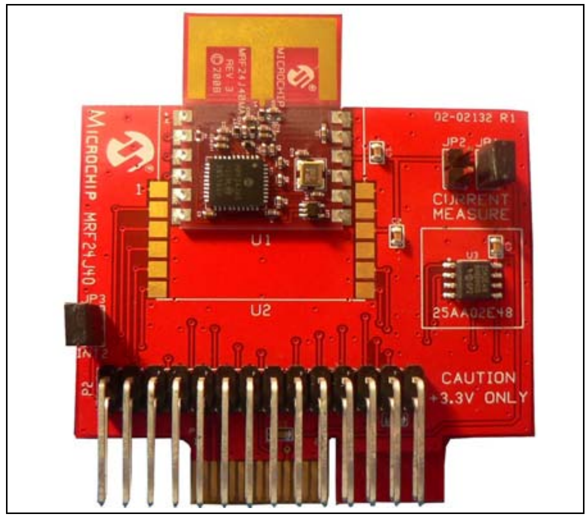
MRF24J40MA is a certified 2.4 GHz IEEE 802.15.4 radio transceiver module with integrated PCB antenna. The module connects to microcontrollers through a four-wired SPI interface and is an ideal solution for wireless sensor networks, home automation, building automation and consumer applications.

Figure A-1 illustrates the MRF24J40MA module mounted on the MRF24J40MA PICtail™/PICtail Plus Daughter Board.

Some basic specifications of the MRF24J40MA module are listed as follows:

- Output power: 0 dBm +/- 0.5 dB
- Current consumption: 19 mA in RX and 23 mA in TX (typical)
- Effective Radiated Power (ERP): 1.5 dBm (including antenna average gain of 1 dB)
- Coverage: 400 ft outdoor Line-of-Sight (LOS), no presence of any interferer in the ISM band. The coverage has been measured outdoors between two identical devices at 2m height from the ground.
- Error Vector Magnitude (EVM): 16% +/- 8 depending on the measured channel and device
- Sensitivity: -95 dBm +/-1 dB for PER ≤ 1%
- Frequency range: 2.405 GHz to 2.480 GHz

FIGURE A-1: MRF24J40MA PICtail™/PICtail PLUS DAUGHTER BOARD



A.2 MRF24J40MB (With PA/LNA)

MRF24J40MB is a 2.4 GHz IEEE 802.15.4 power radio transceiver module with integrated PCB antenna intended for long range applications. The module connects to microcontrollers through a four-wired SPI and is an ideal solution for Automatic Meter Reading (AMR) in metering, wireless sensor networks, home automation, building automation and consumer applications.

Some basic specifications of the MRF24J40MB module are listed as follows:

- Output power: 20 dBm +/- 1 dB
- Current consumption: 25 mA in RX and 130 mA in TX (typical)
- ERP: 22 dBm (including antenna average gain of 2 dB).
- Coverage: 4000 ft LOS, no presence of any interferer in the ISM band. The coverage has been measured outdoors between two identical devices at 2m height from the ground.
- EVM: 20% +/- 5 depending on the measured channel and device
- Sensitivity: -102 dBm +/- 1 dB for PER ≤ 1%
- Frequency range: 2.405 GHz to 2.480 GHz

Figure A-2 illustrates the MRF24J40MB module mounted on the MRF24J40MB PICtail™/PICtail Plus Daughter Board.

FIGURE A-2: MRF24J40MB PICtail™/PICtail PLUS DAUGHTER BOARD

A.3 MRF24J40MC (With PA/LNA and External Antenna)

MRF24J40MC is a 2.4 GHz IEEE 802.15.4 power radio transceiver module with external antenna intended for long range applications. The module connects to microcontrollers through a four-wired SPI interface and is an ideal solution for AMR/AMI metering, wireless sensor networks, home automation, building automation and consumer applications.

Some basic specifications of the MRF24J40MC module are listed as follows:

- Output power: 19 dBm +/- 1 dB.
- Current consumption: 25 mA in RX and 120 mA in TX (typical).
- ERP: 22 dBm (including antenna average gain: 2 dB).
- Coverage: 4000 ft LOS, no presence of any interferer in the ISM band. The coverage has been measured outdoors between two identical devices at 2m height from the ground.
- EVM: 20% +/- 5 depending on measured channel and device.
- Sensitivity: -108 dBm +/- 1 dB for PER ≤ 1%.
- Frequency range: 2.405 GHz to 2.480 GHz

The modularly certified external antennas include portable 2 dBi/5 dBi Aristotle P/N RFA-02-5-F7H1-70B-15 with type whip, dipole.

Figure A-3 illustrates the MRF24J40MC module mounted on the MRF24J40MC PICtail™/PICtail Plus Daughter Board with an external whip antenna.

FIGURE A-3: MRF24J40MC PICtail™/PICtail PLUS DAUGHTER BOARD

Note the following details of the code protection feature on Microchip devices:

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