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FIELD AREA COMMUNICATION IN URBAN ENVIRONMENT

Wi-SUN Protocol

Technology and Communication
2022

ACKNOWLEDGEMENTS

This thesis would not have been possible without the support of many people. I am indebted to my supervisor, Gao Chao, D.Sc, for his continued guidance, patience, and support. His encouraging words, thoughts, and instruction have been very important to me.

I am extremely thankful to my Team Leader Mr. Teemu Rantala and Mr. Risto Pajula, Head Manager, for leading and supporting me with every single problem rising and for the valuable feedback

I gratefully recognize the help of the Wapice family and Wapice Oy, especially Niina Nabb and Juha Junka, who not only helped me to get familiar with the office but also created a very friendly and warm working environment.

A big thanks to my University, all teachers, and Technobothnia laboratory was opened a door to my future career in technology.

Most importantly, I am grateful for my family's unconditional, unequivocal, and loving support.

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ABSTRACT

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Title	Field Area Communication in Urban Environment- Wi-SUN Protocol
Year	2022
Language	English
Pages	48 pages + 3 Appendix
Name of Supervisor	Gao Chao

This thesis focuses on the Wi-SUN FAN standard and studies its performs in urban environments. The study was completed using two test modules. The first one investigates FAN's adaptability in the residential area and the other demonstrates its charisteristics (multi-hop, self-healing, self-forming).

The results of the first test module demonstrate how operating mode, class setting, retransmission process, and environment impact latency. The second test module demonstrates the step-by-step implementation of a multi-hop, self-healing network.

Keywords	Field area network, long-range, urban environment, wireless network, Wi-SUN, IEEE 802.

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LIST OF ABBREVIATIONS

6loWPAN	IPv6 Over Low power Wireless Personal Area Networks
AR	Acknowledge Request
BR	Border Router
CCA	Clear Channel Assessment
CSMA	Carrier Sense Multiple Access
DAO	Destination Advertisement Object
DIO	DODAG Information Object
DIS	DODAG Information Solicitation
DODAG	Destination Oriented Directed Acyclic Graph
ETX	Expected Transmission Count
FAN	Field Area Network
FSK	Frequency Shift Key
GTK	Group Transient Key
GUA	Global Unicast Address
IE	Information Element
LAN	Local Area Network
LLA	Link Local Address
LLC	Logical Link Control
LLM SAP	Logical Link Layer Management Service Access Point
LLN	Low Power and Lossy Network
MAC	Medium Access Control
MHDS	Multi-Hop Delivery Service
MLM SAP	MAC Layer Management Service Access Point
MLME	MAC sublayer Management Entity
MPDU	MAC Protocol Data Unit

MSDU	MAC Service Data Unit
MTU	Maximum Transmission Unit
NAN	Neighborhood Area Network
PA	PAN Advertisement
PAS	PAN Advertisement Solicit
PC	PAN Configuration
PCS	PAN Configuration Solicit
PHR	PHY Header
PMK	Pairwise Master Key
PPDU	PHY Protocol Data Unit
PRF	Pseudo Random Function
PSDU	Physical layer Service Data Unit
PTK	Pairwise Transient Key
RPL	IPv6 Routing Protocol for Low Power and Lossy Networks
RSL	Received Signal Level
RSSI	Received Signal Strength Indication
OFDM	Orthogonal Frequency Division Multiplexing
O-QPSK	Offset Quadrature Phase-Shift Keying

1 INTRODUCTION

In view of global sustainability, we can see rapid technological development and cities around the world turning into smart cities. Smart cities use the Internet of Things (IoT) to efficiently monitor urban resources, assets, and government. The Internet of Things is a vision for connecting nearly everything with everything /15/. Therefore, wireless technologies play an important role in the realization of this vision by enabling IoT devices to communicate wirelessly. But choosing the right IoT connectivity for a given application depends on several factors. If the designer is looking for a low-power, long-range network, they could consider LoRa, Sigfox, or NB-IoT. Zigbee, Bluetooth, or Z-Wave may be selected if the targeted application needs short-range, low-power, and mesh technologies.

Interference is another element to consider when picking a communication system for urban regions. Indeed, in metropolitan locations, signal quality is frequently hampered by static or mobile impediments, as well as interference. The Wireless Smart Ubiquitous Field Area Network, or Wi-SUN FAN for short, is a standard that combines features such as long range, low power, and mesh technology. It is believed as a better solution to the problem of urban interference.

Wi-SUN FAN comes with a concept of scalability, security and interoperability /16/. It supports a wide range of smart applications and is a solid candidate for smart cities, smart utilities and smart grids. Wi-SUN FAN is an IPv6 mesh, frequency hopping, self-healing and self-forming network. The mesh topology provides more redundant connections and reduces the impact of interference. Frequency hopping reduces interference and self healing properties increase robustness and reliability (e.g system can find new communication routes if some nodes in the network fail).

To demonstrate the performance of Wi-SUN FAN in urban evironment, two test modules were created in this thesis. The first module performs range testing in the residential area and typical park. The test result includes connection time, round-trip time, and link metric. The second module demonstrates the ability of multi-hop, self-healing, and self-forming of Wi-SUN FAN.

This document has five chapters in which Chapter I introduces the thesis. The Wi-SUN FAN theory and popular protocols such as IEEE 802.15.4 and Zigbee are discussed in Chapter 2. Chapter 3 focuses on all the tools used (software and hardware), describing the process of conducting tests on key performance such as throughput, reliability and latency. The fourth chapter describes analysis. The final chapter is the summary of this document.

2 THEORETICAL BACKGROUND

This chapter includes three sections, the first section provides the technical background to IEEE 802.15.4. The following section introduces WI-SUN FAN, in particular its network architecture, protocol stack and network components. The last section gives a brief introduction on Zigbee -Wi-SUN competition.

2.1 IEEE 802.15.4 Scope

IEEE 802.15.4 is a low-cost, low data rate wireless access technology for battery-powered devices. This access technology is not only inexpensive and provides a reasonable battery life, but also enables easy installation with a compact protocol stack./19/

The first version of IEEE 802.15.4 released in 2003 specifies PHY layers and a simple MAC layer. The standard uses Carrier Sense Multiple Access with Collision Avoidance medium access mechanism (CSMA/CA) and supports both star and peer topology. CSMA/CA is a method of access in which a device "listens" to make sure the other devices do not transmit before starting their own. IEEE 802.15.4 suffers from interference and multipath fading because it lacks frequency hopping. Multipath fading refers to the fact that the signal reaches the receiver not only through the direct path, but also due to reflections from objects such as buildings, hills, ground, water, adjacent to the main path. The ability to change frequencies can mitigate the effects of multipath fading. This is the premise of IEEE 802.15.4-2015 which is composed of the PHY layer and the MAC layer for WI-SUN FAN. IEEE 802.15.4-2003 standard contains star, cluster tree and peer-to-peer topologies. The peer-to-peer topology allows the development of mesh nets /11/.

2.1.1 IEEE 802.15.4 PHY Layer

IEEE 802.15.4-2003 PHY format frame is shown in Figure 1.

6 Bytes			0-127 Bytes
Preamble	Start of Frame Delimiter	Frame Length	PHY Service Data Unit (PSDU)
Synchronization Header		PHY Header	
5 Bytes		1 Byte	

Figure 1. IEEE 802.15.4 PHY format frame

The maximum PSDU is 127 bytes, which is usually smaller than the MTU settings of upper-layer protocols. For example, IPv6 MTU is 1280 bytes. Thus, If IPv6 datagrams are transmitted over IEEE 802.15.4 frames, fragmentation should be done at the data link layer level.

2.1.2 IEEE 802.15.4 MAC Layer

The MAC (Medium Access Control) layer is responsible for accessing the PHY channel, defining how devices in the same zone will share allocated frequencies /19/.

2.2 Wi-SUN – Wi-SUN FAN

Wireless Smart Ubiquitous Network (Wi-SUN) is a low-power wireless communication technology designed to provide the communication foundation for very large outdoor networks and industrial devices, such as smart meters, streetlights used by utilities, city developers, and other service provider's facility /18/. Wi-SUN Alliance was formed to specify, promote and ensure the interoperability of Wi-SUN technologies. Wi-SUN Alliance defines a FANs (Field Area Network) profile that connects field devices into utility operations, self-forming, and self-healing system. The profile is based on IEEE802.15.4e, IEEE802.15.4g, IPv6, 6LoWPAN, UDP and TCP (optional). IEEE802.15.4e upgrade on the MAC layer and IEEE802.15.4g upgrade on the PHY layer of Wi-SUN FAN, both standards integrated in the IEEE802.15.4-2015 release /11/.

IEEE802.15.4e provide Wi-SUN FAN MAC with certain enhancements such as:

- Frequency hopping

- Information Elements (IE): enable the exchange of information at the MAC layer.
- Enhanced acknowledgement: intergration of a frame counter for the frame being acknowledged.

IEEE802.15.4g increases the maximum PSDU from 127 octets to 2047 octets for Wi-SUN FAN PHY. Upgrade the CRC from 16 to 32 bits and support multiple data rates in bands from 169 MHz to 2.4 GHz /11/.

2.2.1 Network Components

Figure 2 shows the typical network component with the Layer 3 routing method selected.

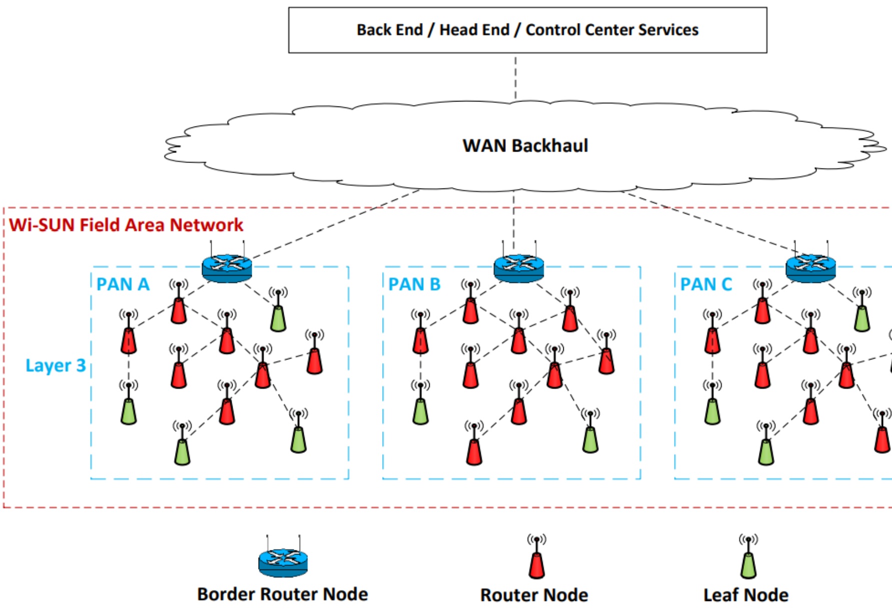

Figure 2. Layer 3 RPL routing method network architecture /5/

Wi-SUN FAN supports star and mesh topology which includes at least one Border router, node router and leaf router /5/.

A border router provides WAN (Wide Area Network) connectivity to the PAN (Personal Area Network). Border routers maintain source routing tables for all their nodes, provide node authentication and key management services, and disseminate information (e.g, broadcast schedules)

A router node provides upstream and downstream packet forwarding within a PAN. Leaf nodes, on the other hand, provide minimal functionality, for example, discover and join PANs, and send/receive IPv6 packets.

Wi-SUN FAN architecture according to the OSI model shows in Figure 3

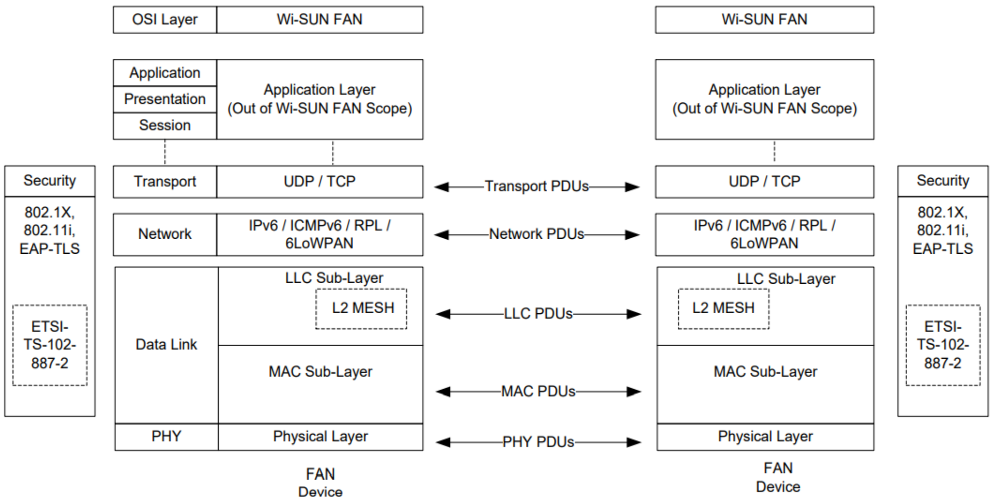

Figure 3. Wi-SUN FAN architecture /5/

The FAN profile includes four layers: physical, data-link, network and transport. Each layer communicates with the adjacent layers through Service Access Point (SAP) including: DL SAP (Data Link), MAC SAP and PHY SAP.

2.2.2 Wi-SUN PHY Layer

The functions of the PHY are radio transceiver activation and deactivation, Energy Detection (ED), Link Quality Indication (LQI), channel selection, Clear Channel Access (CCA), ranging, sending and receiving packets through a physical medium.

IEEE 802.15.4-2015 provides three PHY modulation options for smart utility network: FSK, OFDM, and O-QPSK each supporting multiple data rates /19/. The data rates depend on PHY operating mode option. Different geographic regions need to operate on different frequency bands. In Wi-SUN FAN version 1.0, the FSK mechanism is used, 2-FSK or BFSK /5/.

The FSK mechanism used to transmit digital information that is 1 and 0 by switching a carrier between discrete frequency, and the amplitude remains unchanged. So, it delivers good power efficiency through the constant signal envelope /8/. Another benefit to SUN-FSK is the compatibility with existing systems. For example, most smart meters in the U.S use FSK modulation systems /20/.

A 2-FSK has only two different states (0, 1 for each state). Therefore, symbol rate is equal to bit rate /13/. Modulation index is the ratio of the frequency deviation of the modulated signal to the message signal bandwidth. Use the formula 1 to calculate the modulation index for 2FSK:

$$h = \frac{2 * f_d}{f_b} \tag{1}$$

h - modulation index (MI)

f_d- deviation (distance between carriers and the nomial center frequency)

f_b - bit rate

From the formula we can see that the MI was used to make the distance between "0" and "1" far enough to avoid them interfering with each other. For instance, if the bit rate is 50 kbps and the modulation index is 0.5, then the deviation or shift is 12.5 kHz. The same MI but with a higher bit rate is 100 kbps then the deviation will be 25kHz. In this context, the larger deviation will have a better performance.

Table 2 describes all the PHY operating modes supported by the Wi-SUN profile (2021). Each operational mode has its own sysmbol rate and modulation index /5/.

Table 1. Wi-SUN FAN PHY operating mode

PHY Operating Modes	Symbol Rate (ksymbol/s)	Modulation Index
Operating Mode# 1a	50	0.5
Operating Mode# 1b	50	1.0
Operating Mode# 2a	100	0.5
Operating Mode# 2b	100	1.0
Operating Mode# 3	150	0.5
Operating Mode# 4a	200	0.5
Operating Mode# 4b	200	1.0
Operating Mode# 5	300	0.5

Table 2 outlines the supported channel and frequency band parameters. The Operating Class is used to obtain the desired data rate and channel plan in the regulatory domain /5/.

Table 2. FAN Frequency band and channel

Freq Band (MHz)	Region	Regulatory Domain Value	Operating Class	PHY Modes	ChanSpacing (kHz)	Total Num Chan	Chan Center Freq0 (MHz)
470-510	CN	0x04	1	Operating Mode #1b, #2a, #3	200	199	470.2
779-787	CN		2	Operating Mode #1b & #2a	200	39	779.2
			3	Operating Mode #3, #4a & #5	400	19	779.4
920.5-924.5	CN		4	Operating Mode #1b & #2a & #3	250	16	920.625
863-870	EU	0x03	1	Operating Mode #1a	100[a]	69	863.1
			2	Operating Mode #2a & #3	200[a,b]	35	863.1
870-876[c]	EU		3	Operating Mode #1a	100	55	870.1
			4	Operating Mode #2a & #3	200	27	870.2
865-867[d]	IN	0x05	1	Operating Mode #1a	100	19	865.1
			2	Operating Mode #2a & #3	200	10	865.1

Note: Standard IEEE 802.15.4v-2017 defines the additional use of the 915-921 MHz band in Europe, 902-928 MHz band in Mexico, 902-907.5 MHz band in Brazil, 915-928 MHz band in Australia and New Zealand

The preamble field shall be set depending on the operating mode /5/.

- Mode 1b/2a   8 bytes

- Mode 3 12 bytes
- Mode 5 24 bytes

2.2.3 Data Link Layer

The datalink layer included Logical Link Control (LLC) sub-layer and MAC sublayer. The data link layer is responsible for the control and management of the physical layer, the data transfer and management services to the network layer /5/.

Only data and enhanced acknowledgment frames are used. The frame type fields of data frames (001) and enhanced acknowledgment frames (010) based on the IEEE802.15.4 frame type ID.

2.2.4 Logical Link Control Sub-layer (LLC-sublayer)

LLC sublayer provides a protocol dispatch service supporting both 6LoWPAN and L2 MESH service. Which is L2 MESH under service based on the MHDS (Multi hop delivery service) is optional.

2.2.5 MAC Sub-layer

MAC sublayer operates in non-beacon enabled mode (no superframe structure is used in this mode). The non-beacon mode is an asynchronous network mode of operation where all channel accesses are available for unslotted CSMA/CA with CCA mode 1. In CCA mode 1 only the ED (Energy Detect) result is taken into account. If the energy level is above the ED threshold, the channel is considered busy. The ED threshold level can be set by the manufacturer /5/.

Figure 4 shows IEEE 802.15.4e MAC frame format

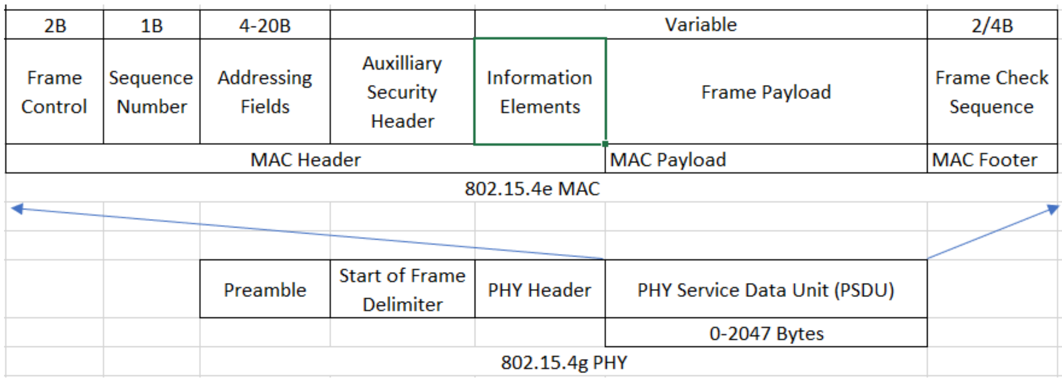

Figure 4. IEEE 802.15.4e MAC frame format

The MAC sublayer supports PAN discovery and joining process with two mechanisms: trickle-based PAN advertisement and secured PAN configuration /5/.

Trickle algorithm basically states that a node is transmitting data unless it hears some other transmission whose data indicates that its own transmission is redundant. The algorithm reduces transmissions in dense networks, saving system energy /17/.

The MAC sublayer also supports adjacent synchronization channel hopping for transmission of unicast and broadcast frames. Each node advertises its channel schedules with information necessary for a neighbor node to determine on which channel a node will be operating at any given time, and the node will be listening to unicast channel schedule or broadcast message when not transmitting /5/.

2.2.6 Discovery and Joining Process

The discovery and joining process described in Figure 5 consist of five states /5/:

- Join state 1: Select PAN
- Join state 2: Authenticate
- Join state 3: Acquire PAN config
- Join state 4: Configure routing
- Join state 5: Operational

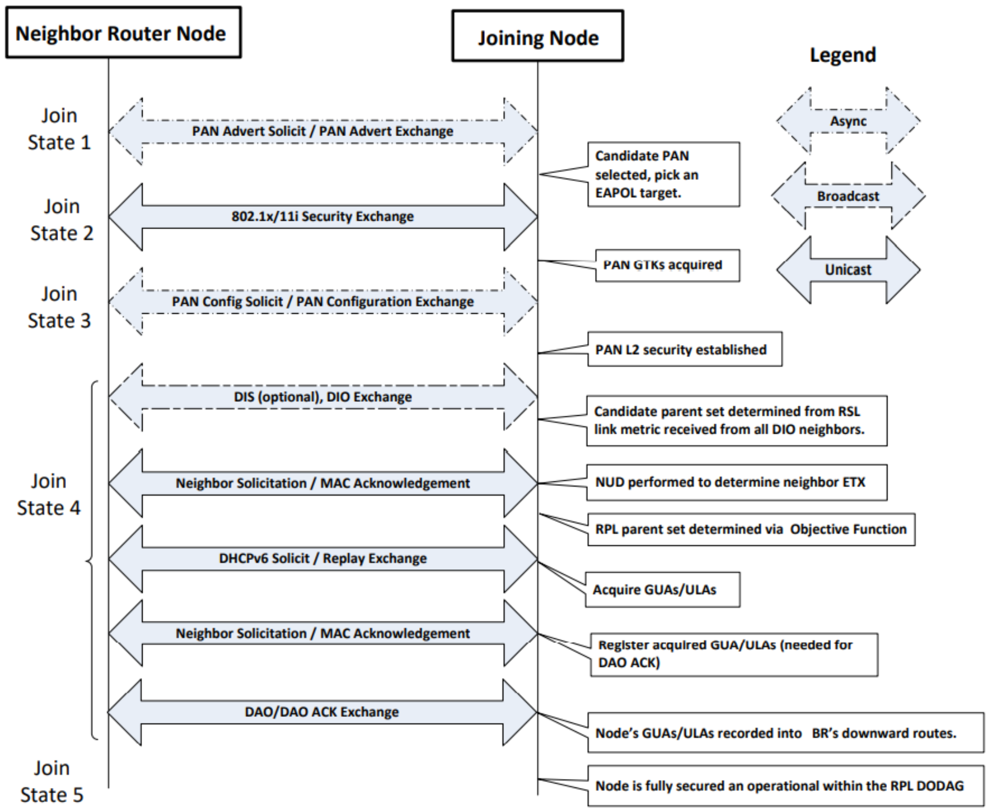

Figure 5. FAN discovery and joining process

When a FAN node wants to join a network, the configurations listed below must be prioritized.

- Network Name
- If the user employs a clear channel plan, the regulatory domain, operating mode, and operating class are all required. If a user uses an explicit channel, they must give the center frequency, channel number, and channel spacing.
- Root certificate, certificate, and private key

2.2.7 Network Layer

FAN nodes are using IPv6 (Internet protocol version 6) which supports MTU up to 1280 bytes. The Wi-SUN FAN specification includes Layer 3 routing and optional Layer 2 multi-hop configuration. Only one routing method is used. Fragmentation is done at 6LoWPAN adaption layer /5/. 6LoWPAN is a standard for IPv6 packet transmit over Low Power Wireless Personal Area Network. It dispatchs value for uncompressed IPv6 Headers, Header Compression and Fragmentation. ICMPv6 is used for control information exchange along with DHCPv6 for automated address management.

Finally, A FAN nodes autoconfigure link-local IPv6 addresses based on well-known link-local prefix FE80::0 and modified EUI-64 format-based interface identifiers (EUI-64 based MAC address defined in IEEE 802.15.4) /2/.

For example, A FAN node with the MAC address b4:e3:f9:a6:04:a3 that uses the EUI-64 functionality will have the hardware address b4:e3:f9:ff:fe:a6:04:a3. (ff:fe is added in the middle of the MAC address), then flip the 7th bit in the MAC address from left and combine with fe80::0 to get fe80::b6 e3:f9:ff:fe:a6:04:a3 as the link-local IPv6 address. Finally, anytime a node finds and joins the BR, it receives GUAs/ULAs from the BR.

2.2.8 Routing Method

Layer 3 routing supported by IPv6 Routing Protocol for Low-Power and Lossy Network (RPL) using non-storing mode. In non-storing mode, Border router (A root) is the only router maintaining routing information. Packets are forwarded from a source node up the DODAG (Destination Oriented Directed Acyclic Graph) to the root using next hop routing. Packets are forwarded down the DODAG to a destination node using source routing determined by the root /5/.

In a FAN, a DODAG originates (has its root) at a Border Router. To form the DODAG, each node will send DODAG Information Objective (DIO) advertising itself as the root (DIO message contain various DODAG metadata and rank), and all DODAG nodes, except the Border Router, transmit DAO RPL (Destination Advertisement Object Routing Protocol for Low-Power and Lossy Networks). Messages to the Border Router announcing the routes of a node to its parents. DIO is distributed in the network, and the entire DODAG is gradually built /12/.

Wi-SUN FAN version 1.0 does not have a leaf node.

2.3 Zigbee vs Wi-SUN

Zigbee is a network-application layer protocol built over IEEE802.15.4, so any ZigBee compliant device is also IEEE 802.15.4 compliant. The Zigbee specification is developed and promoted by the Zigbee Alliance /3/. Zigbee comes in different flavors to suit different market segments.

- Zigbee also known as Zigbee 3.0
- Zigbee Smart Energy Only in UK
- JupiterMesh

A brief comparison between Wi-SUN and Zigbee shows in Table 3.

Table 3. Common information on Zigbee and Wi-SUN /12/

	Zigbee	Wi-SUN
Applicability domain	LAN, NAN	FAN, HAN
Baseline standard	IEEE802.15.4	IEEE802.15.4, IETF, ANSI
Channel Bandwidth (kHz)	600-5000	100-600
Spectrum	Unlicensed	Unlicensed
Frequency Bands	Sub 1-GHz and 2.4GHz	Sub 1-GHz and 2.4 GHz
Transmission scheme	Multiple	FSK (FAN 1.0), OFDM (FAN 1.1)
Data rate (kbps)	250	50-300, up to 2.4 Mbps (OFDM FAN 1.1)
Latency (multiples of millisec-onds)	10x	10x
Application payload	Not limited	Not limited
Network topology	star, mesh	star, mesh
Radio link range	~10 -100 m	~500 m (2-3km LOS)

Many prominent firms, such as Amazon, Phillips, and Ikea, use the Zigbee protocol. They rely on Zigbee for product automation. Furthermore, Zigbee is designed to transmit data in a noisy RF environment, which is common in commercial and industrial settings. Therefore, the Zigbee market has become congested, resulting in aggresive interference. As a result, we may estimate that there are around 50-100 nodes per square kilometer in residential areas. If in a commercial network

(Zigbee's longest range is roughly 100 meters), this number can be higher. These devices are capable of interfering with one another.

Both Zigbee and Wi-SUN use 64-bit addressing, so the maximum number of devices in a network can be 2^{64} or around 1.8×10^{19}. With Wi-SUN FAN 1.0, it supports up to 24 hops, but the maximum network size depends upon the RAM of the border router. From TI equipment, every border router (144KB RAM) can manage up to 300 nodes, and larger memory can support larger networks. Zigbee is up to 240 nodes.

Multiple border routers can be used to expand the network. Another thing to be considered is the ability to handle multi-node border routers in WI-SUN FAN or coordinator in Zigbee. Every mishap on the coordinator or the border router leads to bad performance over the whole network.

In Zigbee a synchronized network beacon enables mode, the coordinator and router can sleep for an inactive period. While the coordinator transmits beacon frame (superframe) periodically over the network, the router and end device listen for the beacon and take a slot in the frame to communicate with each other. For that reason, the beacon mode saves system power. However, if the child device (router and end device) is missing the coordinator beacon, it will miss the synchronization process and lead to a broken network connection. Therefore, the beacon mode might not suitable for a large network as long as the coordinator is powered by battery-powered devices. There could be an accident at some point.

Differential with Zigbee, WI-SUN has used non-beacon mode, which means that no superframe will spread to the network. The child device will send the request data to join the network first (PAN advertising solicit), but then the Border router and the node router should be awakened all the time. The router that already joins the network may allow another device to join the network. From this point we can see that Zigbee has taken more advantage in energy usage than Wi-SUN.

In Zigbee, the maximum MTU is 127 bytes, so fragmentation on the large packet added extra overhead on the network. With WI-SUN FAN, it supported IPv6 MTU 1280 bytes, therefore reducing the overhead.

Like Wi-SUN, Zigbee is a self-healing and self-forming network. When Full Function Device (FFD) establishes itself as the coordinator, other devices can send association messages to join the network without additional supervision. The word self-healing expresses the properties of a mesh network. This means that when building a network, there is more than one way to send a message from one device to another, but the most optimal route is chosen. If a device on the network stops working or if an obstacle is blocking message routing, the network can choose an alternate route.

Zigbee and WI-SUN have their unique strengths and target markets. While Zigbee focuses on indoor automation, WI-SUN build it for outdoor and long-range utilities. But recently, Zigbee introduced a new protocol called Jupitermesh as a competitor in the long-range mesh network with WI-SUN.

3 TESTING

In order to highlight the network performance of Wi-SUN FAN in urban environments, we carry out some range tests. The main characteristics include connection time, latency, throughput, and self-healing network. This section describes the required components such as software, hardware, tools, and test conditions.

This study used hardware and software from two vendors, Texas Instrument- TI and Silicon Labs-SL. The TI equipment was mainly used to test network topology, and the SL equipment was mainly used to test network performance. Both providers have their own certificate for Wi-SUN FAN stacks. TI is still uncertified for the Border Router solution, whereas SL is certified for Border Routers as well as Routers. A test of interoperability (Appendix A) demonstrated the connectivity between the SL Border Router and the TI Node Router.

For better data visualization Silicon Labs SoC is recommended to use.

3.1 Hardware

Texas Instruments Launchpad CC1352P7-1 is shown in Figure 6. It has 144KB of RAM, 704KB of Flash program memory, a 48-MHz Arm Cortex-M4F processor, and an operating temperature range of -40 to 105 degrees Celsius.

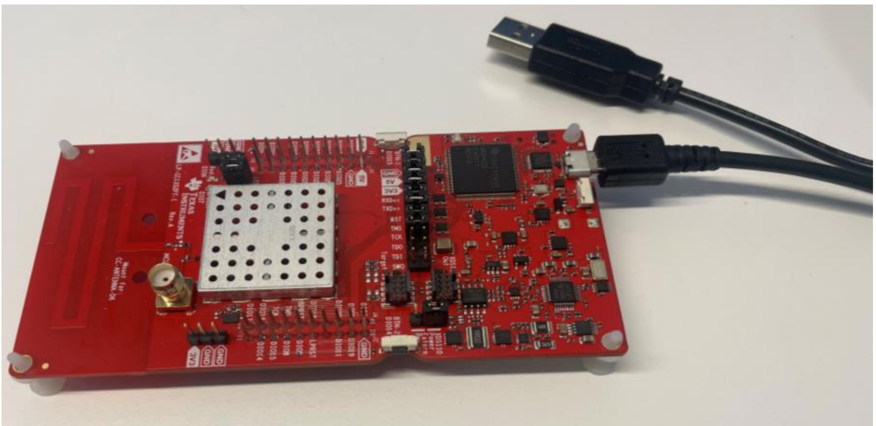

Figure 6 CC1352P7-1

Figure 7 shows Silicon Labs' Mighty Gecko Wireless SoC EFR32MG12. It has 1024 kB of Flash memory and 256 kB of RAM, a 40 MHz ARM Cortex-M4 processor, and an operating temperature range of -40 to 85 degrees Celsius.

Figure 7. EFR32MG12 Mighty Gecko Wireless SoC

3.2 Software

Silicon Labs Simplicity Studio Version 5.3.2.0 with Gecko SDK Suite v4.0.2 was used in the project. Simplicity Studio is the development environment for Silicon Labs' IoT portfolio of systems-on-chips (SoCs) and modules. A beneficial feature is the network analyzer, which allows us to control the device through command line interface (serial 1) and real-time packet capture. The network analyzer includes a partial Wi-SUN protocol analyzer, so it cannot decrypt Wi-SUN payloads. However, it can be used to export traces to another analyzer such as Wireshark. Another drawback on the SL network analyser is that they have limits on Packet Trace Interface (PTI). It limits the number of bytes it is able to display per packet. As a result, if we send a large ping packet (larger than 1024 bytes), it will be truncated.

Texas Instrument Code Composer Studio (CCS) version 11.1.0 with simplelink_cc13xx_cc26xx (SDK 5.40.00.40) was another software used in the project. CCS is also the development environment for Texas instrument 's microcontroller (MCU) and embedded processor portfolios. To support packet sniffer TI provide Smart packet sniffer agent 2 and Uniflash. The limitation of the TI packet sniffer is that only one channel is allowed.

3.3 Test Module 1- Network Performance

3.3.1 Information

Three SL devices were used in Module 1 of the network performance test module. SL chose an unique local address (ULA) for Border Router IPv6 prefix setting. When the device (node router) is turned on, it will auto-configure its link-local address, which will begin with fe80 (2.2.7), and it will get the IPv6 prefix from the Border router if the device connects successfully.

In this module, one device functions as a border router and is connected to a Raspberry Pi via USB. From now it will be called an LBR (Linux Border Router) because it connects to a Raspberry Pi (Linux operating system) or a BR (Border Router) if it connects to a PC (Window operating systems). The second and third devices act as routers (node router 1 and node router 2). Both routers connect to two different PCs. The LBR will be placed inside an apartment, and node routers will be placed at different test locations depending on the test case.

Module 1 aims to measure Wi-SUN network performance over long distances and obstacles in four test cases. Each test scenario were run three times, each time with a different Mode (Mode 1a-2, Mode 2a-2 and Mode 3-2) in EU domain.

Table 4 shows the differences between three modes in the EU domain.

Table 4. Module 1-Testing mode in EU domain

Operating Mode	Operating Class	Data rate kpbs	Modulation Index	Number of channels	Channel spacing kHz	Center Fre-quency at channel 0 MHz
1a	1	50	0.5	69	100	863.1
2a	2	100	0.5	35	200	863.1
3	2	150	0.5	35	200	863.1

For the figures from Figure 8 through Figure 11, Yellow star represents LBR or BR, Red star represents node router 1, and Black star represents node router 2.

Test case 1: The LBR was placed inside an apartment and the node router 1 was located 40 meters away from the LBR. Figure 8 shows Test case 1 location

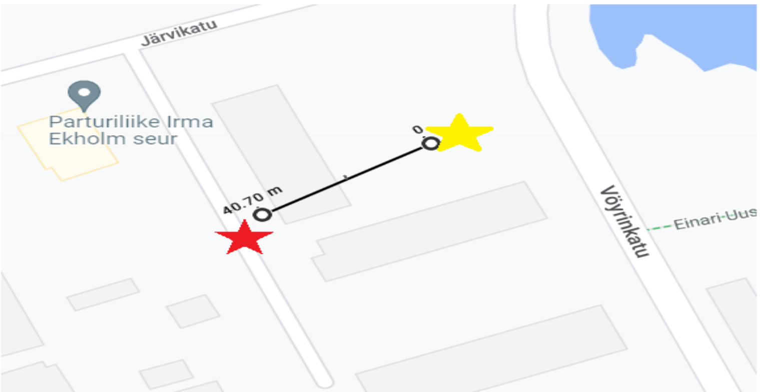

Figure 8. Test case 1 location

Test case 2: The LBR was placed inside an apartment and the node router 1 was placed at 100 meters away from the LBR. After locating Node router 1 and joining the LBR successfully, it moved to location A (280 meters on the street) and location B (280 meters behind the building) , as shown in Figure 9.

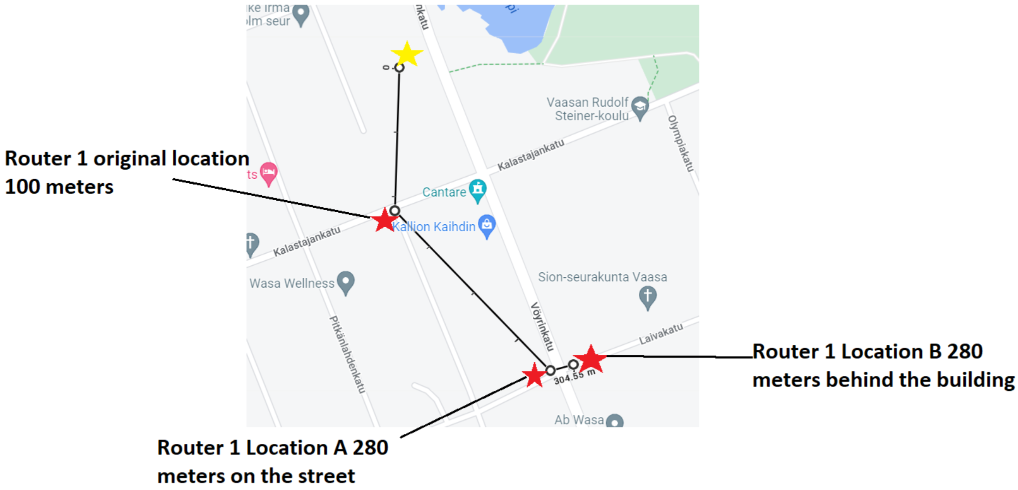

Figure 9. Test case 2 location

Test case 3 was designed to test the LOS (line of sight) between two nodes. So, a BR and router 2 were connected to two PCs via a USB and positioned in test locations 1, 2, 3 with distances of 200, 400, and 650 meters, respectively. In this scenario, the LBR was not used. Figure 10 depicts test case 3 location.

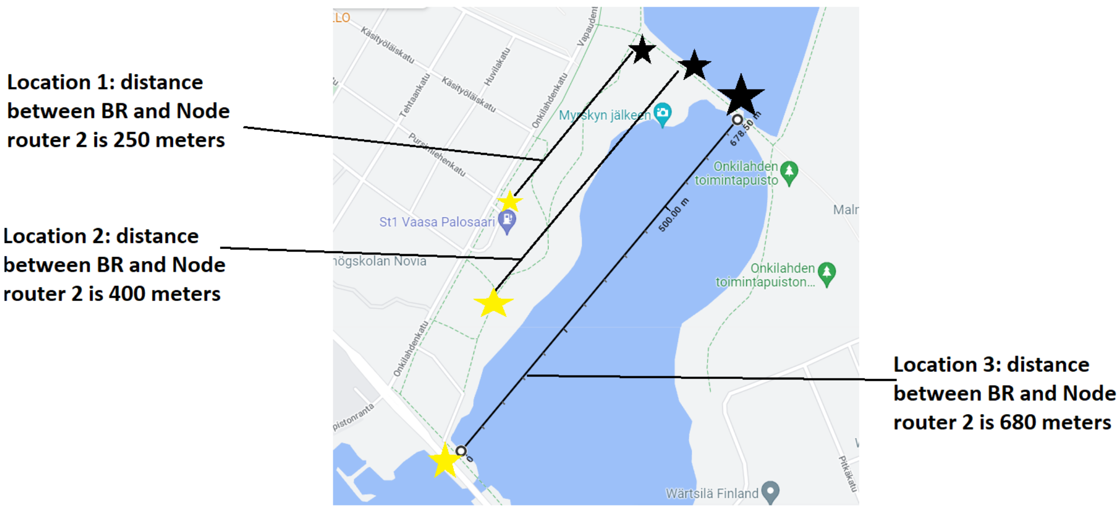

Figure 10. Test case 3 location

Test case 4: The LBR was inside an apartment, Node router 1 100 meters away, and Node router 2 300 meters away from the LBR. After two nodes successfully joined the LBR, node router 2 was relocated to location C (250 meters away from router 1) and location D (300 meters away from router 1). The location of test case 4 is depicted in Figure 11.

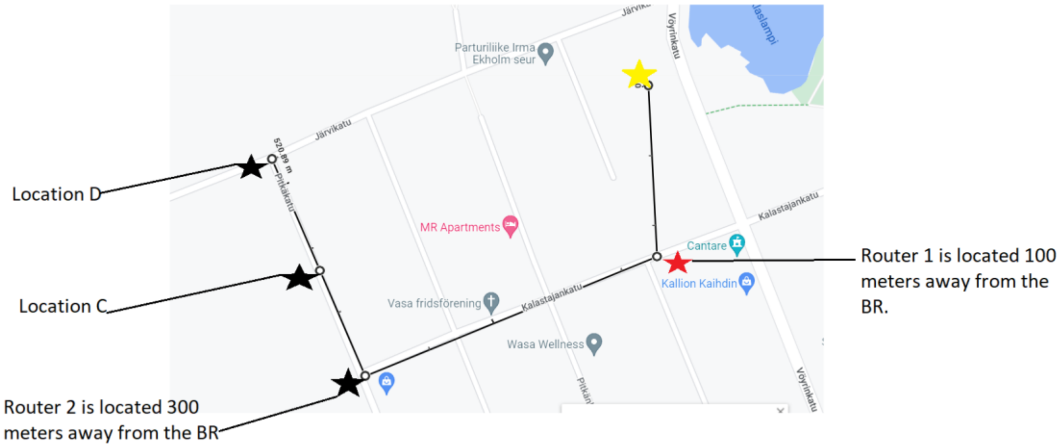

Figure 11. Test case 4 location

The test Conditions were as follows:

- Environment: Test case 1, 2, 4 in a residential area. Test 3 in a typical park
- Temperature indoor: 20 ° C
- Temperature outdoor: 0 – (-6) ° C
- Weather: Sunny, cloudy and windy
- Battery voltage: 5V

Ping packet were the following :

- Payload length: 40 bytes
- Interval between packets: 10 ms
- Number of packets to transmit: 10 packets
- Transmit power: 20 dBm

To determine the delay based on the distance, a node router sent 10 40-byte ping packets to the BR or the LBR. The command-line interface or Router LCD can be used to examine the test results.

3.3.2 Setting on Border Router Linux Solution

To begin, the SoC RCP (Radio Coprocessor) source code was installed onto a single device. Later, the device was linked to the Raspberry Pi via the USB port.

(See Figure 12.) The Raspberry Pi contains a Linux-based solution called ***wsbrd*** daemon, which interfaces with the RCP RF device. The upper layers of the Wi-SUN protocol are handled by the ***wsbrd*** daemon, while the bottom layers and RF activities are handled by the RCP device.

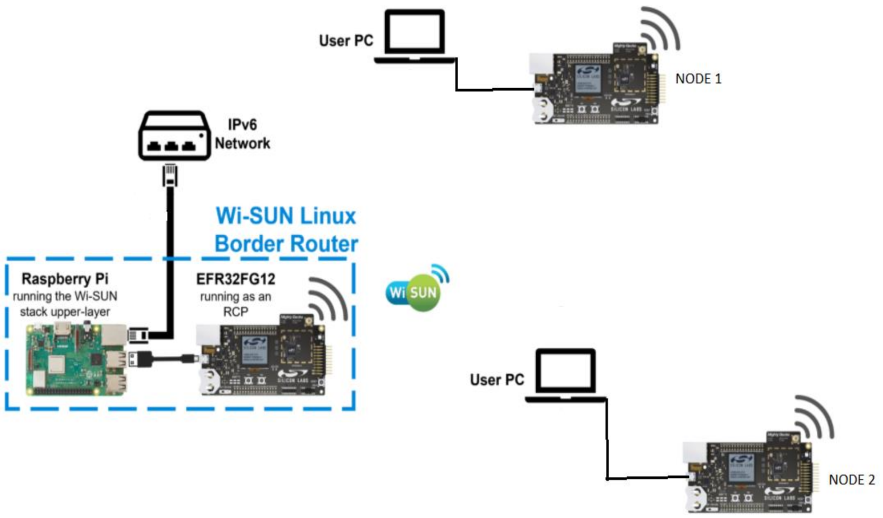

Figure 12. Module 1 Architecture

The following parameters need to be set in the ***wsbrd.conf*** (Appendix C) file before starting the wsbrd daemon and they must match with all the nodes in the network.

- Network name
- IPv6 prefix
- Domain (EU, NA, BR, JP ….)
- Operating mode
- Operating class
- Network size (CERT: development and certification, SMALL (< 100, MEDIUM (100-800), LARGE (800-2500), XLARGE (> 2500))
- Tx_power
- Key, certificate, authority

Other parameters can also be set to suit user application requirements, such as:

- storage_prefix the stored data contains the negotiated key to speed up the connection when the service restarts
- pan_id: Force the network to use a PAN ID, if not, choose a random PAN ID
- allowed_channels or deny_channels
- unicast_dwell_interval
- broadcast_dwell_interval
- broadcast_interval
- GTK: Group Transient Key
- ptk_lifetime (pairwise master key lifetime)
- ptk_lifetime (pairwise transit key lifetime)

For example, setting IPv6 prefix in ***wsbrd.conf.***

 # Prefix lengths different from /64 are not supported yet

ipv6_prefix = fd12:3456::/64

Then launch wsbrd daemon with command

sudo wsbrd -F examples/wsbrd.conf -u /dev/ttyACM0

Finally, while the ***wsbrd*** daemon is running, you may see the ***tun0*** interface. This interface is used to interact with the RCP RF device.

tun0: flags=4305<UP,POINTOPOINT,RUNNING,NOARP,MULTICAST> mtu 1500
inet6 fe80::e568:7e4e:7263:2a6d prefixlen 64 scopeid 0x20<link>
inet6 fd12:3456::*7700:2372:43b2:4a04 prefixlen 64 scopeid 0x0<global>*
unspec 00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00   txqueuelen 10 (UNSPEC)
RX packets 10 bytes 752 (752.0 B)
RX errors 0 dropped 0 overruns 0 frame 0
TX packets 6 bytes 400 (400.0 B)
TX errors 0 dropped 0 overruns 0 carrier 0 collisions 0

And all the node routers that successfully connect with LBR or BR will obtain the IPv6 prefix setting above (fd12:3456::/64).

3.3.3 Setting on Router Node

To configure the following parameters on the node, we can use the command line interface or radio configurator interface. In order for the node to reach the LBR or BR, those characteristics must be compatible with the LBR or BR.

- Network name
- Domain
- Operating mode
- Operating class

3.3.4 Module 1 Result

When the ***wsbrd*** daemon was running on the Raspberry PI and all nodes could connect to the Wi-SUN network, the connection status was displayed on the command line and LCD of node router. When the state Operational (5) can be seen on the command line or on the LCD, it means that the node has joined the network and is ready to connect with LBR. Figure 13 shows a successful node router connects to a LBR or BR.

```
[Connecting to "Wi-SUN"]
>
> [Join state: Authenticate (2)]
[Join state: Acquire PAN configuration (3)]
[Join state: Configuring routing (4)]
[Join state: Operational (5)]

Addresses:
[GLOBAL        : fd12:3456::b6e3:f9ff:fea6:489]
[LINK_LOCAL    : fe80::b6e3:f9ff:fea6:489]
[BORDER_ROUTER : fd12:3456::1615:16ff:fe17:1819]
[166 s]
```

Figure 13. Node Router join state indicates

The round trip time is calculated between the node router to its parent node. In test case 1, 2, 3 primary parent was BR or LBR. However, in test case 4 Router 2 chose the best node to become its primary parent, which is Router 1 (choosing by RPL routing protocol).

ETX-Expected Transmission Count is the number of expected transmissions of a packet necessary for it to be received without error at its destination. The ETX formula as follows:

$$ETX = \frac{frame\ transmission\ attempts}{received\ frame\ acknowledgements} * 128 \qquad (2)$$

ETX measures the quality of path between two nodes, which ranges from 128 to 1024. Value 128 indicates a perfect transmission medium /5/.

The RSL_IN- (dBm) Receive Signal Level IN is an Exponentially Weighted Moving Average (EWMA) of the received signal level for the neighbor-to-node direction.

The RSL_OUT- (dBm) Receive Signal Level OUT is an EWMA of the received signal level for node-to-neighbor direction.

RSL is calculated as the received signal level relative to standard thermal noise (290 ^{o}K) at 1 Hz bandwidth or - 174 dBm. This provides a range of -174 (0) to +80 (254) dBm. The higher value shows the better link quality /5/.

A router node computes the ETX and RSL_OUT, RSL_IN link metrics in order to maintaince and update its neighboring link metrics. It will refresh the link metrics again at least every 30 minutes to clarify its neighbor still available or not. In different places, if we reset the router node, it will re-connect and re-calculate its link metrics to set or reset its parent.

Table 5 gives the connection times, latency results and link measurements for each mode in each test case.

The minus sign (-) in table 5 (Test cases 2 and 4) indicates that the node router did not reconnect to the LBR or BR. It retained the connection from the first time it was connected and then relocated.

Table 5. Module 1 test result

Mode	Connection Time	RTT	Packet Loss	ETX	RSL_OUT	RSL_IN
Test case 1- Router 1 is located 40 meters away from LBR						
Mode 1a	185 s	320 ms	0 %	128	108	114
Mode 2a	159 s	232 ms	0 %	128	119	121
Mode 3	136 s	180 ms	0 %	128	126	125
Test case 2- Router 1 is located 100 meters away from LBR						
Mode 1a	172 s	475 ms	0 %	1024	93	93
Mode 2a	242 s	231 ms	0 %	128	91	90
Mode 3	223 s	179 ms	0 %	170	96	95
Test case 2- Router 1 is located 280 meters away from LBR (Location A- on the street)						
Mode 1a	-	1772 ms	0 %	1024	92	93
Mode 2a	-	884 ms	0 %	128	89	90
Mode 3	-	n/a	100 %	452	91	91
Test case 2- Router 1 is located 280 meters away from LBR (Location B- behind the building)						
Mode 1a	-	n/a	100 %	1024	85	85
Mode 2a	-	n/a	100 %	292	84	83
Mode 3	-	n/a	100 %	730	87	91
Test case 3- Router 2 is 200 meters away from BR- Location 1 (LOS)						
Mode 1a	190 s	294 ms	0 %	128	99	95
Mode 2a	240 s	408 ms	0 %	128	97	101
Mode 3	161 s	134 ms	0 %	128	113	111
Test case 3- Router 2 is 400 meters away from BR- Location 2 (LOS)						
Mode 1a	167 s	318 ms	0 %	128	99	109
Mode 2a	484 s	230 ms	0 %	128	101	98
Mode 3	166 s	108 ms	0 %	128	104	108
Test case 3- Router 2 is 650 meters away from BR- Location 3 (LOS)						
Mode 1a	510 s	342 ms	0 %	128	101	100
Mode 2a	501 s	492 ms	0 %	213	98	98
Mode 3	161 s	177 ms	0 %	128	105	105
Test case 4- Router 1 is 100 meters away from LBR						
Mode 1a	318 s	496 ms	0 %	1024	91	91
Mode 2a	442 s	353 ms	0 %	1024	92	89
Mode 3	370 s	445 ms	0 %	306	95	97
Test case 4- Router 2 is 300 meters away from LBR and LOS with Router 1						
Mode 1a	383 s	285 ms	0 %	128	115	117
Mode 2a	380 s	528 ms	0 %	169	92	92
Mode 3	n/a	n/a	n/a	n/a	n/a	n/a
Test case 4- Router 2 is re-locate to Location C, 250 meters away from Router 1						
Mode 1a	-	5876 ms	75 %	160	102	106
Mode 2a	-	2118 ms	30 %	232	100	97
Mode 3	n/a	n/a	n/a	n/a	n/a	n/a
Test case 4- Router 2 is re-locate to Location D, 300 meters away from Router 1						
Mode 1a	-	5218 ms	50 %	-	-	-
Mode 2a	-	n/a	100 %	418	94	89
Mode 3	n/a	n/a	n/a	n/a	n/a	n/a

Table 6 summarizes the results of four test cases and highlights the mode that performed better than the others.

Table 6. Module 1 test result summary

Test case 1	40 meters distance between node router and LBR: All modes operate correctly. Mode 3-2 has best performance
Test case 2	100 meters distance between node router and LBR: all modes operate, Mode 3-2 still highly efficient. 280 meters distance between node router and LBR (on the street): Mode 1a-1 and 2a-2 still accessible to LBR but mode 3-2 is unreachable to LBR. 280 meters distance between node router and LBR (behind a building): all modes inaccessible to their LBR
Test case 3 (LOS)	Distance 200, 400 or 650 meters between BR and node router: the entire mode is working. Mode 3-2 has best performance
Test case 4	Router 1: 3 modes take a longer connection time than usual, bad link metrics. Mode 2a-2 shows it stability than Mode 1a-1 and 3-2. Router 2: Mode 3-2 cannot successfully join the network.

We can see from the test results (Table 5) that RTT increases with distance. The retransmission process is one component that has an impact on RTT. The retransmission procedure may occur if the channel is busy, no frame is received, or the answer frame is invalid, and a lost ping reply will refer to a loss packet.

3.3.5 Network Throughput

In this study, the network throughput was calculated in three modes: 1a-1, 2a-2, and 3-2. (Wi-SUN PHY). Three modes are in the domain of the EU. In the test four ping packets were sent with a payload size of 1232 bytes from one node to its primary parent, and the average round-trip time was measured (RTT). This test was conducted in the office, with no distance between the node and the BR.

The throughput was calculated using the formula 3:

$$\text{Throughput} = 2 * \frac{\text{Payload data (bit)}}{RTT} \quad (3)$$

Table 7. Throughput calculated result

OPERATING MODE-CLASS	PAYLOAD SIZE (BYTE)	RTT (SECOND) AVERAGE	DATA RATE (KBPS)	NETWORK THROUGHPUT (KBPS)
1A-1	1232	1,158	50	17,022
2A-2	1232	0,375	100	52,565
3-2	1232	0,264	150	74,666

3.4 Module 2- Multi Hop, Self-Healing, Self-Forming

3.4.1 Module 2 Information

The second test involved a multi-hop, self-healing and self-forming test. Since Wi-SUN is a mesh-based solution, IP packets typically have to pass through multiple Wi-SUN routers to reach their destination. The test used 5 TI devices named CC1352P7-1, one as a border router, one as a sniffer, and 3 nodes router. These devices had to be tuned to the same channel so that a sniffer could track the packet hops. All devices were connected to the host computer via a USB interface.

Unlike SL, TI configured its Border Router IPv6 prefix using a global unicast address (GUA). As a result, you can see the difference between the IPv6 addresses of the SL and TI devices.

TI Wi-SUN FAN Spinel-CLI tool provides a command-line interface for interacting and controlling TI devices running TI Wi-SUN FAN stack software. In this test, the

Border router and node router sent commands over the spinel-CLI interface. A Mac filter command was used to force the network topology.

3.4.2 Module 2 Implementation

All parameters such as network name, operating mode, and operating class had to be set the same on border router and node routers, and the same channel selected for all devices. Channel 0 was selected.

The interface of these devices was accessed via spinel-cli tools with command

python spinel-cli.py -u "Serial Port"

On the border router side, we needed to bring up the network interface using the "*ifconfig up*" command. Then the stack was started with the command "*wisunstack start*".

```
C:\ti\ccs1110\simplelink_cc13xx_cc26xx_sdk_5_40_00_40\tools\ti-wisunfan-pyspinel>python spinel-cli.py -u COM13
Module readline unavailable
spinel-cli > role
0 : Border-Router
Done
spinel-cli > ifconfig up
Done
spinel-cli > wisunstack start
Done
```

Whenever a node was powered up, it automatically joined the network. The updated routing table information could be seen on the border router interface and use the "*connecteddevices*" command was used to display all connected node routers.

```
spinel-cli > connecteddevices
List of connected devices currently in routing table:
2020:abcd::212:4b00:14f9:682a
2020:abcd::212:4b00:1cc1:1ff9
2020:abcd::212:4b00:14f9:6727
2020:abcd::212:4b00:14f9:673c
Number of connected devices: 4
Done
```

All features supported by BR were listed with the command: help (Appendix B).

The chosen RPL routing method was that when a node sends a packet to its neighbors, it is first routed hop-by-hop to the BR. The self-healing property is that when a node router in the network cannot send a packet to its destination, it finds another way.

Figure 14 shows the topology of the test network and the global address of each device.

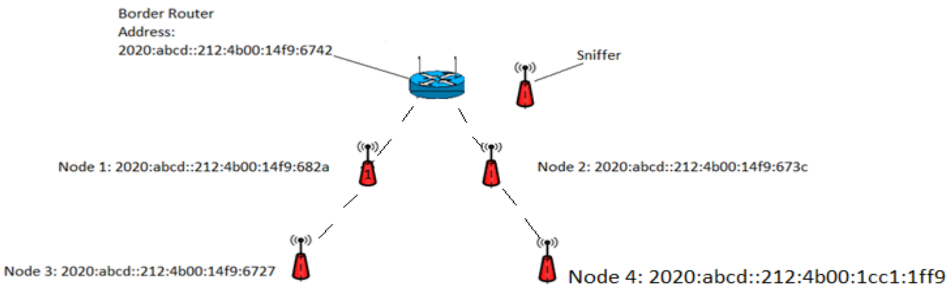

Figure 14. Module 2 network topology

Table 8 displays the global address and hardware address of each network node.

Table 8. Module 2 device address

Device Type	Global Address	Hardware Address
Border Router	2020:abcd::212:4b00:14f9:6742	00124b0014f96742
Node 1	2020:abcd::212:4b00:14f9:682a	00124b0014f9682a
Node 2	2020:abcd::212:4b00:14f9:673c	00124b0014f9673c
Node 3	2020:abcd::212:4b00:14f9:6727	00124b0014f96727
Node 4	2020:abcd::212:4b00:1cc1:1ff9	00124b001cc11ff9

The Mac filter applied on the BR only allowed communication with Node 1 and Node 2(Figure 15). Macfiltermode 1 indicated that the added hardware address could communicate with the Border router.

```
spinel-cli > macfilterlist add 00124b0014f9682a
spinel-cli > macfiltermode 1
Done
spinel-cli > macfilterlist add 00124b0014f9673c
spinel-cli > macfiltermode 1
Done
```

Figure 15. MAC filter applied at BR

So the only way nodes 3 and 4 could talk to the BR was that it reached either node 1 or node 2 first. We check the path of node 3 and node 4 using command *"dodagroute "node router IPv6 global address""* Figure 16.

```
spinel-cli > dodagroute 2020:abcd::212:4b00:1cc1:1ff9
Path cost: 2
2020:abcd::212:4b00:14f9:6742
2020:abcd::212:4b00:14f9:682a
2020:abcd::212:4b00:1cc1:1ff9
Done
spinel-cli > dodagroute 2020:abcd::212:4b00:14f9:6727
Path cost: 2
2020:abcd::212:4b00:14f9:6742
2020:abcd::212:4b00:14f9:682a
2020:abcd::212:4b00:14f9:6727
Done
spinel-cli >
```

Figure 16. Route from Node 3 and Node 4 to BR

If node 1 or node 2 (both nodes enable communication with BR) suddenly become inactive, node 3 and 4 have to choose the remaining nodes to send the packet to BR. Here node 1 was disconnected from the network (USB connection plugged out), see Figure 17.

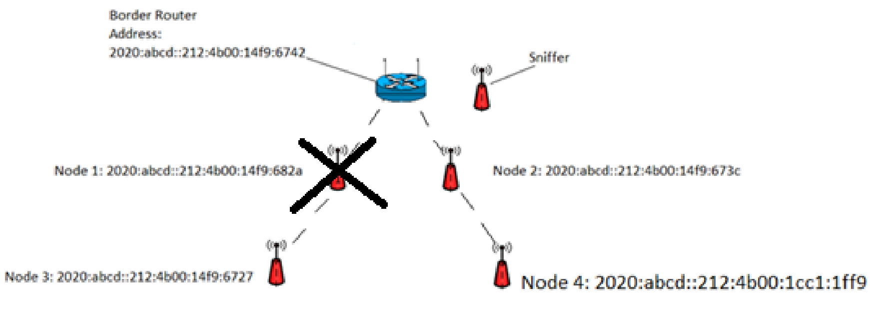

Figure 17. Module 2- Remove Node 1

It took approximately 2 minutes to update the routing table on the BR when the loss of Node 1 was detected. Until the update had been completed, the BR did not receive the frame from Node 3.

When each child node joins the network, it establishes a route to the root (BR) through a primary parent. If that parent is dead, the child node needs to be re-established with the root (BR) via another node. Consequently, the update time is close to the connection time for that node. The other node where the pathway to the root does not pass through the dead parent has not been affected.

Figure 18 shows that the path that node 3 and 4 chose to send the packet to BR changed. Those nodes hopped on Node 2.

```
spinel-cli > dodagroute 2020:abcd::212:4b00:14f9:6727
Path cost: 2
2020:abcd::212:4b00:14f9:6742
2020:abcd::212:4b00:14f9:673c
2020:abcd::212:4b00:14f9:6727
Done
spinel-cli > dodagroute 2020:abcd::212:4b00:1cc1:1ff9
Path cost: 2
2020:abcd::212:4b00:14f9:6742
2020:abcd::212:4b00:14f9:673c
2020:abcd::212:4b00:1cc1:1ff9
Done
```

Figure 18. New Route from Node 3 and 4 to BR

4 ANALYSIS

As we see from Test module 1, distance and environmental conditions affect the latency and connection quality. The link was still maintained and reliable in residential areas with a distance of up to 200 meters, whether the node was mobile or stable. In a typical park location, the link between 2 nodes could reach more than 680 meters. The range can be up to 1 km if both BR and the Node router can be in the high position.

Wi-SUN has a long wavelength because it operates at SUB gigahertz. As a result, it can more easily bend between obstacles, and frequency hopping is a significant advantage of Wi-SUN in avoiding interference and collisions when multiple nodes can communicate at the same time using different channels.

The City of London has completed the implementation of a streetlight system using the Wi-SUN technology, demonstrating its ability to adapt to the urban environment, where the buildings are very tall, full of steel and glass, making that the RF environment is quite inhospitable.

In Test case 2, we discover that mode 2a-2 was more stable than the other modes (1a-1, 3-2). From a theoretical standpoint, mode 2a-2 has a higher data rate and bandwidth than mode 1a-1, which explains why mode 2a-2 performs better than mode 1a-1 (connection time and latency). However, on test case 3 the exceptional performance of Mode 2a-2 was seen the reason for that may come from a short time of testing and small quantity of test Ping packet. As a result, many factors can cause radio link fluctuations.

Mode 3-2 gives substance to connection time, latency, throughput in clear space. However, In test case 2 Location A (residential area), it produced an unexpected result, as it had a higher data rate than mode 2a-2 but was unable to reach the LBR. Mode 3-2 has a distance limitation in an urban environment. Beside that, In test case 4, undetectable factors made router 2 unable to join the network. More practical tests should be performed to give concrete information on this situation.

In the urban area and if the distance between node is greater than 100 meters, the mode with low data rate and less channel shows the advantage (Mode 2a-2).

Beside that, the critical configuration impacting the latency is the Wi-SUN PHY. A point-to point ping is composed of four message over the air (Figure 19) , so larger payloads may take longer to send messages on the radio medium.

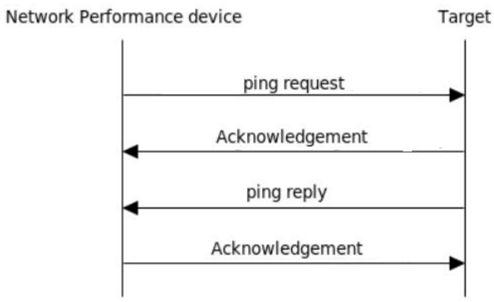

Figure 19. Transmission of packets via air.

The Wi-SUN PHY also impacts the transmissions triggered to manage the Wi-SUN network. For example, with Wi-SUN PHY EU domain 50kpbs mode 1a-1 using 65 channels, a device send PAN advertising holds the radio for around 1 second. As Figure 20 shows, node router devices with MAC address B4E3F9FFFEA6048F takes about 16 ms to send PAN advertisement on each channel.

Events   total:969 shown:143   Decoders: Auto-detecting decoder stack, Default

Time	Type	Summary	MAC Src	MAC ...	Event err...
345,960360	Packet	PAN Advertisement	B4E3F9FFFEA60489		
417,441243	Packet	PAN Advertisement	B4E3F9FFFEA60489		
490,181350	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,197302	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,213235	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,229183	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,245113	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,261099	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,277106	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,293135	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,309362	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,325440	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,341410	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,357359	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,373316	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,389253	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,405195	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,421184	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,437451	Packet	PAN Advertisement	B4E3F9FFFEA6048F		
490,453415	Packet	PAN Advertisement	B4E3F9FFFEA6048F		

Figure 20. Mode 1a-1 takes time to send PA

If we use a Wi-SUN PHY with a higher modulation speed and fewer channels, such as Mode 3-2 with 150 kbps and 35 channels, the node router will take less time on each channel, approximately 10 ms per channel (Figure 21). As a result, the total time spent sending PAN Advertisment is around 350 ms. This decreases the effect of these events on latency. So, we can easily see from the test result that Mode 3-2 usually has the low latency compared with Mode 1a-1, 2a-2 (excluded the unknown factors effect on Mode 3-2 in test case 2 and test case 4).

Events total:4 139 shown:4 039 Decoders: Auto-detecting decoder stack, Default

Time	Type	Summary	MAC Src
1 512,135511	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,144993	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,154606	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,164116	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,173614	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,183107	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,192646	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,202142	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,211622	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,221245	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,230752	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,240236	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,249788	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,259325	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,268829	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,278334	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,287943	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,297449	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,306938	Packet	PAN Advertisement	B4E3F9FFFEA6048F
1 512,316734	Packet	PAN Advertisement	B4E3F9FFFEA6048F

Figure 21. Mode 3-2 takes time to send PA

The average connection time with distance from 0 – 200 meter is around 200s "Network size" setting does not have an effect on ability to join and discover the node router but on the connection time. All testing from test module 1 using "small" setting for "Network size".

Comparing with Silicon Labs test result Figure 22, "small" setting applied in "network_size" shows that the average time is about 180 seconds. The reason for the difference between routers 1 and 7 is that these nodes choose other routers than their parents to improve communication. This behavior is determined by the RPL protocol. The parent of router 7 is router 9, while the parent of router 1 is router 10.

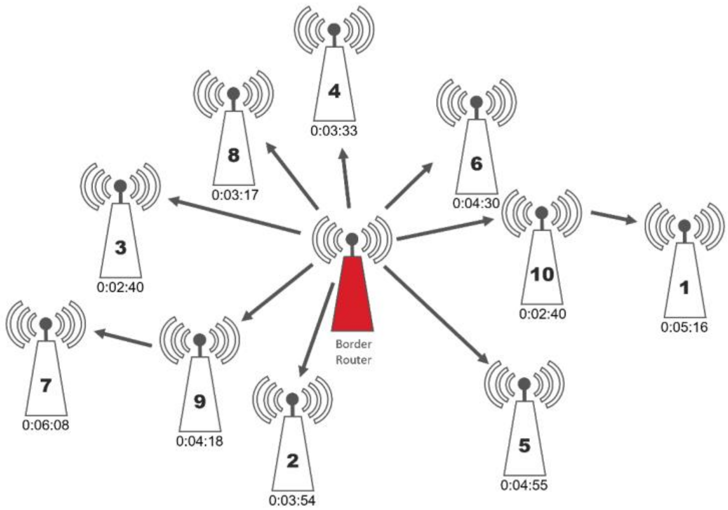

Figure 22. SL connection time test result

5 CONCLUSIONS

Wi-SUN concentrates on smart city and smart utility applications with key features such as IPv6 network, 6LoWPAN adaption layer allows IPv6 header compression, RPL routing method, frequency hopping, mesh topology and world -wide region support. Wi-SUN operates on SUB GHz so that the long wavelength makes it easy to penetrate through obstacle, more reliabinle in dense environments. The mesh protocol enables a maximum connection of up to 24 hops. Therefore, Wi-SUN can be used for large outdoor IoT wireless communication networks.

To conclude, the WI-SUN protocol demonstrates its good performance in the urban environment with its reliability, low latency and long-range network. It is a potential protocol by demonstrating the great capacity to adapt to IoT market. Of course, there is not one perfect protocol for everything. It is consistent with the goal, features and location of the project. However, at this time WI-SUN FAN stack suppliers just released version 1.0 consist of 2 types of devices (Border router and node router). Version 1.1 of the battery-powered device and new modulation implement will be released in the fourth quarter of 2022.

We can see from this thesis that Wi-SUN FAN 1.0 takes a long time to connect (which promises to be improved in Version 1.1). It takes around 100-300 seconds for the node to connect to the Border router for the first time. However, re-establishing the node router with Border Router will be faster than the first time because the node router has already stored all keys obtained from Border Router (The node router will jump directly to state 3 of joining process).

In order to maintain the resistance of the network Border router the router may need a backup power supply.

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APPENDICES

Appendix A

This appendix shows the interoperability test between SL BR and TI Router. The obstacle in this implementation arises from different configurations on the ***channel control plan*** between 2 suppliers on EU domain.

The "Channel Plan" field is defined as 0 if the channel plan of the node is determined by Regulatory Domain and the Operating Class field. Otherwise, the "Channel Plan" fields are set to 1 if specified values are given for the CH0 channel plan, channel spacing and number of channel fields.

The TI node defined "Channel Plan" is 1 Figure 23, this means that they will use "Explicit Channel Plan".

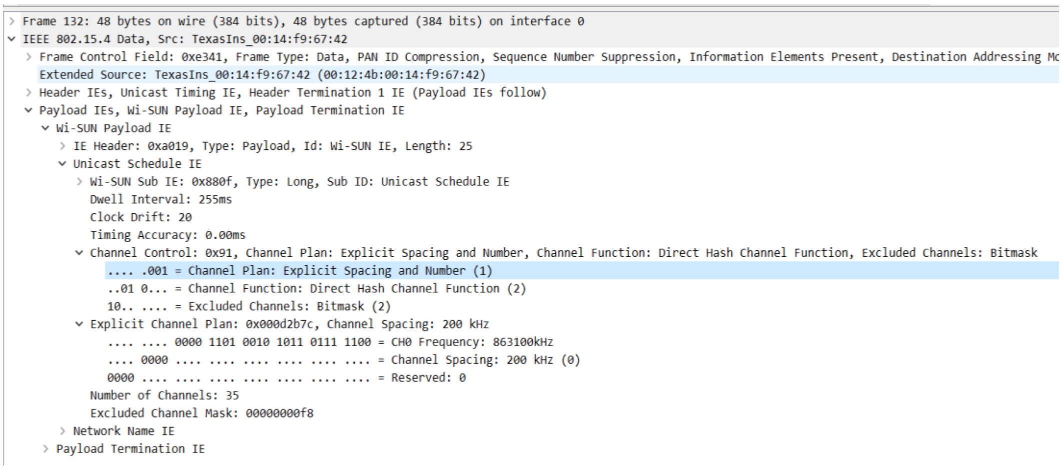

Figure 23. TI node "Channel Plan"

From the TI system configuration interface Figure 24, even information about the Region, Regulatory Domain, Operating mode were displayed. But the parameter for RF is based on CH0 frequency, channel spacing and number of channels because they have already set "Channel Plan" to 1.

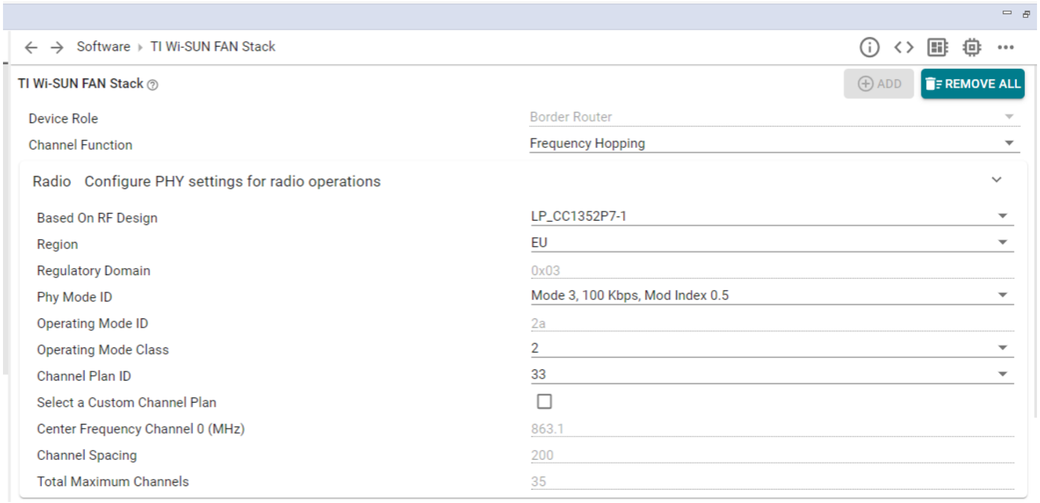

Figure 24. TI system configuration interface

From SL, they set "Channel Plan" to 0 Figure 25. We can see clear information about the Regulatory Domain is EU and the Operating Class is 2.

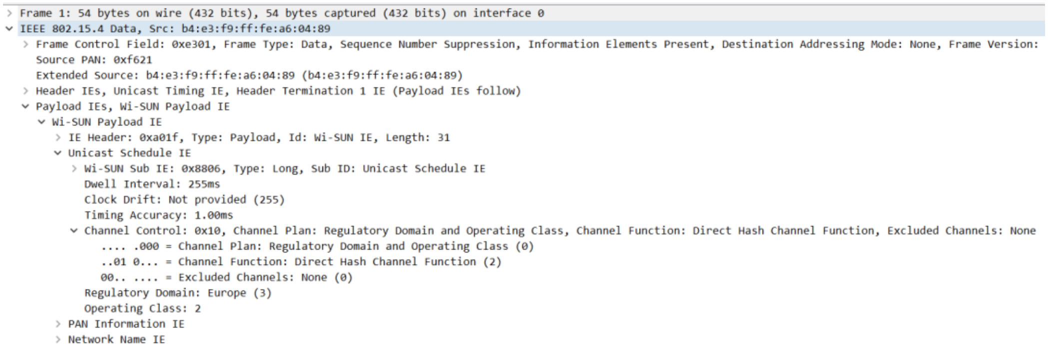

Figure 25. SL devices “Channel Plan”

They can't communicate with each other until we change them to the same bit configuration on "Channel Plan". The TI side has not yet given the method to set "Channel Plan" to a different bit, so we will do it on the SL LBR side.

This implementation used 1 SL Border Router, 1 SL Router and 1 TI Router.

Step 1: Using Simplicity studio Serial 1 command line to access to SL’s Border Router. Use the following command to set CH0 frequency, number of channel and channel spacing.

wisun set wisun.phy.ch0_frequency 863100

wisun set wisun.phy.number_of_channels 35

wisun set wisun.phy.channel_spacing 1 (1 corresponding to 200 kHz)

Figure 26 shows the complete configuration on the SL Border router.

```
> wisun get wisun
wisun get wisun
wisun.state = started (2)
wisun.network_name = "Wi-SUN"
wisun.regulatory_domain = application (255)
wisun.operating_class = 2
wisun.operating_mode = 0x2a
wisun.network_size = small (1)
wisun.tx_power = 20
wisun.unicast_dwell_interval = 255
wisun.broadcast_interval = 1020
wisun.broadcast_dwell_interval = 255
wisun.unicast_channel_mask.000-031 = 0xffffffff
wisun.unicast_channel_mask.032-063 = 0xffffffff
wisun.unicast_channel_mask.064-095 = 0xffffffff
wisun.unicast_channel_mask.096-127 = 0xffffffff
wisun.unicast_channel_mask.128-159 = 0xffffffff
wisun.unicast_channel_mask.160-191 = 0xffffffff
wisun.unicast_channel_mask.192-223 = 0xffffffff
wisun.unicast_channel_mask.224-255 = 0xffffffff
wisun.fixed_channel = disable
wisun.gak1 = 0e:e4:2b:31:31:dd:e5:b2:c1:00:00:1a:c2:7a:c0:f1
wisun.gak2 = 00:00:00:00:00:00:00:00:00:00:00:00:00:00:00:00
wisun.gak3 = 00:00:00:00:00:00:00:00:00:00:00:00:00:00:00:00
wisun.gak4 = 00:00:00:00:00:00:00:00:00:00:00:00:00:00:00:00
wisun.ip_addresses = [ll: fe80::b6e3:f9ff:fea6:489 gua: fd00:7283:7e00:0:b6e3:f9ff:fea6:489 dodagid: fd00:6172:6d00:0:b6e3:f9ff:fea6:489]
wisun.phy.ch0_frequency = 863100
wisun.phy.number_of_channels = 35
wisun.phy.channel_spacing = 200kHz (1)
wisun.trace_filter.000-031 = 0xffffffff
wisun.trace_filter.032-063 = 0xffffffff
```

Figure 26. SL Border router configuration

Step 2: The same setting applied to the SL node router.

Step 3: On the TI node router, we need to modify its client certificate to the SL client certificate in ***application.c*** file.

```
const uint8_t WISUN_ROOT_CERTIFICATE_SL[] = {
   "-----BEGIN CERTIFICATE-----\r\n"
   "-----END CERTIFICATE-----"
};
const uint8_t WISUN_CLIENT_CERTIFICATE_SL[] = {
   "-----BEGIN CERTIFICATE-----\r\n"
   "-----END CERTIFICATE-----"
};
const uint8_t WISUN_CLIENT_KEY_SL[] = {
   "-----BEGIN PRIVATE KEY-----\r\n"
   "-----END PRIVATE KEY-----"
};
#define MBED_CONF_APP_OWN_CERTIFICATE
WISUN_CLIENT_CERTIFICATE_SL
#define MBED_CONF_APP_OWN_CERTIFICATE_KEY      WISUN_CLIENT_KEY_SL
```

#define MBED_CONF_APP_ROOT_CERTIFICATE WISUN_ROOT_CERTIFICATE_SL

wisun_tasklet_remove_trusted_certificates();

wisun_tasklet_set_trusted_certificate(MBED_CONF_APP_ROOT_CERTIFICATE,strlen((const char)MBED_CONF_APP_ROOT_CERTIFICATE)+1);*

wisun_tasklet_remove_own_certificates();

*wisun_tasklet_set_own_certificate(MBED_CONF_APP_OWN_CERTIFICATE,strlen((const char *)MBED_CONF_APP_OWN_CERTIFICATE)+1,MBED_CONF_APP_OWN_CERTIFICATE_KEY,strlen((const char*)MBED_CONF_APP_OWN_CERTIFICATE_KEY)+1);*

Step 4: Added GTH hash set network key: ***d8528f94e7d4d527000000000000*** retrieved from SL BR debug trace to TI node router ***pre-shared key in syscfg***. The number of listed preamble should conform to the Wi-SUN standard (Mode 1a/2a is 8 bytes, Mode 3 is 12 bytes and Mode 5 is 24 bytes).

Step 5: Whenever the Border router starts, these nodes will manage to join the network. We can test the connection by sending a ping packet from SL node router to the TI node router Figure 27.

```
>
> w p fd00:7283:7e00:0:212:4b00:14f9:6742
PING fd00:7283:7e00:0:212:4b00:14f9:6742: 40 data bytes
> 40 bytes from fd00:7283:7e00:0:212:4b00:14f9:6742: icmp_seq=1 time=568 ms
w p fd00:7283:7e00:0:212:4b00:14f9:6742
PING fd00:7283:7e00:0:212:4b00:14f9:6742: 40 data bytes
> 40 bytes from fd00:7283:7e00:0:212:4b00:14f9:6742: icmp_seq=1 time=3017 ms
```

Figure 27. SL node router communicates with TI node router

However, the TI node and SL Border router connection is unstable. The TI node will break down after a while. This interoperability requires further investigation and clarity on whether it is being used.

Appendix B

```
spinel-cli > help

Available commands (type help <name> for more information):
============================================================
asyncchlist       connecteddevices  multicastlist     region
bcchfunction      exit              ncpversion        reset
bcdwellinterval   help              networkname       role
bcinterval        history           nverase           routerstate
broadcastchlist   hwaddress         panid             txpower
ccathreshold      ifconfig          phymodeid         ucchfunction
ch0centerfreq     interfacetype     ping              ucdwellinterval
chspacing         ipv6addresstable  protocolversion   unicastchlist
clear             macfilterlist     q                 v
coap              macfiltermode     quit              wisunstack
```

Figure 28. All command support by TI spinel-cli

Appendix C- Silicon Labs Wi-SUN Linux Border Router configuration.

Please refer to Silicon Labs git hub /21/ for more details.

\# Path of the serial port connected to the RCP.
uart_device = /dev/ttyACM0
\# Wi-SUN network name. Remind that you can use escape sequences to place special
\# characters. Typically, you can use \x20 for space.
network_name = Wi-SUN

\# Prefix used to generate IP addresses for RPL traffic (DODAGID will derive from
\# it). This prefix does not aim to change during network lifetime.
\# You can directly use your GUA (eg. 2001:db8::/64) prefix here. However, for
\# more flexibility, you may prefer to set an ULA here and add an extra GUA (not
ipv6_prefix = fd12:3456::/64
\# Domain (EU/NA/BR/JP…)
domain = EU
\# Operating mode in EU used in test module 1 is 1a/2a/3.
mode = 2a
\# Operating class in EU used in test module 1 is 1/2.
class = 2
\# Network size (CERT- development and certification, SMALL < 100 nodes, MEDIUM- from 100 to 800 nodes, LARGE- from 800 to 2500 nodes, XLARGE - >2500 nodes). (S, M, L and XL are also accepted).
size = SMALL
\# TX power (dBm)
tx_power = 20
\# Path to private key (keep in secret). PEM or DER formats are accepted.
key = examples/br_key.pem
\# Path to Certificate for the key. PEM or DER formats are accepted.
certificate = examples/br_cert.pem
\# Path to Certificate of the Certificate Authority (CA) (shared with all devices). PEM
\# or DER formats are accepted.
authority = examples/ca_cert.pem
\# Where to store working data. This value is prepended to the file paths. So
\# it is possible to configure the directory where the data is stored and an
\# optional prefix for your data (ie. /tmp/wsbrd/br1_).
\# The stored data mainly contains negotiated keys to speed-up connections when
\# service restarts.
\# Ensure the directories exist and you have write permissions.
storage_prefix = /var/lib/wsbrd/br1
\# By default, wsbrd tries to retrieve the previously used PAN ID from the
\# storage directory. If it is not available a new random value is chosen.

It is also possible to force the PAN ID here.
pan_id = 1234
This parameter accepts a comma-separated list of "ranges". Each "range" can
be two numbers separated by a dash or one unique. Example: 0,3-5,10-100
allowed_channels = 0-255
Unicast Dwell Interval (UDI) is the duration (ms) the border router will
listen to each channel in the FHSS sequence.
Valid values: 15-255 ms
unicast_dwell_interval = 255
Broadcast Dwell Interval (BDI) is the duration (ms) the border router will
listen/advertise to broadcast channel.
Valid values: 100-255 ms
broadcast_dwell_interval = 255
Broadcast Interval (BI) is the interval (ms) between each listen of the
broadcast channel. Recommended value for BI is 4.0 times the maximum of
(UDI, BDI).
Valid values: BDI < BI < 2^24 ms (~4h30)
broadcast_interval = 1020
Pairwise Master Key Lifetime (minutes)
pmk_lifetime = 172800 # 4 months

Pairwise Transit Key Lifetime (minutes)
ptk_lifetime = 86400 # 2 months

GTK expire offset as described in the Wi-SUN specification. (minutes)
This value is also used to set the lifetime of the first GTK.
gtk_expire_offset = 43200 # 30 days