NXP Semiconductors
Application Note

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How to Achieve Optimal RF Range on a Wireless System Using KW41

Contents

1 Overview

For RF designs deployed in the field, achievable RF range or wireless coverage is an important topic, which is impacted by many system design factors. A simple and quick RF range test is used to determine the feasibility of an RF system and determine the RF link margin in an application. Such a test can also be used to verify end-to-end RF performance for several critical system parameters as well as choosing critical external components such as an antenna or an external front-end module.

Using the downloadable KW41 software, you can configure a simple test mode in firmware that repeatedly sends packets between two devices. The receiver monitors the incoming packets and displays the test statistics using a serial interface to provide visual feedback of the test results.

It is suggested that both one-way and two-way radio functionality is tested. One-way or simplex transceiver testing is typically useful to isolate either a transmit or a receive problem. Two-way or duplex testing allows you to test the bidirectional communication and adherence to the protocol timing. Sophisticated firmware test programs are also developed to exercise detailed radio functionality and/or test for regulatory compliance.

Key radio performance metrics are influenced by a harsh test environment. It is always good to start testing of a radio system in a relatively simple and straightforward manner to understand the raw performance of the radio system. Once key radio metrics are measured, you can introduce imperfections in the wireless path to understand the impact of each ambient and/or system variable. For example, tests conducted in an office environment can get affected by microwave ovens, Wi-Fi access points, cellular phones, and metal structures such as cubical walls.

2 Theory

Many factors are accounted to determine the effective range that a wireless system can achieve. Some of the salient components include:

- Transmit Power
- Receiver Sensitivity
- Transmit and Receive Antenna Gains
- Transmit and Receive Antenna Heights
- Fading/Polarization effects
- Cabling/routing losses
- Interference patterns
- Multipath effects

- Absorption/reflections from surrounding objects
- Weather (incl. temperature, moisture and atmospheric pressure)

The application designers need to take care of the antenna choice/design, the PCB layout, the power supply design, and the software package to meet the system needs.

As per IEEE Std 145-1983, free-space path loss (FSPL) is the loss in signal strength of an electromagnetic wave that would result from a line-of-sight path through free space (usually air), with no obstacles nearby to cause reflection or diffraction.

Free-space path loss is proportional to the square of the distance between the transmitter and receiver, and also proportional to the square of the frequency of the radio signal (using Friis equation): `FSPL (dB) = 32.44 + 20*log10(fc) + 20*log10(d)`

where

fc – Carrier Frequency (in GHz)

d - distance in meters

Plotting Free Space Path Loss equation, Line of sight (LOS) loss at 50m in ISM 2.4GHz Band is 74.31 dB (at 2.48GHz).

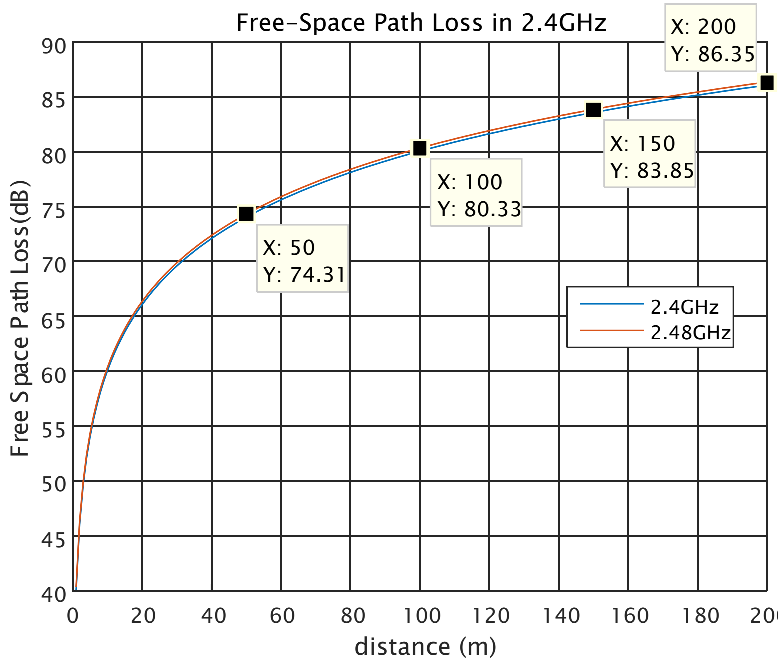


Figure 1. Plotting free space path loss equation

Theoritically, if you know exactly the trasmit output power, power loss, recever sensitivity and antenna specifications, you can calculate the effective line-of-sight RF coverage followed by the field management results for the comparison.

It is quite helpful to have a wireless link budget calculation based on the use case. The example below includes TX output power, distance, free space path loss, signal at Rx antenna, worst case receiver sensitivity and the link margin.

Table 1. Link component and values

Link Component	Typical Value	Comments
TX Output Power (dBm)	2	Typical Antenna Pout = 4dBm, assuming 2dB loss over frequency and temperature

Table continues on the next page...

Table 1. Link component and values (continued)

Distance (m)	100	Line of Sight (LOS) distance between Tx and Rx
Free Space Path Loss (dB)	-80.33	LOS Path Loss
Signal at Rx Antenna (dBm)	-78.33	Tx signal after Free Space Path Loss
Worst Case Receiver Sensitivity (dBm)	-88	Typical Rx Sensitivity =-95dBm, assuming 2dB degradation over temperature
Link Margin (dB)	9.67	Budget for fading, multipath, interference, cabling and antenna losses

3 Hardware

3.1 Transmit output power

Transmit output power is one of the most critical system parameters for achieving the desired wireless range and link robustness of the system. The output power can be degraded by several factors:

- Improper antenna impedance match
- Circuit layout issues
- Poor antenna design
- Attenuation from the product enclosure
- Improper radio register configuration
- Inadequate power supply

One method for evaluating the transmit output power is to simply compare the empirical performance against a FRDM reference design. Compare the maximum operating range of a pair of NXP reference devices to a pair of test devices.

It is suggested to use the spectrum analyzer to verify the output power of the designed boards and check the mentioned items if the result does not meet the specifications.

3.2 Receiving sensitivity

Receiver sensitivity is an important parameter for long-range applications. It is important to note that the achievable receiver sensitivity can be severely degraded in environments that have a significant amount of co-channel, adjacent/alternate channel or a blocking interference. If you require good long-range performance, you should carefully evaluate the system's receiver sensitivity.

You can use a variety of techniques to evaluate receiver sensitivity. Range testing is the first step to determine if there is a potential receiver problem. The accurate receiver sensitivity measurements require sophisticated test equipment and techniques, it is recommended that a simpler comparison test be performed against a known-good reference design such as the FRDM board.

It is recommended that you use the R&S CMW or the CBT tester and configure KW chips in the Bluetooth-LE DTM mode to test the reference receiver sensitivity of the design, if it is far from specification. You should also check the hardware design such as power design and matching network circuit and so on.

3.3 Antenna impedance matching and antenna design

For the antennas to function as an efficient radiators, the antenna impedance at 2.4 GHz must be very close to 50 ohms. Practically, maintaining a VSWR of less than 1.5:1 over the entire frequency band is sufficient to ensure good performance. This corresponds to a return loss of more than 14 dB.

It is important to check the plastic enclosure or product packaging in place because the dielectric constant of the plastic can significantly lower the resonant frequency of the antenna. Additionally, the product should be tested in the target environment to verify the impact of surroundings and environment.

Antenna testing normally consists of two phases: impedance matching and radiation pattern measurement (polar plots). Impedance matching is required to deliver the maximum possible power coupling between the radio and the antenna. You typically do this by inserting a matching network into a circuit between the radio chip and the antenna, which is normally composed of inductors and capacitors. The antenna impedance and return loss measurements are made with a vector network analyzer. These measurements require significant skill, so it is recommended that an RF expert be consulted to obtain accurate measurements.

3.4 Crystal oscillator

A critical system component, the crystal's accuracy requirements for the KW41 design depend on several factors. The primary determining factor in meeting the IEEE Std 802.15.4 of ±40 ppm is the tolerance of the crystal oscillator reference frequency as set by the crystal. A number of factors can contribute to this tolerance, and a crystal specification quantifies each of them as follows:

1. The initial tolerance, also known as make or cut tolerance, of the crystal resonant frequency itself (at a specified load capacitance).
2. The variation of the crystal resonant frequency with temperature.
3. The variation of the crystal resonant frequency with time, also commonly known as aging.
4. The variation of the crystal resonant frequency with load capacitance, also commonly known as pulling. This is affected by:
    a. The external load capacitor (CL) values — initial tolerance and variation with temperature.
    b. The internal trim capacitor (Ctrim) values — initial tolerance and variation with temperature.
    c. Stray capacitance (Cstray) on the crystal pin nodes — including stray on-chip capacitance, stray package capacitance and stray board capacitance.

3.5 Power supply

Power supply voltage level and noise are very important to the RF performance of the KW41 radio. Power supplies that have proven to work with the KW 41 radio can be seriously degraded when built with improper substituted components.

KW41 systems that include a switching voltage regulator can have RF performance issues. Products using a switching power supply must include a noise-filtering network on VCC Pin of the WirelessUSB QFN radio chip. The filtering network consists of a 5.1-ohm resistor in series with the VCC power supply from the switching regulator and a 10-μF shunt capacitor to ground very close to VCC Pin.

Based on test results for various systems, it appears that peak-to-peak noise voltage of approximately 20 mV or less on VCC Pin is acceptable. To isolate power supply noise as a possible cause of an RF performance problem, it is a good idea to substitute a clean linear power supply to compare performance measurements of the whole system.

The supply voltage to the radio module might come from a linear regulator or from a switching regulator. The current rating of the regulator should be at least 100 mA, and the output noise of the regulator should be less than 20 mV peak to peak.

4 Software

The software supplied with this Application Note allows Packet Error Rate (PER) test using the KW41 board. You must load the application binary files, suppplied with this application note, into two KW41 boards. Packets (frames) are sent between the boards and the PER results are calculated.

NOTE

The PER Test tool is developed based on the KW41 connectivity software 1.0.2.

The PER Test tool can support two mode of operation, TTY and Switch Key. By default, the TTY operation mode is enabled.

In TTY operation mode, user need to connect the board to PC and open a TTY console, knock in commands and do PER calculations. PER result will be shown on TTY console and user can read them directly.

In Switch Key mode, user use SW3 and SW4 on FRDM-KW41 board to active packets TX and RX. The LED indicator on board will show the TX/RX status. The PER result will be stored on flash and user can output the PER results after testing via Shell command.

4.1 Theoretical explanation

Part F in <<Bluetooth Specification v4.2>> has described testing PER in Direct Test Mode (DTM).

In this part, three HCI commands are used, LE_TRANSMITTER_TEST, LE_RECEIVER_TEST and LE_TEST_END.

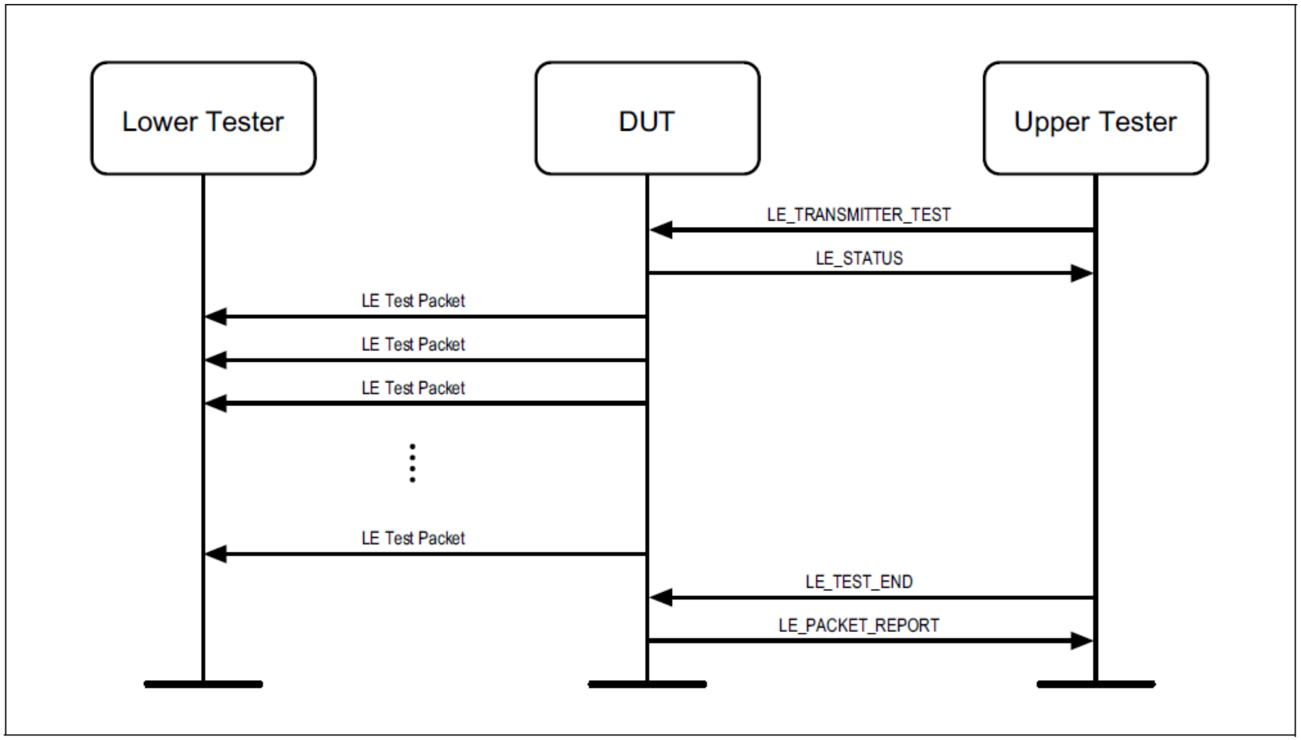


Figure 2. Transmitter test

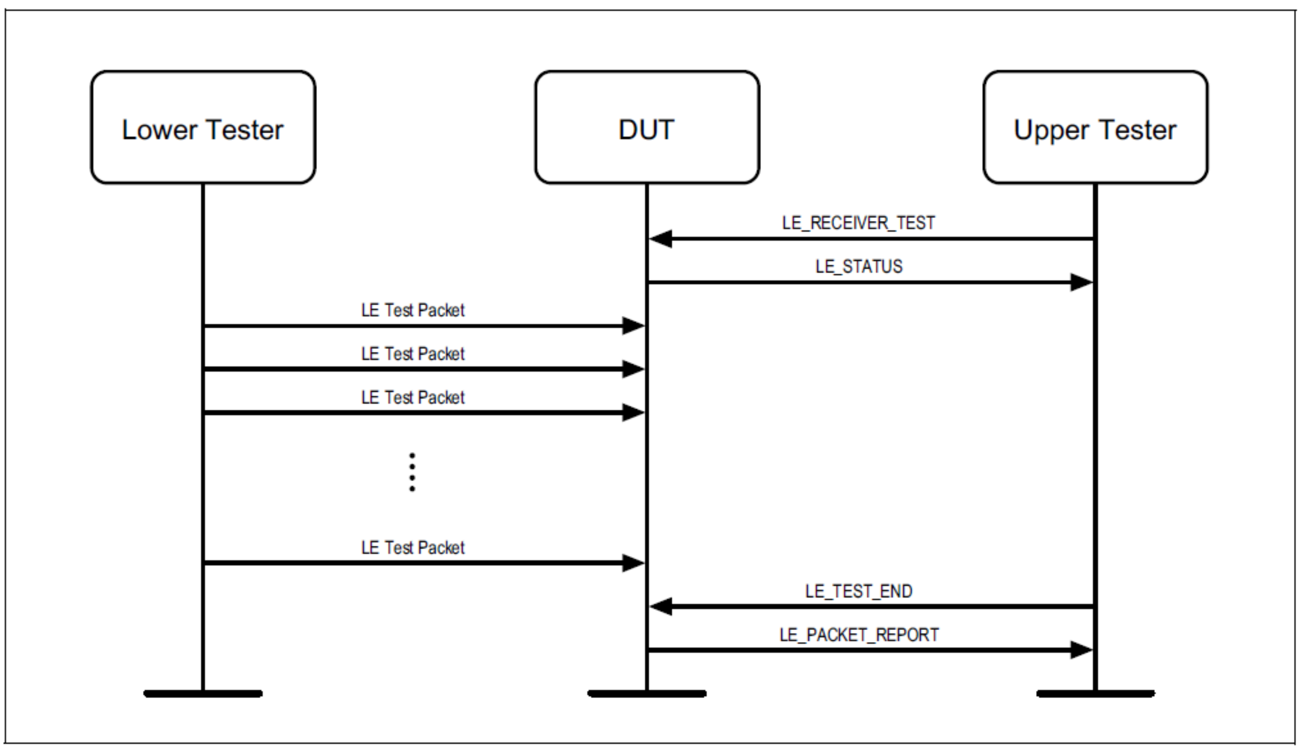


Figure 3. Receiver test

This software uses the DTM mode to test PER.

Part F in <Bluetooth Specification v4.2>> states that when test packet length changes, the package interval will also change. See table below:

Table 2. Test packet length changes

LTE Test Packet Length	Packet Interval
<= 376 µs	625 µs
>= 377 and <= 1000 µs	1250 µs
>= 1001 and <= 1624 µs	1875 µs
>= 1625 and <= 2120 µs	2500 µs

BLE physical speed is 1 Mb/Sec, that is, 1 b/us and total packet range is 0 – 32767 (3.4.2, Part F). You can calculate packets per seconds and max RX test duration with equation:

```
Packets Per Seconds = 1000000 / 625
```

```
Max Duration = 32768 / (Packets Per Seconds)
```

The following table lists packets per seconds and max duration in one test.

Table 3. Packets per seconds and maximun duration in one test

LE Test Packet Length	Packet Interval	Packets/Seconds	Max Duration (Second)
<= 376 µs	625 µs	1600	20
>= 377 and <= 1000 µs	1250 µs	800	40
>= 1001 and <= 1624 µs	1875 µs	533	61
>= 1625 and <= 2120 µs	2500 µs	400	81

You can calculate the overall PER with equation below:

```
PER = (1 – (received packets) / (transmitted packets)) * 100%
```

NOTE

You need take care of the data length of one packet. According to 4.1, Part F, the LE test packet consists of the following fields; preamble (8 bit), synchronization word (32 bit), PDU header (8 bit), PDU length (8 bit), payload (296-2040 bit) and CRC (24 bit), totaling 376-2120 bits. LE test packets do not incorporate a PDU address field.

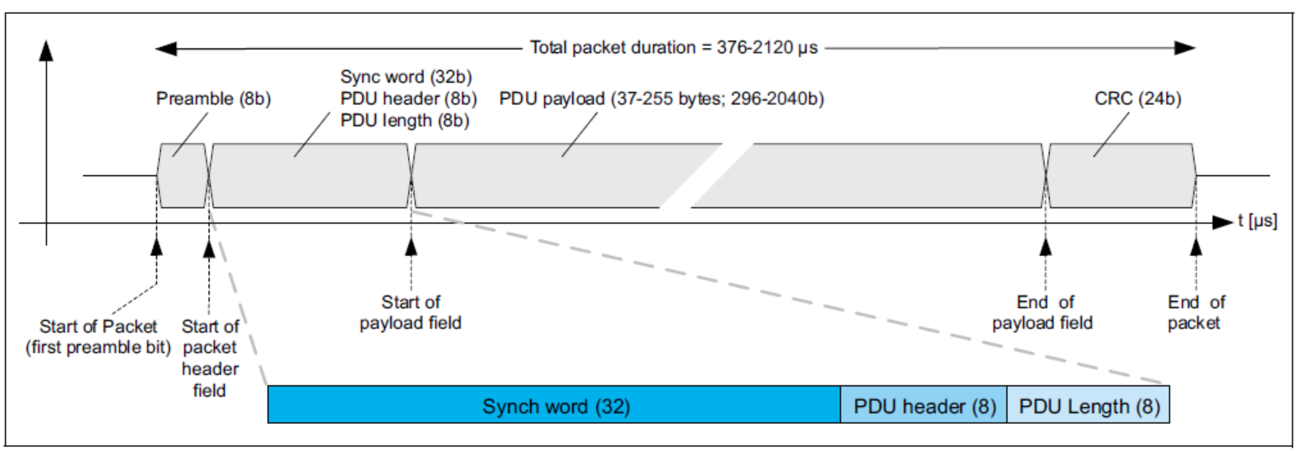


Figure 4. LE test packets

Thus, the total data length of one LE Test data packet should be:

```
(Total Bytes of LE Test Packet) =(LE Test Packet) + Preamble(1B) + (Synch Word)(4B) + (PDU Header)(1B)
+ (PDU Length)(1B) + CRC(3B) = (LE Test Packet) + 10
```

Normally, in PER testing, we may need to get PER with different packet length. Please take this into account when setting test packet length.

4.2 Building and downloading application

This section provides build instructions in case you need to rebuild the PER tester applications. If you simply wish to use the supplied application binaries, go to the Installation section.

NOTE

The PER Test tool is developed based on the KW41 connectivity software 1.0.2.

NOTE

The software provided with this Application Note can be built for the KW41 microcontroller.

1. Open the project in IAR.

   Open: *smart_home/connsw /boards/frdmkw41z/wireless_examples/bluetooth/ble_per_shell/bare_metal/iar/ble_per_shell.eww*

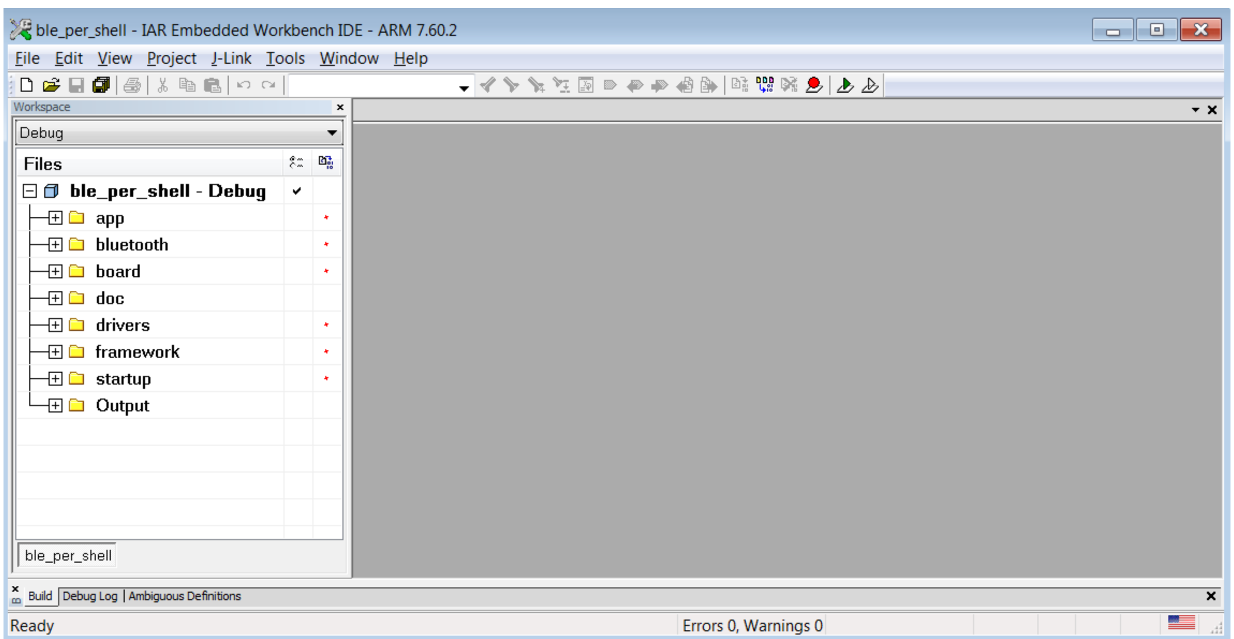
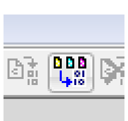


Figure 5. Open project

2. Build the project.

   Click  to build the project.

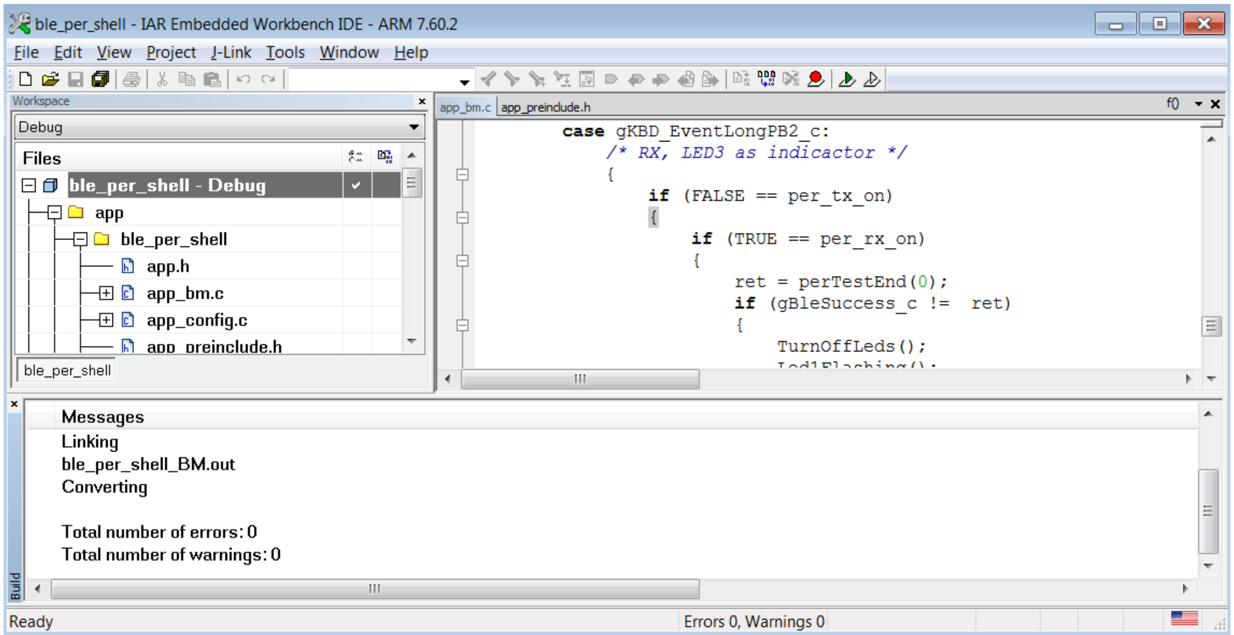


Figure 6. Build the project

3. Download the image.

Click  to download the image.

4.3 Operation instruction: PER tool TTY version

1. Download the firmware to two KW41 FRDM boards.
2. Open a serial terminal, baudrate 115200 on boards. One for TX and one for RX.
3. In terminal console, you can see:

Figure 7. Terminal console

4. Type help, you can see all supported commands.

```
Kinetis BLE Shell> help
help     print command description/usage
version  print version of all the registered modules
history  print history
per
per reset
per config [-len dataLength] [-payload pkgPayLoad] [-time testDuration] [-txdbm TxdBmPowLevel] [-conndbm ConndBmPowerLevel]
    dataLength   - Length in bytes of payload data, value 0 - 255
    pkgPayload   - Package type, values can be 0(PRBS9), 1(11110000), 2(10101010), 3(Vender specific)
    testDuration - Test duration. Default value is 10 seconds
    TxdBmPowLevel   - Value for TX Power level on advertising channel, values can be 0 - 31
    ConndBmPowLevel - Value for TX Power level on connection  channel, values can be 0 - 31
User need to do configuration one by one!
per tx -ch channelNum
per rx -ch channelNum
per end
per printnvm
```

Figure 8. Supported commands

5. Configure data length (0-255), package type (0 - 3), test duration and adv power level (0 - 31), connection power level (0 - 31) if needed.

NOTE

You can change only one parameter at a time.

For example: Change adv tx power level:

```
Kinetis BLE Shell> per config -txdbm 31

--> Set ADV Tx power level DONE!

Kinetis BLE Shell>
```

Figure 9. Change adv tx power level

```
Kinetis BLE Shell> per  config -len 255

--> Set new data length DONE!

Kinetis BLE Shell>
```

Figure 10. Change data length

6. Start TX on one board. Use –ch to specify a channel.

```
Kinetis BLE Shell> per rx -ch 38

--> Start receiving for 10 Seconds! Please make sure Tx is ON before Rx!
--> Receiving ......
Kinetis BLE Shell>
```

Figure 11. Start TX

7. Start RX on another board. Use –ch to specify a channel.

```
Kinetis BLE Shell> per rx -ch 38

--> Start receiving for 10 Seconds! Please make sure Tx is ON before Rx!
--> Receiving ......
Kinetis BLE Shell>
--> Le Test Ended!

--> PER(%): 0.0%
```

Figure 12. Start RX

NOTE

The TX and RX boards must have the same configuration on channel number.

8. Wait for some time (default 10s). The PER result is shown.

```
Kinetis BLE Shell> per tx -ch 38

--> Data Len: 30
--> Payload type: 0
--> ADV TX Power level: 20
--> Connection TX Power level: 20
--> Start Transmitting! You should use 'per end' command to end it

Kinetis BLE Shell>
```

Figure 13. PER result

9. Start RX on another board. Use –ch to specify a channel.

```
Kinetis BLE Shell> per rx -ch 38

--> Start receiving for 10 Seconds! Please make sure Tx is ON before Rx!
--> Receiving ......
Kinetis BLE Shell>
--> Le Test Ended!

--> PER(%): 0.0%
```

Figure 14. Start RX

4.4 Operation Instruction: PER tool switch key version

In this mode, the TX board will work continuosly unless you long press SW3 to stop it.

The parameters for this mode, for example: channels, tx power, connection power, payload type, duration, are defined as macros in app.h. You can change those macros via shell commands.

```
/* App Configuration */
#define PER_TEST_LOOP_COUNT                    (10)
#define PER_TEST_RECORD_COUNT                  (10)

#define PER_DEFAULT_TEST_CHANNEL               (gBleFreq2478MHz_c)      /* CH38 */
#define PER_DEFAULT_DATA_LEN                   (29)
#define PER_DEFAULT_PAYLOAD                    (0)
#define PER_DEFAULT_TEST_DURATION              (10)
#define PER_DEFAULT_TXDBM                      (24)
#define PER_DEFAULT_CONNDBM                    (24)
```

Figure 15. Macros defined in app.h

The RX board will do 10 times of 10s PER RX. After testing, the green LED turns off automatically and the blue LED turns. In case of an issue in RX, the blue LED starts flashing. You need to reset the board for next test.

NOTE

Currently, rhe software code is designed to store 10 sets of RX results on flash, which means, 10 Sets * 10 Times = 100 PER results. Each time, when SW3 key is pressed in IDLE mode, one PER testing startd. It needd about 10 * 10 = 100 seconds for one test.

To test:

1. Download the firmware to two KW41 FRDM boards.
2. For meanings and actions with SW key and LED indicator, check below table.

Table 4. Key behavior and functionality

Key Behavior	Fuctionality
SW3 Release after Short Press	Start RX.
SW3 Release after Long Press	Stop RX.
SW4 Release after Short Press	Start TX.
SW4 Release after Long Press	Stop TX.

Table 5. LED behavior and functionality

LED Behavior	Functionality
Blue LED On	Idle mode. No TX/RX.
Blue LED Flashing	Something wrong happens in TX/RX. User can reset the board for testing.
Red LED On	Board is in RX status.
Green LED On	Board is in TX status.

3. Run the board. The blue LED is On. Board is in idle mode with no TX/RX.

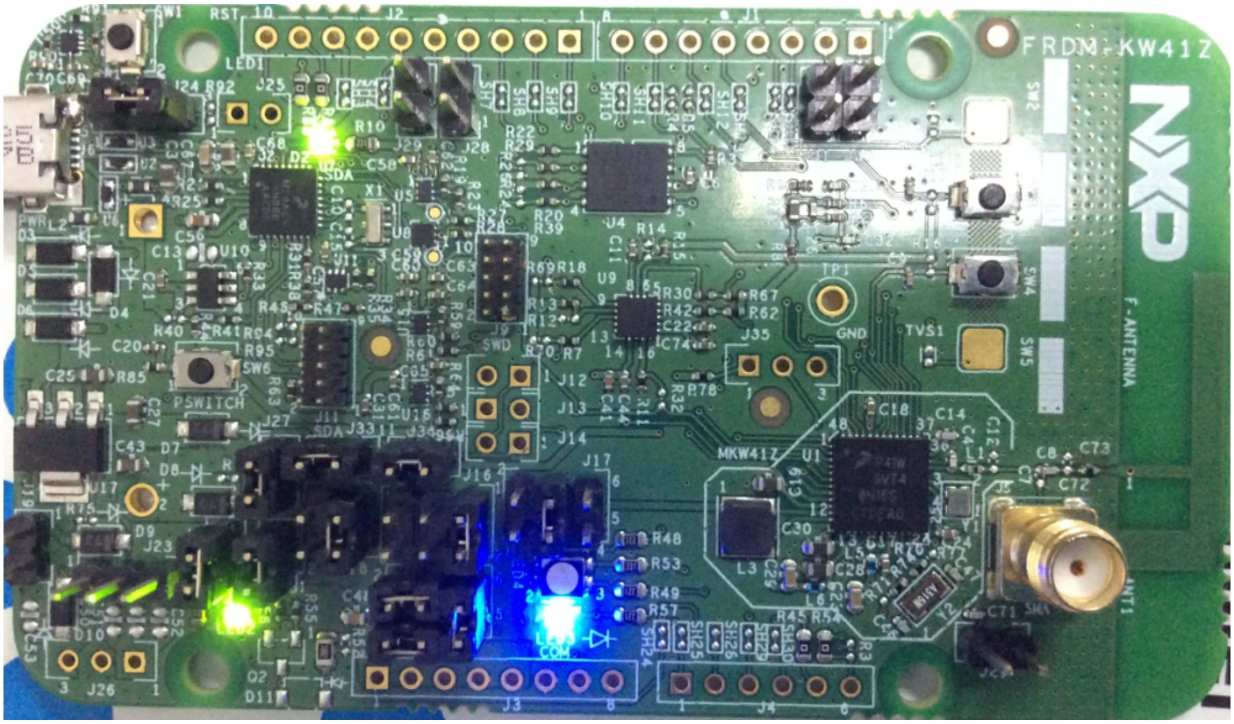


Figure 16. Blue LED is On

4. Press SW4 on one board. The board will start TX. Red LED is On.

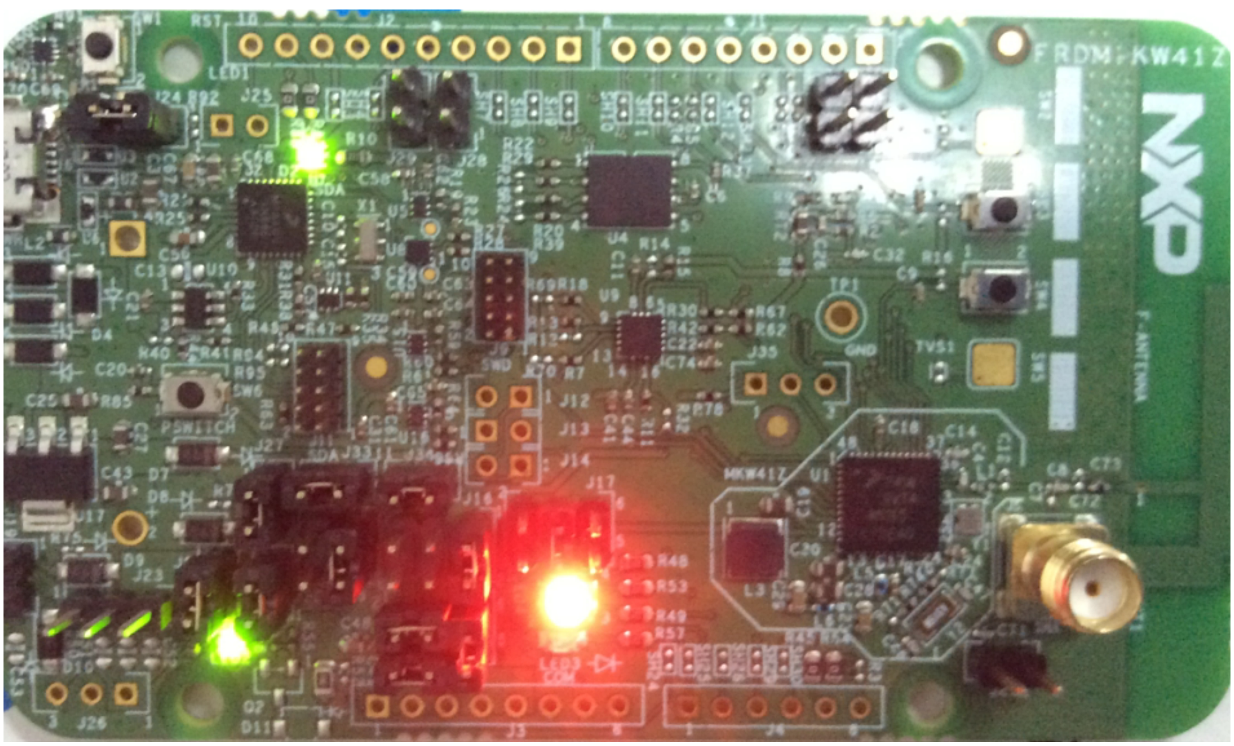


Figure 17. Red LED is On

5. Press SW3 on another board. The board will start RX. Green LED is On.

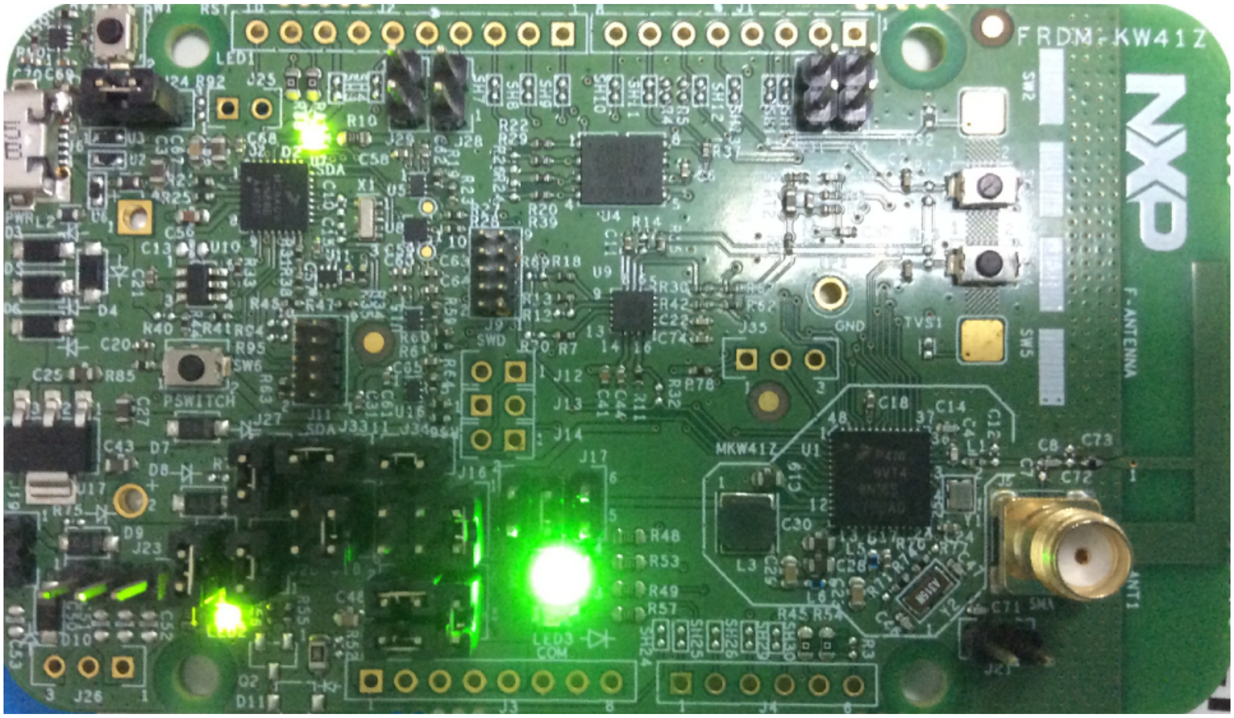


Figure 18. Green LED is On

6. After testing, connect the board to PC and use command “per printnvm” to get data.

5 Conclusion

The following table shows that the range of test results is related to many factors including the design points. At the same time, environmental factors can have a drastic effect on the range, making it one of the key aspects to understand when deploying a radio frequency (RF) solution. Whether the goal is to connect across 10 meters in a crowded hall or 10 kilometers outdoors, the environment plays a significant role in the maximum range that can be achieved. The following factors can limit range:

- Frequency
- Antenna and Cable Selection
- Antenna Height

Below are some test results for KW41 reference design. The test results indicate that the communication is quite stable up to a distance of 85 meter or more when performing line-of-sight communication.

Table 6. Test results for KW41 reference design

Test Condition	**TX Test result**		**RX Test result**	
Test Duration: 10s; Package Type: PRBS9; Length: 39 Bytes; Parameter: TX Power: 2.9 dBm; Distance: 85 meter; Temperature: 20	Index	PER (%)	Index	PER (%)
	1	1.81%	1	15.33%
	2	1.34%	2	4.23%
	3	1.50%	3	3.20%
	4	1.15%	4	4.80%

Table continues on the next page...

Table 6. Test results for KW41 reference design (continued)

Degree; Humidity: 80%; Test Location: IKEA parking, Suzhou;	5	0.96%	5	10.43%
	Average	1.35%	Average	7.60%

6 Revision history

Table 7. Revision history

Rev.No.	Date	Substantive Changes
0	02/2017	Initial release

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