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Design Improvements of WirelessHART Enabled Field Device

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Abstract

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Design Improvements of WirelessHART Enabled Field Device

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WirelessHART, as an improvement of HART (Highway Addressable Remote Transducer), provides a simple, reliable, and cost-effective method to deliver information without the trouble of wiring in the field. WirelessHART is being used more and more in field devices. Several years ago, Endress + Hauser (U.S.) Automation Instrumentation Inc. designed a WirelessHART solution by attaching a wireless adapter to a field device. The goal of this thesis is to improve the WirelessHART solution of Endress + Hauser to make it less expensive, smaller, and less power-consuming. The work is done in two parts. The first part is to redesign an I/O board on the field device to reduce the power consumption. In this part, a debug version of the I/O board is made. The second part is to redesign the WirelessHART mote to make it less expensive and smaller. The LTP5900-WHM-SmartMesh IP Mote Module (referred to as the LTP5900-WHM module) by Linear Technology is used as a reference design in this part. Impedance matching of the mote antenna feeder trace to 50Ω at 2.4GHz is implemented and analyzed. Radiated power measurements of the redesigned mote are made and compared to that of the LTP5900-WHM module. Though the radiated power of redesigned mote is 2 to 4 dBm less than that of the LTP5900-WHM module, the size of the new mote is only half of the LTP5900-WHM module. Recommendations are also provided in this thesis for further improvements on WirelessHART devices.

Acknowledgements

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Glossary

Antenna – An electrical device that converts electric energy to electromagnetic wave or vice versa

CPW – Coplanar Waveguide

CST – Computer Science Technology (CST), a 3D electromagnetic simulation software company

Endress + Hauser Automation Instrumentation Inc. – A global leader in measurement instrumentation, services and solutions. Endress + Hauser (U.S.) is located at 2350 Endress Place, Greenwood , IN 46143.

Eterna – A dust networks' low power radio system-on-chip architecture, a registered trademark by Linear Technology,

FCS – Frame Check Sequence

FieldCare – Endress+Hauser's universal tool for configuring field devices, it provides a range of functionality from device parameterization to engineered condition monitoring solutions

Field Device – A device that measures a physical parameter like temperature, pressure, flow etc.

HART – Highway Addressable Remote Transducer (HART) protocol, an industrial standard for sending and receiving information between smart devices and control or monitoring systems

HDLC – High-Level Data Link Control (HLDC), a bit-oriented code-transparent synchronous data link layer protocol developed by the International Organization for Standardization

High Frequency PCB Design – Design of a printed circuit board (PCB) that works at high frequency, usually more than 100MHz

ISM bands – radio bands (portions of the radio spectrum) reserved internationally for the use of radio frequency energy for industrial, scientific and medical purposes other than telecommunications

MMCX connector – Micro-miniature coaxial (MMCX) connector

Mote – Wireless node in a WirelessHART network

QFN – Quad-flat no-lead package

TDR – Time-Domain Reflectometry

UART – Universal Asynchronous Receiver/Transmitter, a serial data communication protocol on computers

Zuken CR-5000 – Zuken's advanced PCB design software that offers highly sophisticated functionality for the layout of multi-layer high-speed PCBs and IC packages

1. Introduction

HART (Highway Addressable Remote Transducer) is the world's most widely used field communication protocol for intelligent process instrumentations. WirelessHART, the wireless version of HART protocol, was proposed in early 2004. A typical HART network architecture is provided in Figure 1. As an improvement of HART protocol, WirelessHART supports operation in the 2.4 GHz Industrial, Scientific and Medical (ISM) band using IEEE 802.15.4 standard radios. It has created much enthusiasm in the world today due to its flexibility and mobility. With more than 30 million wired HART devices in use, it is not surprising that WirelessHART has a promising future.

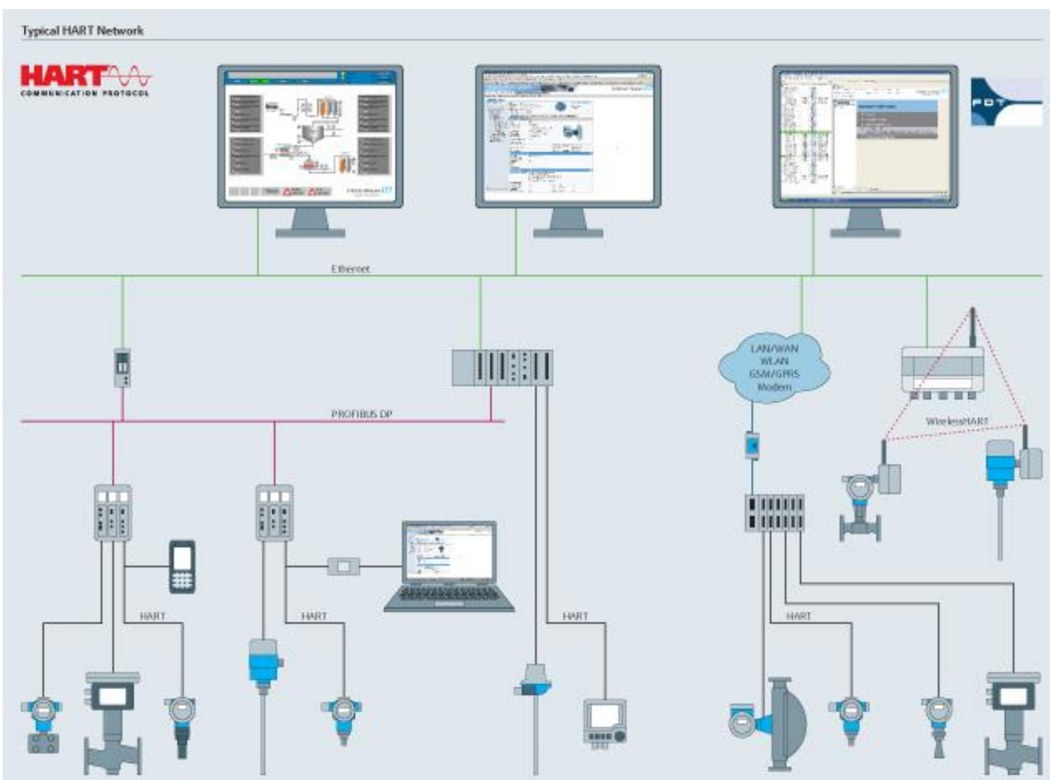

Figure 1 A typical HART network

(Source: http://www.endress.com/en/solutions-lowering-costs/field-network-engineering/hart-communication-fieldbus-technology)

Since wired HART field devices have already been installed in the field, a simple way to make a wireless HART field device is to attach a wireless adapter to it [1], which is how the original WirelessHART solution was created by Endress + Hauser (U.S.), a global leader in measurement instrumentation, services and solutions for industrial process engineering. Customers who want to install WirelessHART in the field don't have to throw their wired HART devices away.

However, there are obvious problems with this design. The wireless adapter is required to be compliant to any field devices. To fulfill this requirement, the wireless adapter is designed to connect the field device through a 4-20mA current loop, which is a part of HART protocol for signal transmission between the wireless adapter and the field device. More importantly, the current loop consumes power from the battery on the wireless adapter. When the signaling current flows through the current loop, all the components drop voltage and drain power from that battery [2] on the wireless adapter. This battery is usually depleted up in three months. A major improvement in battery life is required to compete in this market. In cooperation with Endress + Hauser (U.S.), this thesis is aimed at designing and improving the WirelessHART solution.

To save power and extend battery life, the 4-20mA current loop has to be removed. This can be done by redesigning the I/O board of the HART device and installing a WirelessHART mote (Wireless node in a WirelessHART network) on the I/O board. The WirelessHART mote accepts measured value from the HART device and modulates the value into the WirelessHART directly. Instead of the original of wireless adapter + wired HART device solution, an integrated

WirelessHART device is described in this thesis. The design improvements for the WirelessHART device are discussed in Section 2.

By removing the 4-20mA current loop, the power consumption of the I/O board is reduced. A Universal Asynchronous Receiver/Transmitter (UART) port is also provided on the I/O board for communication between the WirelessHART mote and the main board. The schematic and board design of the I/O board are done on Zuken CR-5000, an advanced PCB design software. The redesign of the I/O board is discussed in Section 3.

In order to install the WirelessHART mote on the I/O board, the size of the WirelessHART mote needs to be minimized. An LTP5900-WHM-SmartMesh IP Mote module (referred to as the LTP5900-WHM module) by Linear Technology is used as a base design in the project. The LTP5900-WHM module is an IEEE 802.15.4 System-on-Chip [3] compliant with the WirelessHART standard (IEC62591) [3]. It is also the mote that is used on the wireless adapter. The WirelessHART mote runs networking embedded software from Linear Technology [5]. The schematic and board design of the WirelessHART mote are also done on Zuken CR-5000. The redesign of the WirelessHART mote in presented in Section 4.

One of the most important parts of redesigning the mote is to match characteristic impedance of the antenna feeder trace to the input impedance of the antenna, which is 50Ω in this case. Impedance mismatching will increase the reflection coefficient at the antenna end of the trace and hence reduce radiation power. To match the impedance to 50 Ω, siding ground is placed around the antenna feeder trace, making the antenna feeder trace a grounded coplanar waveguide. Equations of grounded coplanar waveguide [6] are not available to calculate the characteristic impedance. To calculate the impedance, simulations are done on CST, a 3D electromagnetic simulation software. The simulation and analysis of antenna feeder trace impedance are presented in Section 5.

After the WirelessHART mote is redesigned and fabricated, its radiated power is measured and compared to the LTP5900-WHM module. A high-frequency spectrum analyzer and an anechoic chamber are used for measurements. The radiated power on 16 channels of the new mote are 2 or 4 dBm less than those of LTP5900-WHM module, but the new mote is almost in half of the size of the LTP5900-WHM module. Measurements and comparisons are presented in Section 6.

Section 7 presents conclusions based on the measurements and comparisons. Recommendations for further improvements are also presented.

2. WirelessHART Device Analysis and Improvements

This section introduces the original WirelessHART solution and how it can be improved. The original WirelessHART solution consists of a wired HART device and a wireless adapter, as shown in Figure 2. Both of the wired HART device and the wireless adapter are powered up by one single battery on the adapter's side. Section 2.1 explains in detail how the original WirelessHART solution works.

The first improvement is to redesign the I/O board on the wired HART device. The 4-20mA current loop on the I/O board is removed to save power. The UART port utilized by the 4-20mA current loop is retrofitted to the WirelessHART mote. The function of the I/O board and the design to improve it are detailed in Section 2.2.

The second improvement is to reduce the size of the WirelessHART mote. Improvements of WirelessHART mote are referred on Section 2.3.

2.1. Original WirelessHART Solution Analysis

Before WirelessHART hits the market, HART dominates the industry. Field devices varying from flow measurement instruments to press measurement instruments are all HART enabled. To retrofit all these HART enabled devices to WirelessHART can be challenging, for a WirelessHART solution has to be compliant to all wired HART field devices.

One fast and easy way to make those wired HART field devices wireless is to attach wireless adapters to them through the HART output port, for all the field devices provide a HART output port. A wireless adapter and a field device form a simple WirelessHART solution, which in this thesis is referred to as the original WirelessHART solution.

A diagram of the original WirelessHART solution is shown in Figure 2. The grey blocks on the figure are not concerned in the thesis. As shown in the diagram, there are three modules on the HART device side. A sensor measures value and passes the value to the device main board. The device main board then sends the value to the I/O board, which modulates the data into HART and sends it to the wireless adapter.

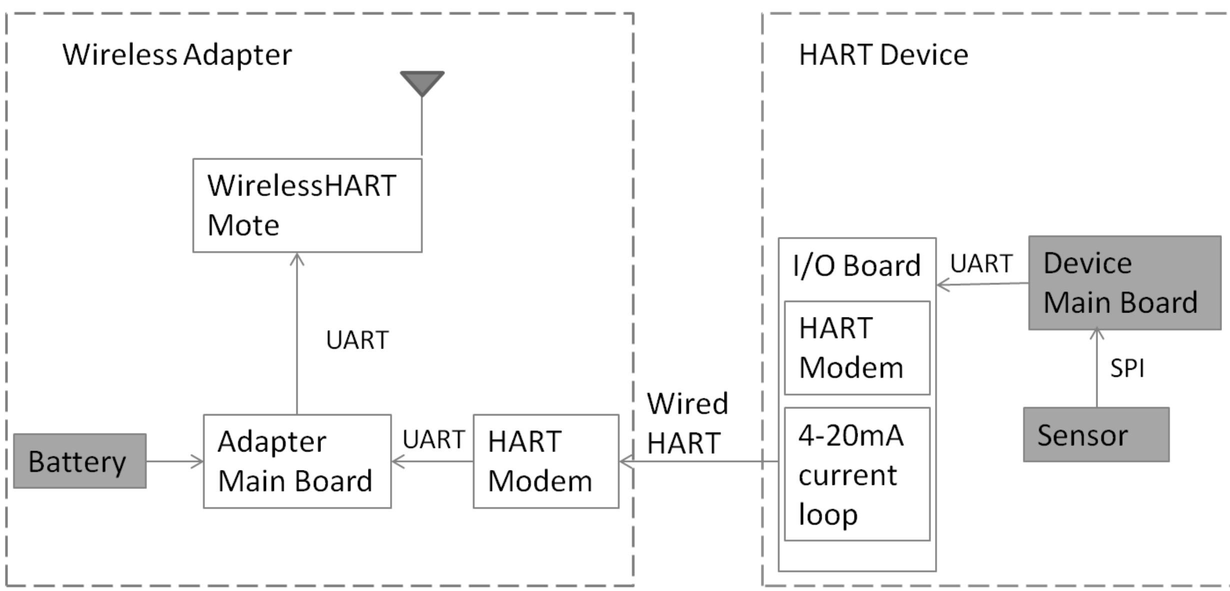

Figure 2 Diagram of the original WirelessHART solution

On the wireless adapter, the HART modem demodulates HART data from the HART device. After the adapter main board receives data, it sends the data to the WirelessHART mote, which is an LTP5900-WHM module. The LTP5900-WHM module is connected a 50Ω monopole antenna to transmit and receive radio signals. The battery on the wireless adapter provides power for both the wireless adapter and the HART device.

From the diagram shown in Figure 2, the value measured by the sensor is transmitted through a UART, a HART and another UART before it is accepted by the WirelessHART mote. The redundant data transmission link consumes power, which can be reduced.

Another power consumption that can be reduced is made by the 4-20 mA current. The 4-20 mA current is utilized by HART protocol as a communication channel, on the top of which the HART protocol makes use of the Bell 202 Frequency Shift Keying (FSK) standard to superimpose digital communication signals, as shown in Figure 3. The 4-20 mA current loop is used to transmit the primary measured value between the wireless adapter and the HART device. All of the components in the current loop drop voltage due to the signaling current flowing through them [2]. According to a performance calculation document by Endress + Hauser, the 4-20mA current loop dissipates 41.6mW at 4mA and 208mW at 20mA.

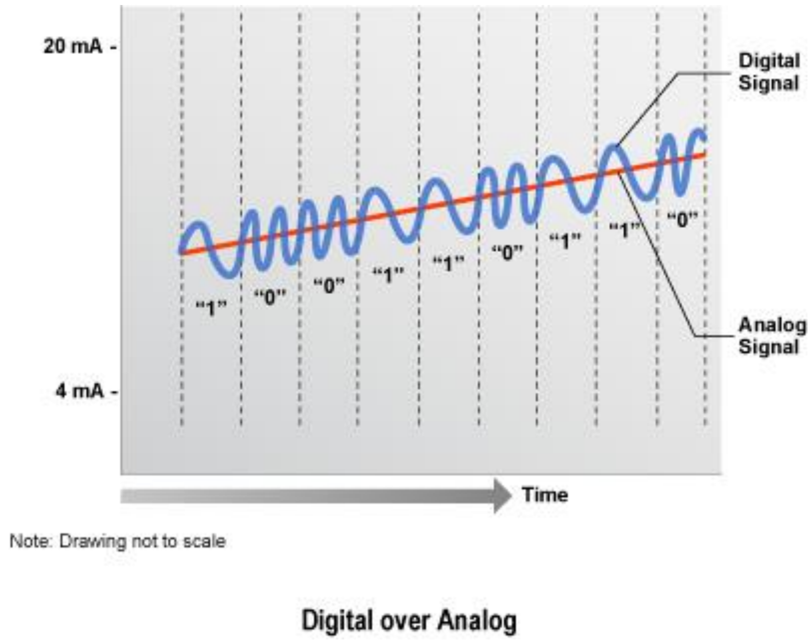

Figure 3 Frequency shift keying modulation of HART on top of the 4-20 mA current

(Source: http://en.hartcomm.org/hcp/tech/aboutprotocol/aboutprotocol_how.html)

In conclusion, the original solution has already been used in commercial products. It offers a rapid and flexible installation, and it doesn't require any changes on the device side. The disadvantage of the solution, as mentioned in the Introduction section, is that the battery is depleted up too quickly, usually in three months.

2.2. Power Reduction on the I/O Board

The reduction of the power consumption on the original WirelessHART solution can be done by redesigning the I/O board. One idea is to remove the 4-20 mA current loop on the I/O board. Without the 4-20 mA current loop, the wired HART communication between the wireless adapter and the HART device no longer exists. The HART modem on the wireless adapter is no longer needed. A UART communication could be set up between the wireless adapter and the device to transmit the measured value, as shown in Figure 4.

A better design of the I/O board, as shown in Figure 5, is to put the WirelessHART mote on the device I/O board. Once the device main board receives the measured value from the sensor, it transmits the value in UART to the WirelessHART mote, which modulates the value into WirelessHART directly. In this design, the WirelessHART mote needs to be improved and redesigned, too, in order to customize the mote size and reduce the cost.

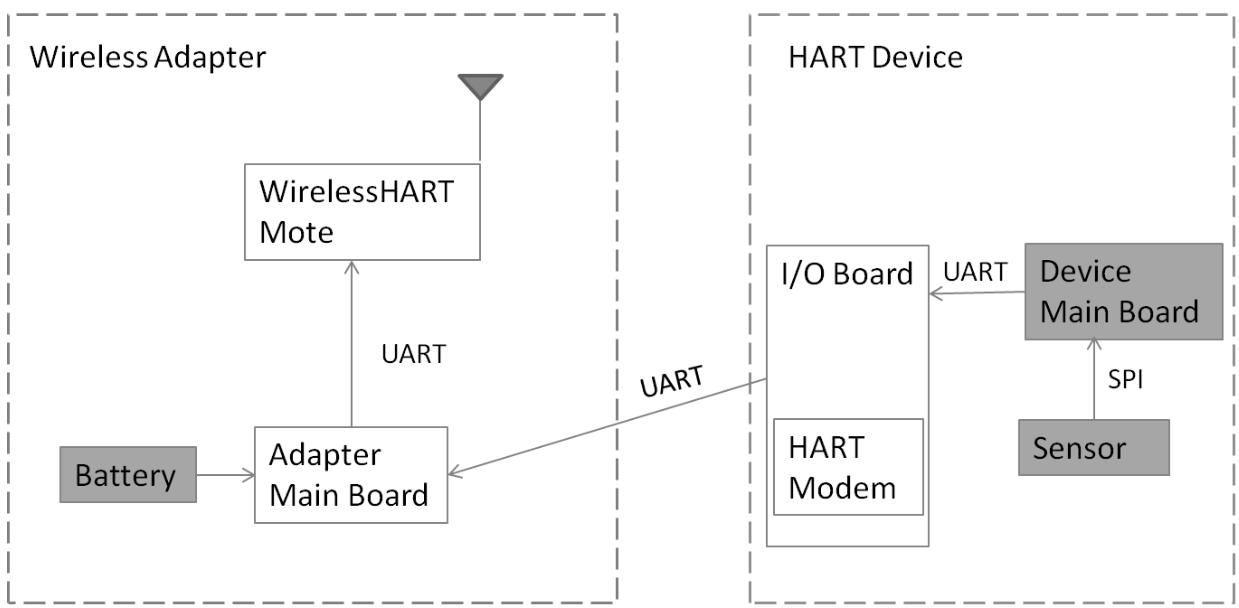

Figure 4 Diagram of the wireless adapter and the HART device without the 4-20mA current loop

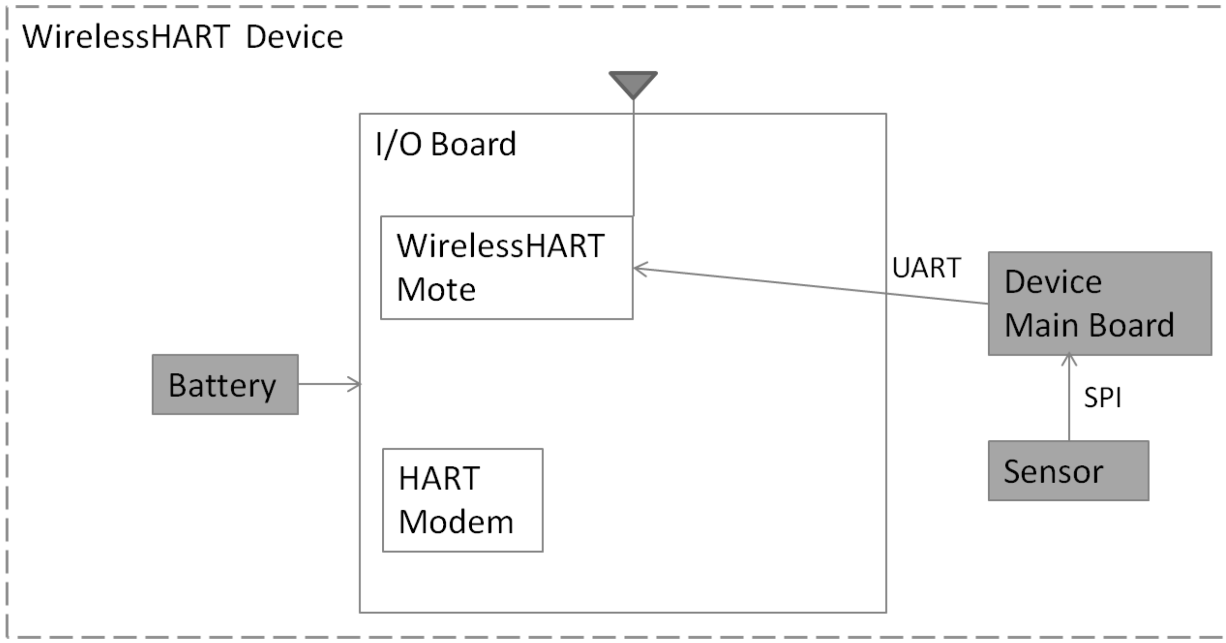

Figure 5 Diagram of the improved WirelessHART device

The design shown in Figure 5 saves a lot of power. First of all, the 4-20mA current loop on the device I/O board is eliminated. Two microcontrollers are also removed, one is previously on the wireless adapter main board and the other one is on the I/O board. The HART modem on the wireless adapter is removed. The HART modem on the WirelessHART device is rarely used – actually it is only used to configure some WirelessHART parameters like join keys.

The power saved by the improved I/O board can be calculated. The 4-20mA current loop consumes 41.6mW at 4mA and 208mW at 20mA, according to a performance calculation document by Endress + Hauser. According to the same document, each of the microcontrollers consumes 2.9mW power.

The HART modem (AD5700-1) on HART device runs in internal reference mode (with pin REF_EN tied high). According to its datasheet [7], the supply voltage is 3V; the typical current is 124μA. The power consumed by this HART modem is $\mathrm{P1} = 3\mathrm{V} \times 124\mu\mathrm{A} = 372\mu\mathrm{W}$. The other HART modem (HT2015) on wireless adapter runs under a 3.3V voltage with a 150uA current [8]. The power consumption is $\mathrm{P2} = 3.3\mathrm{V} \times 150\mu\mathrm{A} = 495\mu\mathrm{W}$. By removing those two HART modems, a total of $867\mu\mathrm{W}$ power is saved.

The sum of power consumption of the improved design is $867\mu\mathrm{W} + 208\mathrm{mW} + 2.9\ \mathrm{mW} \times 2 = 214.667\ \mathrm{mW}$. The improved I/O board saves as much as 214mW power.

2.3. PCB Size Reduction of the WirelessHART Mote

The size of the WirelessHART mote needs to be minimized prior to being installed on the improved I/O board. The size reduction can be done by removing some of the unnecessary I/O pins on the WirelessHART mote. Compared to the size of the LTP5900-WHM module, which is 24mm * 39mm, the size of the mini mote is reduced to 24mm * 21 mm, almost half the size as the module. The new designed mote is also referred to as the mini mote. Figure 6 shows the sizes between an LTP5900-WHM module (left), a mini mote (right upper) and a US quarter coin (right lower).

The mini mote is also designed to be less expensive than the LTP5900-WHM module. When making more than 5000 pieces of the new motes, the components of the new mote cost $42.53 per board, comparing to $56 of the LTP5900-WHM module. The components cost is shown in Table 7 in Appendix A.

In conclusion, the advantages of this improved design are substantial. Instead of attaching a wireless adapter to a HART device, this improved design creates one integrated WirelessHART enabled device. Comparing to the original solution, the power consumption is reduced due to the elimination of the 4-20 mA current loop and the wireless adapter. The cost is also reduced, for the redesigned WirelessHART mote is less expensive than the LTP5900-WHM module.

Figure 6 Size comparison between an LTP5900-WHM module, a mini mote and a US quarter coin

3. Design and Implementation of the I/O Board

The I/O board connects the main board of the HART device to the surrounding modules. The redesign of the I/O board eliminates several modules on board and enables the WirelessHART on the device. This section describes the design improvements of the I/O board.

3.1. Design Requirements

The I/O board of the HART device has several functions, as shown in Figure 7. First of all, it monitors the usage of the battery which is plugged on the wireless adapter. Secondly, the I/O board converts voltage of the battery to provide the operating voltage for the HART device. But most importantly, the I/O board communicates with the wireless adapter through a HART port.

The HART port provides two simultaneous communication channels, the 4-20 mA current loop, which is maintained by the MSP 430 microcontroller of Texas Instruments, and the digital signal, which is generated by the HART modem. There are two UART ports between main board and I/O board, as shown in Figure 7. The UART0 is utilized by the MSP430 microcontroller and UART1 is utilized by the HART modem.

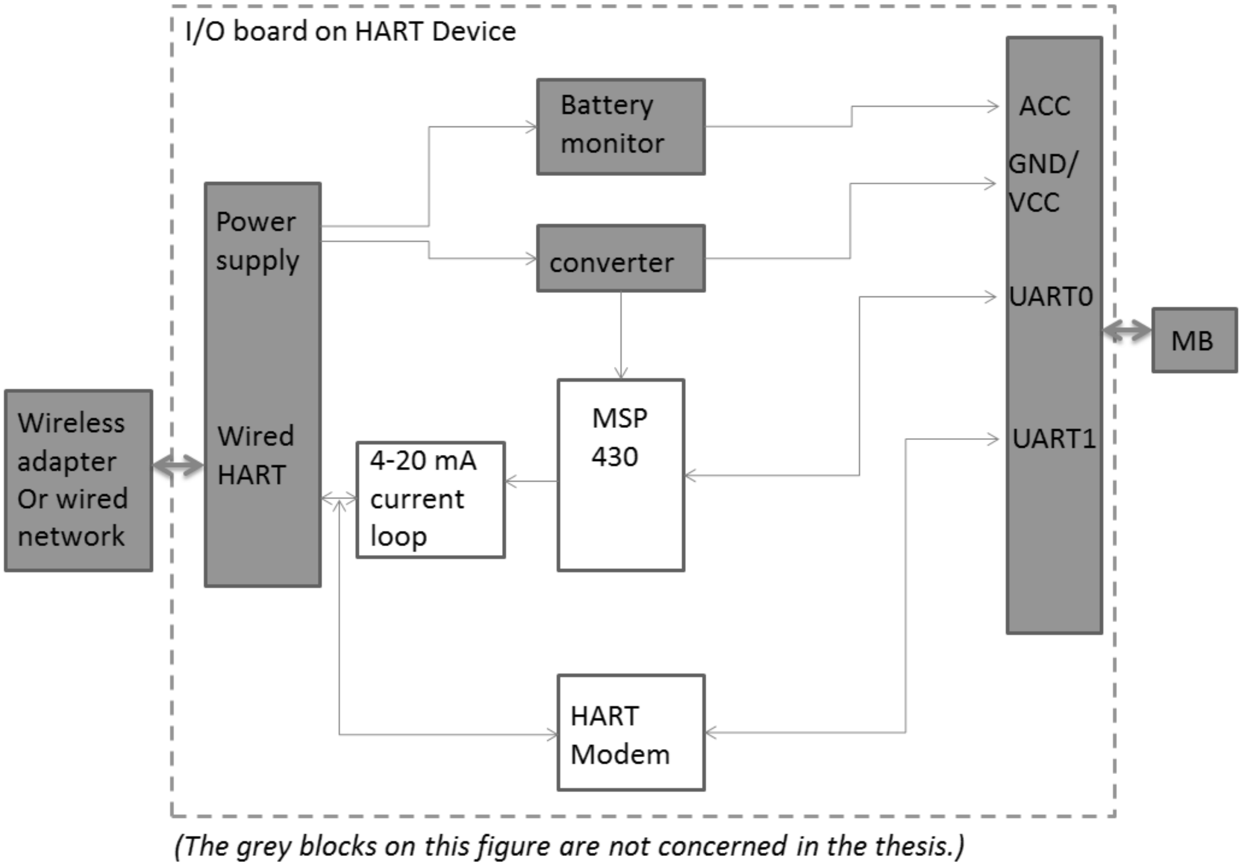

Figure 7 Diagram of the I/O board on the HART device

The improvement of the I/O board requires as little effect on the main board as possible. For this reason, after the removing of the 4-20mA current loop, the UART0 port used to be employed by the current loop will be reused by the WirelessHART mote, as shown in Figure 8. The battery monitor port and the UART1 port will remain the same.

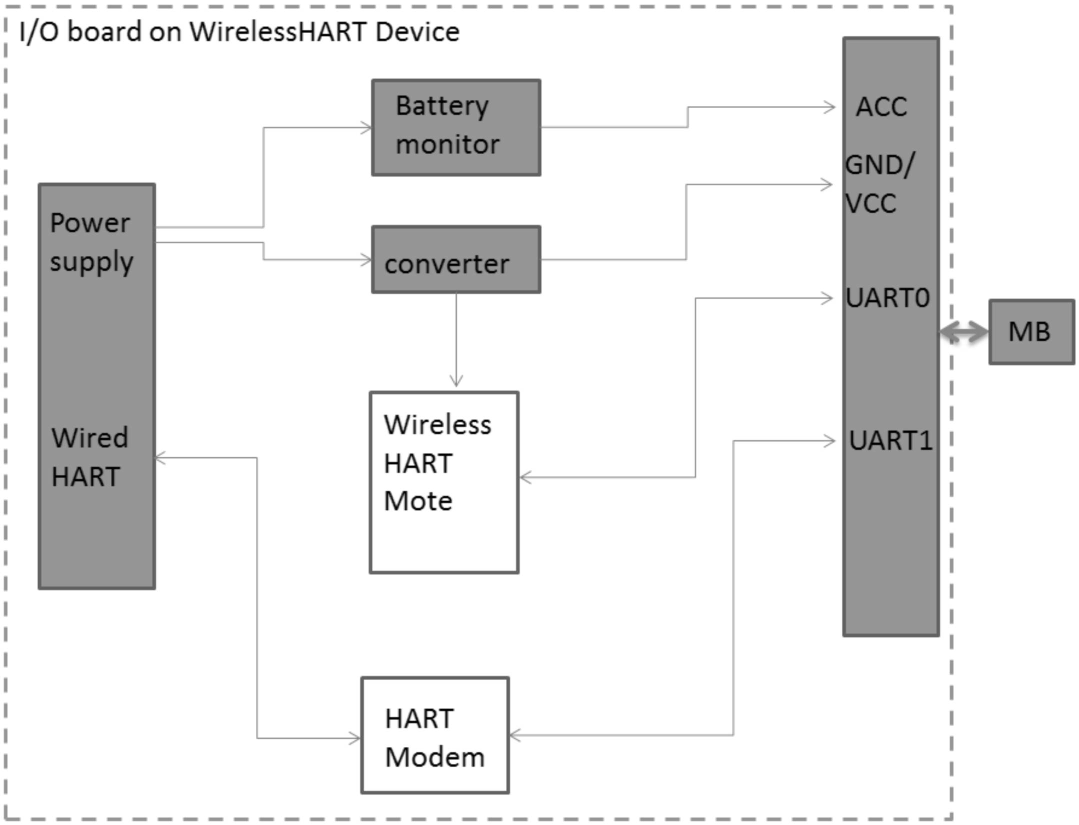

Figure 8 Diagram of the improved design of I/O board on the WirelessHART device

3.2. Schematic and Printed Circuit Board Designs

The I/O board is significant in the improved design. It interacts with both the main board and the WirelessHART mote. The idea of the improved I/O board is to set up the communication between the main board and the WirelessHART module and the WirelessHART connectivity [1]. For this reason, three options of WirelessHART mote are provided, an LTP5900-WHM module, or a mini mote and an LTC5800-WHM IC with an antenna connector.

When design the schematic of the I/O board, many debug pins, jumpers, and LEDs are put for the convenient of debugging. The schematics are shown in Figure 9, Figure 10 and Figure 11. A picture of the I/O board is also provided in Figure 12.

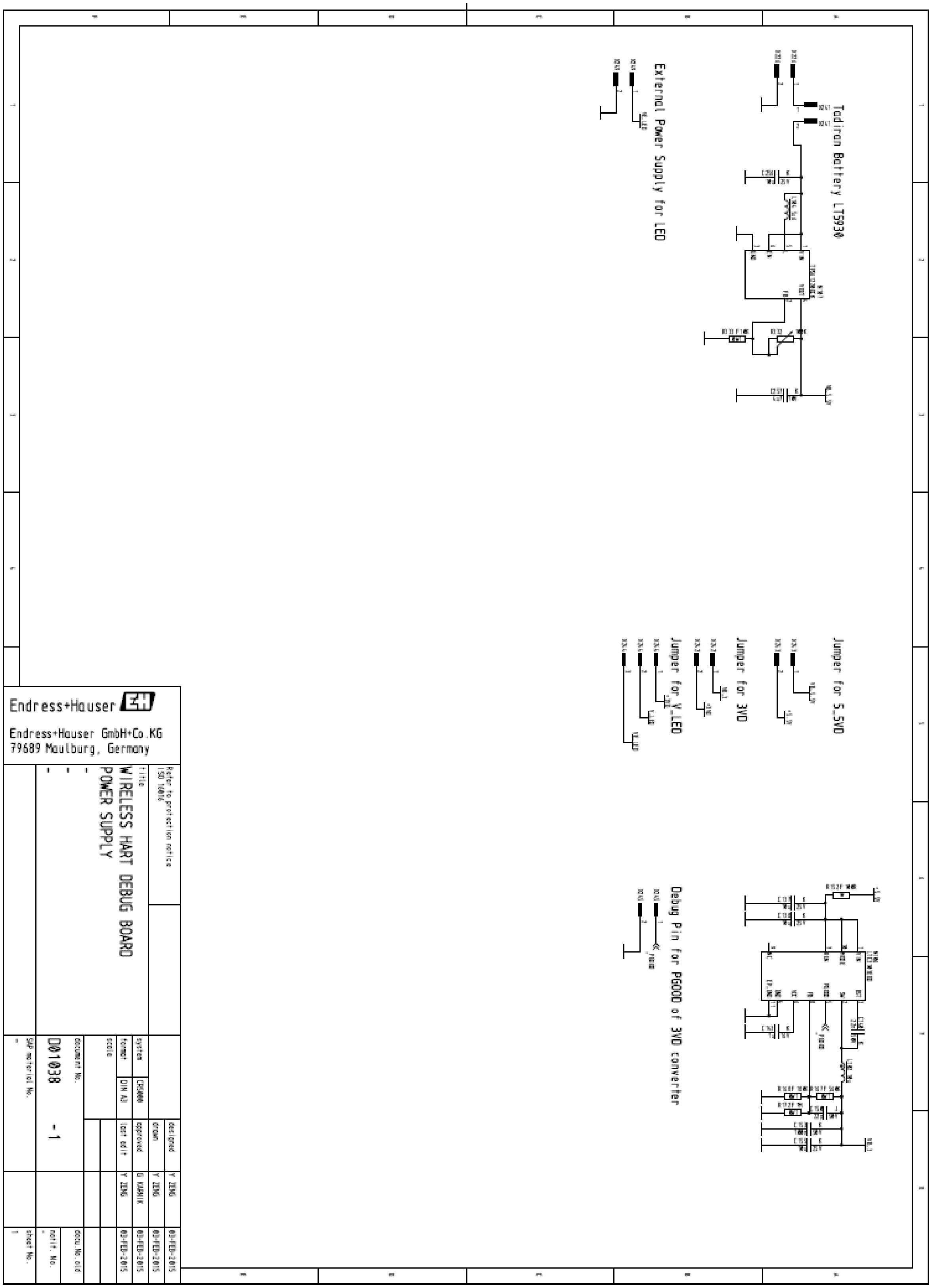

Figure 9 The improved I/O board schematic (page 1)

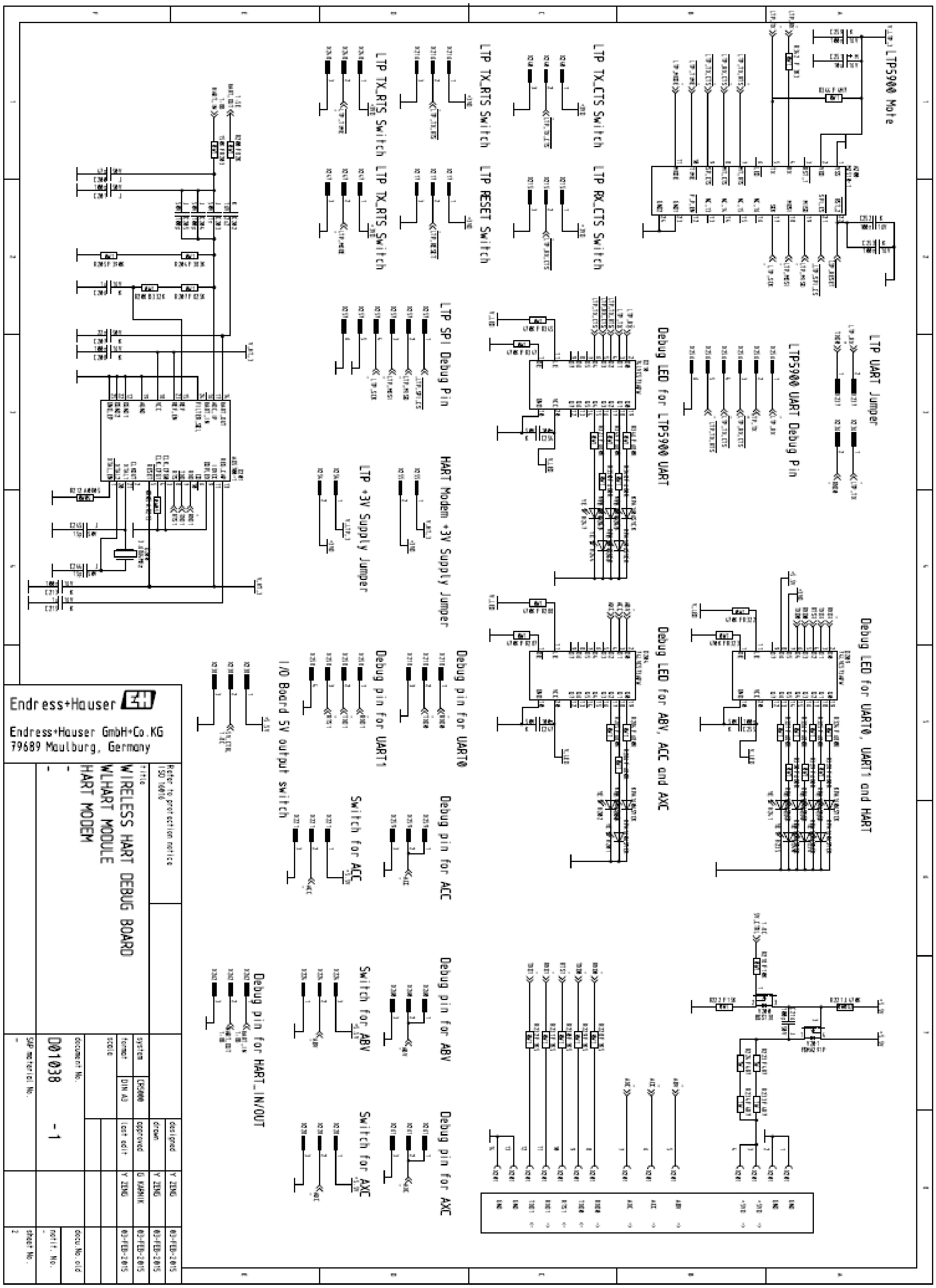

Figure 10 The improved I/O board schematic (page 2)

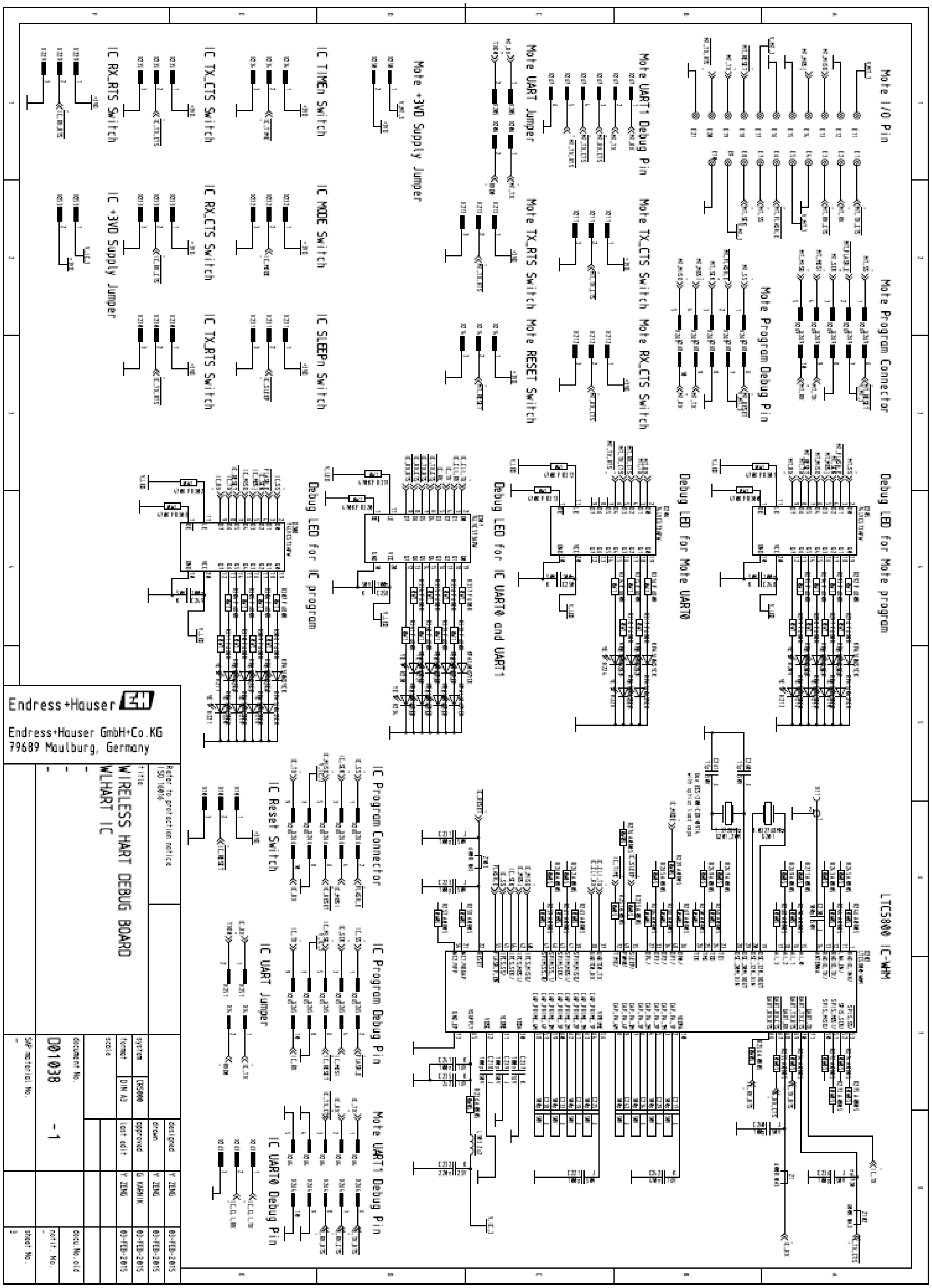

Figure 11 The improved I/O board schematic (page 3)

Figure 12 A picture of the debug version of the I/O board

4. Design and Implementation of the WirelessHART Mote

On the wireless adapter, the LTP5900-WHM module from Linear Technology is used as a WirelessHART mote. The LTP5900-WHM module is a complete radio transceiver and embedded processor with networking software for forming a self-healing mesh network. The module is a 22-Pin PCB assembly with MMCX (Micro-Miniature Coaxial Connector) antenna connector.

Section 3.1 discusses the design and the improvement of the new mote. Because the new mote is almost half the size of the LTP5900-WHM module, it is referred to as the mini mote below.

Section 3.2 provides the details of schematic and board design of the mini mote. The schematic of the mini mote is designed with reference to the schematic of the LTP5900-WHM module. The mini mote has an LTC5800-WHM SmartMesh WirelessHART Node IC (referred to as LTC5800-WHM IC below). LTC5800-WHM IC is a radio transceiver and embedded processor without software pre-programmed on it [9]. The selection of the electrical components of the mini mote is based on the components list of the LTP5900-WHM module provided by Linear Technology. Instead of the 22-pin PCB assembly, the mini mote has a QFN (Quad-flat no-lead package) package.

4.1. Design Requirements

The improvement of the WirelessHART mote needs to meet several requirements. Firstly, the WirelessHART device has to work at temperature from -20 to +80 ˚C, which means all the components on the mini mote must have the same or larger working temperature range. Secondly, according to IEEE 802.4.15, which is the physical layer standard of WirelessHART protocol, the mini mote should be able to support 16 channels. Each channel is separated by 5MHz in the 2.4GHz band.

The mini mote is smaller but has the same functionality as the LTP5900-WHM module. The mote will be connected to the same antenna. Also, the mote will be programmed with the same software as the LTP5900-WHM module. After programmed, the mote should perform the same activity to join the WirelessHART network.

4.2. Schematic and Printed Circuit Board Designs

The design of the mini mote is based on the guidelines provided by Linear Technology for WirelessHART mote design. Linear Technology also provides recommended schematics, PCB layout, device configuration and manufacturing considerations in *Eterna Integration Guide* [10]. The schematic and board design of the mini mote are done with Zuken CR-5000, an advanced PCB design software.

Though the schematic of the mini mote, as shown in Figure 13, is mostly the same as what Linear Technology recommends, it has several differences from the LTP5900-WHM module. The first difference is the 100pF capacitor in series with the antenna connector. Linear Technology recommends a Pi-filter composed of three 100pF capacitors to filter out noises at low frequency, but the Pi-filter is not present on the LTP5900-WHM module board. The second difference is that the MODE_PIN_B pin is tied low internally to select UART mode 1 on the mini mote, while the pin is an I/O pin on the LTP5900-WHM module. The third difference is the SLEEPn pin internally tied low through a 0Ω resistor because SLEEPn function is not currently supported in software. By connecting it to a 0Ω resistor, it is possible to change it high or floated for debugging purpose.

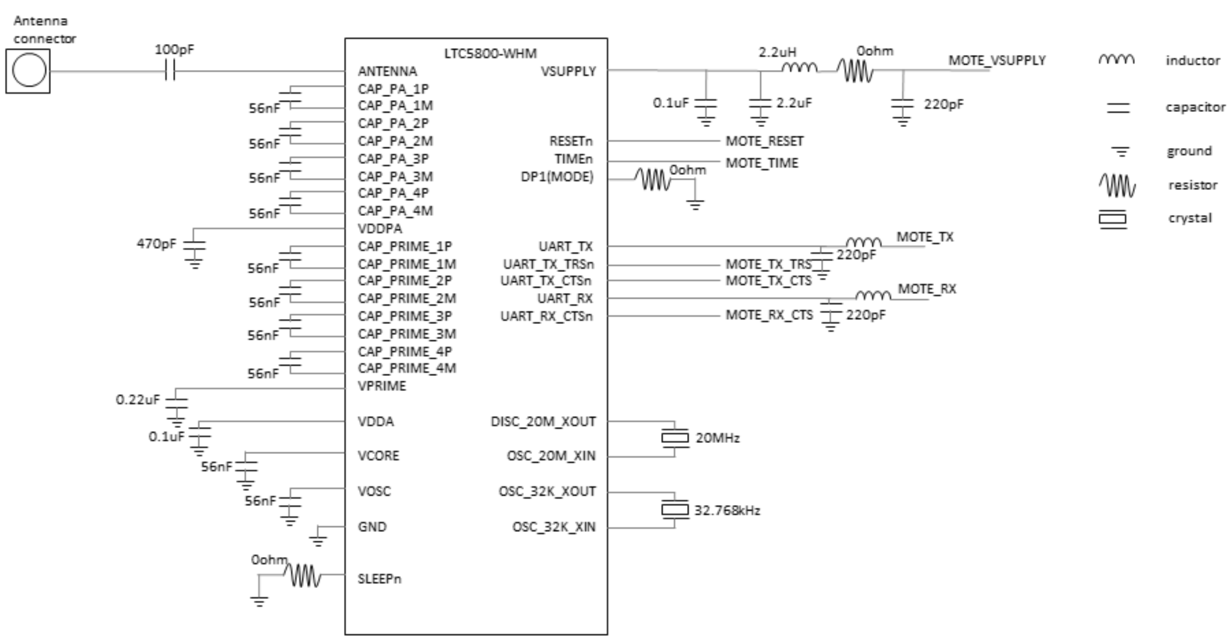

Figure 13 Schematic of the mini mote

Besides the differences on schematic, the mini mote uses some components different from those recommended by Linear Technology. The most significant difference is the selection of the crystals. There are two external crystals on the mini mote, a 32.768 kHz crystal for long term precise timing and a 20 MHz crystal for radio operation. Linear Technology recommends incorporating crystals, the performance of which is verified from Table 1 and Table 2 [10]. On the LTP5900-WHM module, the ECS-200-CDX-0914 is used as the 20 MHz crystal and ECS-.327-12.5-17X is used as the 32.768 kHz. However, the Abracon ABM8G-20.000MHZ-18-D2Y-T (a 20 MHz crystal) and ECS-.327-12.5-34B (a 32.768 kHz crystal) are used on the mini mote because they are more easily available and smaller in size. Both of the crystals on the mini mote work well. Besides the crystals, some capacitors and resistors on the mini mote are different from those used on the LTP5900-WHM module. The components lists of the mini mote and the LTP5900-WHM module can be found in Table 7 and Table 8 in the Appendix A.

Table 1 20MHz crystals recommended by Linear Technology (Source: Eterna Integrated Guide)

Vendor	Part Number	Form Factor
ECS	ECS-200-CDX-0914	7.6x4.1x2.3mm, SMD
Abracon	TBD	12.7x4.7x3.3mm, SMD
ECS	TBD	3.2x1.5x0.9mm, SMD
Abracon	TBD	3.2x1.5x0.9mm, SMD

Table 2 32 kHz crystals recommended by Linear Technology (Source: Eterna Integrated Guide)

Vendor	Part Number	Form Factor
ECS	ECS-.327-12.5-17X	8.7x3.7x2.5mm, SMD
Abracon	ABS25-32.768KHZ-4-T-ND	8.0x3.8x2.5mm, SMD
ECS	ECS-.327-12.5-34B	3.2x1.5x0.9mm, SMD
Abracon	ABS07-32.768kHz-4-T	3.2x1.5x0.9mm, SMD

The I/O pins of the mini mote are designed based on the I/O pins of the LTP5900-WHM module. The I/O pin description of the LTP5900-WHM module is shown in Table 3, while the I/O pin description of the mini mote is shown in Table 4.

Table 3 I/O Pin description of the LTP5900-WHM module

Pin #	Function	Description	Is in the mini mote
1	Vss	Ground	Yes
2	V_{dd}	Power	Yes
3,20	Key	No pin	No
4	RX	UART RX. Direction = In	Yes
5	TX	UART TX. Direction = Out	Yes
6, 13-16	Reserved	Not connected	No
7	$\overline{\text{MT\_RTS}}$	UART active low mote ready to send. Direction = Out.	Yes. Same as pin TX_RTS on the mini mote
8	$\overline{\text{MT\_CTS}}$	UART active low mote clear to send. Direction = Out.	Yes. Same as pin RX_CTS on the mini mote
9	$\overline{\text{SP\_CTS}}$	UART active low serial peripheral clear to send. Direction = In	Yes. Same as pin TX_CTS on the mini mote
10	$\overline{\text{TIME}}$	Falling edge time request. Direction = In. The TIME input pin is optional, and must either be driven or pulled up with a 5.1M resistor.	No
11	MODE_PIN_B	Selects between mode 1 and mode 3 operation. Direction = In.	No
12	$\overline{\text{FLASH\_P\_EN}}$	Active Low Flash Power Enable. Direction = In. Used for programming	Yes
17	SCK	SPI Clock. Direction = In. Used for programming	Yes
18	MOSI	SPI Master Out Slave In Serial Data. Direction = In. Used for programming	Yes
19	MISO	SPI Master In Slave Out Serial Data. Direction = Out. Used for programming	Yes
21	$\overline{\text{SPI\_CS}}$	Active Low Flash Chip Select. Direction = In. Used for programming	Yes
22	$\overline{\text{RST}}$	Active Low Reset. Direction = In. Used for programming	Yes

The pins on the LTP5900-WHM module but not on the mini mote are key pins, reserved pins, $\overline{\text{TIME}}$ and MODE_PIN_B. The key pins are used for matching when trying to plug the LTP5900-WHM module into a socket. The reserved pins are actually SPIM port, which is not necessary on the mini mote. The $\overline{\text{TIME}}$ pin is pulled up on the mini mote board internally and is not made an I/O pin. The MODE_PIN_B pin is used to select UART mode 1 or UART mode 3. When MODE_PIN_B is externally tied low, the module works at mode 1 which implements an 8-bit, no parity, 9600bps baud serial interface. When MODE_PIN_B is externally tied high, the module works at mode 3 which implements an 8-bit, no parity, 115.2kbps baud serial interface. MODE_PIN_B is not made an I/O pin but is internally tied low on the mini mote.

For further development, the command line interface (CLI) UART pins of the LTC5800-WHM IC can be made I/O pins on the mini mote. Different from the API UART port, the CLI UART port is intended for human interaction and interactive troubleshooting and is very useful when programming and debugging the mini mote [11].

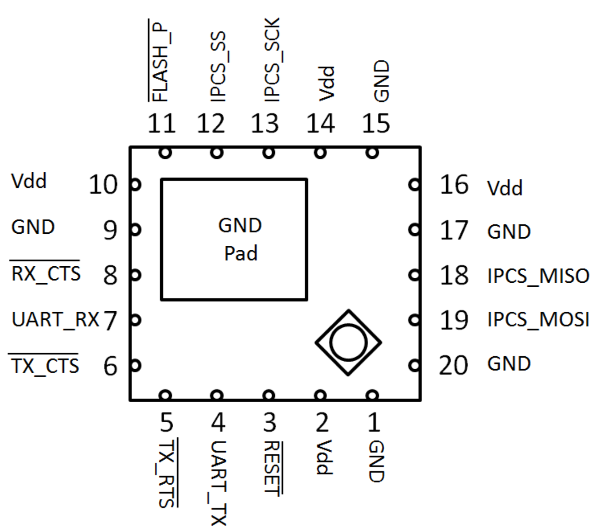

Figure 14 Pin configuration of the mini mote

There are a total of 13 functioning pins selected as I/O pins on the mini mote, as shown in Figure 14. Extra V_{dd} and GND pins are added to balance the number of pins on each side.

Table 4 I/O pin description of the mini mote

Pin #	Function	Description
1	GND	Ground
2	VDD	Power supply
3	$\overline{\text{RESET}}$	Active Low Reset. Direction = In. Used for programming
4	UART_TX	API UART TX. Direction = Out
5	$\overline{\text{TX\_RTS}}$	UART Active Low Mote Ready to Send. Direction = Out.
6	$\overline{\text{TX\_CTS}}$	UART Active Low Serial Peripheral Clear to Send. Direction = In
7	UART_RX	API UART RX. Direction = In
8	$\overline{\text{RX\_CTS}}$	UART Active Low Mote Clear to Send. Direction = Out.
9	GND	Ground
10	VDD	Power supply
11	$\overline{\text{FLASH\_P}}$	Active Low Flash Power Enable. Direction = In. Used for programming
12	IPCS_SS	Active Low Flash Chip Select. Direction = In. Used for programming
13	IPCS_SCK	SPI Clock. Direction = In. Used for programming
14	VDD	Power supply
15	GND	Ground
16	VDD	Power supply
17	GND	Ground
18	IPCS_MISO	SPI Master In Slave Out Serial Data. Direction = Out. Used for programming
19	IPCS_MOSI	SPI Master Out Slave In Serial Data. Direction = In. Used for programming
20	GND	Ground

5. WirelessHART Mote Antenna Feeder Trace Impedance Analysis and Matching

Matching the characteristic impedance of the antenna feeder trace to the input impedance of the antenna, which is 50Ω in this case, is extremely important and necessary. Impedance is the opposition by a system to the flow of energy from a source. Impedance mismatching will lead to strong wave reflection and reduction the radiation power. This section discusses the impedance analysis and matching of the antenna feeder trace on the mini mote.

The structure of the antenna feeder trace is analyzed in Section 4.1. Because of the presence of the siding ground around the antenna feeder trace, the trace is neither a microstrip line nor a slot line, but really a coplanar waveguide with a backing ground.

Because CST does not provide a characteristic impedance calculator, the S_{11} parameter of the antenna trace is calculated instead. The lower the S_{11} is, the closer the trace impedance matches to 50Ω. The reason of calculating S_{11} instead of impedance is provided in Section 4.2

To match the impedance, a 3D model is built on CST, a 3D electromagnetic simulation software, with board design files exported from Zuken CR-5000. The steps of exporting files from Zuken and building the 3D model are provided in Appendix C.

After the mini mote is fabricated, measurements of the trace impedance are done on a TDR (Time-Domain Reflectometry) with comparison to the LTP5900-WHM module antenna feeder trace. The results are shown in Section 4.3.

5.1. Antenna Feeder Trace and Coplanar Waveguide

When transmitting in an insulation layer with a dielectric constant of 4 [12], the wavelength of the working frequency is 6.25 cm, as calculated in Equation (4-1).

$$\lambda = \frac{lightspeed\ in\ the\ substrate}{frequency} \approx \frac{\frac{3\times10^8}{\sqrt{4}} m/s}{2.4\times10^9 Hz} = 6.25cm \qquad (4\text{-}1)$$

The 2cm-long antenna feeder trace is about 32% of the wavelength. Since the lengths of traces are in the range of the signal wavelength, the user has to consider the effects of transmission lines [13].

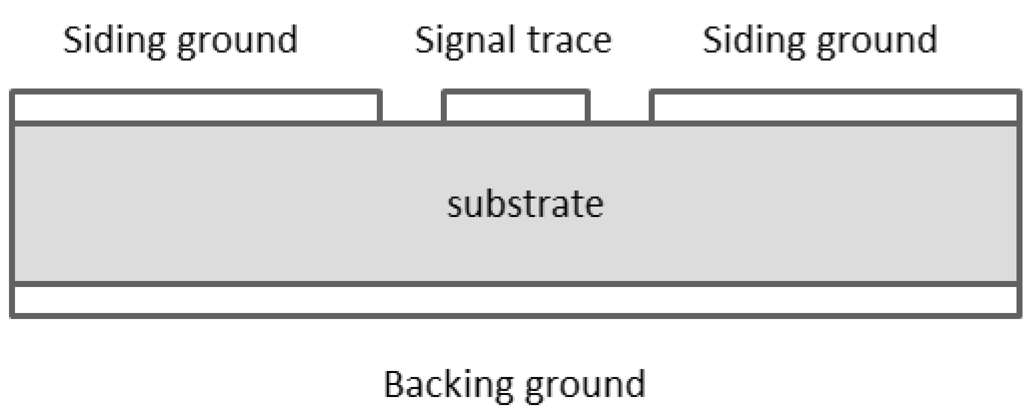

Figure 15 Cross-section of a grounded Coplanar Waveguide (CPW)

However, the antenna feeder trace on the board is neither a microstrip line nor a slotline. It has a reference layer beneath and ground metal around it, as shown in Figure 15. It's more like a coplanar waveguide with a backing ground. The siding ground is used to reduce noise on signal trace, but it also helps to reduce the characteristic impedance to 50 ohm. It makes the trace a slotline with backing ground [14], introducing more factors into the antenna trace when calculating the impedance.

The parameters of the antenna trace that affect the S_{11} parameter are trace width, distance between the trace and the siding ground, thickness of the insulation layer, dielectric constant and the thickness of the trace. Of all these parameters, the thickness of the insulation layer, dielectric constant of the insulation material and the thickness of the trace rely much on the manufactory. The distance between the trace and the siding ground is limited by the PCB design rule. Trace width is the only parameter that can be adjusted during board design.

There are equations to calculate the characteristic impedance of uniform CPW. Unfortunately, the antenna feeder trace on board in non-uniform due to space limitation. The other way to configure the trace to match the impedance is simulation on CST.

5.2. S Parameter Simulation of the Antenna Feeder Trace

Since the CST doesn't have a calculator for characteristic impedance, an alternative way to match the impedance is connect the trace to a 50Ω load, as shown in Figure 16 [15], and match the S_{11} parameter to 0dB.

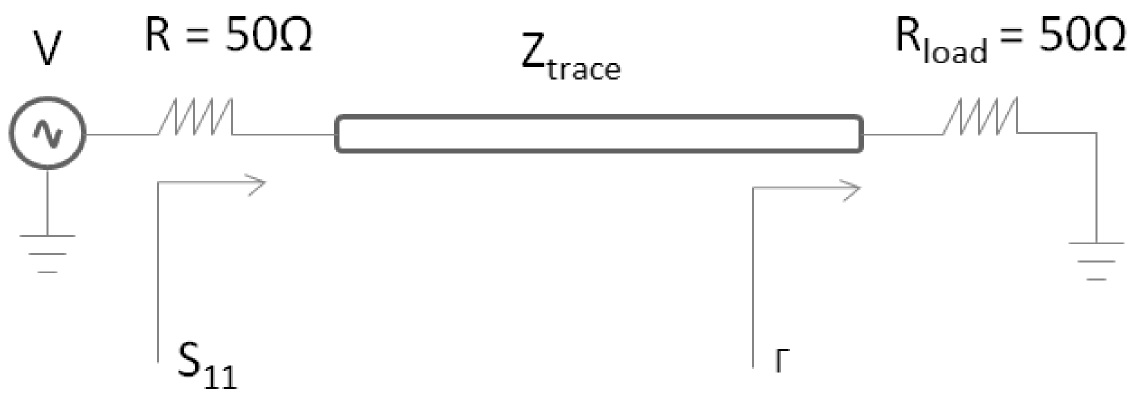

Figure 16 S_{11} parameter of a transmission line

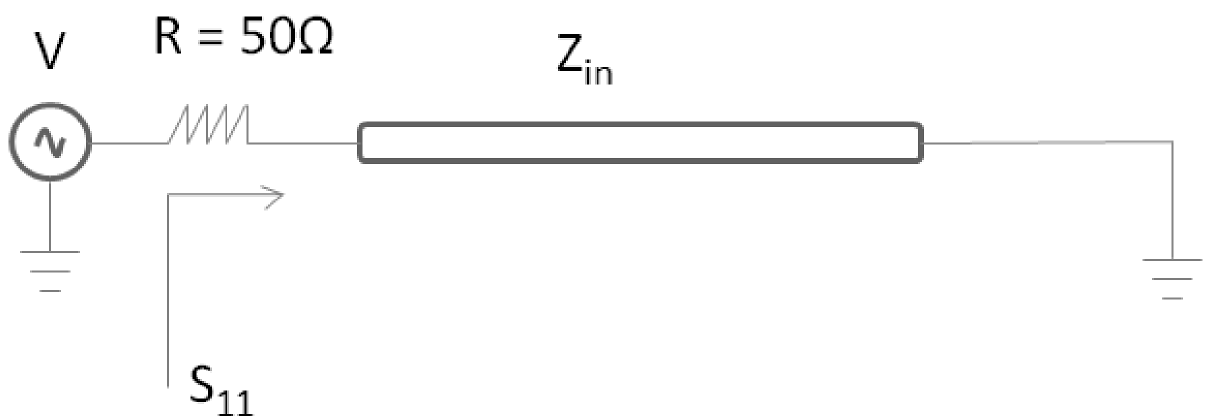

Figure 17 An equivalent circuit for return loss

The term S_{11} is often referred to as the return loss, as shown in Equation 4-2, because it is a measure of power reflected, or returned to the source.

$$S_{11} = \sqrt{\frac{Power\ reflected\ at\ port\ 1}{power\ injected\ into\ port\ 1}} \tag{4-2}$$

$$S_{11} = \frac{v_1^-/\sqrt{R}}{v_1^+/\sqrt{R_{load}}} = \frac{v_1^-}{v_1^+} = \Gamma_0 \frac{Z_{in}-50\Omega}{Z_{in}+50\Omega} \tag{4-3}$$

$$Z_{in} = Z_{trace}\frac{1+\Gamma e^{-i2\beta L}}{1-\Gamma e^{-i2\beta L}} \tag{4-4}$$

The term S_{11} is calculated as in Equation 4-3, where Z_{in} is the input impedance looking into the network from the port (the equivalent circuit is shown in Figure 17). The calculation of Z_{in} is given in Equation 4-4.

In Equation 4-4, L is the length of the trace, β is given by $\beta = \frac{\omega}{v}$, where ω is the radio frequency and v is the velocity of propagation on the trace. Γ is the reflection coefficient at the load and is given in Equation 4-5.

$$\Gamma = \frac{R_{load}-Z_{trace}}{R_{load}+Z_{trace}} \tag{4-5}$$

Z_{in} can also be written as follows [13].

$$Z_{in} = Z_{trace}\frac{R_{load}+jZ_{trace}\tan\beta L}{R_{load}-jZ_{trace}\tan\beta L} \tag{4-6}$$

Generally, the closer the trace impedance is to 50Ω, the closer the network input impedance is to 50Ω, the lower the S_{11} will be. If the impedance of the trace Z_{trace} matches to 50Ω, Z_{in} will be 50Ω, and S_{11} will be 0 dB.

To calculate S_{11} of the antenna feeder trace, a 3D model of the whole board is built with CST, as shown in Figure 18. Steps to build the 3D model can be found at Appendix C [16].

3D models with trace width 0.3mm, 0.4mm and 0.5mm are simulated with CST. The S_{11} parameters at 2.4GHz of the traces are -19.14dB, -26.96dB and -12.89dB, as shown in Figure 19, Figure 20 and Figure 21. The 0.4mm wide trace is chosen to be the antenna feeder trace.

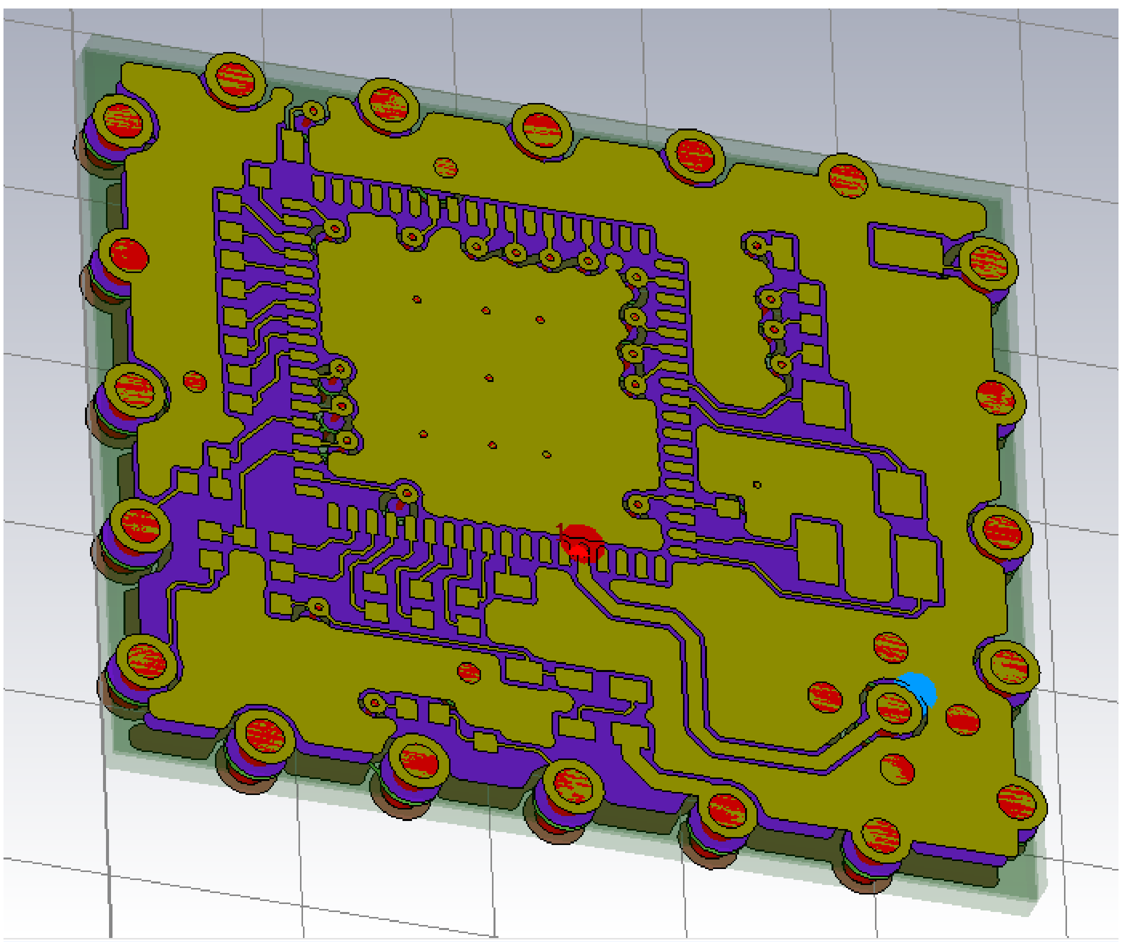

Figure 18 A mini mote 3D model on CST

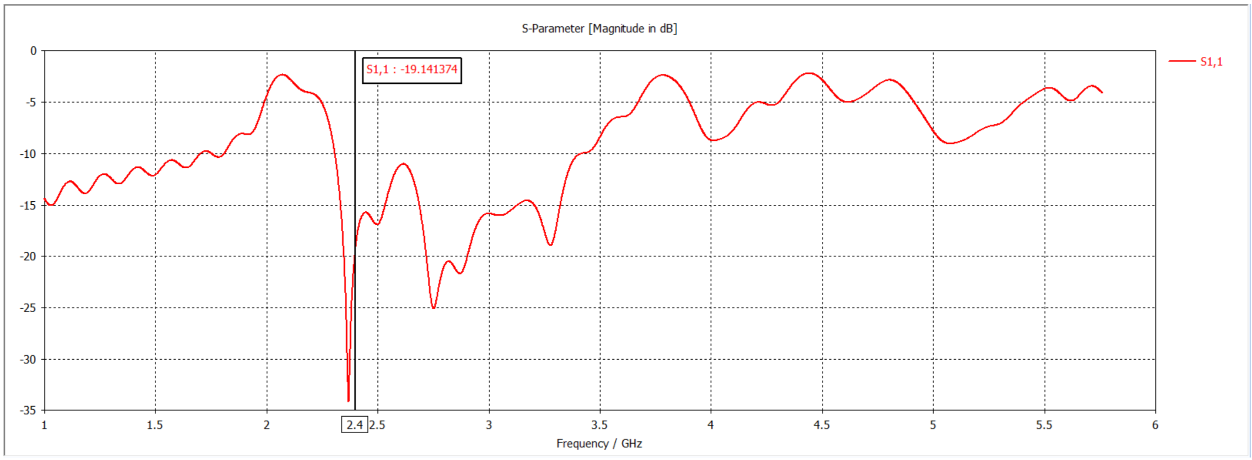

Figure 19 S_{11} parameter graph of the 0.3mm wide trace

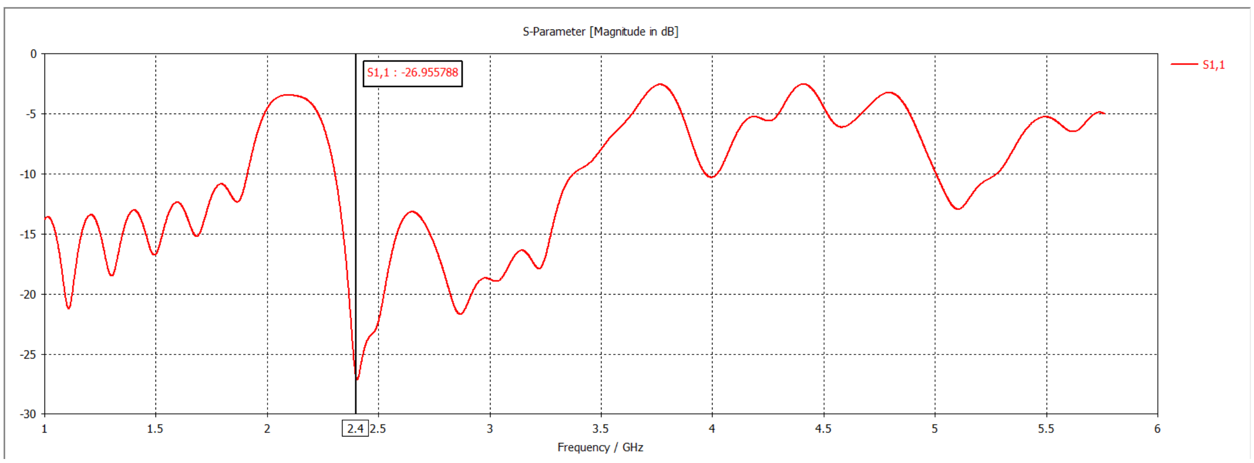

Figure 20 S_{11} parameter graph of the 0.4mm wide trace

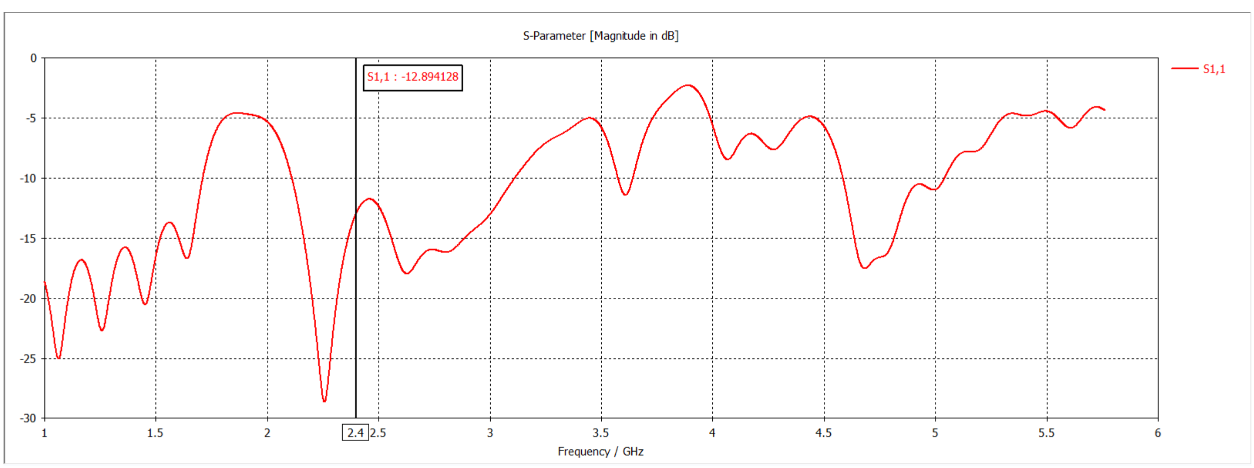

Figure 21 S_{11} parameter graph of the 0.5mm wide trace

5.3. TDR Measurements of the Antenna Feeder Trace

After the mini mote is fabricated, the impedance of the antenna feeder trace is measured on a TDR scope. On the board, the antenna trace is connected to an MMCX antenna connector on one end, which can be connected to the TDR scope for testing, as shown in Figure 22.

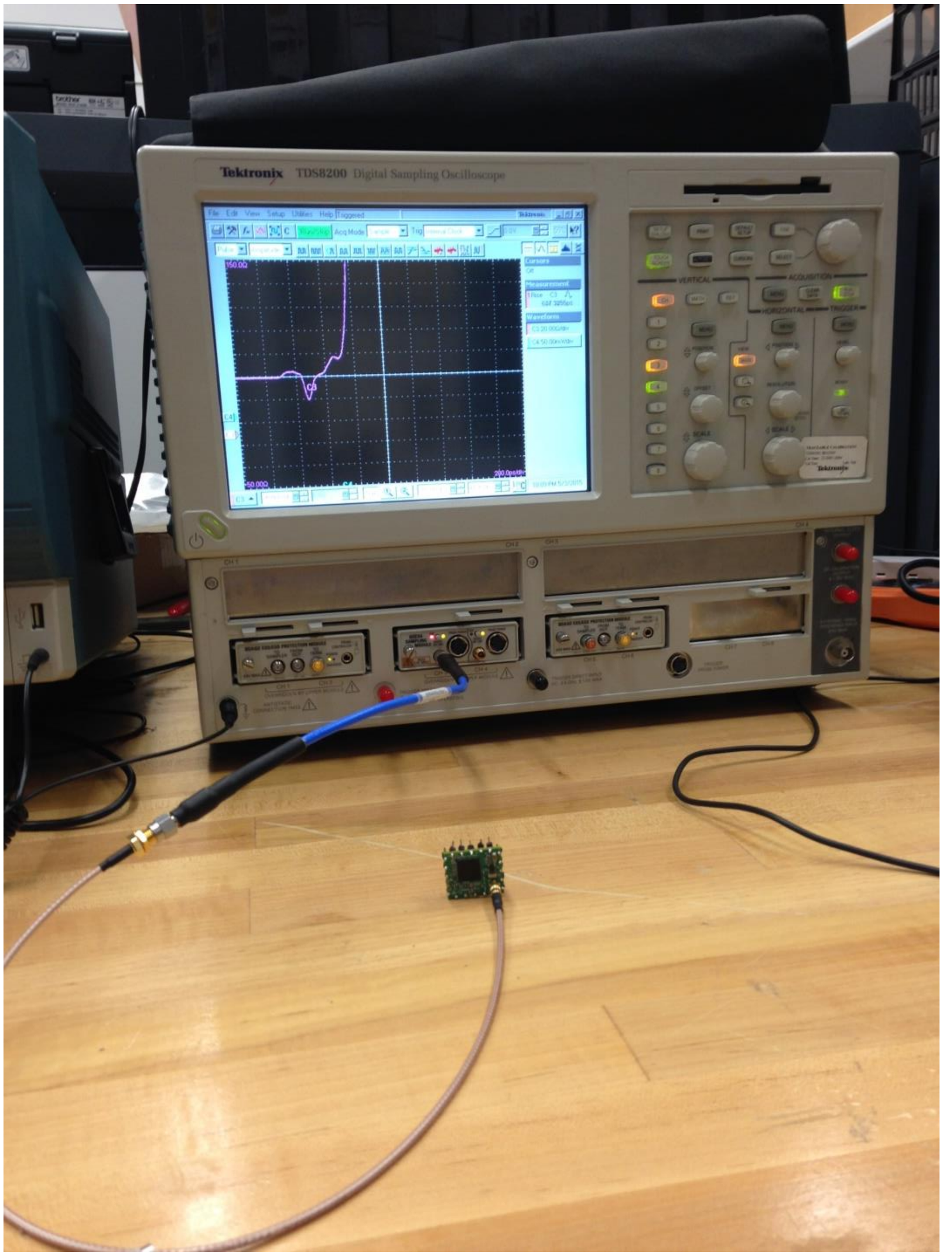

Figure 22 Impedance measurement of the mini mote on a TDR scope

To observe the reflection of the antenna feeder trace, first connect a cable to the TDR scope. Since the cable is open at the end, find the full reflection on the screen and adjust it to the left part of the screen. When the mote is plugged in, the reflection of the antenna trace will occur at the position of the full reflection on the time axis. As shown in Figure 23, the full reflection happens at the beginning of the third division.

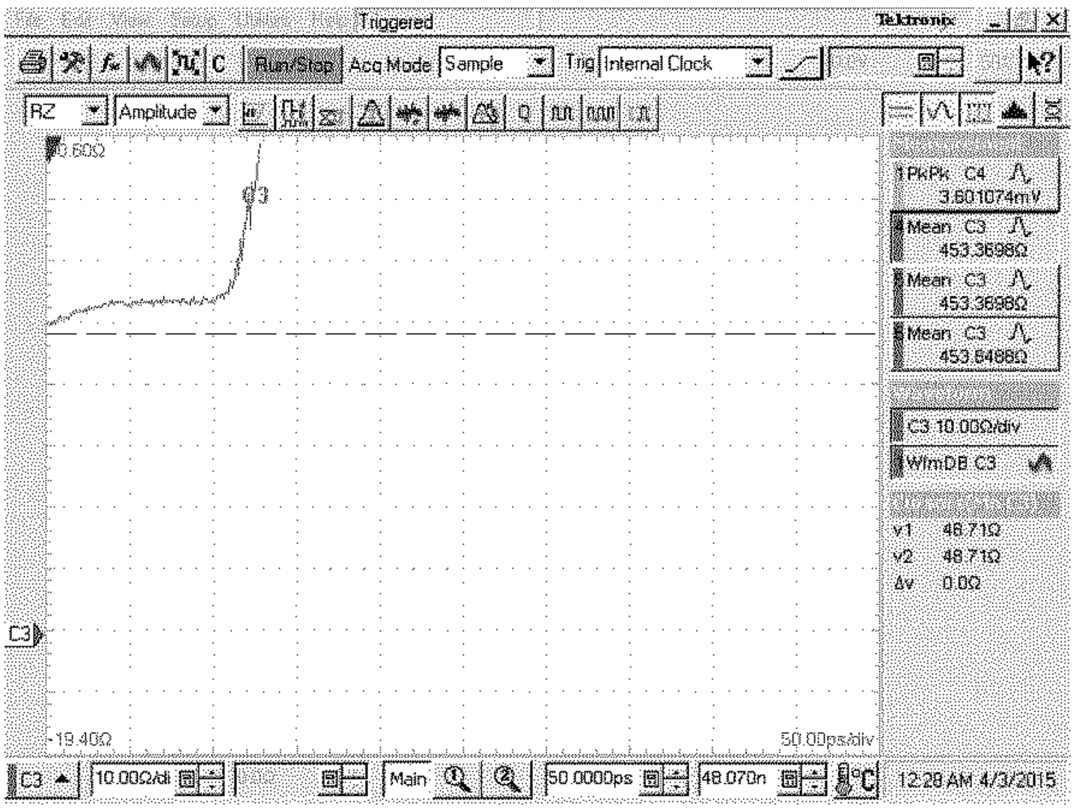

Figure 23 Open circuit reflection waveform with a TDR scope

The antenna feeder trace on the mini mote is about 1cm long, so the time it takes to round travel the trace is about 134ps, which is equal to 2.68 divisions on the time axis of the TDR scope. The calculation is shown in Equation 4-7 and Equation 4-8.

$$t_{mini} = 2 \times \frac{length\ of\ the\ trace}{velocity\ of\ propogation\ on\ trace} \approx 2 \times \frac{1cm}{\frac{3\times10^8}{\sqrt{4.02}}\, m/s} = 134ps \qquad (4\text{-}7)$$

$$\frac{134ps}{50ps/div} = 2.68\ div \qquad (4\text{-}8)$$

The reflection waveform on the antenna feeder trace of the mini mote is shown in Figure 24. The reflection starts after the second division from left. Count 2.68 divisions from the starting point, find the impedance using cursors. The impedance of the trace of the mini mote is about 48.71Ω.

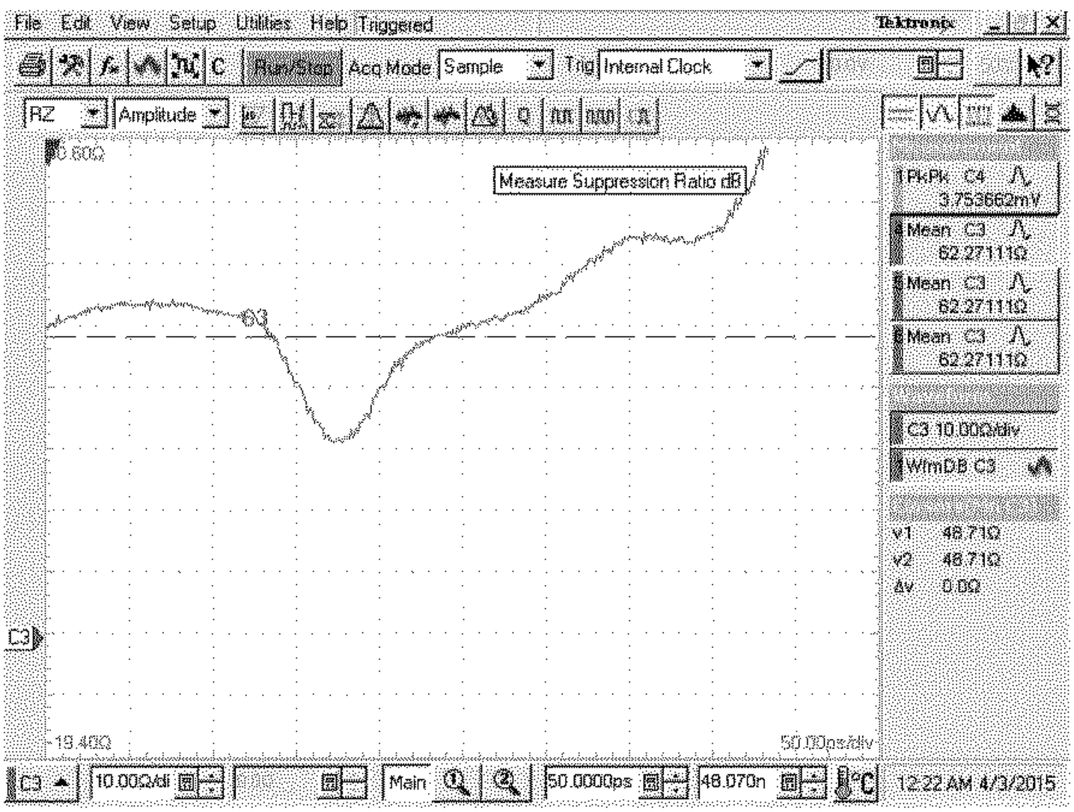

Figure 24 Reflection waveform of the mini mote with a TDR scope

The antenna feeder trace on the LTP5900-WHM module is about 1.5cm.

$$t_{LTP} \approx 2 \times \frac{1.5cm}{\frac{3\times10^8}{\sqrt{4.02}}m/s} = 200ps \quad (4\text{-}9)$$

$$\frac{200ps}{50ps/div} = 4\ div \quad (4\text{-}10)$$

Count 4 divisions from the starting position, the impedance of the trace on the LTP5900-WHM module is about 22.76Ω, as shown in Figure 25. The impedance of the LTP5900-WHM module is less than 50Ω. It might be the output impedance of the LTC5800-WHM IC is less than 50Ω, and the trace on the LTP5900-WHM module is designed to match the output impedance of the LTC5800-WHM IC.

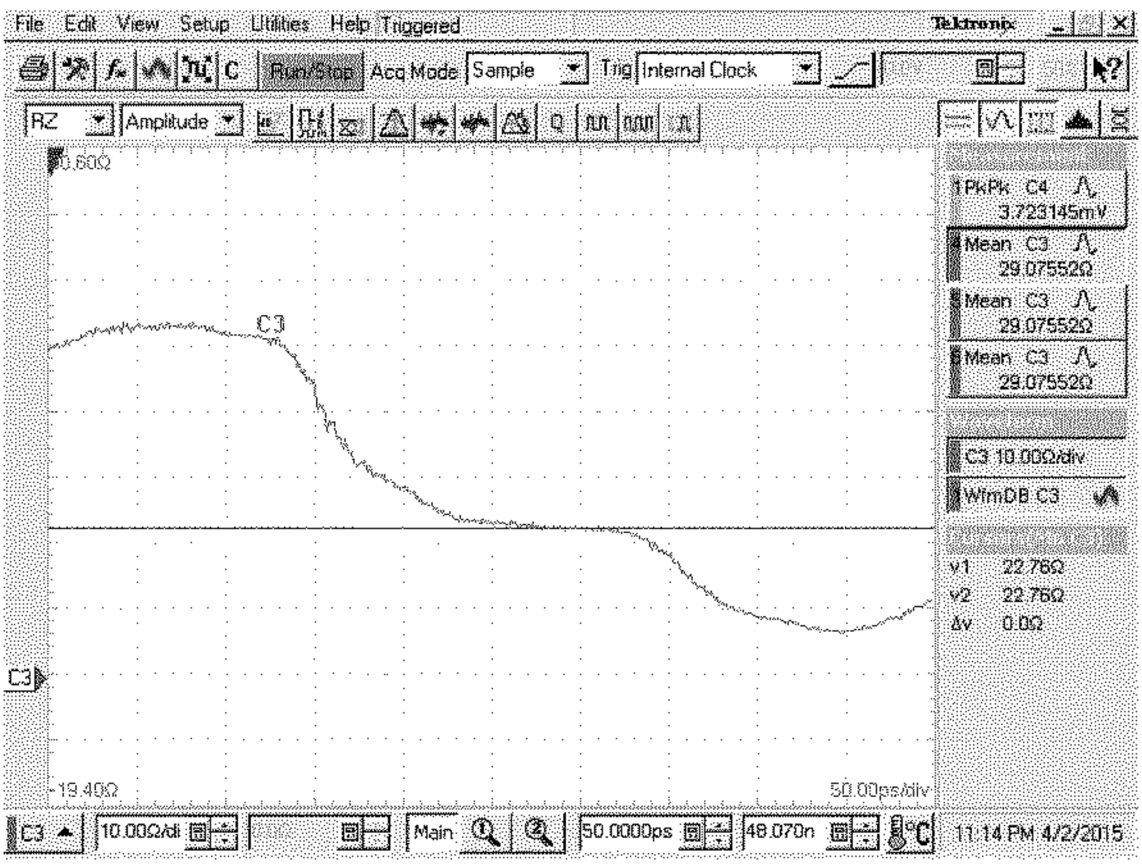

Figure 25 Reflection waveform of the LTP5900-WHM module on a TDR scope

6. WirelessHART Mote Radiated Power Measurement and Comparison

The power measurements are done on all the 16 channels on the mini mote, numbering from 0 to 15 corresponding to IEEE 2.4GHz channels 11-26. Each channel is separated by 5MHz (as shown in Figure 26) [3].

The output power transmitted by the LTC5800-WHM IC is measured on a spectrum analyzer. The measurement setup and the results are provided in Section 5.1.

The radiated power, when the mote is connected to a monopole antenna, is measured in an anechoic chamber. The measurement setup and the results are provided in Section 5.2.

Both of the output power and radiated power measurements are done when the mote is in radio test mode [17], which is selected by the testRadioTx command [18]. The instructions to program and put the mote into radio test mode are provided in Appendix E.

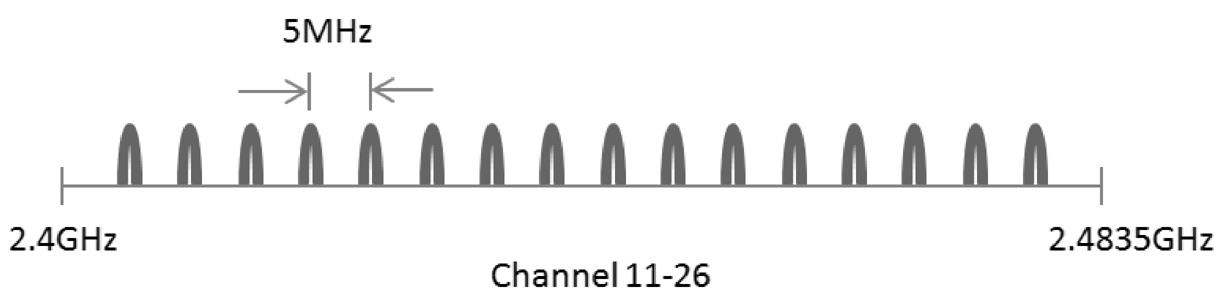

Figure 26 IEEE 802.15.4 Channels

6.1. Output Power Measurement with a Spectrum Analyzer

To set up the measurements on the spectrum analyzer, connect the MMCX antenna connector (Jack) on the mini mote to the spectrum analyzer, a connector adapter may be needed.

On the spectrum analyzer, the frequency span is set to 1 MHz, RBW to 1 kHz and VBW to 100 Hz. The center frequency is set to the center frequency of the channel under measurement. The measurement results are shown in Table 5 and Figure 28.

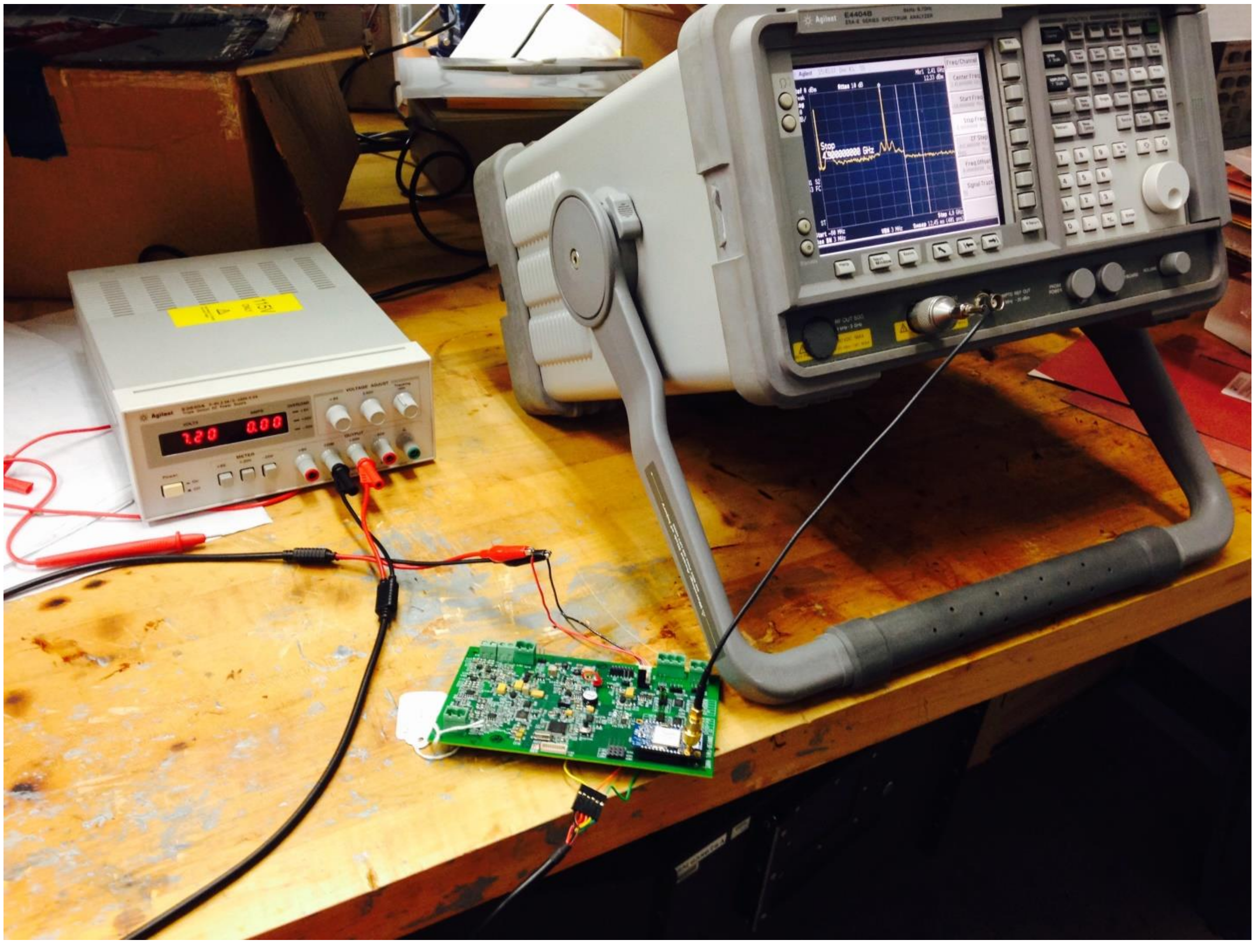

Figure 27 Output power measurement setup with a spectrum analyzer

Table 5 The output power level measurement results on the spectrum analyzer

Channel	Center Frequency(GHz)	The mini mote		The LTP5900-WHM module		Power Difference (dBm)
		Peak Frequency(GHz)	Peak Power(dBm)	Peak Frequency(GHz)	Peak Power(dBm)	
0	2.405	2.405	8.048	2.404998	10.45	-2.402
1	2.410	2.41	8.384	2.409998	10.18	-1.796
2	2.415	2.415	8.028	2.414998	10.12	-2.092
3	2.420	2.42	7.952	2.419998	10.09	-2.138
4	2.425	2.425	7.865	2.424998	10.09	-2.225
5	2.430	2.43	7.853	2.429998	10.28	-2.427
6	2.435	2.435	7.852	2.434998	10.3	-2.448
7	2.440	2.44	7.794	2.439998	10.02	-2.226
8	2.445	2.445	7.77	2.444998	10.06	-2.29
9	2.450	2.45	7.738	2.449998	10.05	-2.312
10	2.455	2.455	7.74	2.454998	10.18	-2.44
11	2.460	2.46	7.696	2.459998	10.44	-2.744
12	2.465	2.465	7.769	2.464998	10.2	-2.431
13	2.470	2.47	7.831	2.469998	10.27	-2.439
14	2.475	2.475	7.115	2.474998	9.618	-2.503
15	2.480	2.48	7.146	2.479998	9.391	-2.245

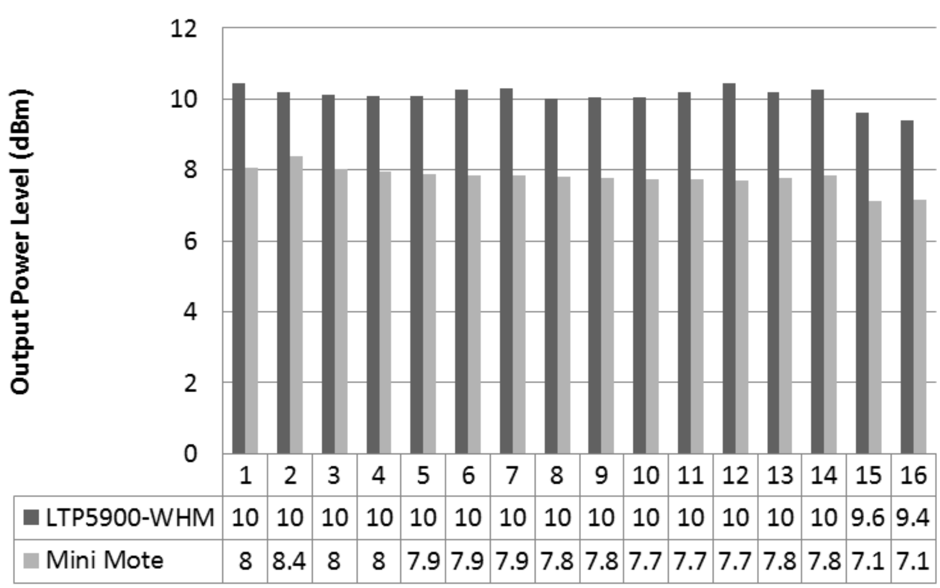

Figure 28 The output power level of the mini mote and the LTP5900-WHM module

6.2. Radiated Power Measurement in an Anechoic Chamber

When used in the field, the WirelessHART is connected to a monopole antenna with an input impedance of 50Ω. It is necessary to test the radiated power of the mini mote.

The radiated power level of the mote can be done in the anechoic chamber, as shown in Figure 29 and Figure 30. The mote transmits an unmodulated tone through an antenna. On the other side of the chamber, a receiving antenna receives the radio energy and displays it on a spectrum analyzer which can be observed outside the chamber. The measurement results are shown in Table 6 and Figure 31.

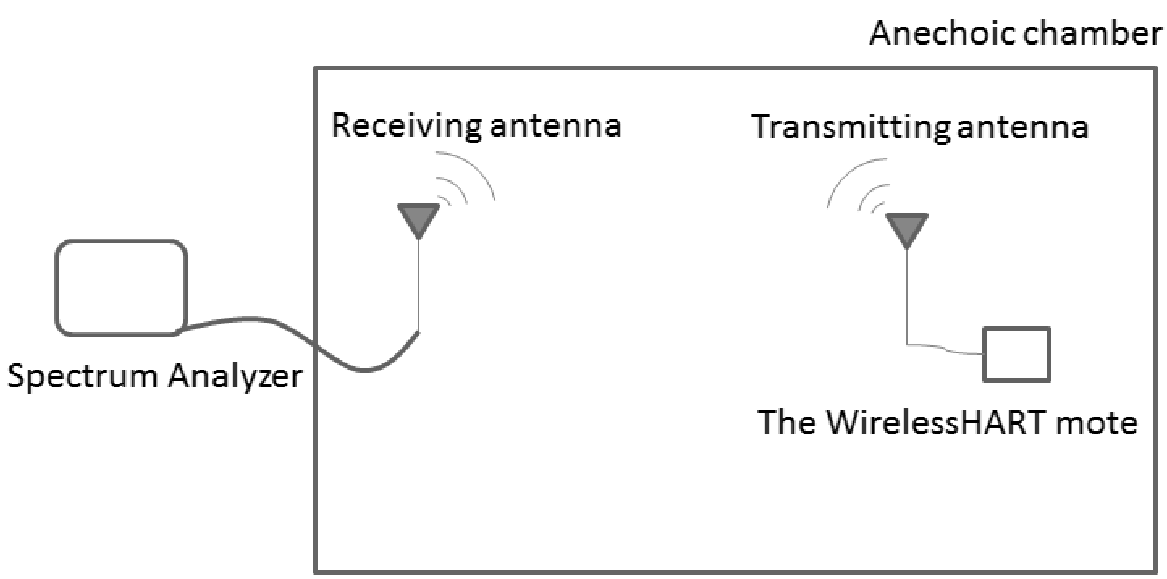

Figure 29 Radiated power measurement principle diagram

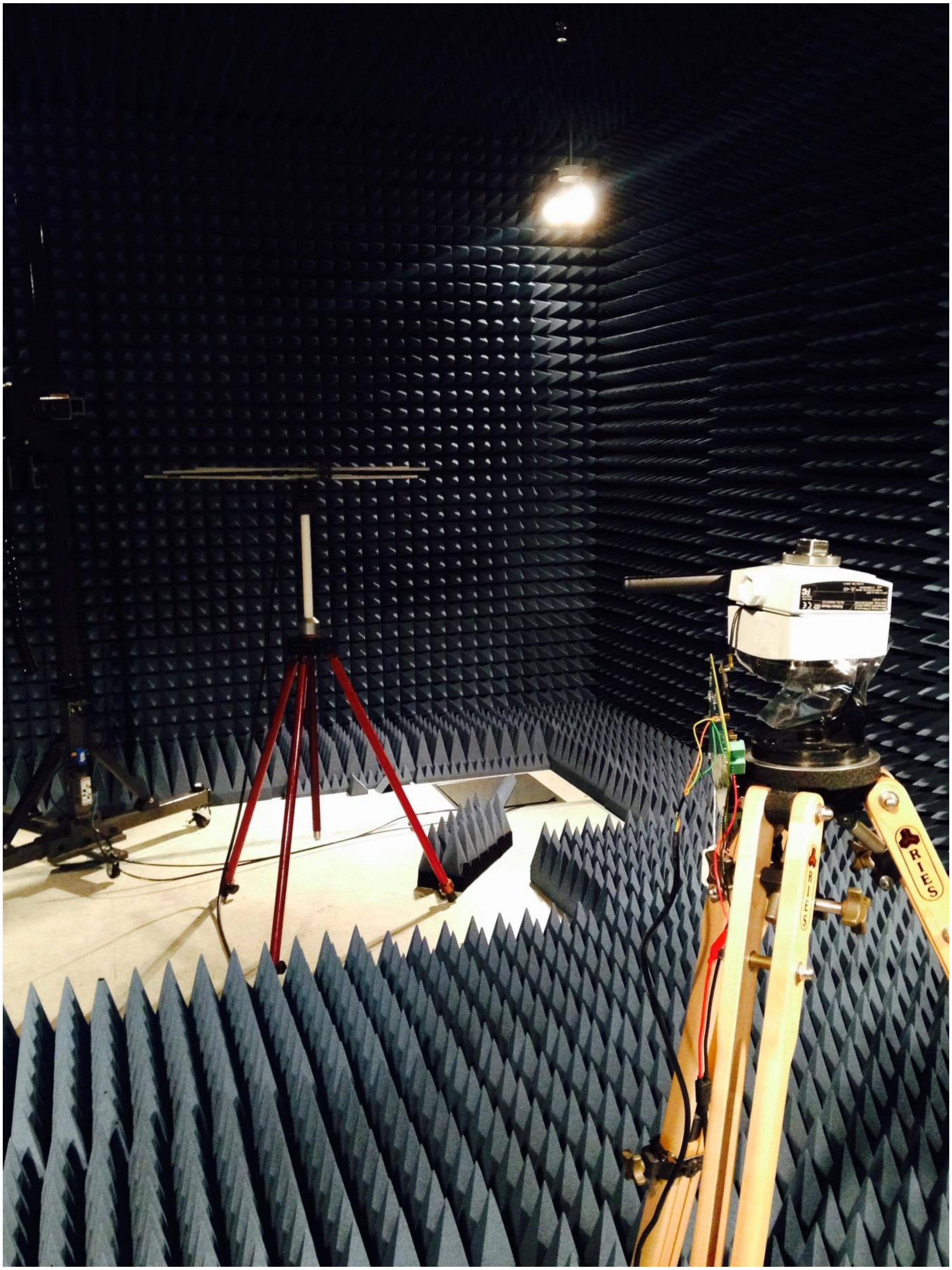

Figure 30 Radiated power measurement setup inside an anechoic chamber

Table 6 The radiated power level measurement results in the anechoic chamber

Channel	Center Frequency(GHz)	The mini mote		The LTP5900-WHM module		Power Difference (dBm)
		Peak Frequency(GHz)	Peak Power(dBm)	Peak Frequency(GHz)	Peak Power(dBm)	
0	2.405	2.405	-35.71	2.404998	-33.86	-1.85
1	2.410	2.41	-35.69	2.41	-33.09	-2.6
2	2.415	2.415	-35.52	2.415	-32.99	-2.53
3	2.420	2.42	-35.56	2.42	-33.15	-2.41
4	2.425	2.425	-36.32	2.425	-33.35	-2.97
5	2.430	2.43	-36.64	2.43	-33.68	-2.96
6	2.435	2.435	-37.81	2.435	-34.71	-3.1
7	2.440	2.44	-38.4	2.44	-34.95	-3.45
8	2.445	2.445	-37.97	2.444993	-34.63	-3.34
9	2.450	2.45	-39.12	2.449986	-34.8	-4.32
10	2.455	2.455	-38.81	2.454993	-34.76	-4.05
11	2.460	2.46	-39.98	2.459993	-35.04	-4.94
12	2.465	2.465	-39.13	2.464993	-34.83	-4.3
13	2.470	2.47	-40.06	2.469986	-35.83	-4.23
14	2.475	2.475	-39.96	2.475	-36.22	-3.74
15	2.480	2.48	-40.43	2.479986	-36.17	-4.26

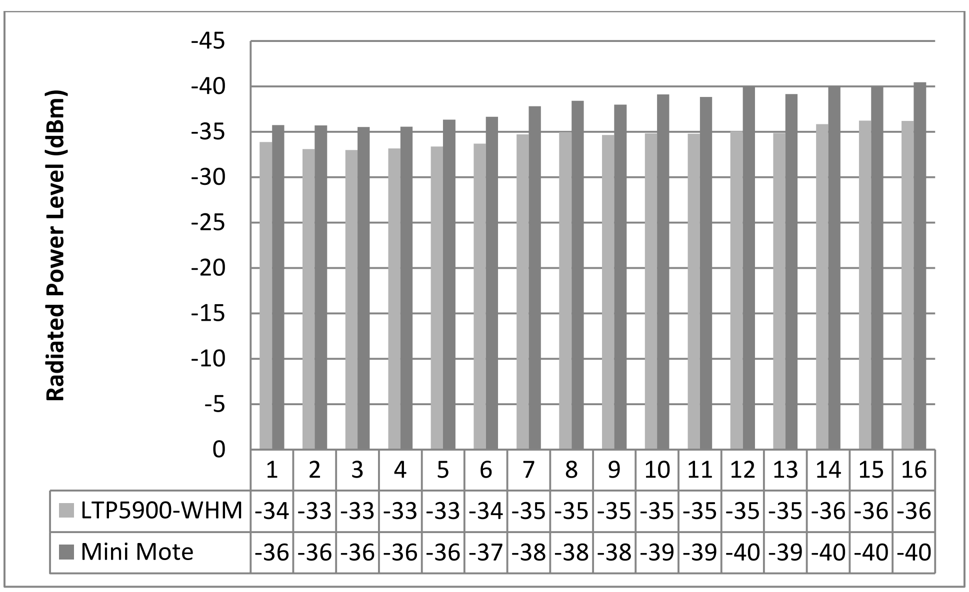

Figure 31 The radiated power level of the mini mote and the LTP5900-WHM module

6.3. Comparison and Analysis

According to the measurement results, the power sent to the antenna is about 2dBm less from the mini mote than from the LTP5900-WHM module. This is attributed to the output impedance of the LTC5800-WHM IC being less than 50Ω. Because the output impedance does not match the antenna feeder trace, more power is reflected on the mini mote than on the LTP5900-WHM module. The radiated power level on the mini mote is about 2 to 4 dBm less than the LTP5900-WHM module.

7. Conclusion and Recommendations

Compared to the original WirelessHART solution, the improved design removed the 4-20 mA current loop between the device and adapter, redesigned the I/O board to integrate the WirelessHART mote, and redesigned the WirelessHART mote to fit on the I/O board. In general, the improved design results in a more power efficient, less expensive, and more integrated WirelessHART enabled device.

The PCB size of the mini mote is almost half of the size of the LTP5900-WHM module, though the power level is lower than the LTP5900-WHM module. This is because the output impedance of the LTC5800-WHM IC is lower than 50Ω.

To improve the power level, it is worth trying to match the impedance to less than 50Ω, between the output impedance of the IC and 50Ω. Another possible improvement on the mini mote is to make the CLI UART port as I/O pins, for the CLI UART provides human debugging interaction.

The I/O board can be reduced in size in the future. Once the mini mote on the I/O board is successfully connected the wireless gateway [19], the architecture of the improved WirelessHART device is generally proved to be successful and all the debug pins and programming headers can be removed. The I/O board also needs mechanical design to retrofit inside the device.

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Appendix A: WirelessHART Mote and I/O Board Components List

Table 7 The mini mote components and price list

Value	Description	Manufacturer part number	Quantity per board	Unit price	Total price
0R05	RES 0.0 OHM 1/10W 0603 SMD	ERJ-3GEY0R00V	3	0.00209	0.00627
20MHz XTAL	CRYSTAL 20MHZ 18PF SMD	ABM8G-20.000MHZ-18-D2Y-T	1	0.5265	0.5265
100n	Ceramic Capacitor NMC Series 0402 0.1uF 16 V ±10 %	NMC0402X7R104K16TRPF	2	0.002	0.004
2u2	CAP CER 2.2UF 16V 10% X5R 0603	CL10A225KO8NNNC	1	0.02565	0.02565
470n	CAP CER 0.47UF 16V 10% X7R 0603	CL10B474KO8NNNC	1	0.011	0.011
32.768 KHz	CRYSTAL 32.768KHZ 12.5PF SMD	ECS-.327-12.5-34B	1	0.546	0.546
100pF 0402	CAP CER 100PF 50V 5% NPO 0402	CC0402JRNPO9BN101	5	0.00198	0.03168
600 Ohm bead	FERRITE CHIP BEAD 600 OHM SMD 0402	BLM15HD601SN1D	3	0.0509	0.1527
1UF	CAP CER 1UF 25V 10% X7R 1206	1206YC105KAT4A	1	0.0703	0.0703
220nF	CAP CER 220PF 50V 1% NP0 0603	CL10C221FB8NNNC	1	0.026	0.026
2u2H Inductor	FIXED IND 2.2UH 120MA 400 MOHM	LQM18FN2R2M00D	1	0.04403	0.04403
WL HART IC	IC SMARTMESH MOTE 2.4GHZ 72QFN	LTC5800IWR-WHMA#PBF	1	36	36
MMCX Jack	CONN MMCX JACK STR 50 OHM PCB	1408150-1	1	4.53001	4.53001
56nF 0402	(CAP, CER, 56nF, 6.3V, +/-10%, X7R, 0402	C0402C563K9RACTU	10	0.0555	0.555
0.22uF	CAP, 0.22uF, 6.3V, 10%, X7R, 0402	JMK105B7224KV-F	1	0.0084	0.0084
					42.5375

Table 8The I/O board components list

Value	Description	Manufacturer part number	Quantity per board
1.5K	RES THKFLM 0603 1.5K OHM 1% 1/10W 100PPM/ C SMD - Tape and Reel	NRC06F1501TRF	5
0R05	RES 0.0 OHM 1/10W 0603 SMD	ERJ-3GEY0R00V	37
470K	RES 470K OHM 1/10W 1% 0603 SMD	NRC06F4703TRF	14
1M	RES 1.00M OHM 1/10W 1% 0603 SMD	NRC06F1004TRF 1-1879417-9 CRCW06031M00DHEAP	1
680R	RES 680 OHM 1/10W 1% 0603 SMD	RMCF0603FT680R	44
10K	RES 10.0K OHM 1/10W 1% 0603 SMD	NRC06F1002TRF	2
150K	RES 150K OHM 1/10W 1% 0603 SMD	RMCF0603FT150K	1
4R7 (1W)	CRCW Series 2512 1 W 4.7 Ohm ±5 % ±200 ppm/K Rectangular SMT Chip Resistor	CRCW25124R70JNEG	4
100K POT	TRIMMER 100K OHM 0.25W SMD	3224W-1-104E	1
180K	RES 180K OHM 1/10W 1% 0603 SMD	RC0603FR-07180KL	1
560K	RES 560K OHM 1/10W 1% 0603	AC0603FR-07560KL	1
4M7	RES 4.70M OHM 1/10W 1% 0603 SMD	RC0603FR-074M7L	1
470K 0402	RES 470K OHM 1/16W 1% 0402 SMD	RC0402FR-07470KL	1
390K	RES 390K OHM 1/10W 1% 0603 SMD	RC0603FR-07390KL	1
332K	RES 332K OHM 1/10W 1% 0603 SMD	RC0603FR-07332KL	1
383K	RES 383K OHM 1/10W 1% 0603 SMD	RC0603FR-07383KL	1
825K	RES 825K OHM 1/10W 1% 0603 SMD	RC0603FR-07825KL	1

3K3	RES 3.30K OHM 1/10W 1% 0603 SMD	RC0603FR-073K3L	1
82K	RES 82.0K OHM 1/10W 1% 0603 SMD	RC0603FR-0782KL	1
22n	CAP CER 0.022UF 50V 10% X7R 0603	CL10B223KB8NNNC	2
1n	CAP CER 1000PF 50V 10% X7R 0603	CL10B102KB8NNNC	1
10u	CAP CER 10UF 25V 10% X5R 1206	CL31A106KAHNNNE	4
100n	CAP CER 0.1UF 50V Y5V 0603	CL10B104KB8NNNC	8
2u2	CAP CER 2.2UF 16V 10% X5R 0603	CL10A225KO8NNNC	2
470n	CAP CER 0.47UF 16V 10% X7R 0603	CL10B474KO8NNNC	1
47p	CAP CER 47PF 50V 5% NP0 0603	CL10C470JB8NNNC	1
100p	CAP CER 100PF 50V 5% NP0 0603	CL10C101JB8NNNC	4
1u	CAP CER 1UF 16V 10% X7R 0603	CL10B105KA8NNNC	3
22pF	CL10 Series 0603 22 pF 50 V ±5% C0G Surface Mount Multilayer Ceramic Capacitor	CL10C220JB8NNNC	1
100n	Ceramic Capacitor NMC Series 0402 0.1uF 16 V ±10 % Tolerance X7R SMT Ceramic Capacitor	NMC0402X7R104K16TRPF	7
4u7	0603 4.7uF 10 V ±10% X5R Surface Mount Multilayer Ceramic Capacitor	NMC0603X5R475K10TRPF	1
15pF	CAP 15pF 50V 5% NPO 0603	C1608C0G1H150J	4
100pF 0402	CAP CER 100PF 50V 5% NPO 0402	CC0402JRNPO9BN101	6
10uF 16V	CAP TANT 10UF 16V 20% 1206	T491A106M016AT	1
0.22uF (1206)	CAP CER 0.22UF 50V 5% X7R 1206	C1206C224J5RACTU	1

56nF (0402)	CAP CER 0.056UF 16V 10% X7R 0402	GRM155R71C563KA88D	10
2.2uH	INDUCTOR POWER 2.2UH 1.8A SMD	74451022	1
600 Ohm bead	FERRITE CHIP BEAD 600 OHM SMD 0402	BLM15HD601SN1D	3
2u2H Inductor	FIXED IND 2.2UH 120MA 400 MOHM	LQM18FN2R2M00D	1
10uH (1212)	FIXED IND 10UH 870MA 260 MOHM	LQH3NPN100MM0L	1
LED Blue	LED 470NM BLUE CLEAR 0603 SMD	LNJ937W8CRA	44
74LVC573	74LVC573A Series 3.6 V 3-State Octal D-Type Transparent Latch - TSSOP-20	74LVC573APW,118	7
FMDA291P	MOSFET -20V Single P-Ch. Power Trench MOSFET	FDMA291P	1
TPS61220	IC DC-DC CONVERTER, BOOST, 2MHZ, SC-70-6; Primary Input Voltage:5.5V; No. of Outputs:1; Output Current:200mA; No. of Pins:6;	TPS61220DCKR	1
2 x 5.08mm (P)	CONN HEADER VERT 2POS 5.08MM	1755736	2
1 x 2 x 2.54mm	Headers & Wire Housings 2 POS 2.54mm Solder Conn Unshrouded HDR	5-146274-2	14
1 x 3 x 2.54mm	Conn Unshrouded Header HDR 3 POS 2.54mm Solder ST Thru-Hole	5-146274-3	29
2 x 5 x 2.54mm BOX	BHR Series 10 Position Through-Hole Dual Row Straight Shrouded Box Header	BHR-10-VUA 5103308-1	3
2 x 3 x 2.54mm	3 Position Through-Hole Dual Row Straight .100 Header	PH2-06-TA9-146256-0-03	3
1 x 4 x 2.54mm	Header 4 position, 2.54mm pitch through hole	825433-43-644456-468002-404HLFTSW-104-23-F-S	1
3.6864MHz	CRYSTAL 3.6864MHZ 18 PF SMD	ATS037BSM-1	1

2 x 7 x 2.00mm (S)	CONN RCPT 2MM 14POS DL VERT SMD	MMS-107-02-T-DV	1
100R (2512)	RES 100 OHM 1W 1% 2512 SMD	ERJ-1TNF1000U	1
15K	RES SMD 15K OHM 1% 1/10W 0603	MCR03ERTF1502	1
AD5700	IC HART MODEM LP INT OSC 24LFCSP	AD5700-1ACPZ-RL7	1
BSS138	MOSFET N-CH 50V 220MA SOT-23	BSS138	1
WL HART IC	IC SMARTMESH MOTE 2.4GHZ 72QFN	LTC5800IWR-WHMA#PBF	1
LTC3103	IC REG BUCK SYNC ADJ 0.3A 10DFN	LTC3103EDD#PBF	1
MMCX Jack	CONN MMCX JACK STR 50 OHM PCB	1408150-1	1
32KHz XTAL	CRYSTAL 32.768KHZ 12.5PF SMD	ECS-.327-12.5-17X-TR	1
2 x 5 x 2mm (P)	Strip, header(SMD) 10p(2 x 5 x 2mm) TOP	TMM-105-06-F-D-SM-P	2
20MHz XTAL	CRYSTAL 20MHZ 10PF SMD	ECS-200-CDX-0914	1
1 x 11 x 2mm (S)	CONN RCPT 2MM VERT SGL ROW 11POS	25631101RP2	1

Appendix B: WirelessHART Network Connectivity

There are five steps for the original WirelessHART solution to join a wireless network.1) configure the wireless adapter; 2) configure the gateway; 3) setup WirelessHART connection; 4) connect HART device to the adapter and configure burst modes and measuring period; 5) setup Wireless HART IP connection between adapter and gateway. Once the HART device is connected to the wireless adapter, it shares the power provided by adapter battery through HART connection as shown in Figure 32 (source: http://www.us.endress.com/en/solutions-lowering-costs/field-network-engineering/wirelesshart-communication-fieldbus-technology).

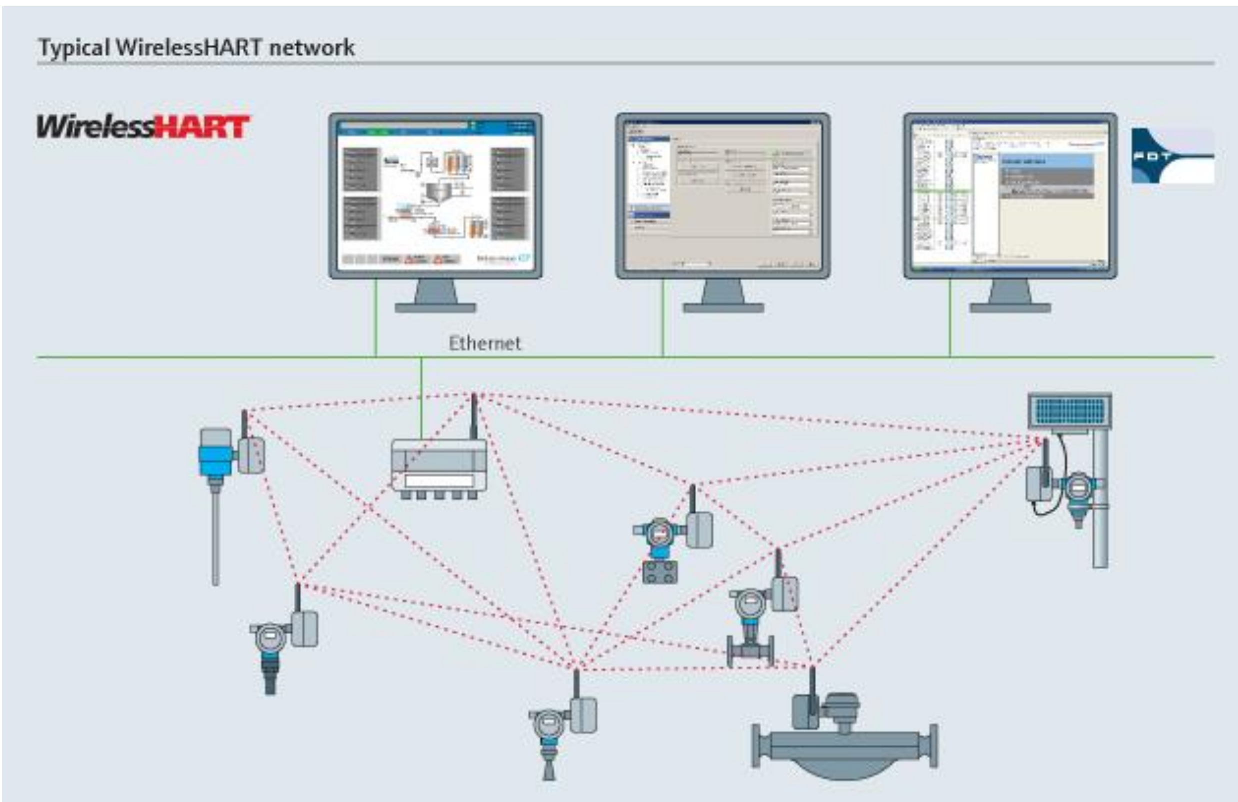


Figure 32 A typical WirelessHART network formed by the original WirelessHART solution

The network is formed by Endress + Hauser wireless adapter SWA70, wireless gateway SWG70 and level flexFMP51. Configurations are done on FieldCare, the Endress+Hauser's universal tool for configuring field devices.

Before trying to connect the wireless network, download HART-IP CommDTM, WirelessHART Adapter DTM and WirelessHART Fieldgate DTM. Execute the .exe file to install the DTMs.

Open Field Care, DTM Catalog -> Update. After updating, the DTMs should be shown on the left pane. Move them to the left pane and click OK. After creating an empty project on Field Care and add a device to it, HART CommDTM and HART IP CommDTM should appear.

Wireless Adapter Configuration

Make sure that DTMs of SWA 70 and FMP50 are loaded to Field Care. The HART modem is connected to PC through USB (COM3) in this case. Check Control Panel/System/Device Manager to see if the modem connected to PC successfully. Turn on the 270Ohm communication resistor on FXA 195. The adapter is powered up by 7.2V DC power.

Create an empty FieldCare project, right click on Host PC and Add Device. Select HART Communication and click OK as shown in Figure 33.

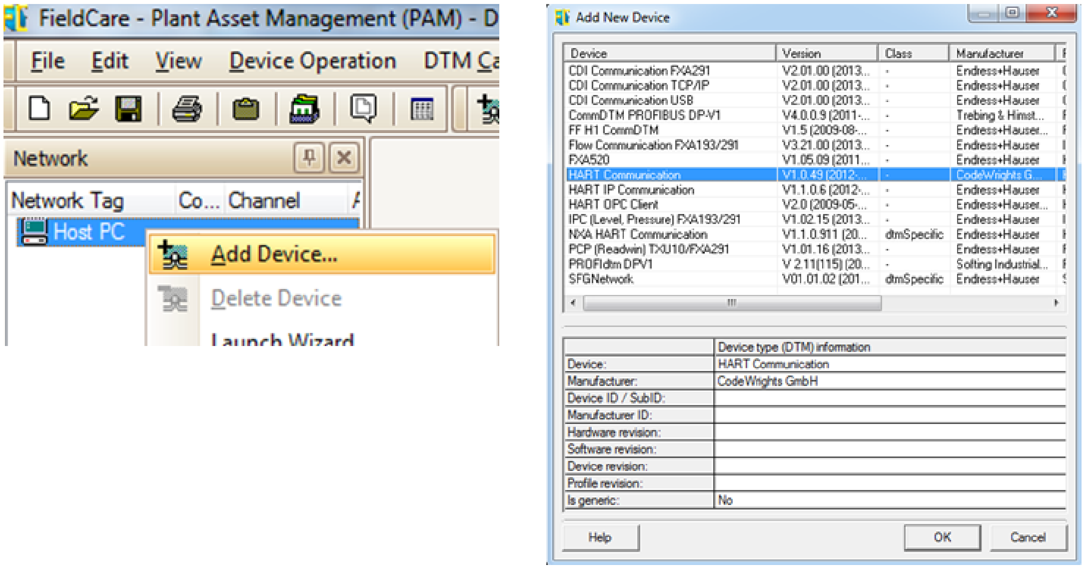


Figure 33 A new HART Communication project on FieldCare

Right click on HART Communication DTM and select Configuration. The Communication interface using is HART modem, Serial Interface is COM3 (USB). There is no need to worry about HART protocol. The HART protocol is selected by default. Address scan is critical. Default address of SWA70 is 15, one can scan from address 0 to address 15 but it will take a little more time. Details are provides in Figure 34.

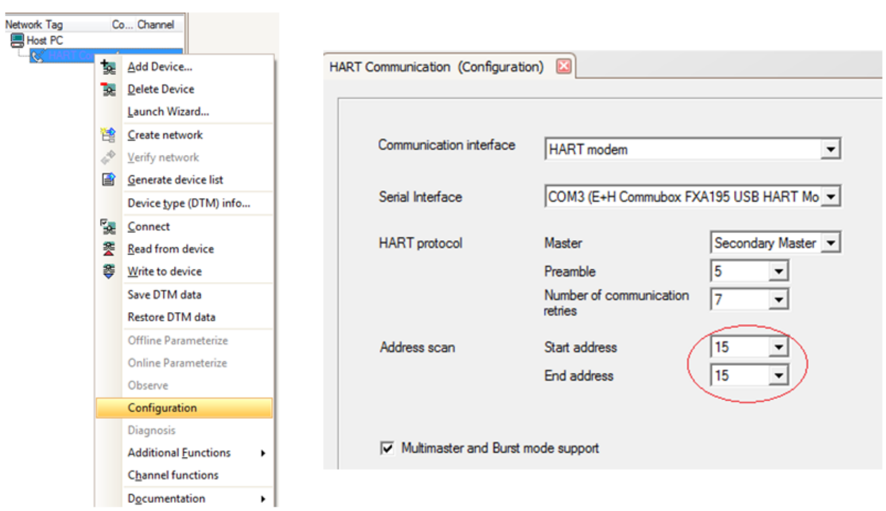


Figure 34 HART communication configuration on FieldCare

Click Create Network in the content menu. FieldCare would start to scan the address that was configured in previous step, as shown in Figure 35. The wireless adapter should be able connect the wireless gateway. If not, check that the connection between the modem to the PC is correct, and then the connection between the modem and the SWA 70. If none of these steps work, try to reset the adapter and start from the beginning.

Now the adapter on FieldCare can be configured. Expand the DTM navigation tree. Identification and Wireless Communication will be used for this project. Names should be created for the Long Tag and Device Tag. For more details of Identification Parameters see Page 62, *SWA70 Operating Instructions* [1]. The country code controls the signal strength. Note that if Japan is selected, there will be a power limitation.

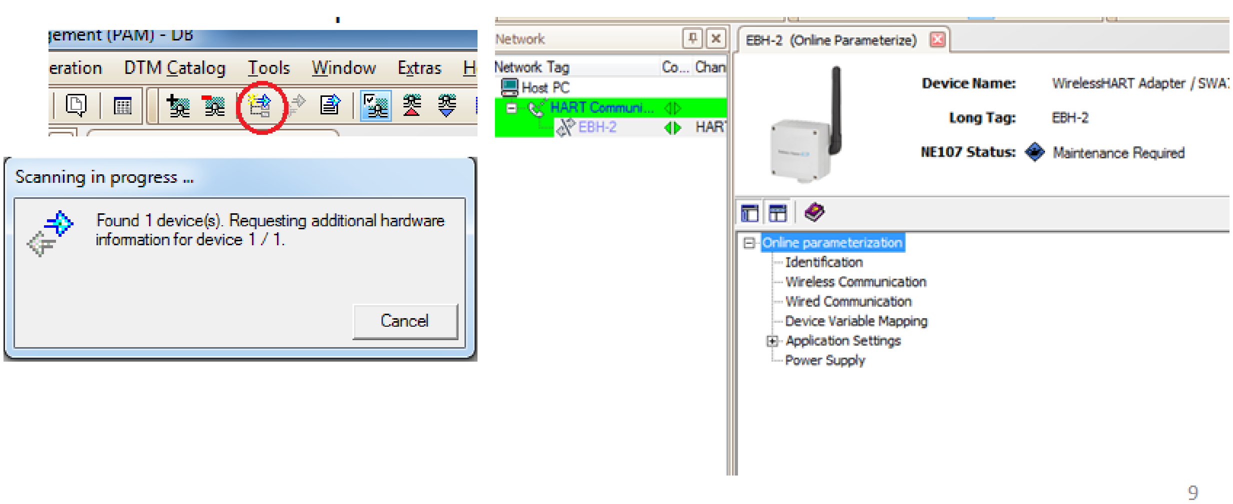


Figure 35 Device address scanning on FieldCare

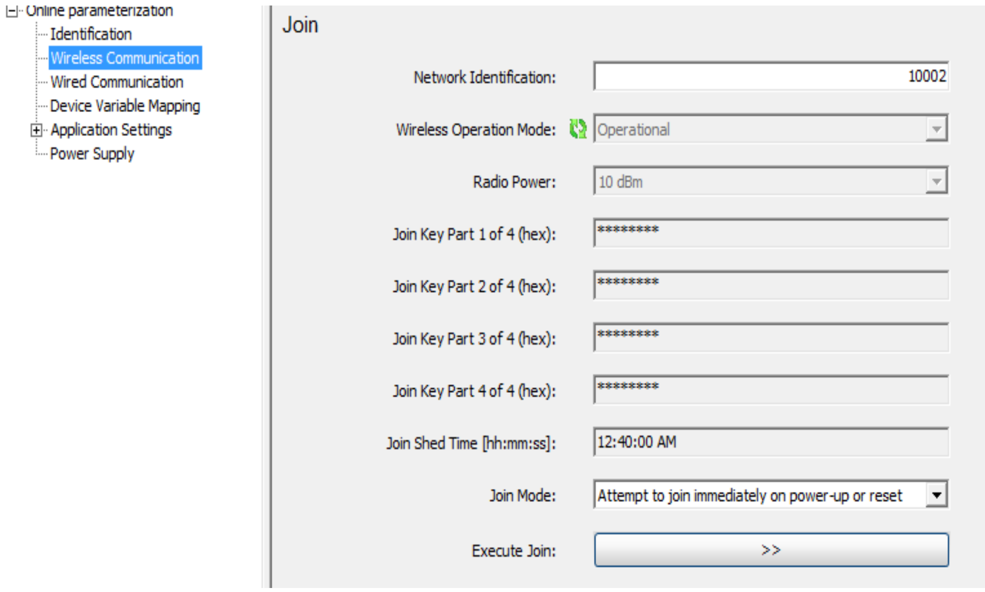


Figure 36 Join keys on the wireless adapter

Wireless Communication Parameters are essential to building wireless communication. Record the Network Identification, as it will be used on the gateway side. Configure the four Join Keys as shown in Figure 36, and record them. (00000001, 00000002, 00000003 and 00000004 were used for this report). They are also needed on the gateway side.

Wireless Gateway Configuration

The Gateways should be connected to the Ethernet port. Follow the following steps to make the connection.

1. Check that the power is switched off

2. If applicable, unscrew the four screws of the housing cover and remove the housing cover.

3. Route the Ethernet cable through the cable gland in the middle of the gateway housing.

4. Connect the Ethernet cable to the terminal block labelled "Ethernet" according to the table on in Figure 29.

If it’s the first time the Gateway ever connected to Ethernet, the default IP of the Gateway is 192.168.1.1. The Gateway needs to be connected to the PC through a cable and the IP address of the PC should be changed to 192.168.1.xx. Record the original IP settings in case it ever needs to be reset. If it’s not the first time the gateway connected to the Ethernet port, the Gateway may already have a configured IP address. Try to connect the gateway through Ethernet if the IP address is known. If it’s not the first time the Gateway was connected to the Ethernet port and the IP address is unknown, it can always be reset to default (192.168.1.1).

Open 192.168.1.1 in a browser and log in with the User Name: admin and Password: admin as shown in Figure 38.

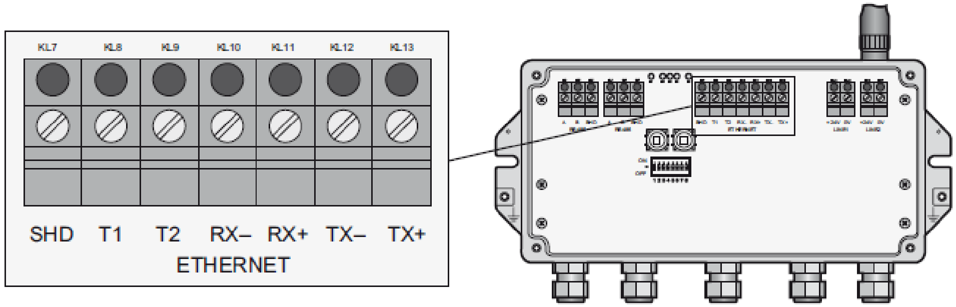


Figure 37 The wireless gateway SWG70 Ethernet port

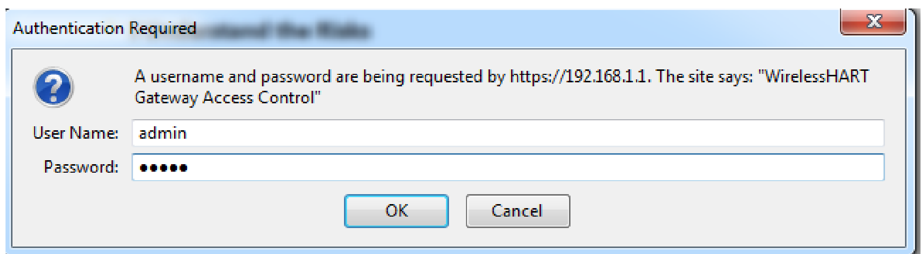


Figure 38 The wireless gateway login

There are many alternative ways to connect to the gateway if it cannot be reached through a web browser. If the gateway is using the default IP (192.168.1.1), make sure that the gateway is connected directly to the PC, not through the Ethernet port. Also, check that the IP address of the PC is in the form of 192.168.1.xx. If the gateway is not using the default IP address and it can't be connected, there is a high possibility that the wrong IP address is used. Reset the gateway and try to connect to it using the default IP address. If none of these solutions work, refer to Page 30, Section 7.2 Ethernet Connection, *SWG70 Operating Instructions* for help. The Identification of the gateway can now be configured as shown in Figure 39.

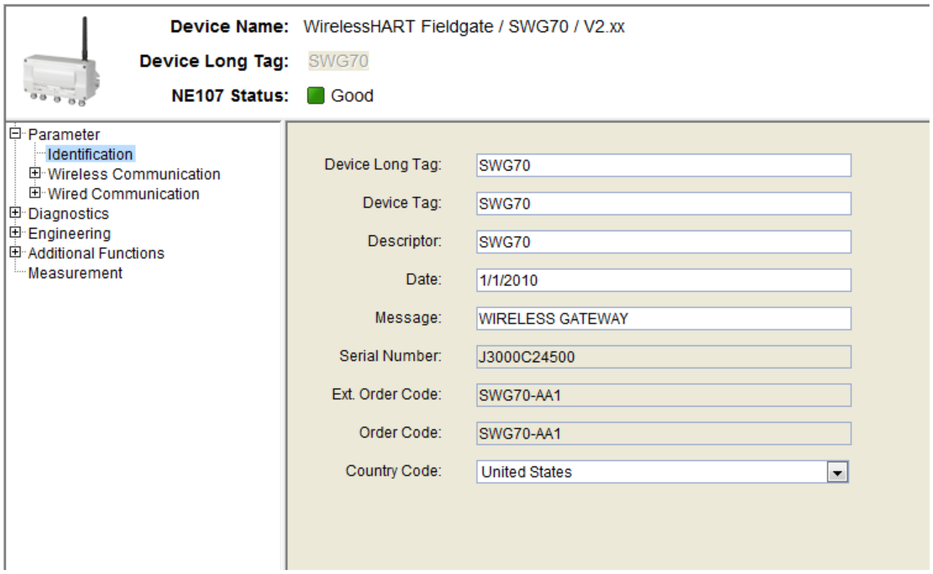


Figure 39 Gateway configuration in a web browser

Navigating to Wireless Communication --> Setup, displays all the parameters needed to setup the wireless communication with the wireless adapter. Create a name for the Network Tag. Finally, Configure the Network ID and the four Join Keys (00000001, 00000002, 00000003 and 00000004), as shown in Figure 40.

After completing the configuration, click “Write Join Information” and click “Yes”. A window should display that the configuration was successful.

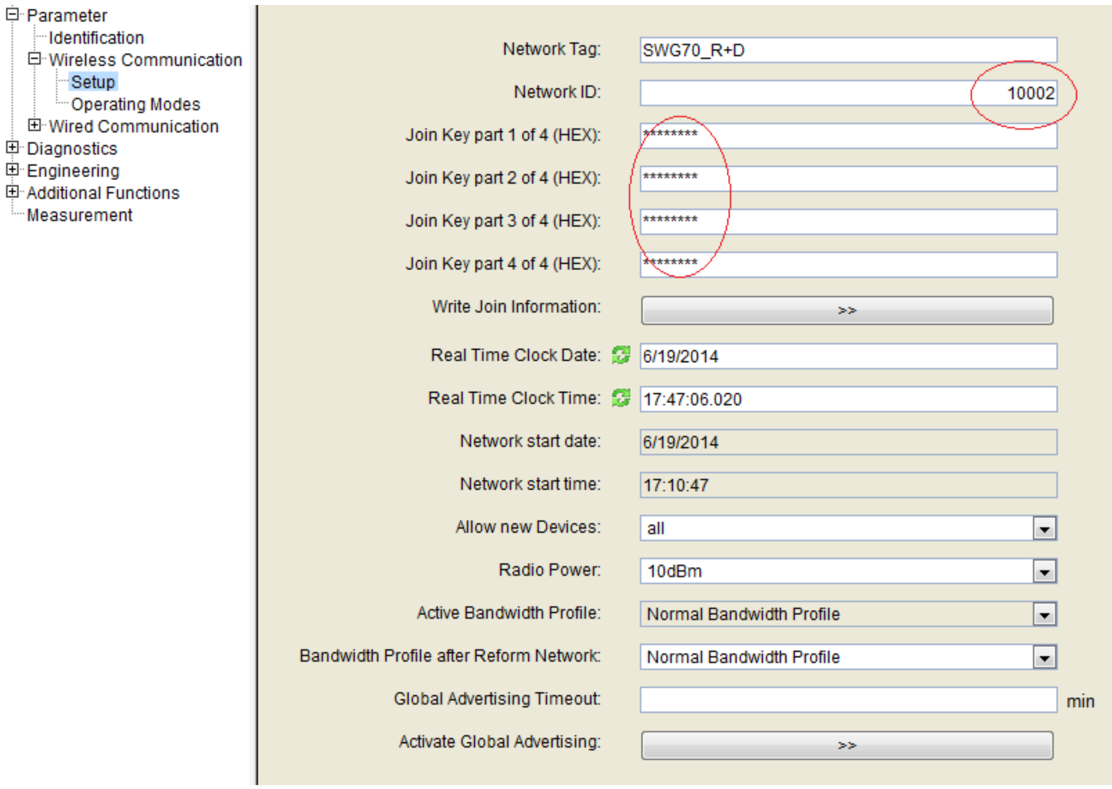


Figure 40 Network ID and join keys on the wireless gateway

Setting up Wireless HART Connection

Now that both the gateway and the adapter are configured, they are able to connect to each other.

In FieldCare, navigate to Wireless Communication. If the current Join Shed Time [hh:mm:ss] is in the form of hh:mm:ss a.m. or hh:mm:ss p.m., the time setting on Window needs to be changed as shown in Figure 33. Click “Execute Join”, should be able to see Join Status updating.

After connection set up, unplug the HART modem. In the web browser, click on “Measurement” to display the adapter list.

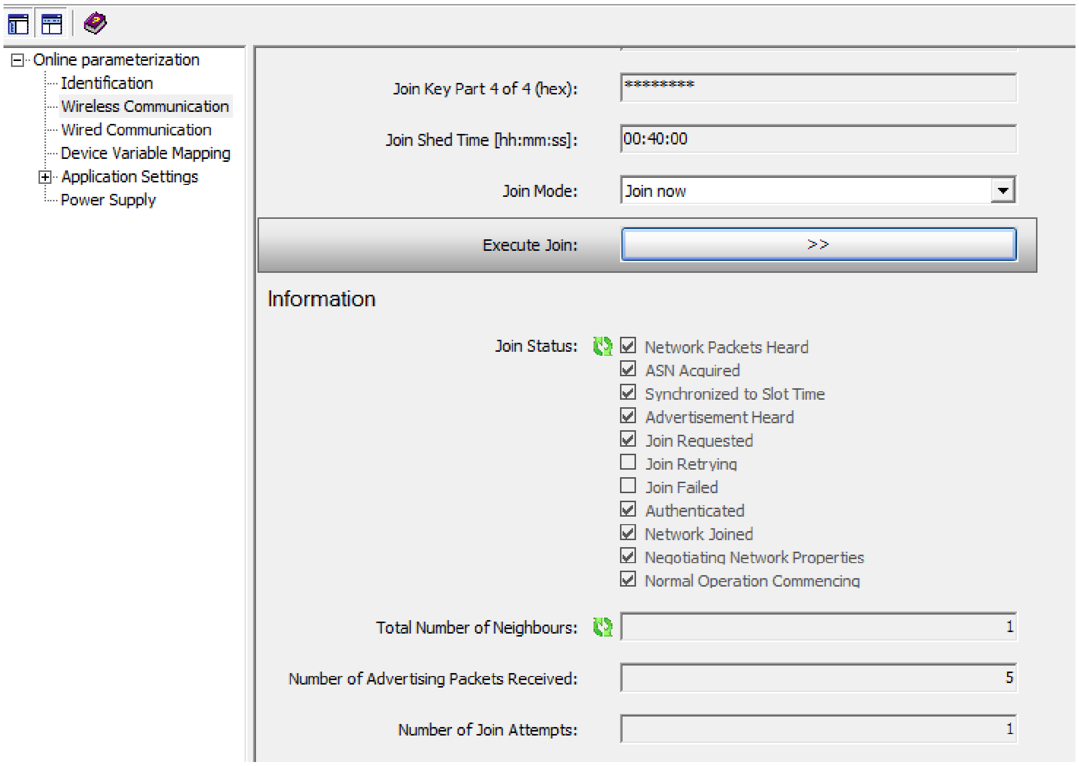


Figure 41 Join execution on the adapter side

Note that there is a possibility that the connection fails due to poor positioning. Please refer to Page 16, *SWG70 Operating Instructions* [1] for further instruction.

Connecting a HART Device to a Wireless Adapter

After the Wireless HART Connection set up, the next step is to attach the HART device to the wireless adapter through the HART port. The HART device powers up once connected to the adapter.

Go to FieldCare project. On Application Settings -> Burst Mode -> Burst Mode 1, as shown in Figure 42 set Burst Mode Control Code to Wireless, Device Index to the long tag of adapter, Period to be 1 min, and Burst Command Number to CMD3. Click on Apply. It should take a few minutes before it finished applying.

Go to Wired Communication and Scan Subdevices, as shown in Figure 43. The device should be found and displayed in the Field Device Table. If not, change the Scan Address to a wider range.

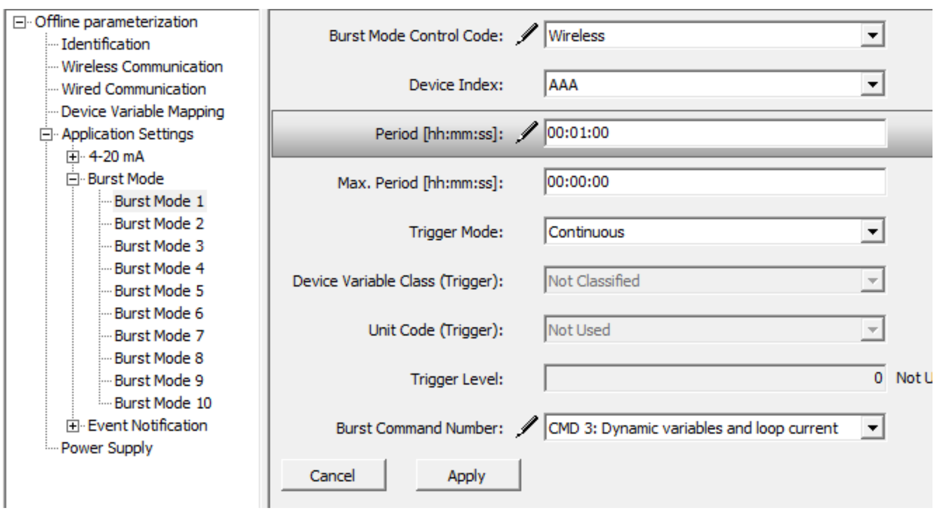


Figure 42 Burst modes of the wireless adapter on FieldCare

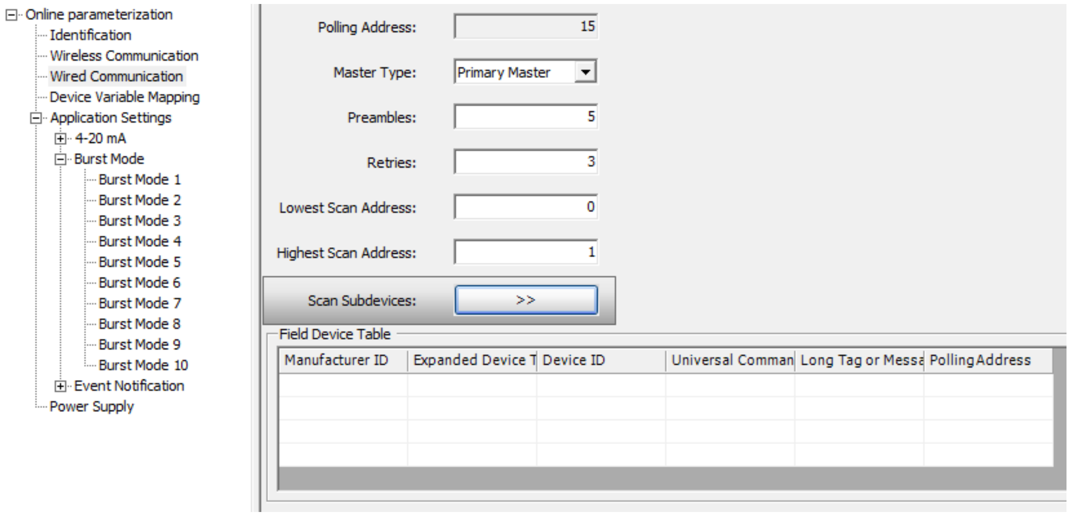


Figure 43 HART device Scanning on FieldCare

Go to back to Application Settings -> Burst Mode -> Burst Mode 2, set Burst Mode Control Code to Wireless, Device Index to the long tag of Sensor, Period to be 1 min, and type 3 to Burst Command Number, as shown in Figure 44. Click on Apply.

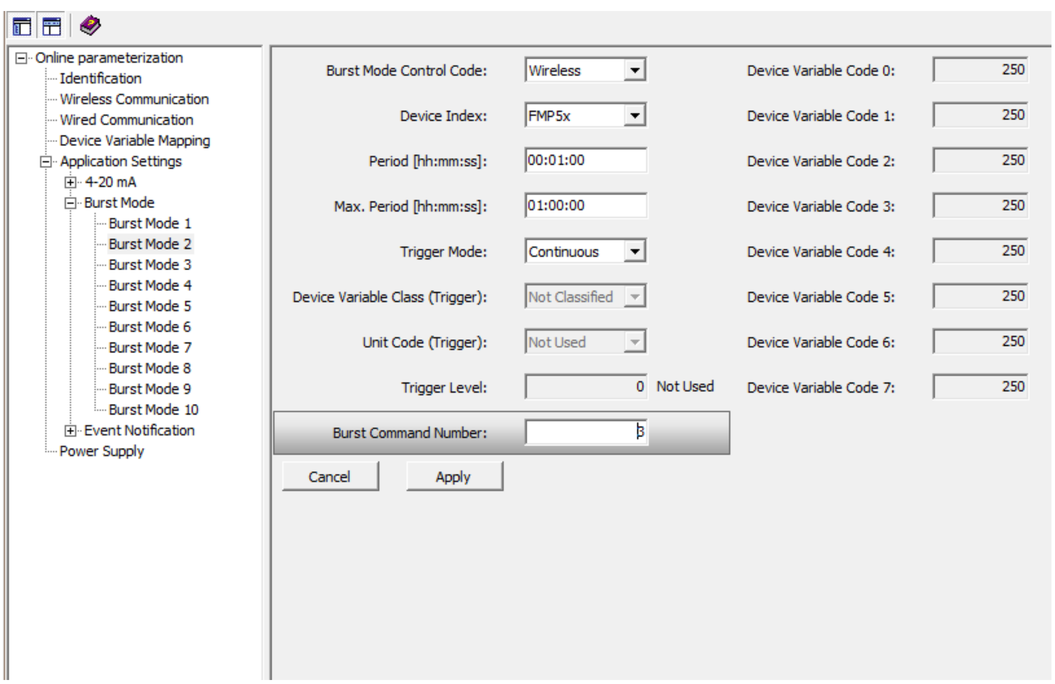


Figure 44 HART device burst modes on FieldCare

After configuration, close FieldCare, repower the adapter and wait for 1 minute. The green LED light should be on, the yellow LED flash at 1Hz and probably the red LED light flashes at 1Hz. That is caused by the level flex not measuring anything and returning errors. On web browser, go to Measurement and the Sensor is displayed on the window as well as its returned value under adapter, as shown in Figure 45. This means the Sensor has been added to the network successfully. Note that the Device Status of level flex FMP5x is in error (Loop Current Saturated) because the level flex is not working under right condition.

Setting up Wireless HART IP Connection

After setting up the WirelessHART connection, it is time to set up the WirelessHART IP Connection. In WirelessHART IP Connection, there is no need to use a HART Modem to configure the adapter.

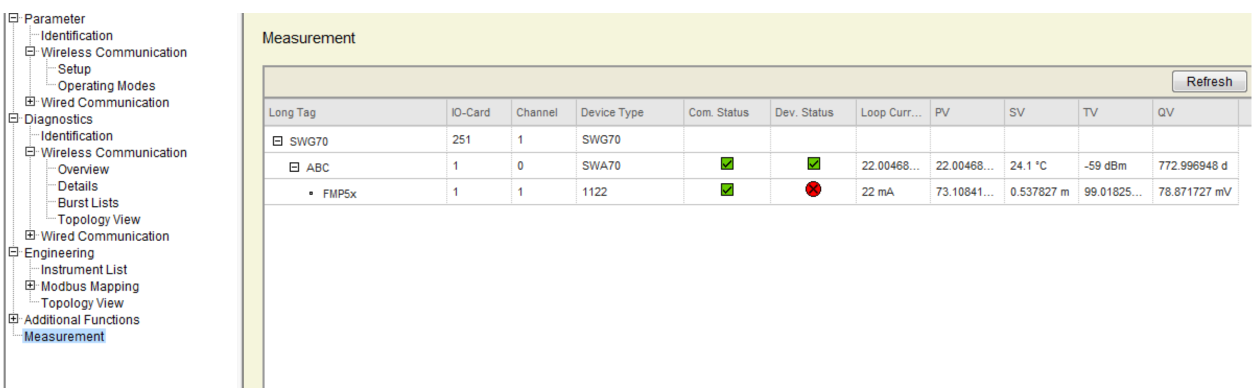


Figure 45 Measurements of a level flex on web browser

Create a new project. Right click on Host PC and Add New Device, choose HART IP Communication. Right click on HART IP Communication and Add New Device, choose WirelessHART Fieldgate/SWG70 V2.0. Details are shown in Figure 46.

Right click on HART IP Communication -> Additional Functions->Set DTM Addresses, as shown in Figure 47.

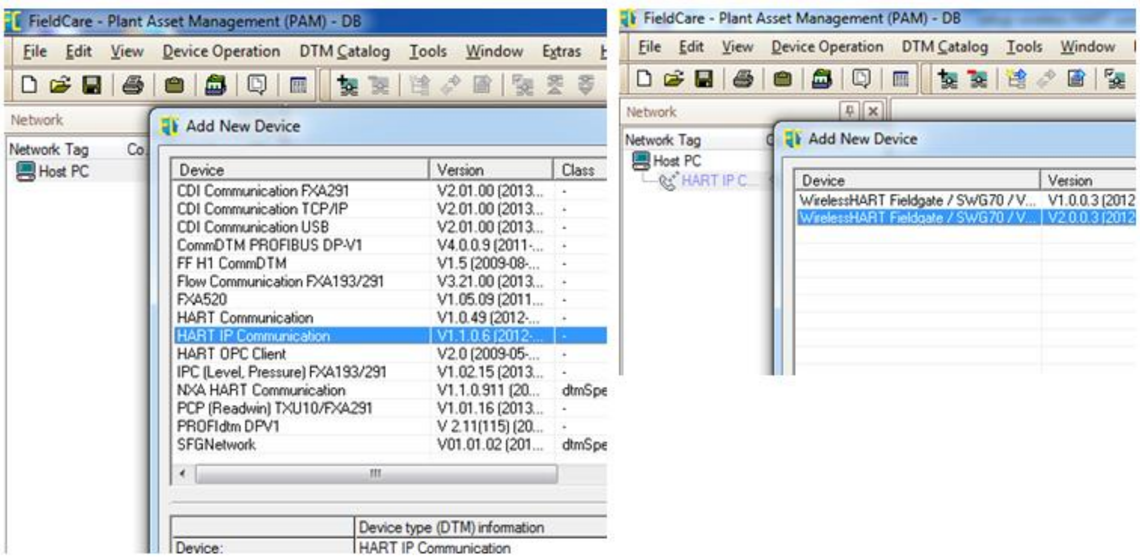


Figure 46 A new HART IP communication project on FieldCare

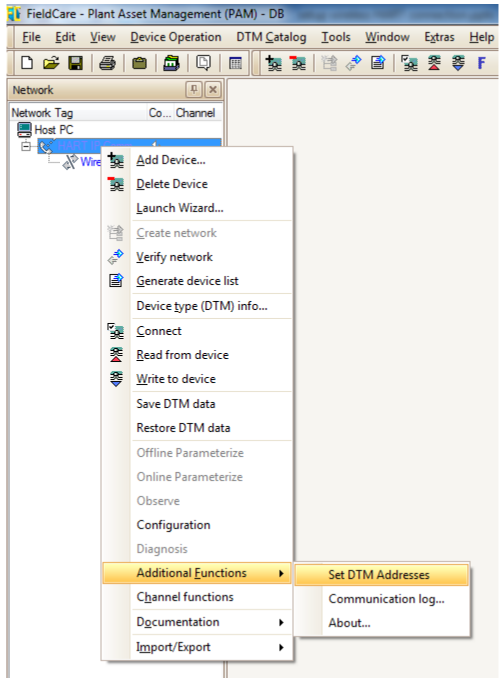


Figure 47 DTM address for HART IP communication

Change the IP Address (UDP Address) of gateway to the IP address it’s using and Update Change. Click the Connect Icon. The FieldCare will be connected to gateway as shown in Figure 48.

Select Wireless HART Fieldgate and click on Create network to scan the devices attached to it. DTM of adapter would be displayed on the content as shown in Figure 49.

Right click on the Adapter and Create Network. The online parameterize of the Sensor will show up as in Figure 50. Now configure the Sensor through FieldCare.

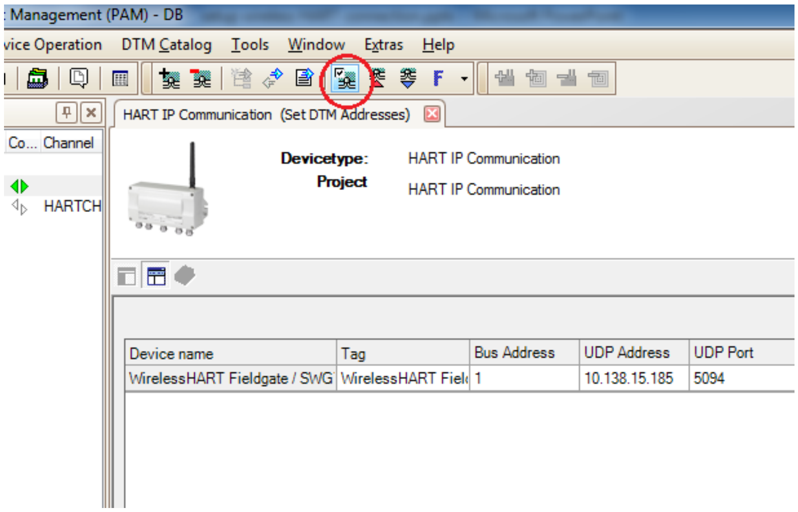


Figure 48 Connecting the gateway on FieldCare

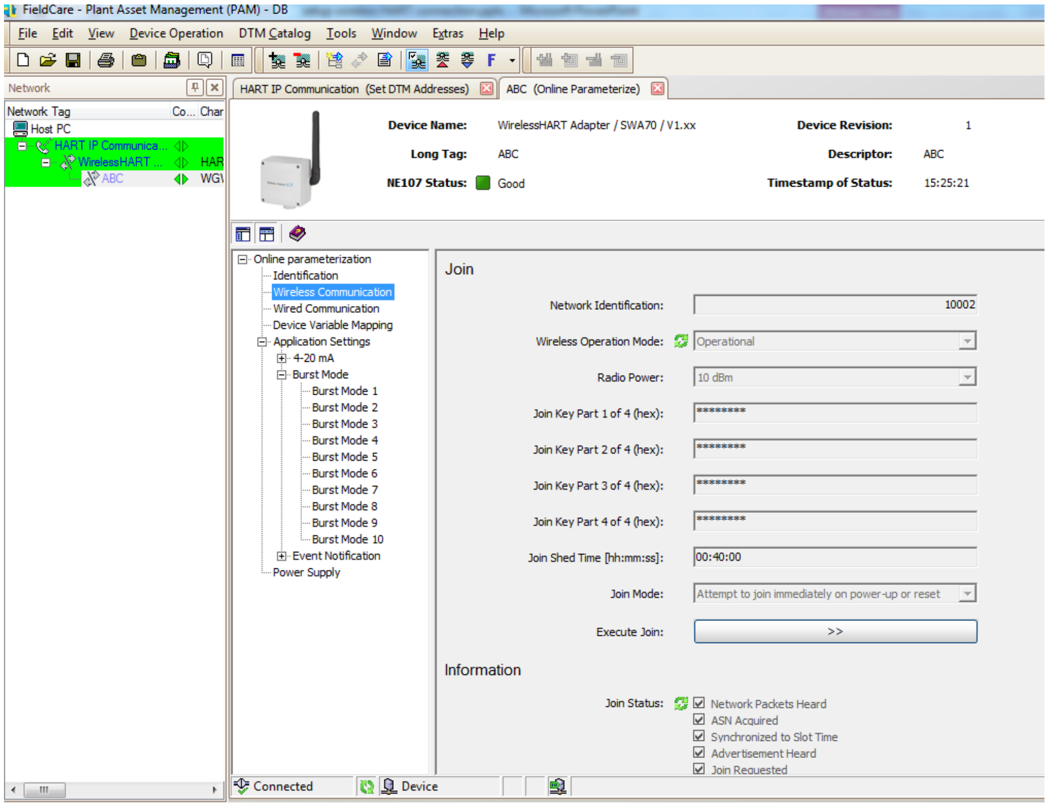


Figure 49 The wireless adapter scanning on HART IP communication project

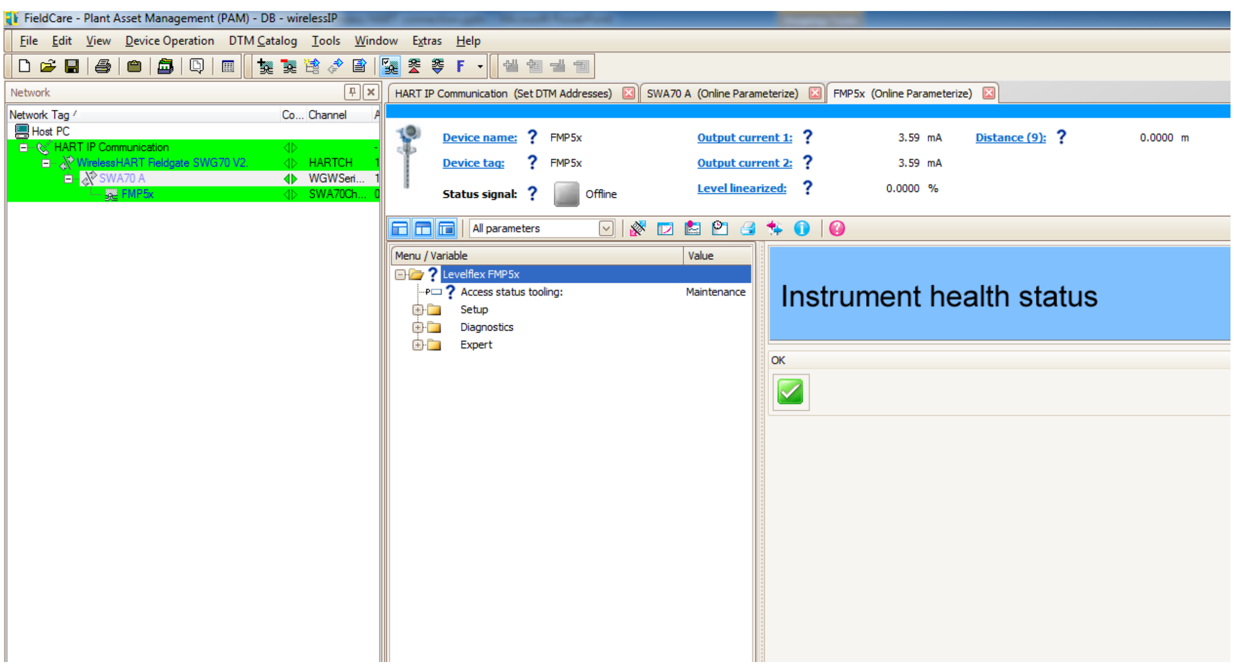


Figure 50 HART device scanning on HART IP communication project

Appendix C: CST Simulation Set-up

The schematic and PCB designs of this project are all done in Zuken. To set-up the CST simulation, the .pcf and .ftf files need to be exported from Zuken, import .pcf file to CST and build 3D model. The following is how to set up CST simulation.

Export .pcf and .ftf files from PCB Design Software

The .pcf file is ASCII board layout file (placement and layer symbol file, layer count, units, etc.). The .ftf file is the ASCII representation of the footprints used in the design (package description file). The .pcf and .ftf files will provide a 2D model in CST.

One can generate .pcf and .ftf with the command line. The right commands are:

```
ftout -r %sourcedatafile% -o %outfile%
pcout -r %sourcedatafile% -o %outfile%
e.g. ftout -r test.pcb -o test.ftf
```

Creating a Project and Building the 3D Model

Open the CST studio suite and create a new project, choose MW&RF&Optical area and select circuit and components. Click next. Select Planar Filters workflow and click next. Choose Time Domain solver among all the solvers. The steps are shown in Figure 51.

Leave the units as default. CST suggests that the center frequency should be the geometric mean of the start and end frequency, so set start frequency and end frequency to 1GHz to 5.76GHz. Monitor E-field and power flow. Click next and finish.

Now an empty project is created. Go to Modeling, Import/Export, 2D/EDA files and Zuken CR-5000/8000. Choose the .pcf file saved before. Click OK. Because .pcf only provides 2D data, CST will complain about some layers have zero thickness, click OK to continue. Then, a project with a 2D model is created, as shown in Figure 52.

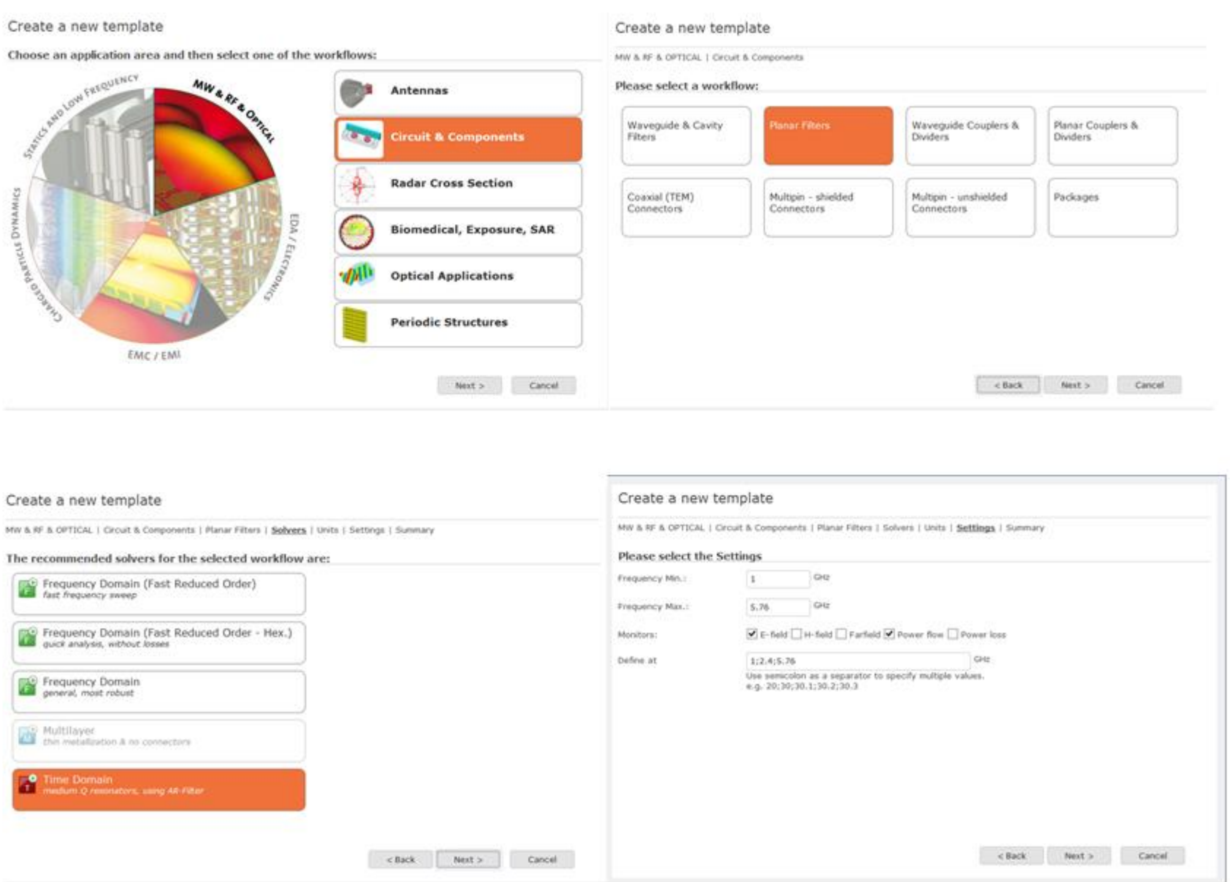


Figure 51 Steps to create a new template on CST

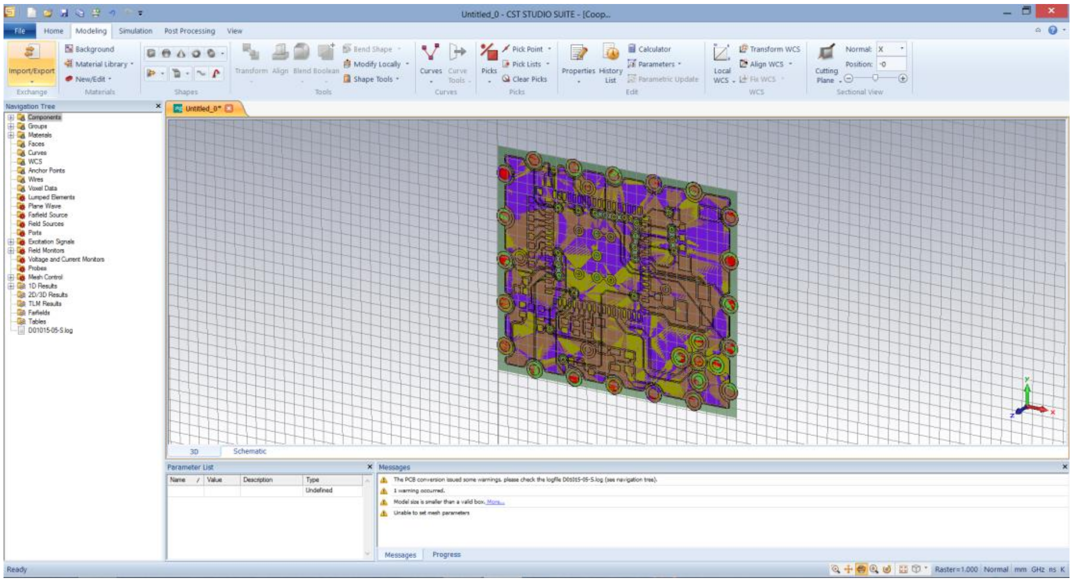


Figure 52 The CST project with a 2D model

The next step is to build the 3D model out of the 2D model. Expand the navigation tree, Components, PCB and substrates. Ignore the top and bottom masks, select substrate 1. Go to the project window, press F on the keyboard to select face. Double click on the PCB model, the surface will turn red to show being selected, as shown in Figure 53.

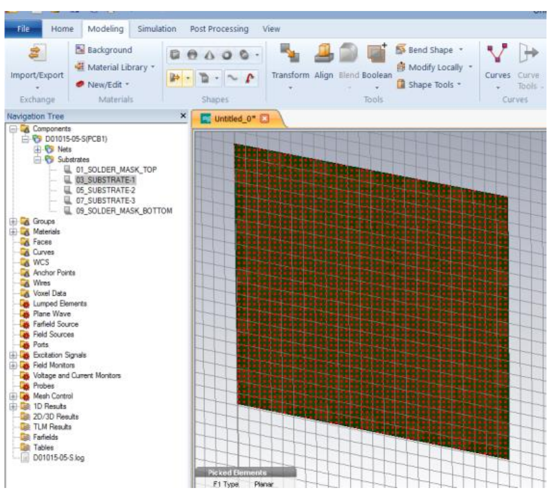


Figure 53 Substrate surface selection on CST

Go to Modeling, shapes, extrusions and extrude. Name the substrate sub1 and the height hsub1, as shown in Figure 54. Click OK. CST will ask to set a value for the new parameter hsub1, set it to 0.63, for the thickness of the first substrate is 0.63mm, provided by the PCB manufactory. Repeat to extrude the other two substrates. Set the height of the substrate 2 to 0.15 and the height of the substrate 3 to 0.64.

Note that the three substrates overlapping each other completely. The sub2 should be on top of sub1, sub3 on top of sub2. Select the surface of sub2, go to modeling and transform. As shown in Figure 55, transform sub2 along axis Z with a distance of the height of sub1, which is hsub1. Transform sub3 along axis Z with a distance of hsub1 + hsub2.

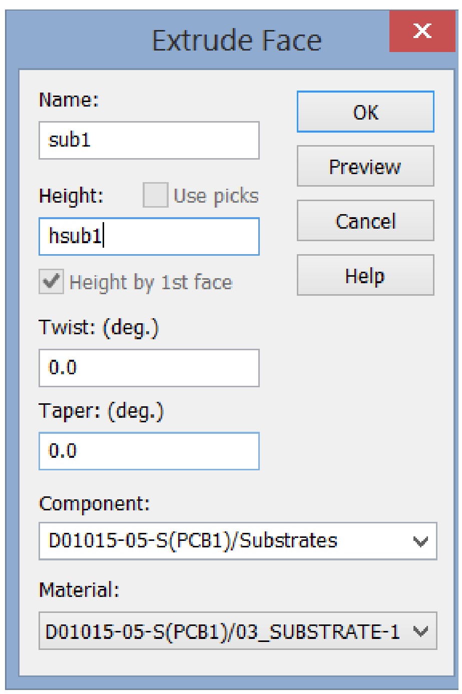


Figure 54 Extrusion of the substrate on CST

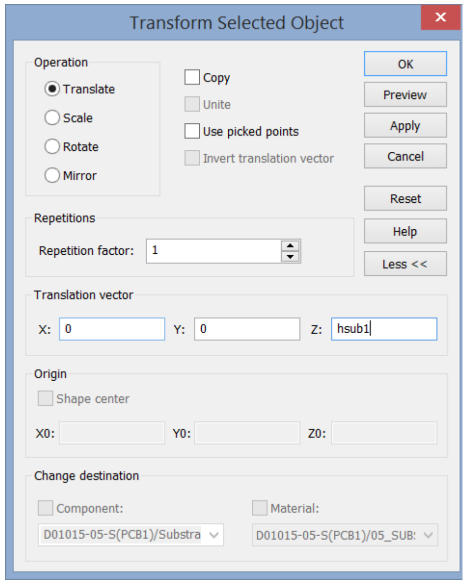


Figure 55 Transformation of the substrate on CST

Now three substrates of the PCB board are built, there are four layers between these three substrates. However, all the component footprints and traces are on the bottom. Expand the navigation tree, go to PCB, Nets. Expand all the footprints and traces under Nets. Select the footprints and traces and transform them to the corresponding layers.

After transforming the footprints and traces, extrude all the VIAs.

The last step to build the 3D model is to configure the material property of all the substrates, footprints, traces and vias. Right click the components in the navigation tree, select material parameters. Set the substrates to normal, also set its epsilon to the value that the PCB manufactory provides. Set all the footprints and traces to PEC.

Setting up the Simulation

Before running the simulation, a discrete port should be added on one end of the antenna feeder trace (the highlighted yellow trace in Figure 56) and a 50Ω resistor at the other end. The discrete port will monitor S_{11} parameter.

Press E on the keyboard to select the edge of the trace end. Press F to select the layer beneath it. Go to Simulation and select Discrete Port. Set the impedance of the port to 50Ω, click OK, a port between the trace and the reference layer is added. Details can be found in Figure 57.

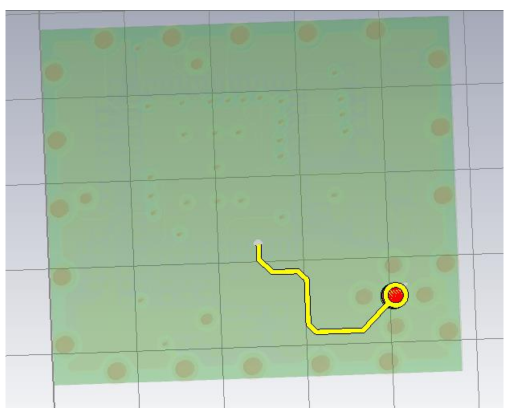


Figure 56 The antenna feeder trace on the PCB board

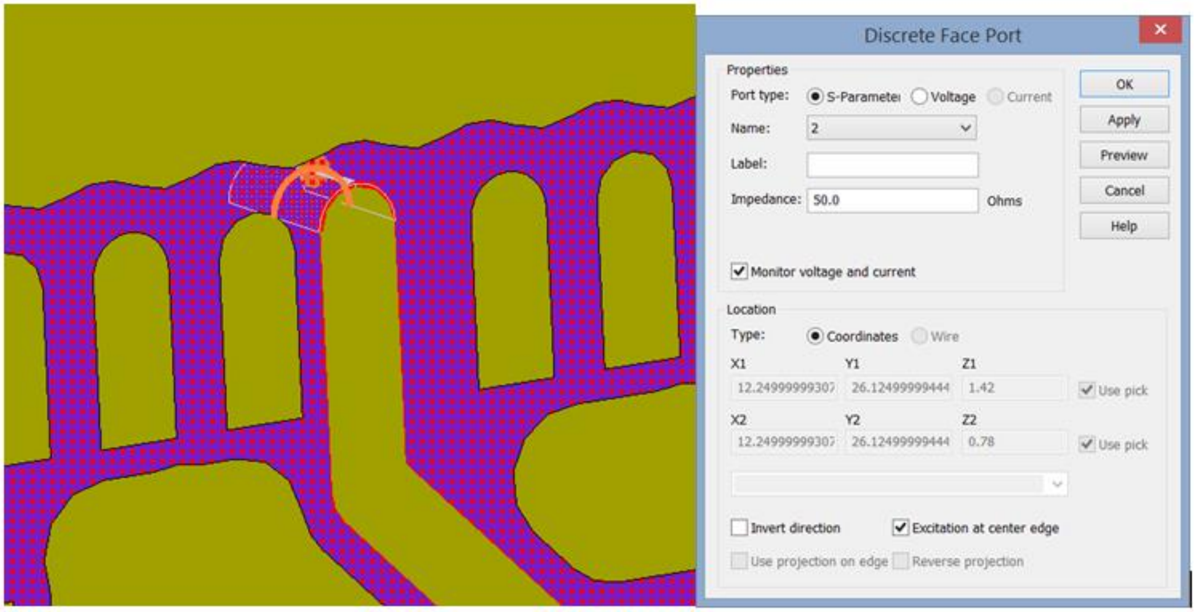


Figure 57 The discrete port on the antenna feeder trace

Repeat to add a 50Ω resistor at the other end. Use the rotate tool in View to get a better view.

After this, it's time to configure the solver. Go to simulation and setup solver. Go to adaptive properties, set the maximum number of passes to 4. Frequency should be from 1 to 5.76 GHz. Set the boundaries open and apply in all directions. Click setup solver and start. Now the simulation begins.

After the simulation is done, go to Post Processing and Template Based Post Processing. Select S-parameters and Z parameter, as shown in Figure 58. Add the real and imaginary part of Z parameter to the table. Z parameter is Z11. The closer Z11 to 50Ω, the better the trace matches to 50Ω.

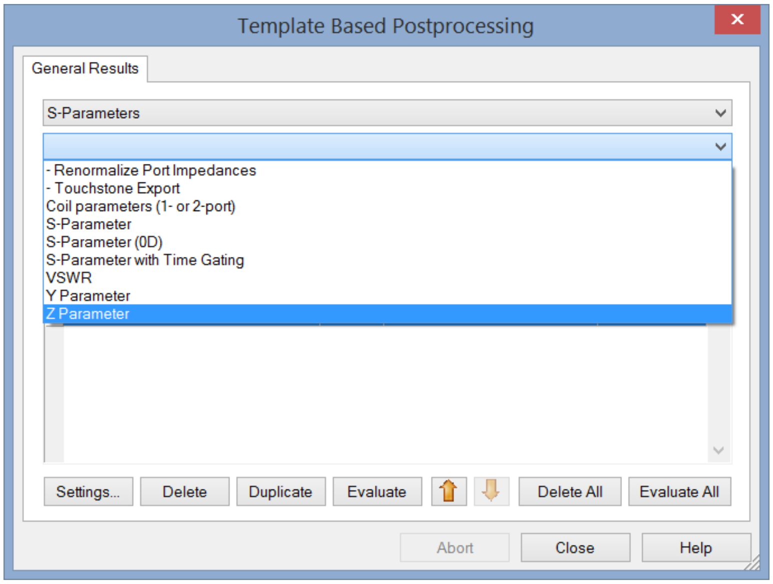


Figure 58 Post-processing of the Z parameter on CST

Appendix D: WirelessHART Mote API UART Commands

This section describes the commands used by an external processor to communicate with the SmartMesh WirelessHART mote through its API serial port. The API is intended for machine-to-machine communications (e.g. a sensor application talking to the mote).

The Packet Format

HDLC (High-Level Data Link Control) protocol is used for all API communication between mote and serial microprocessor. All packets are encapsulated in HDLC framing described in RFC1662. Packets start and end with a 0x7E flag, and contain a 16-bit CRC-CCITT FCS. Note that packets do not contain HDLC Control and Address fields that are mentioned in RFC1662. Also note that in HDLC, the least significant bit is sent first.

The HDLC packet encapsulation is shown in Table 9, Table 10, Table 11and Table 12. For more details please refer to *SmartMesh WirelessHART Mote Serial API Guide* by Linear Technology.

Table 9 HDLC packet encapsulation

Start Flag (Byte 0)	HDLC Payload (Byte 0- Byte n)	FCS (Byte n+1 – Byte n+2)	End Flag (Byte n+3)
0x7E	HDLC escaped API payload	(2 bytes)	0x7E

Table 10 HDLC payload contents

API Header	API Payload
Command ID| Length | Flags	Response code (responses only) | Message Payload

Table 11 API header contents

Field	Type	Description
Command ID	INT8U (1 byte)	Command identifier
Length	INT8U (1 byte)	Length of API Payload (excludes this header)
Flags	INT8U (1 byte)	Packet Flags

Table 12 API header flags contents

Bit	Description
0(LSB)	0=Request, 1=Response
1	Packet ID
2	Ignore Packet ID; 0=do not ignore, 1=ignore
3	Sync
4-7(MSB)	Command-specific flags

Here is an example to encode a testRadioTx command. After acknowledging for the boot event, the mote goes to idle status, at which time, there is a chance to put the mote into radio test mode to test the radio performance of the mote. The testRadioTx command packet consists of a payload of up to125 bytes, and a 2-byte 802.15.4 CRC at the end. Bytes 0 and 1 contain the packet number (in big-endian format) that increments with every packet transmitted. Bytes 2..N contain a counter (from 0..N-2) that increments with every byte inside payload. Transmissions occur on the specified channel. If number of packets parameter is set to 0x00, the mote will generate an unmodulated test tone on the selected channel. The parameter of testRadioTx request is shown in Table 13.

Table 13 testRadioTx request command parameter contents

Parameter	Type	Description
Channel	INT8U (1 byte)	RF channel number (0-15)
numPackets	INT16U (2 bytes)	Number of packets to send(>=1). 0x00=send unmodulated test tone

To let the mote generate an unmodulated test tone on channel 14, set the Channel to 0x0F and numPackets to 0x00. The testRadioTx command API payload is shown in Table 14.

Table 14 testRadio Tx command API payload

Channel	numPackets	
1 byte	1 byte	1 byte
0x0F	0x00	0x00

Now let's fill the API header of the command. The Command ID of testRadioTx will be 0x0B according to Command Identifiers. The length of the API payload would be 0x03. The Flags will be a little complicated. Set Bit0 to 0 for it's a request command, Bit1 to 0 for it's the first packet from the manager to the mote, Bit2 to 0 to do not ignore the packet and Bit3 to 0 because it's the first request from the manager after the mote boots up. The Bit4-7 doesn't specify anything in testRadioTx command so simply set it to 0 and the HDLC payload contents of testRadioTx is shown in Table 15.

Table 15 testRadio Tx command HDLC payload

HDLC Payload					
API Header			API Payload		
Command ID	Len	Flags	Channel	numPackets	
1 byte	1 byte	1 byte	1 byte	1 byte	1 byte
0x0B	0x03	0x00	0x0E	0x00	0x00

After filling the HDLC payload, let's add the 2-byte FCS at the end of it. There is an online calculator at http://www.zorc.breitbandkatze.de/crc.html (a screenshot is shown in Figure 59). On the calculator, select CRC-CCITT, set Final XOR value to FFFF, select reverse data bytes and reverse CRC result before Final XOR. Type the HDLC payload in the Data Sequence frame and separate each byte with %. Click on compute button, the result should be displayed in 2

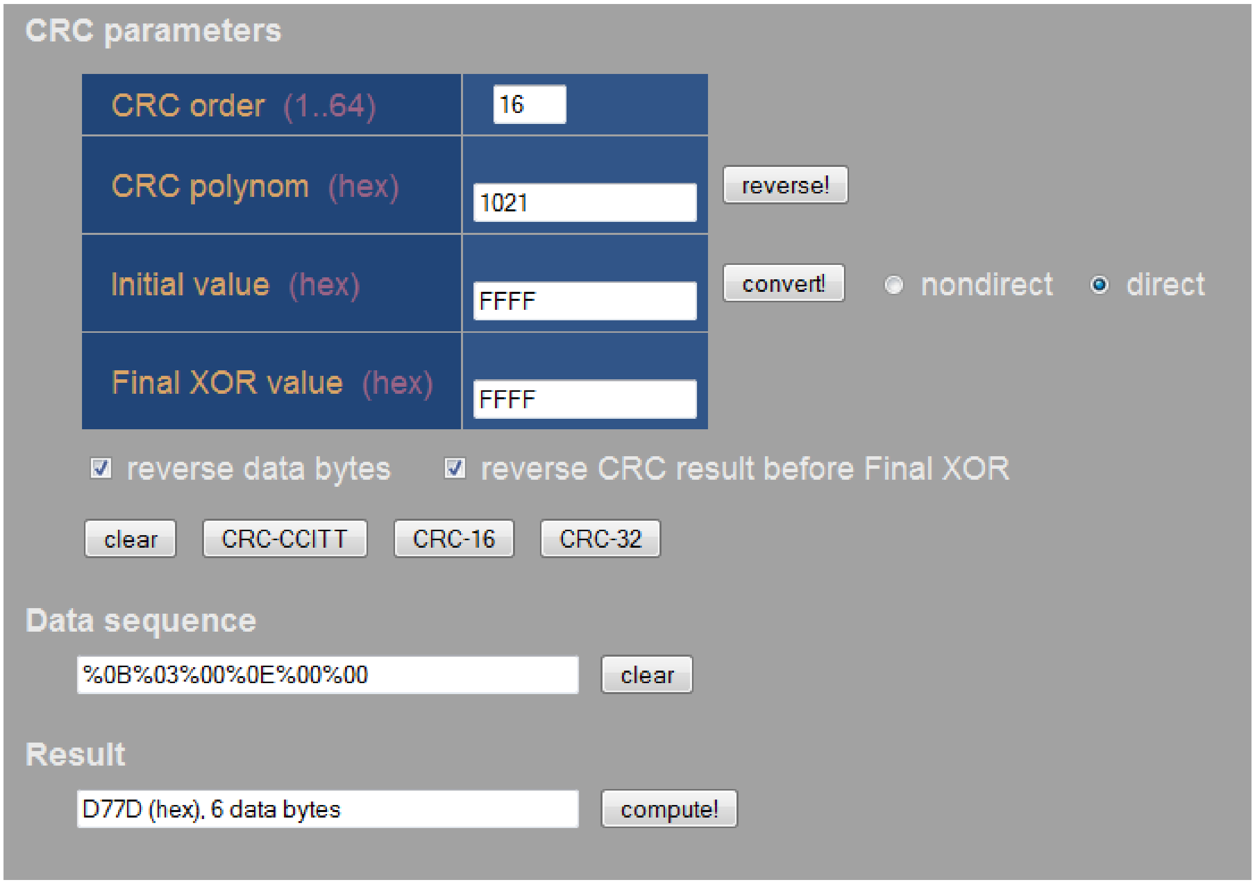


Figure 59 The on-line CRC-CCITT calculator

bytes. Switch the two bytes to get the final results. For example, in the following figure, the result is D77D (hex), but 7DD7 (hex) is the result for FCS.

Append FCS to the payload, and the HDLC payload of the testRadio Tx command is encrypted as shown in Table 16.

Table 16 testRadio Tx command HDLC payload with FCS

HDLC Payload						FCS	
0x0B	0x03	0x00	0x0E	0x00	0x00	0x7D	0xD7

After FCS computation, the transmitter examines the entire frame between the starting and ending Flag Sequences. Each 0x7E and 0x7D (excluding the start and end flags) is then replaced by a two-byte sequence consisting of the Control Escape (0x7D) followed by the XOR result of the original byte and 0x20. In this case, replace 0x7D in the FCS part with 0x7D 0x5D. After examination, the sequence would be like what shown in Table 17.

Table 17 testRadio Tx command stuffed HDLC payload and FCS

HDLC Payload and FCS (stuffed)								
0x0B	0x03	0x00	0x0E	0x00	0x00	0x7D	0x5D	0xD7

Finally add start and end flags. The packet as shown in Table 18 is ready for transmission:

Table 18 testRadio Tx command packet

Flag	HDLC Payload and FCS (stuffed)									Flag
0x7E	0x0B	0x03	0x00	0x0E	0x00	0x00	0x7D	0x5D	0xD7	0x7E

Some of the most common commands are given in Table 19. For more details in HDLC packet, please refer to *SmartMesh WirelessHART Mote Serial API Guide* by Linear Technology

Table 19 Common commands used in the mini mote API UART communication

Event	Command	Note
Boot	7E 0F 09 08 00 00 00 01 01 00 00 00 00 D7 67 7E	
Ack for boot event	#7E#0F#00#01#00#FF#57#7E	
Network ID	#7E#03#07#80#00#00#00#00#03#03#EA#49#B8#7E	For Network ID 1002
	7E 03 01 03 00 03 FF 13 7E	Response from Mote
Join Key	#7E#03#15#8A#00#00#00#00#02#25#29#92#92#00#00#00#00#00#00#00#00#00#00#00#00#AA#A1#7E	Join key 0x252992920000000000000000000000000

	7E 03 01 03 00 02 76 02 7E	Response from Mote
Join duty cycle	#7E#01#02#08#06#FF#2F#60#7E #7E#01#02#08#06#00#57#6F#7E	Max duty cycle Min duty cycle
	7E 01 01 01 00 06 62 E7 7E	Response from Mote
Join	#7E#06#00#04#31#56#7E	Issued join command
	7E 06 00 05 00 FC C9 7E	Response from Mote
testRadioTx	#7E#0B#03#00#00#00#00#66#C7#7E	
	7E 0B 00 01 00 13 25 7E	Response from Mote
Get Network ID	#7E#02#00#02#ff#ff#66#50#7E	
Get Mote Info	#7E#02#01#00#0C#18#55#7E	
	7E 02 11 01 00 0C 00 00 17 0D 00 00 60 19 EC 10 01 01 00 02 00 0E 80 76 7E	Response from mote
Get Antenna Gain	#7E#04#05#02#00#00#00#00#14#FD#3B#7E	
	7E 04 02 03 00 14 02 85 05 7E	Response from mote
Get Power info	#7E#04#05#00#00#00#00#00#05#A3#32#7E	
	7E 04 0C 01 00 05 01 03 E8 FF FF FF FF 00 00 00 00 8A FF 7E	Response from mote
setParameter <hartdeviceinfo>	#7E#01#37#02#0A#FE#11#F0#05#07#02#01#14#0C#01#23#45#05#0A#00#04#00#00#11#00#11#8D#44#45#56#49#43#45#4E#49#4B#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#5F#8A#29#7E	Setting the HART device name to “DEVICENIK”
	7E 01 01 03 00 0A B6 98 7E	Response from mote
Set Hart Device status	#7E#01#03#00#09#70#00#B2#82#7E	
	7E 01 01 01 00 09 95 1F 7E	Response from mote
Set Battery life	#7E#01#04#02#07#06#82#00#05#2B#7E	
	7E 01 01 03 00 07 53 43 7E	Response from mote
Set Join dutycycle	#7E#01#02#02#06#80#25#98#7E	
	7E 01 01 03 00 07 53 43 7E	Response from mote

Appendix E: WirelessHART Mote Programming

The IC used on WirelessHART Mote, LTC5800-WHM is provided without software programmed. To make the mote work, we need to program the IC first. The programmer used here is DC9010 Eterna Serial Programmer (referred to as ESP). Software utilities can be found at http://www.linear.com/solutions/4260. Advanced Serial Port Monitor is also used to send command to API UART port of the mote.

Programmer Set-up

The ESP consists of an enclosed circuit board with a USB interface and a 2x5 2mm ribbon cable, as shown in Figure 60. Connect the DC9010 to the windows PC via USB and connect the mote to the DC9010 via the ribbon cable.

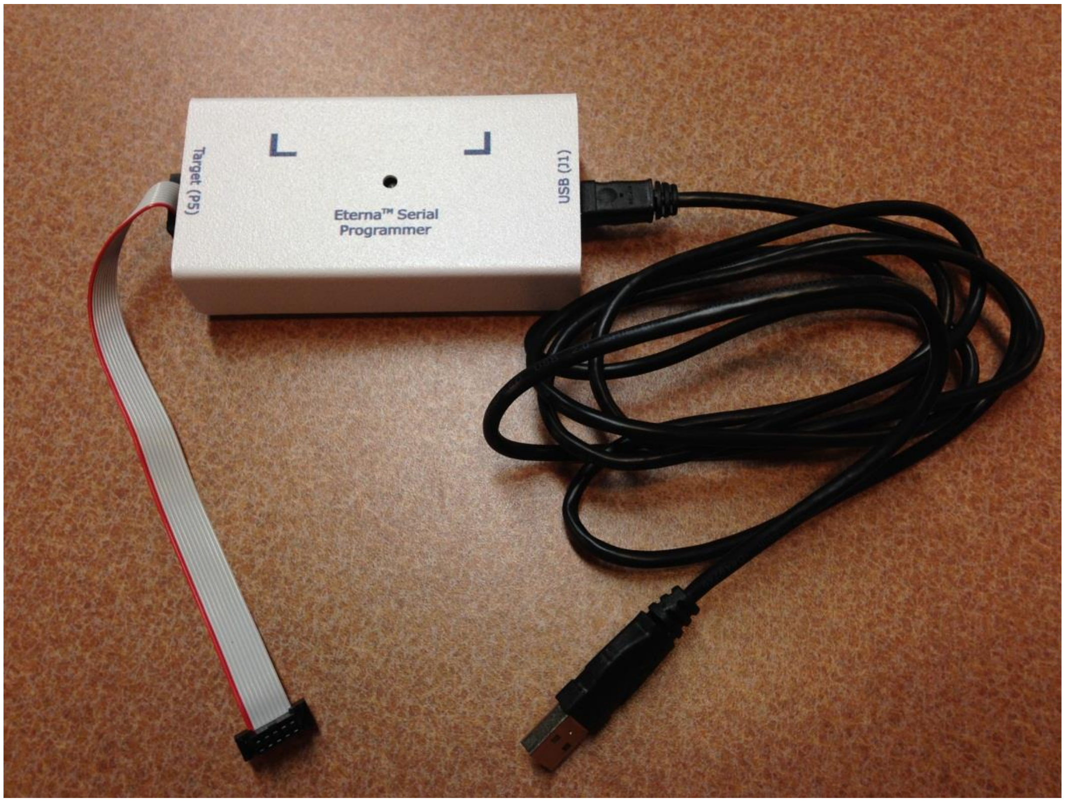


Figure 60 The DC9010 Eterna Serial Programmer

There isn't a 2x5 programming pin header left on the mote. To connect the mote to ESP, wire the I/O pins of the mote out to connect the ribbon cable. The UART0_TX and UART0_RX are not accessible as I/O pins on the mote, simply ignore them. A complete ESP pin description can be found in Table 20.

Table 20 ESP serial programming header pin description

Pin #	Signal	Direction	Pin #	Signal	Direction
1	IPCS_SSn	O	2	FLASH_P_ENn	O
3	IPCS_SCK	O	4	IPCS_MOSI	O
5	IPCS_MISO	I	6	RESETn	O
7	VSUPPLY	-	8	GND	-
9	UART0_TX	I	10	UART0_RX	O

When connecting the programmer to PC, four COM ports will be displayed on Device Manager. If not, install FTDI drivers on the PC. The FTDI drivers can be found at http://www.ftdichip.com/Drivers/D2XX.htm and are referred to by FTDI as "D2XX Drivers".

Once the four COM ports on Device Manager are displayed after plugging the EPS USB interface,

a. Right-click on a COM port and click Properties

b. Click the Port Settings tab, and then click Advanced.

c. Deselect the Serial Enumerator option, as shown in Figure 61, and click OK.

d. Click OK to return to the Device Manager.

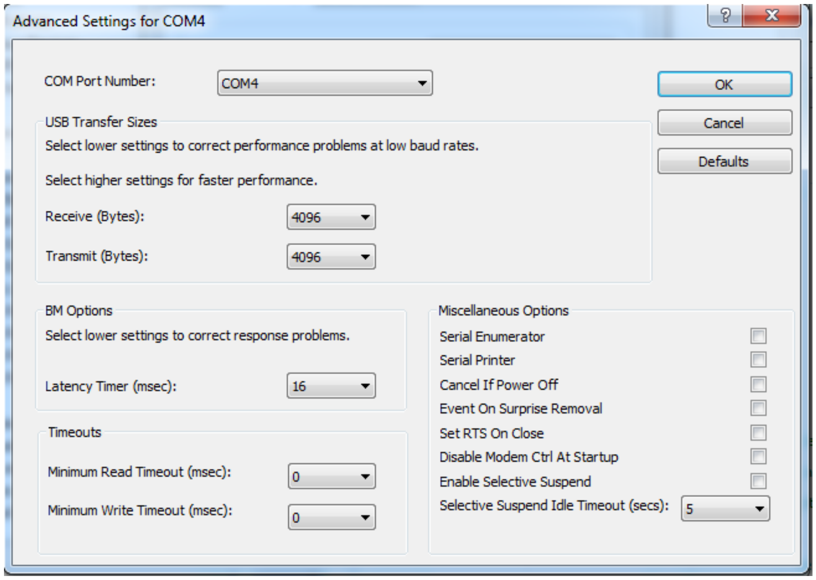
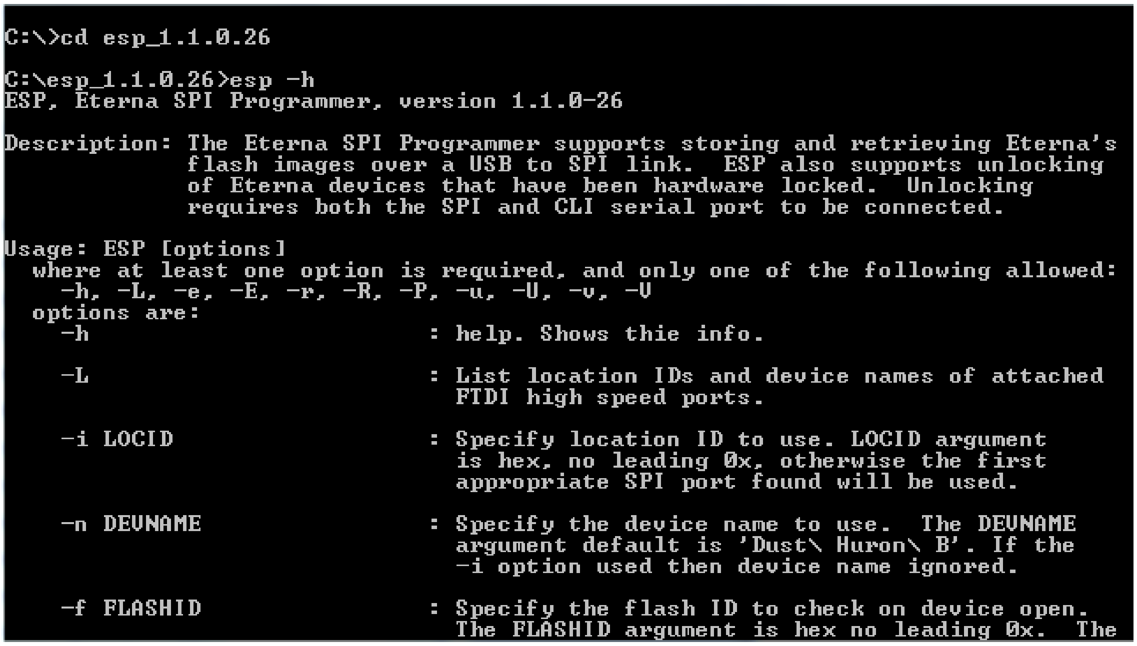


Figure 61 Serial Enumerator option for all four COM ports

e. Repeat this step for each of the four new COM ports. When finished, close the Device Manager.

Next step is to download the ESP software, which can be found at http://www.linear.com/designtools/software/#Dust. To install, un-archive all files into a directory (e.g. C:\esp). Open cmd.exe on Windows, go to the directory where the files locates. The utility should be executed from there. Type ESP –h (all the commands are highlighted grey in the following content) to get help of all ESP commands, as shown in Figure 62.



```
C:\>cd esp_1.1.0.26

C:\esp_1.1.0.26>esp -h
ESP, Eterna SPI Programmer, version 1.1.0-26

Description: The Eterna SPI Programmer supports storing and retrieving Eterna's
             flash images over a USB to SPI link.  ESP also supports unlocking
             of Eterna devices that have been hardware locked.  Unlocking
             requires both the SPI and CLI serial port to be connected.

Usage: ESP [options]
  where at least one option is required, and only one of the following allowed:
    -h, -L, -e, -E, -r, -R, -P, -u, -U, -v, -V
  options are:
    -h                         : help. Shows thie info.

    -L                         : List location IDs and device names of attached
                                 FTDI high speed ports.

    -i LOCID                   : Specify location ID to use. LOCID argument
                                 is hex, no leading 0x, otherwise the first
                                 appropriate SPI port found will be used.

    -n DEVNAME                 : Specify the device name to use.  The DEVNAME
                                 argument default is 'Dust\ Huron\ B'. If the
                                 -i option used then device name ignored.

    -f FLASHID                 : Specify the flash ID to check on device open.
                                 The FLASHID argument is hex no leading 0x.  The
```

Figure 62 ESP commands on the command window

Try ESP –R test.bin 0 80000 to read the flash of the mote to binary file test.bin. ESP –R FILENAME OFFSET BYTES is the command to read the flash, where OFFSET and BYTES are in hexadecimal with no leading 0x and bytes. If reading succeeds, the mote is connected to ESP. If reading fails and shows an error code, check the code in Table 21 and try to find a solution. A FLASHID error could be a cold solder on the mote.

Table 21 Common error codes

Error Code	Number	Description
HSP_ERR_OPENDEV	3	USB device already open or internal error
HSP_ERR_NODEV	4	USB device not found (when not using -i option)
HSP_ERR_LOADLIB	7	FTDI/FTCSPI installation error
HSP_ERR_FLASHID	12	ETERNA Flash ID not found; target not present or locked
HSP_ERR_MAXNUMDEV	17	USB configuration error, too many high speed devices found (64 units max)
HSP_ERR_BADTYPE	18	Incorrect target type passed via the -t option
HSP_ERR_NOCOM	19	Invalid COM port or already open; Fail to open

		COM port in case of an unlock command
HSP_ERR_NOTLOCKED	21	Unlocked ETERNA part (in case of an unlock command)
HSP_ERR_NOTUNLOCKED	22	Failed to unlock ETERNA part, invalid key
HSP_ERR_BADPARAM	26	Parameter error, incorrect address, bytes or pages value

Image Configuration

Now that one can access the flash of mote, all other valid ESP commands should function. Before programming the mote, an image is needed with correct fuse table. To do that, copy the image of the LTP5900-WHM module out, and edit the fuse table on Board Specific Configuration Application, which can be downloaded at http://www.linear.com/solutions/4260.

To copy the image, unplug the mote and open the enclosed circuit box (as shown in the left part of Figure 61). On the board, there is a 26-pin socket. Plug the LTP5900-WHM module into socket, making sure to match the key (as shown in the right part of Figure 61).

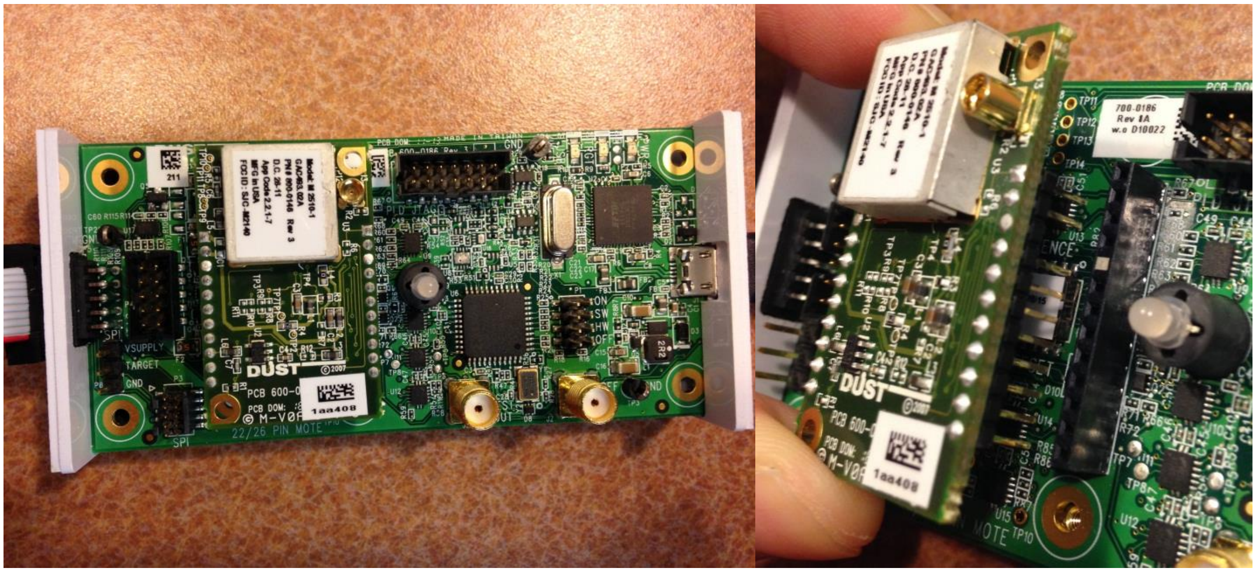


Figure 63 Steps to open the enclosed circuit box and plug the LTP5900-WHM module to the ESP socket.

ESP –R FILENAME OFFSET BYTES can be used to read the image out from the LTP5900-WHM module flash. The construction of flash image is shown in Table 22.

Table 22 ESP flash image construction

	Starting Address	Stop Address	Length(bytes)
Board Specific Para	0	7ff	800 (2KB)
Partition Table	800	fff	800 (2KB)
Main exec	1000	77fff	76800 (474KB)
Loader	77800	80000	8800 (34KB)

The commands can be used are:

C:\...\ESP\ESP –R FuseTable.bin 0 800

C:\...\ESP\ESP –R PartitionTable.bin 800 800

C:\...\ESP\ESP –R Main.bin 1000 76800

C:\...\ESP\ESP –R Loader.bin 77800 80000

After that, four binary files: FuseTable.bin, PartitionTable.bin, Main.bin and Loader.bin are generated. Now, edit the fuse table before programming it into the mote. Download Board Specific Configuration Application at http://www.linear.com/solutions/4260. Place the FuseTable.zip file into an empty directory (e.g. "\Program files\FuseTable") and extract the contents in place using Windows extract utility. Note: Microsoft Visual C++ 2008 SP1 Redistributable Package must be installed on the computer prior to running the FuseTable utility. This package may be downloaded directly from Microsoft website.

Now double click on FuseTable.exe, click File-> Open and choose the FuseTable.bin. Move between the windows via View -> Board Support Parameters and View -> IO Configuration, the fuse table will be displayed as Figure 64. In the window, set API UART Mode to Mode1 and Baud Rate to 9600. Save the fuse table.

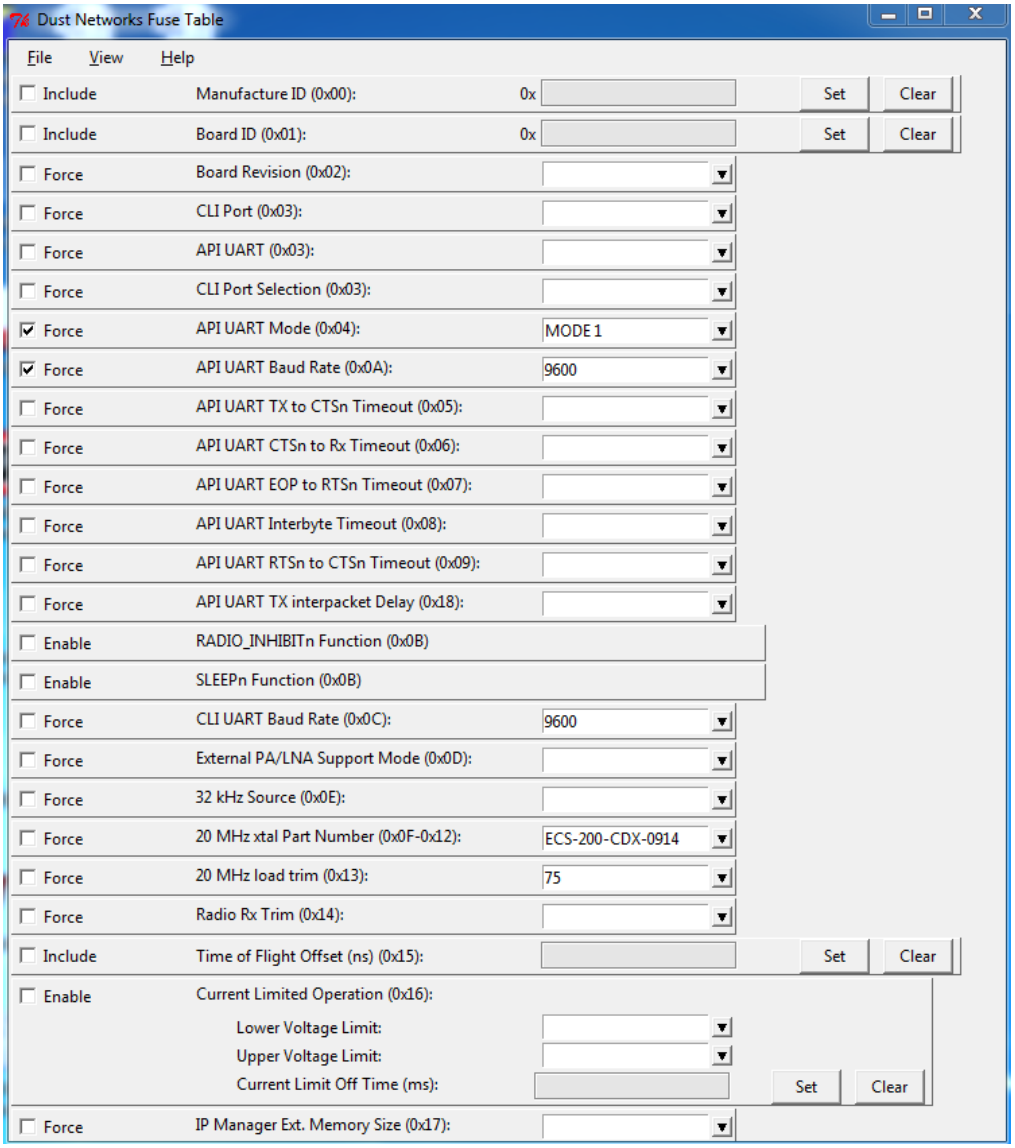


Figure 64 Fuse table configuration of the board support parameters

Make sure the configurations are saved in FuseTable.bin. Check the Force box. After saving, re-open the binary file and make sure the configuration is saved.

Eventually everything is ready to program the mote. Now unplug the LTP5800-WHM and plug the mote back. Erase the flash before programming. To erase and program, type:

C:\...\ESP\ESP –P FuseTable.bin 0

C:\...\ESP\ESP –P PartitionTable.bin 800

C:\...\ESP\ESP –P Main.bin 1000

C:\...\ESP\ESP –P Loader.bin 77800

Verification information will be displayed as Figure 65 if the programming is successful. Note that if the image is not erased before program, the ESP will return error.

Boot Event and Radio Test Mode

When the mote boots up, it will send a sequence on the API UART port. This is one way to verify if the mote is successfully programmed or not.

Use a USB TTL Serial cable (as shown in Figure 66) to connect the API UART port of the mote to PC. Only connect Rx, Tx, and Ground. Open Advanced Serial Port Monitor, select COM port (check the port on Device Manager, the port pops out when USB is plugged in) and click Open to start Port Monitor. On the TTL Serial cable, connect GND pin of the mote to black wire, API UART Rx pin of the mote to orange wire and API UART Tx pin of the mote to yellow wire

Figure 65 Verification information after a successfully programming

Power the mote up. If the mote is successfully programmed, the boot event packet will be sent out by the mote as in Figure 67.

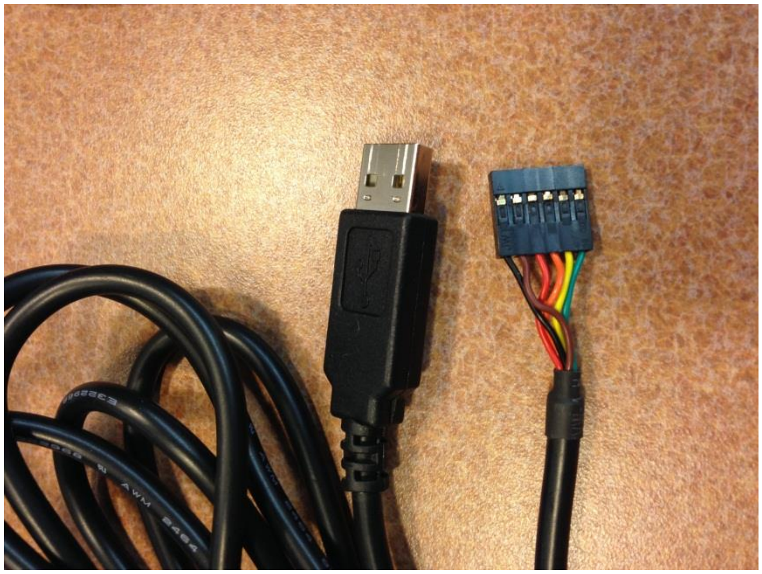


Figure 66 The USB TTL serial cable

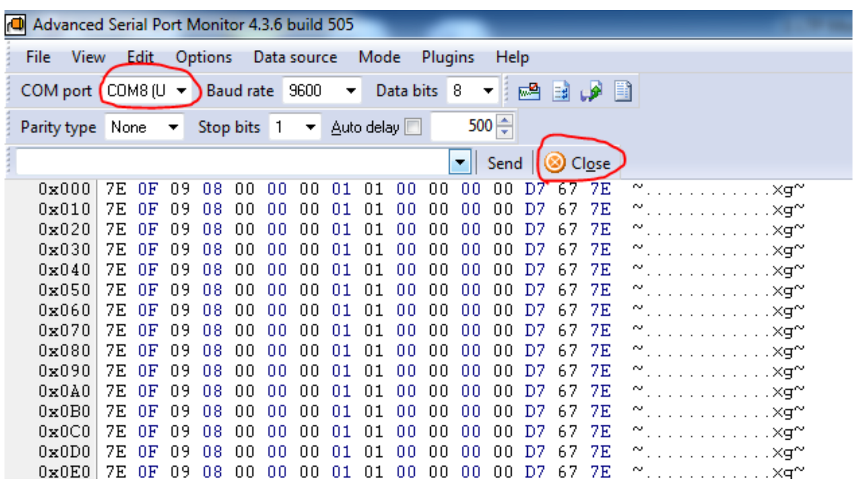


Figure 67 Boot event packet on the advanced serial port monitor

Acknowledge boot event by sending #7E#0F#00#01#00#FF#57#7E on Port Monitor. The mote stops sending out the packet as soon as it receives acknowledge packet. If it doesn't stop, check the USB connection and UART connection.

After acknowledging boot event, the mote is in the idle status prior to joining. Use testRadioTx command initiates transmission over the radio and display the transmission spectrum on a spectrum analyzer. Send #7E#0B#03#00#00#00#00#66#C7#7E to initiate transmission on channel 0, corresponding IEEE 2.4GHz channel 11 with a center frequency of 2.405GHz. The mote will responses 7E 0B 00 01 00 13 25 7E.

Now connect the MMCX connector to a spectrum analyzer, which works at 2.4GHz or higher frequency, a peak will show up at round 2.405GHz. Change Frequency Trim parameter on the fuse table to set frequency offset.