IEEE 802.15.4 Now and Then: Evolution of the LR-WPAN Standard

Alberto Gallegos Ramonet*, Taku Noguchi**
College of Information Science and Engineering
Ritsumeikan University
Shiga, Japan
ramonet@fc.ritsumei.ac.jp, **noguchi@is.ritsumei.ac.jp**

***Abstract*—For 15 years, the popular IEEE 802.15.4 standard has served as de facto standard for applications with low latency and small energy consumption requirements. During this time, it has evolved and dramatically extend its original purpose. With thousand of possible parameters and combinations, its objectives are not as clear as they were when it was first introduced. In this paper, we present a concise and chronological description of the standard highlighting the main features introduced by each one of its revisions as well as a notion of its usage. A compendium of this kind can be valuable to researchers working on implementations and improvements and to users seeking a general reference. This is relevant now more than ever because the standard must coexist with hundreds of other standards that are also constantly evolving. As presented in this document and despite its popularity and importance, there are very few capable IEEE 802.15.4 simulators and these are often outdated and incomplete. The aim of this paper is to provide a quick reference but also present the evolution of the standard and its future directions. Similarly, we hope that this study fosters the creation of new implementations, particularly new simulations modules.**

***Index Terms*—LR-WPAN, protocols, survey, WSN, simulations, Zigbee, IEEE 802.15.4, modulations**

I. INTRODUCTION

Networks in our homes, offices, and mobile devices are constantly evolving. Not all network-enabled devices are connected to the Internet nor do they need to be. For example, devices found in our homes such as electric doors, televisions, and air conditioning systems may benefit from sharing information between each other, but in most cases, using the internet to connect these appliances may not be a cost effective solution because of the unnecessary added complexity, communication overhead, and unwanted privacy concerns. In such cases, internet independent networks are a preferred choice. Independent networks used in Wireless Sensor Networks (WSN) are an example.

The IEEE 802.15.4 standard was released in 2003 [1] to describe such types of networks. WSN have been developed for strict power constraints in specialized applications with low latency or for applications characterized by disruptive connections. In this paper, we present a chronological description of the IEEE 802.15.4 standard known as Low-Rate Wireless Personal Area Networks (LR-WPAN). Furthermore, this study describes the MAC behaviors and the available options of its physical layers and also clarifies the often overlooked formation of semi-mesh networks and available simulations. Despite the popularity of the IEEE 802.15.4 standard, to our knowledge, no other authors have presented any similar evolutionary summary of the standard. The present work is an extension of our own observations first introduced in [2]. This document is relevant for multiple reasons. For instance, the standard includes an extensive collection of physical layer options and MAC layer improvements that are not available in all revisions. In some cases, drastic changes make certain implementations obsolete or incompatible. Moreover, official IEEE standard descriptions assume the knowledge of prior revisions, making such documents hard to navigate without having a general idea of the standard such as the one presented in this study. Consequently, new improvements and implementations can be convoluted and time consuming to develop. It is also worth noting that implementations and simulations of the standard are considerably behind the most recent revisions. For example, Zigbee, arguably the most popular commercial implementation of the IEEE 802.15.4 standard, only until recently (V3.0) supported the 2011 revision of the standard [3] despite the existence of amendments as late as 2019. Owing to these reasons, we believe that users and implementers will find the summary presented in this document relevant and useful. This paper is organized as follows: Section II describes the complete evolution of the IEEE 802.15.4 standard, highlighting differences between each revision. Section III presents a brief description of some of the most popular simulation and physical implementations, followed by our conclusions. Finally, a complete IEEE 802.15.4 PHY evolution Table can be found in the Appendix. The Table summarize all datarates and modulations of the standard to date (2019).

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Alberto Gallegos Ramonet, is an Assistant Professor at College of Information Science and Engineering, Ritsumeikan University, Shiga prefecture, 1-1-1 Noji-Higashi, Kusatsu, CO 525-8577 Japan (Corresponding author e-mail: ramonet@fc.ritsumei.ac.jp).

Taku Noguchi, is a Professor at College of Information Science and Engineering, Ritsumeikan University, Shiga prefecture, 1-1-1 Noji-Higashi, Kusatsu, CO 525-8577 Japan (e-mail: noguchi@is.ritsumei.ac.jp).

II. EVOLUTION OF THE IEEE 802.15.4 STD.

A. IEEE 802.15.4 (2003)

Initially released in 2003, the IEEE 802.15.4 standard [1] defines the interconnection of LR-WPAN devices. It uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to access the medium and support star and peer-to-peer topologies. Its architecture layout can be described in terms of blocks based on the open systems interconnection (OSI) seven-layer model in which each block (also called layer) has a specific task and provides services to upper blocks. The Physical layer (PHY) or layer 1, contains the radio frequency (RF) transceiver with a low-level control mechanism. The 2003 standard defines two PHYs: a *2450 MHz band* PHY operating with a Optional Offset Quadrature Phase-Shift Keying (O-QPSK) modulation and a maximum data rate over-the-air of 250 kb/s. The standard also describes the less commonly used *915/868 Mhz band* PHY with a Binary Phase-Shift Keying (BPSK) modulation and data rates of 40 kb/s and 20 kb/s, respectively. Both of these PHY use a direct sequence spread spectrum (DSSS). The MAC layer (Media Access Control or layer 2) provides access to the physical channel. Although the standard primarily consists of these two layers, the standard also describes an additional Logical Link Control (LLC) and a Service Specific Convergence Sublayer (SSCS) between the MAC layer and the next layer to facilitate communication. The implementation details of the upper layers are beyond the scope of the standard. Transmission of data can be performed with or without the help of beacon messages. In a beacon-enabled Personal Area Network (PAN), a single Full Functional Device (FFD) acts as a PAN coordinator while the remaining devices are either FFD or Reduced Functional Devices (RFD). Different from a beacon-enabled PAN, in a non-beacon enabled PAN, devices compete for the medium at all times.

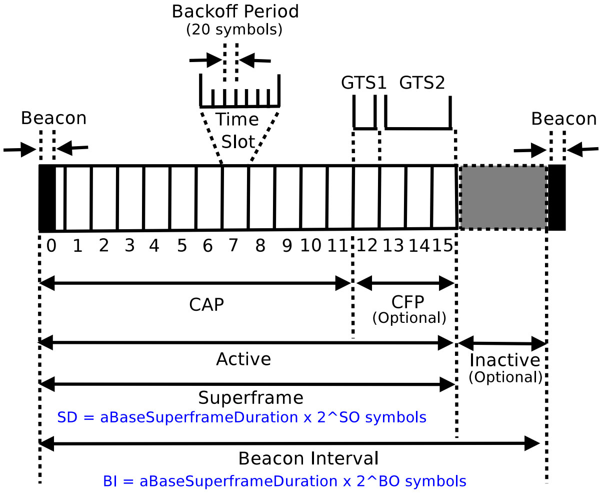


Fig. 1: Beacon-enabled mode superframe description.

In a beacon-enabled PAN, the PAN coordinator transmits in intervals beacons containing a *superframe* structure that defines an active period of time between beacons. The superframe is used to realize synchronized communication between the PAN devices. Figure 1 summarizes the structure of a superframe. A superframe is formed by 16 time slots in which a beacon is always sent during the first time slot. Similarly, each of these time slots consist of multiple *backoff periods* formed by *symbols*. A symbol is a representation of time in bits. For example, in the IEEE 802.15.4 standard that uses a O-QPSK modulation, 1 symbol is equivalent to 4 bits (0.016 ms in a 250-kbps connection). A Beacon Interval (BI) is defined by $aBaseSuperframeDuration \times 2^{BO}$ symbols. The Beacon Order (BO) is a user defined integer between 0 and 14 and $aBaseSuperframeDuration$ is a constant equal to 960 symbols. The BI includes both the active and inactive periods of time. The inactive period is optional with no transmissions, and the radio transceiver can be turned off to preserve energy. The active portion depends on the user defined variable Superframe Order (SO) and its length is described by the Superframe Duration (SD). The SD is equal to $aBaseSuperframeDuration \times 2^{SO}$ symbols for $0 \leq SO \leq BO \leq 14$. The active portion is further divided into a Contention Access Period (CAP) and Contention Free Period (CFP). In the CAP, devices contend for the transmission of data using a slotted version of the CSMA/CA algorithm. Time slots are formed by multiple *backoff periods* (1 backoff period is equivalent to 20 symbols). Operations within the CAP always occur on the boundary of a backoff period. The CFP is an optional part of the active period but if it is used, it must always be located at the end of the active period. The CFP is divided into Guaranteed Time Slots (GTS), which are assigned to specific devices for transmission without contention. A maximum of 7 GTS can be assigned. Their length directly depends on the maximum size of the CFP and the total number of GTS assigned.

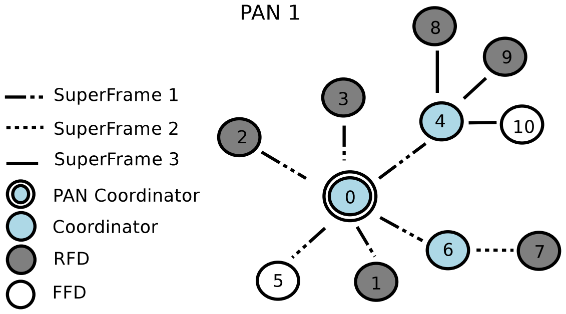


Fig. 2: IEEE 802.15.4 Semi-mesh topology in single PAN.

One aspect often overlooked by official IEEE 802.15.4 standard documents and researchers is the beacon-enabled function in semi-mesh topologies (full-mesh or mesh is only achievable by implementation on higher layers). While the standard states that this configuration is possible, little to no details are provided on the means to achieve this in multiple revisions. Figure 2 presents an example of the ways of achieving a semi-mesh topology. While only one PAN coordinator exists in a star topology PAN, it is possible to have extra coordinators to create a semi-mesh network (tree topology). PAN coordinators differ from coordinators in the sense that only PAN coordinators can initialize the network (association process) and give commands to other coordinators for administering the network. Each coordinator transmits its own beacons that

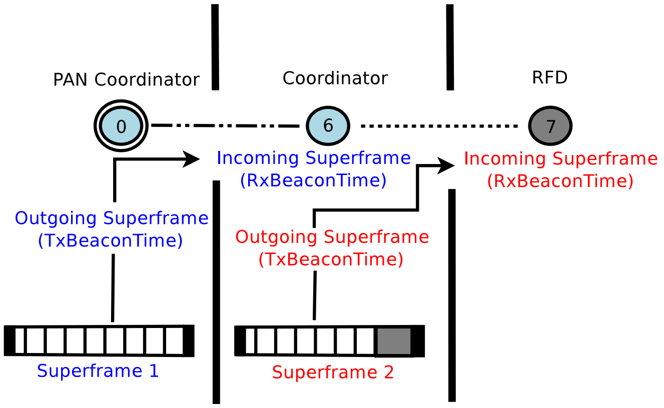


Fig. 3: Outgoing and Incoming superframe relationship in a semi-mesh Network.

contain the information of its superframe. The transmitted superframe helps synchronize data transmissions between a coordinator and its associated devices. In a semi-mesh topology, a PAN coordinator transmits a superframe to its associated devices, but also, one or more of these devices can act as coordinators and therefore, transmit another superframe to its own associated devices. The transmitted superframe is known as the outgoing superframe and the received superframe is known as incoming superframe. In Figure 3, it is possible to observe this superframe relationship for one segment of the semi-mesh network previously presented in Figure 2. When the coordinator 6 wishes to transmit data to its PAN coordinator 0, the coordinator 6 uses the incoming superframe information (superframe 1). Similarly, if the coordinator 6 wishes to transmit data to its associated device node 7, it will use the outgoing superframe information that originated from itself (superframe 2). An incoming superframe uses the beacon reception time from its coordinator (RxBeaconTime) as a reference to the beginning of the superframe. An outgoing superframe uses its beacon transmission time (TxBeaconTime) as a reference to the beginning of the superframe.

B. IEEE 802.15.4 (2006)

The 2006 revision [4] was the first revision after the standard was introduced in 2003. In this revision, a field in the Frame Control Field (FCF) of the MAC Header was added to easily verify the version in use. The biggest changes in this revision are in the physical layer. The 2003 original 868/915 MHz bands employed a BPSK modulation. Optionally, an Amplitude Shift Keying (ASK) modulation on the 868/915 MHz bands can be used in this revision. This modulation effectively increases the offered data rate to 250 kb/s for both bands. The same data rate could only be achieved on the 2450 MHz band in the 2003 revision. In addition to the 868/915 MHz bands BPSK and ASK modulations, an O-QPSK modulation was added. This modulation offers an increased data rate of 100 kb/s and 250 kb/s, respectively, when compared to the original BPSK modulation. O-QPSK modulation was only possible on the 2450 MHz band in the 2003 revision. As for MAC layer enhancements, the 2006 revision enables specification beacons start times via a parameter in the MAC layer primitives. Pre-establishing the start time helps reduce beacon collisions among PAN coordinators.

C. IEEE 802.15.4a (2007) - Amendment 1

IEEE 802.15.4a [5] is the first amendment to the 2006 revision. It introduces two new PHYs: the Ultra-wide Band (UWB) and the Chirp Spread Spectrum (CSS). UWB operates at frequencies of 3 GHz, 5 GHz, 6 GHz to 10 GHz, and less than 1 GHz (16 channels). UWB has a maximum over-the-air data rate of 851 kb/s with optional data rates of 110 kb/s, 6.81 Mb/s, and 27.24 Mb/s using a combined modulation of Burst Position Modulation (BPM) and BPSK. On the other hand, CSS operates in the PHY 2450 MHz with supports for data rates of 1000 kb/s or 250 kb/s. The UWB enables the use of precision ranging (calculation of the distance between two devices) using the Two-Way Ranging (TWR) protocol that enables ranging calculation without a common time reference.

D. IEEE 802.15.4c (2009) - Amendment 2

The second amendment [6] to the 2006 revision adds two extensions to the physical layer: One 780 MHz PHY with the O-QPSK modulation and another 780MHz PHY with the new modulation M-ary Phase Shift Keying (MPSK). Both these additions are meant to be used in China and have a maximum data rate of 250 kb/s, regardless of the modulation used.

E. IEEE 802.15.4d (2009) - Amendment 3

Similar to 2nd, the 3rd amendment to the 2006 revision [7] adds extensions to the physical layer exclusively for Japan. These extensions include two additional PHY: a PHY in the 950 MHz band with a Gaussian Frequency-Shift Keying (GFSK) modulation with a maximum data rate of 100 kb/s and a PHY in the 950 MHz band using the BPSK modulation with a data rate of 20 kb/s.

F. IEEE 802.15.4 (2011)

The 2011 revision [8] compiles all changes made in the last 3 amendments after the 2006 revision into a single document. In this revision, the standard dropped the concept of Service Specific Convergence Sublayer (SSCS) and instead exclusively focuses on PHY and MAC layer topics. Because of the lack of a flexible MAC layer, the 2011 revision gave birth to numerous alternative MAC layer proposals that satisfy the requirements of different types of applications. In time, the standard addressed these concerns and officially introduced variants to the MAC layers in the form of *MAC behaviors* in subsequent amendments.

G. IEEE 802.15.4e (2012) - Amendment 1

While most amendments prior to this one focus on PHY layer additions, IEEE 802.15.4e [9] proposed significant changes to the MAC layer. These changes impacted the standard in 2 ways. First, it relegated the previous MAC layer to an all-purpose legacy status. Second, it reworked the MAC layer to a modular and specialized design in the form of

MAC behaviors. These MAC behaviors introduce a level of flexibility never present in the previous versions and, therefore, include a point of interest often surveyed and evaluated by researchers [10]. IEEE 802.15.4e describe 5 MAC behaviors:

RFID. The standard specifies the MAC behavior called BLINK, which is a specific kind of Radio Frequency Identification (RFID) [11]. RFID BLINK transmits encrypted data and is well suited for applications that involve sensitive information, which is the reason for its wide use in contactless credit card transactions and transportation systems worldwide. Devices connecting with RFID do not require prior association or acknowledgement.

AMCA. The Asynchronous Multichannel Adaptation MAC behavior is designed to work in environments with low channel quality because of noise or the presence of a large number of devices in a non-beacon enabled network. These problems can cause link asymmetry, which leads to a rapid degradation in communication. To combat this, during an active scan, AMCA tests the link quality on all available channels through requests made by the coordinator. This way, AMCA selects the channel with the highest link quality for either listening or transmitting at any given time.

DSME. The Deterministic Synchronous Multichannel Extension MAC behavior is targeted at applications that require high levels of reliability or deterministic latency. Examples include applications in industrial automation in which the loss of data represents a serious problem and applications in health monitoring where a guaranteed timely response is necessary. Simultaneously, DSME can also handle densely populated networks such as sensor networks. Similar to the beacon-enabled mode in the legacy MAC, synchronized transmissions are performed using *superframes* structures, but these superframes are contained in *multiframes* structures. DSME multi-superframe structures are described in Figure 4. Like before, a superframe is formed by a CAP and a CFP. In DSME, a single channel is used for the association process, which involves the transmission of Enhanced Beacons (EB) and transmissions during the CAP. The EB is a new addition to the standard and is composed of Information Elements (IE). IE are introduced for the first time in this amendment but are also used in other standards such as the IEEE 802.11. IE enables a more flexible use of the fields because they possess variable sizes, greatly extending the functionality of the frame that uses them. Different from the legacy MAC beacon-enabled, the CFP in DSM is capable of allocating up to 7 GTS for each available channel (16 channels). Alternatively, the slots can be assigned to perform Group Acknowledgment (GACK). With a GACK, it is possible to combine several acknowledgments to be sent to all devices communicating within the same superframe. This feature helps reduce latency and energy consumption.

Another unique feature of DSME is CAP reduction. Except for the first superframe CAP in the multi-frame, DSME can completely eliminate subsequent CAPs in the multi-frame and use the time gained to effectively increase the time for exclusive transmissions in CFP operations. DSME Beacon Interval (BI) is equal to $aBaseSuperframeDuration$ x 2^{BO} symbols where $aBaseSuperframeDuration$ is equal to 960 symbols and the Beacon Order (BO) is an integer between 0 and 14. The superframe duration (SD) is equivalent to $aBaseSuperframeDuration$ x 2^{SO} symbols, where SO is the superframe order and is related to the BO in $0 \leq SO \leq BO \leq 14$. Likewise, the Multi-superframe Duration (MD) is the result of $aBaseSuperframeDuration$ x 2^{MO} symbols where MO is the Multi-superframe Order and relates to both SO and BO in $0 \leq SO \leq MO \leq BO \leq 14$. To overcome interference as a result of noise present in a given channel, DSMA can check the link quality and use *channel adaptation* to switch a GTS (assigned to a specific device) to a different channel in a consecutive time slot. On the other hand, *channel hopping*, a well-known technique, can be used to set a predefined sequence to hop between channels during the whole frame transmission.

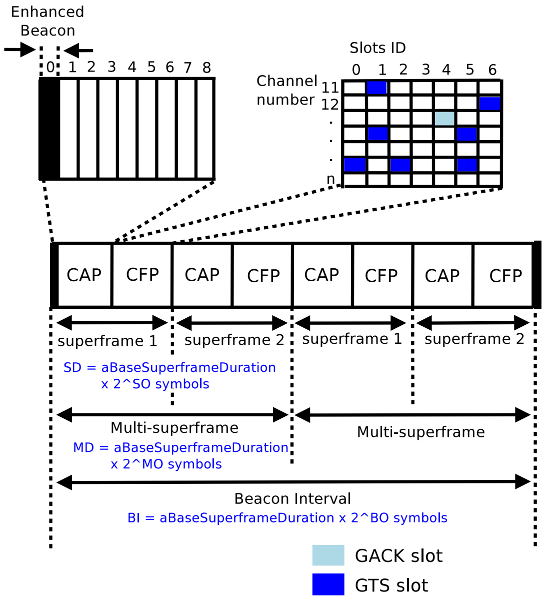


Fig. 4: DSME multi-superframe structure.

LLDN. The Low Latency Deterministic Networks MAC behavior was specifically designed for factory automation or implementations with similar requirements and limitations. LLDN is exclusive used in centralized networks (star topology) that require latencies as low as 10 ms for more than 100 devices connected to a single coordinator. Examples of LLDN applications include, but are not limited to robots, airport logistics, conveyors, automatic packing, cargo, etc.

In LLDN there can be two types of devices; devices that can only send data to the coordinator (uplink capable) or devices that can do both, send and receive data from the coordinator (uplink and downlink capable). LLDN has a *superframe* structure in which the first time slot is assigned to the beacon and the remaining slots of equal size are assigned to specific devices in the network. Multiple devices can be assigned to a single slot and they contend for the medium using CSMA/CA. In LLDN, superframe time slots have a specific order and purpose: a) The *beacon timeslot* which is always present. b) The *management timeslots*: *downlink* and *uplink* timeslots. The existence of management slots is optional and depends on whether or not the *macLLDNmgmtTS* flag is set

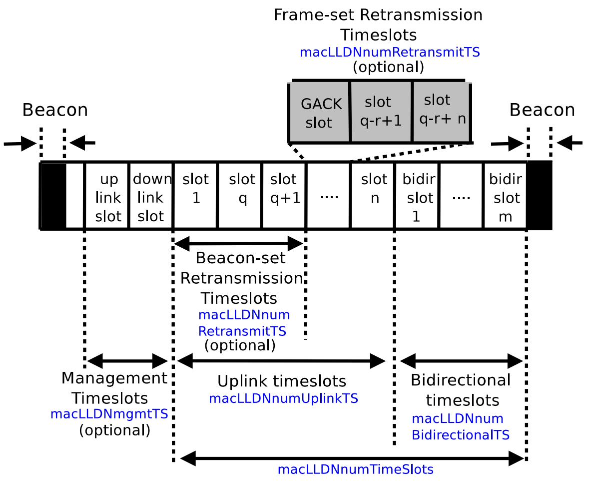


Fig. 5: LLDN superframe structure.

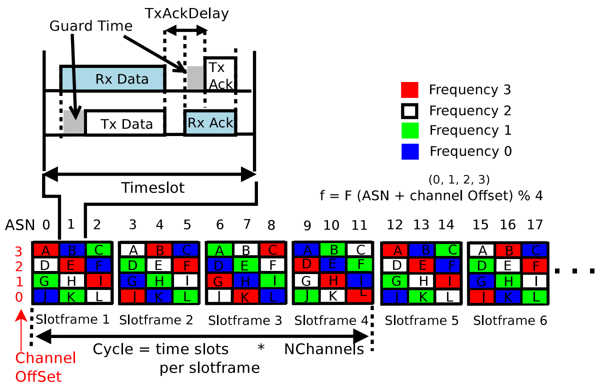


Fig. 6: TSCH frequency hopping mechanism.

true. c) The *uplink timeslots* are used for transmissions from the devices to the coordinator. In addition, the first uplink slots can be used for re-transmissions if specified by the Group Acknowledgment (GACK) field in the beacon. Alternatively, re-transmissions can also be set using an LL-Acknowledgment frame (command frame) sent in the *bidirectional timeslots*. d) *Bidirectional timeslots* are used for multi-link communication between the coordinator and its devices. The slot size and number of slots for each usage are indicated by the *macLLDN* attributes, as shown in Figure 5.

TSCH. The Time Slotted Channel Hopping MAC behavior was created for robustness. TSCH applications include the oil and gas industry, chemical and pharmaceutical production, or applications prone to collisions caused by the saturation of the network. TSCH considers a deterministic response as the most important aspect of communication. Different to DSME, TSCH support semi-mesh and star topologies. In TSCH, *superframes* are replaced with *slotframes*. Slotframes repeat cyclically and are formed by a sequence of *timeslots*. Each timeslot has an incremental Absolute Slot Number (ASN) that indicates the total number timeslots elapsed since the beginning of the network. Transmissions inside these timeslots can occur with or without contention. In addition, in TSCH, it is possible to use concurrent slotframes, each with independent timeslot configurations. However, all slotframes are aligned to the same timeslot boundaries. Unlike the channel diversity used in DSME, TSCH relies on a channel hopping mechanism to achieve communication. The frequency f used in a transmission between two nodes is defined by $f = F[(ASN + channelOffset)\%NChannels]$ where *channel Offset* is an integer between 0 and 15, *NChannels* is the hopping sequence length, and F denotes a lookup table. In this manner, a different frequency is obtained for the same link in different time slots. TSCH behavior is summarized in Figure 6.

H. IEEE 802.15.4f (2012) - Amendment 2

The 2nd amendment [12] to the 2011 revision has two new PHY. First, the Low-rate PRF Ultra-Wide Band (LRP UWB) optimized for low complexity RFID transmitters (tags) exhibits a level of interoperability only present with the UWB PHY in previous revisions. LRP UWB offers 3 modes: a) *Base mode* with an On-Off-Keying (OOK) modulation and a bit rate of 1000 kb/s. b) *Extended mode* with an OOK modulation and a bit rate of 250 kb/s. c) *Long-range mode* with a Manchester Pulse Position Modulation (PPM) and a maximum bit rate of 31.25 kb/s.

The second PHY is a 2450 MHz band PHY with a Minimum Shift Keying (MSK) modulation and a maximum bit rate of 250 kb/s for RFID applications. The 2450 MHz band is the Industrial, Scientific and Medical (ISM) band and therefore, multiple standards operate on this band (e.g. Wifi, Lr-Wpan, etc). Moreover, small unused gaps in the spectrum on the edges of these frequencies tend to exist. MSK 2450MHz PHY takes advantage of those spaces and is capable of using up to 42 possible narrowband channels that fall on these unused gaps, gracefully coexisting with existing devices using the same band. Alternatively, MSK can operate on the much less saturated 433 MHz band with bit rates of 31.25, 100 or 250 kb/s.

I. IEEE 802.15.4g (2012) - Amendment 3

IEEE 802.15.4g [13], known as the Smart Utility Networks (SUN) standard, was created to be used in the emerging Smart Grids (SG). SGs are electrical grids capable of bidirectional energy flow and communication [14]. SUN PHYs are often used in smart metering applications with long-range, low-power requirements. This amendment introduces three PHY with multiple data rates to choose from. The PHY names are described by its modulation names: a) Frequency Shift Keying (FSK). b)Offset Quadrature Phase-Shift Keying (O-QPSK), which extends the frequency ranges of the 2011 modulation O-QPSK. c) The Orthogonal Frequency Division Multiplexing (OFDM), which uses DSSS and MDSSS. All of these PHY are designed to be used with Multiple data rates and in multiple regions (MR). However, smart-metering applications tend to use the internationally agreed *920 Mhz band* (frequencies 902 Mhz to 928Mhz) with a 2FSK and 50 kbps as the most common modulation and data rate choice [15]. While FSK and O-QPSK are well known modulations techniques used in multiple standards, OFDM is generally reserved for more specialized systems, and it was until 2012 that was adapted to the IEEE 802.15.4 standard to be used on low powered devices. OFDM purpose is to offer higher data rates over longer distances and combat multi-path fading. Multi-path fading occurs when transmitted signals bouncing off obstacles take different paths and arrive to the receiver at slightly different times. As a result, the overall received signal becomes the sum of these reflections which can be interpreted by the receiver as interference [16]. To combat multi-path fading, OFDM divides a frequency band into multiple sets of frequencies called subcarriers. Subcarriers are far apart enough from each other to avoid interfering with one another. Each subcarrier is modulated according to a *Modulation and Coding Scheme* (MCS): BPSK, QPSK or 16-QAM. Additionally, subcarriers must be grouped in one of four different ways formally called *options*. In other words, the transmitted OFDM symbol is the result of the combination of multiple modulated subcarriers grouped by an option. Each one of these subcarries carries pieces of the transmitted information. With this technique OFDM can achieve data rates as high as a high order modulation. A complete list of OFDM data rates according to the option and MCS can be found on Table III. Furthermore, OFDM can recover lost data using *Forward Error Correction* (FEC) or reducing the amount of lost data with *Frequency repetition* on some MCS (More than two subcarriers transmit the same information as a redundancy measure) [17].

Vendors often offer a SUN PHY paired with a portion of the IEEE 802.15.4e for its MAC implementation (TSCH behavior).

Some of the SUN PHY frequencies established in this amendment have been updated or discarded in later amendments.

J. IEEE 802.15.4j (2013) - Amendment 4

This amendment [18] introduces a single PHY for the 2380 MHz band with a maximum bit-rate of 250 kb/s. Its use is restricted to transmission data (no voice) in devices for monitoring, diagnosing, and treating of patients. These devices must be compliant with the Federal Communications Commission (FCC) rules for Medical Body Area Networks (MBAN).

K. IEEE 802.15.4k (2013) - Amendment 5

This amendment added 2 more PHYs: a) A DSSS PHY with either BPSK or O-QPSK modulation schemes. b) A FSK PHY with 3 possible modulations; a Gaussian FSK (GFSK), Position-based FSK (P-FSK), and Position-based Gaussian FSK (P-GFSK). These PHY are designed for Low Energy, Critical Infrastructure Monitoring (LECIM) applications. Different to its IEEE 802.15.4 PHY counterparts, LECIM PHY are designed to operate with extremly low energy because they are required to last with the original battery supply for many years (in the order of 20 years or more). To achieve this, LECIM uses low data rates but favors long range operations. LECIM can use a wide range of low data rates using either BPSK or O-QPSK modulations (Table II). LECIM data rates are calculated using the Equation 1 [19, pp. 58-61].

$$DataRate = FEC * \frac{ModulationRate * ChipPerSymbol}{SpreadFactor} \tag{1}$$

In the Equation 1, BPSK modulation is used when $ChipPerSymbol = 1$ and O-QPSK modulation is used when $ChipPerSymbol = 2$. The Forward Error Correction (FEC) is equal to 0.5. With the combination of the available $ModulationRates$ and $SpreadFactors$ LECIM datarates can be obtained. For example, the lowest possible O-QPSK data rate with a $ModulationRate$ of 200 ksym/s and the largest $SpreadFactor$ of 32768 would be 3 b/s. Usage of particular data rates or restrictions of specific bands depend on local regulations. One of the main features introduced in the 802.15.4k MAC layer is the ability to use *priority channel access* (PCA). PCA enables the allocation of high-priority messages in the CAP period of the superframe structure. Experiments performed by Gebremedhin et al. [20] demonstrated that under some conditions, PCA messages can greatly improve the latency of emergency messages while slightly affecting the performance of normal messages.

L. IEEE 802.15.4m (2014) - Amendment 6

The IEEE 802.15.4m amendment [21] objective was to re-purpose the unused frequency space left by some TV channels in the VHF and UHF TV broadcast bands. Originally, some space occupied by some TV channels was left unused to prevent TV channels from interfering with one or in some cases TV channels were left unused to comply with local regulations. These empty spaces are known as TV White Spaces (TVWS) and its value depends on its wide availability, uniformity among regions and its potential for longer range communications. A 2.4 Ghz signal might travel several kilometers in the right conditions, but UHF (470 - 698 MHz) can travel for many miles. Such characteristics make it an attractive cost-effective solution to be use in rural areas. However, it is worth noting that in urban areas, the existing TVWS (i.e. 600 - 700 MHz) are increasingly becoming unavailable because of a high demand in cellular frequencies and other wireless services. The IEEE 802.15.4m TVWS PHY support multiple data rates in bands ranging from 54 MHz to 862 MHz, aided by 3 modulation schemes: FSK (2FSK and 4FSK), OFDM (BPSK, QPSK, 16-QAM), and NB-OFDM (BPSK,QAM,16-QAM,64-QAM). The availability of TVWS channels change from region to region as well as channel usage and the TV channel length. In the US, Canada, Japan and other countries that comply with the FCC (Federal Communications Commission) rules, the TV channels length is 6 MHz while in UK and Europe channels length is 8 MHz. The US use both, VHF as well as UHF TV broadcast bands (37 possible channels of 6 Mhz), however, most countries use TVWS in the UHF TV band exclusively, each one with their particular channelization and regional rules. For example, UK and Europe both use the UHF band from 470 to 790 MHz (40 possible TV channels of 8 Mhz) while Japan [22] uses the UHF band from 470 to 710 MHz (40 possible TV channels of 6 Mhz). The coexistence of IEEE 802.15.4m with other standards using TVWS such as IEEE 802.11af and 802.22b have been explored in [23]. IEEE 802.15.4m MAC layer supports a superframe variant called TMCTP (TVWS Multichannel Cluster Tree PAN). The TMCTP superframe (Figure 7) is a modified version of the superframe first introduced in the IEEE 802.15.4-2003 [1] (Section II-A). The main difference to the original superframe is that this version includes a Beacon Only Period (BOP) in the last part of the superframe Active Period. BOPs are subdivided into Dedicated Beacon Slots (DBS) one of which is allocated to each PAN coordinator connected to a Super PAN Coordinator (SPC). DBSs are formed by a different number of Base Slots as required for each PAN. Using the BOP, a SPC maintain exclusive communication with other PAN coordinators to keep synchronization among multiple PANs (Figure 8).

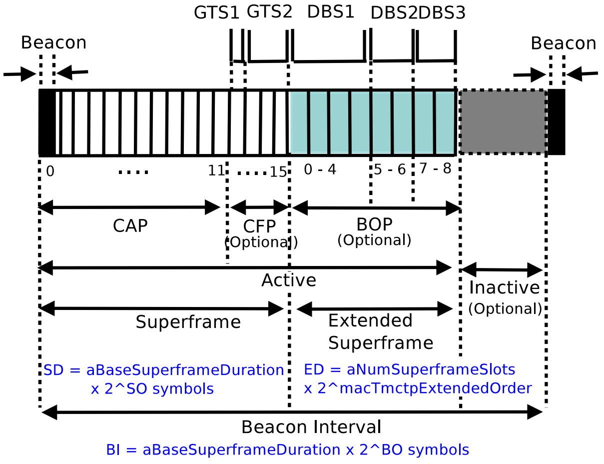


Fig. 7: TMCTP Superframe.

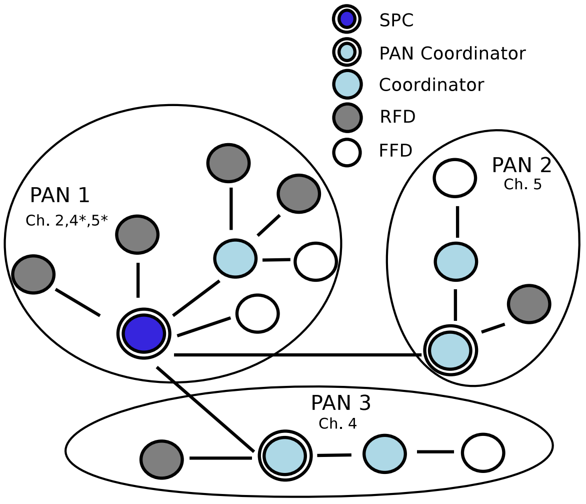


Fig. 8: TVWS Multichannel Cluster Tree PAN (TMCTP).

M. IEEE 802.15.4p (2014) - Amendment 7

This amendment [24] addressed the need for a communication standard in Rail Communications Control (RCC) systems. Previous to this standard, there were no IEEE 802 standards specifically designed for vehicles capable of moving up to 600 km/h. IEEE 802.15.4p devices are deployed on locomotives, base stations, railyard locations and can be useful to vehicular networks in general. This standard enable data rates of up to 1 Mbit/s over frequencies in the narrow bands VHF, UHF, and SHF bands (161, 216, 217, 220, 450, 770, 896, 915, 928, 2450, 4965, 5800 MHz) operating in contiguous and non-contiguous channel bandwidths as narrow as 12.5 kHz and as wide as 2Mhz [25, pp. 386]. The standard includes multiple modulation technique options: GMSK, QPSK, and DPSK among others. A full list of the frequencies and modulations introduced for this amendment can be found in Table I. Railroads and transit authorities around the globe often use proprietary protocols and communication systems, the adoption of the IEEE 802.15.4p standard allows these authorities to overcome these systems interoperability challenges plan for flexible and scalable future railroad communication networks.

N. IEEE 802.15.4 (2015)

IEEE 802.15.4-2015 [25] is the third revision of the standard. As its predecessors, this combines all the PHYs additions and MAC enhancements since the 2011 revision in a single document. Additional corrections to the document are editorial in nature.

O. IEEE 802.15.4n (2016) - Amendment 1

The first amendment [26] to the 2016 revision present another PHY alternative for the transmission of medical information in China. The China Medical Band (CMB) defines the 174-216 MHz, 407-425 MHz, and 608-630 MHz bands. The standard restricts the use of these bands for voice applications.

P. IEEE 802.15.4q (2016) - Amendment 2

IEEE 802.15.4q [27] introduced two PHY for 2.4 GHz and multiple sub-gigahertz bands with data rates up to 1 Mb/s. These PHYs were designed for ultra low-cost (low complexity) and ultra-low power applications. To achieve this, the standard used two new modulations: the Rate Switch Gaussian Frequency Shift Keying (RS-GFSK) and the Ternary Amplitude Shift Keying (TASK). TASK use a ternary sequence spreading followed by an ASK modulation.

IEEE 802.15.4q RS-GFSK modulation uses a simple but ingenious way to combine 2GFSK and 4GFSK during the transmission of the Physical Protocol Data Unit (PPDU) also known as frame. RS-GFSK main characteristic is that the combined resulting modulation bandwidth is close to identical. RS-GFSK switching rate mode is optional and must use 2GFSK modulation when disabled. However, when enable (indicated by the *Rate Switch* bit in the PHR) the frame's synchronization Header (SHR) and PHY header (PHR) shall be transmitted using 2GFSK while the PHY Service Data Unit (PSDU) shall be transmitted using 4GFSK with the same symbol rate used by the 2GFSK transmission of the SHR and PHR (Figure 9). Nodes communicating with sufficient link budget can use Rate Switch to reduce the active time for transmitting and receiving and therefore, save energy. The highest data rate specified in in RS-GFSK modulation is 2.5 times higher than the available SUN FSK PHYs with the added advantage of lower interference due to the use of the Gaussian filter, resulting in fewer collisions and retransmissions. Furthermore, IEEE 802.15.4q utilize shorter preambles. Therefore, is more energy efficient than standards IEEE 802.15.4f, 802.15.4g and 802.15.4k.

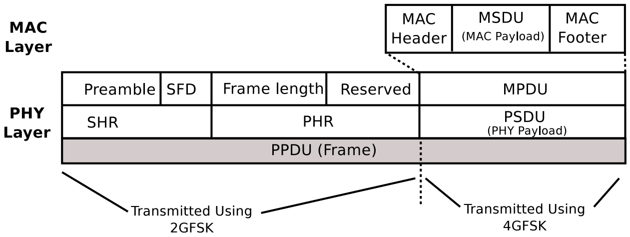


Fig. 9: PPDU (frame) to be transmitted using RS-GFSK with rate switching option enabled.

RS-GFSK provided options to interoperate with existing SUN FSK PHYs. Consequently, smart metering, smart irrigation, and home network applications benefit from these PHYs.

Q. IEEE 802.15.4u (2016) - Amendment 3

The third amendment to the 2015 revision [28] brought the 866 Mhz PHY to India. This PHY defined the 865-867 MHz band with an option for multiple bit-rates to choose from and 3 possible modulations: SUN FSK, OFDM, O-QPSK.

R. IEEE 802.15.4t (2017) - Amendment 4

A new PHY was introduced in this amendment [29], which was designed to operate on devices that require a short burst of information at high speeds (up to 2 Mb/s) followed by long sleep periods, contributing to extended battery life. This amendment uses the same 2400-483.5 MHz frequencies occupied by the O-QPSK PHY in place of MSK modulation.

S. IEEE 802.15.4v (2017) - Amendment 5

This amendment [30] changed multiple SUN PHY frequency ranges, including their channel ranges. The changes conceded the use of the 870-876 MHz and the 915-921 Mhz in Europe, the 902-928 MHz in Mexico, the 902-907.5 in Brazil and the 915-928 MHz in Australia, Brazil, and New Zealand. In addition, frequency range changes are made to the LECIM and TVWS PHYs.

T. IEEE 802.15.4s (2018) - Amendment 6

In this amendment [31], several MAC layer primitives and commands were added as part of the Spectrum Resource Measurements (SRM) toolkit. These changes are the most significant additions to the MAC layer since 802.15.4e-2012. SRM enables the measure, transmission, and request of information concerning the state of the channel. The MAC layer can report this information to higher layers for its usage. For example, SRM information can be used to create more precise and cost effective routing protocols in upper layers. Some of the SRM introduced features include:

- *Failed Transmissions measurement.* It estimates the propagation quality of specific links as part of the channel selection algorithm.
- *Deferred Transmissions measurement.* It helps to determine the level of congestion in the channel caused by other coexisting networks.
- *Retry Histogram.* It provides a histogram with the number of retries from a single transmission during a determinate space of time.
- *Noise Histogram.* Reports the noise power of non-IEEE 802.15 devices in a specific channel during a specific period of time.
- *Channel Usage.* Display the total Channel time used during a sequence of Rx and Tx frames during a period of time.
- *Received Signal Strength Indicator (RSSI)* Measurement of the Radio Frequency power received. While RSSI is a common management function in other standards, it was first introduced to the IEEE 802.15.4 in this amendment.
- *Energy Detection (ED).* The ability of the receiver to detect energy level present on the current channel from other transceivers or ambient energy.

U. IEEE 802.15.4x (2019) - Amendment 7

IEEE 802.15.4x [32] is the last amendment to date. Similar to the IEEE 802.15.4v-2017 standard, this amendment further extends the SUN PHYs (first introduced in IEEE 802.15.4g-2012). New 2FSK modulation data rates to be use in narrow bands are added as well as the extension of the SUN OFDM PHY with a data rates up to 2.4 Mb/s and SUN O-QPSK with additional data rate options in multiple regions.

III. IEEE 802.15.4 IMPLEMENTATIONS

At times, the accuracy of simulation results can be questionable; however, without the simulation results, large scale and costly experiments cannot be performed. The IEEE 802.15.4 is a popular protocol with multiple revisions. Despite its popularity, new revisions are gradually being adopted. By far, the 2003 and 2006 revisions are the most implemented. 2012 revisions or later, brought highly specialized PHYs and MAC behaviors limited to specific industries and applications. Their implementation in simulations is somehow rare in comparison to the legacy standard. Examples of popular IEEE 802.15.4 implementations include the following:

The Ns-2 WPAN module [33] is among the first simulations of the standard. Its latest version (2.35) completely supports the IEEE 802.15.4-2003 protocol, and is to date, one of the most complete implementations of the standard with beacon and non-beacon support for semi-mesh and star topologies (No support for inactive periods). Unfortunately, it exhibits certain disadvantages that were inherited from ns-2; lack of documentation and coding standards, unrealistic packet formats, unnecessary overhead, and lack of maintenance. Its modules are coded in C++ while scenarios require OTcl scripting language.

Castalia (v3.3) [34] is an OMNET++ based simulator. In addition to the basic 802.15.4-2006 MAC standard, Castalia supports 3 more MAC layers: TunableMac, TMAC, and IEEE 802.15.6. Castalia only supports beacon-enabled modes in star topologies with the optional GTS (No support for non-beacon, Indirect-transfers or semi-mesh topology). Castalia supports PHYs modulations QPSK, BPSK, PSK, and FSK, unlike the 2006 revision of the standard. C++ and NED languages are used in OMNET++ modules.

Ns-3 [35] is a simulator with an active community that develops new modules. Some of these modules even include emulation and hardware integration support. The latest version of the Ns-3 (V3.29) LR-WPAN module supports a full PHY IEEE 802-15.4-2006 set with a non-beacon mode MAC for a star topology PAN (No association or beacon-enabled mode MAC options). The module exhibits promising performance; however, the module still has several limitations compared to other simulators. Its code base is C++ and it supports Python bindings.

The OPNET simulator provides an IEEE 802.15.4-2003 model [36] that supports beacon-enabled modes in star typologies (No support for association, Non beacon-enabled mode or semi-mesh topology). Similar to OMNET++, OPNET provides a robust GUI. Modules are build using Proto-C, C, or C++. A major drawback of OPNET is the requirement of a license.

OpenZB [37] is an open source, real hardware implementation of the IEEE 802.15.4-2003 with beacon-enabled modes for star and mesh topologies on CrossBow MICAz and TelosB motes. TinyOs, as its name implies is an operative system specifically designed to create easy modules for microcontrollers. Some of the most popular modules are created for microcontrollers commonly used in Wireless Sensor Networks (WSN). OpenZB is completely programmed using the nesC language (as required by TinyOS). OpenZB is not the only implementation of the IEEE 802.15.4 on TinyOS. In fact, other authors have documented [38], [39] their experiences implementing parts of the IEEE 802.15.4 standard for TinyOS.

Zigbee [40], used by the industry and hobbyist alike is arguably the most popular implementation of the IEEE 802.15.4 standard. A common misconception is that IEEE 802.15.4 is Zigbee. Zigbee includes IEEE 802.15.4 PHY and some of its MAC layers but it also includes upper layers (routing, security, applications, etc). In other words, Zigbee is a full-stack solution. Zigbee is developed by the Zigbee Alliance which is formed by various groups (manufacturers, users, etc) with the objective of solving IEEE 802.15.4 interoperability problems and ensure that products from different vendors that use the Zigbee stack are compatible with one another. Its latest revision (Zigbee V3.0) includes a 2011 revision of the IEEE 802.15.4 standard. Additionally, the PHY IEEE 802.15.4g bundle with the IEEE 802.15.4e TSCH MAC behavior can be found in the Zigbee product formally named ”JupiterMesh”. Zigbee mayor drawback is that its a closed source solution and none of its conforming layers can be modified in any way.

IV. CONCLUSIONS

In this paper, we presented a complete and uptodate compendium of the IEEE 802.15.4 standard. The standard was initially envisioned for applications with low range and low energy consumption requirements. In recent years, the standard have evolved to handle an extensive range of application operating on multiple bands and modulations. While monitoring and medical were the most common implementations when the standard was first introduced, its focus have now turned to grid networks and smart metering applications in recent revisions. Vendors and users alike, however, have not be able to keep pace with the changes. Most of the standard introduced features are little known by most users. Likewise, simulations and hardware implementations of the standard are rarely complete and even popular simulators are significantly behind from the latest revisions of the standard. It is the wish of the authors that the current document help users to navigate these differences and better understanding each one of the standard specifications for any given situation. Future networks performance will depend on the standard choice and the ability of these standards to support smooth coexistence with other protocols. With, literally, thousands of possible combinations to choose from, network specialists will have to depend more on simulations and a deep understanding of the available standards.

APPENDIX

Table I list all IEEE 802.15.4 PHY with their modulations and data rates, sorted by year of introduction. Channeling specifications and regional restrictions are not specified in this Table.

Amendments v-2007 and x-2009 are extensions on the IEEE 802.15.4g-2012 and for this reason, in Table I are included in the SUN PHYs differentiated by their font color.

Table II list all the LECIM data rates used for narrow bands while Table III list all possible data rate combinations for the OFDM modulation in the standard (IEEE 802.15.4x OFDM data rates additions are indicated with different font color).

In the Table I, IEEE 802.15.4q RS-GFSK modulation data rates are described in pairs (2GFSK, 4GFSK). For example, the band 901 can transmit its PPDU with modulation RS-GFSK (rate switch enabled) with either the data rate pair [4.8 (2GFSK), 9.6 (4FSK)] or the pair [9.6 (2GFSK), 19.2 (4GFSK)]. If the rate switch is not enabled only the 2GFSK data rate is used (see Section II-P).

TABLE I
IEEE 802.15.4 PHY evolution.

PHY Band Name	**Frequencies (MHz)**	**Modulation - Spread Spectrum**	**Bit-Rate (kb/s)**	**Symbol Rate (ksym/s)**
IEEE 802.15.4-2003 2450 (World Wide)	2400-2483.5	O-QPSK *DSSS	250	62.5
915 (US)	902-928	BPSK *DSSS	40	40
868 (EUR)	868-868.6		20	20
IEEE 802.15.4-2006 915 (US)	902-928	ASK*PSS	250	50
		O-QPSK*DSSS	250	62.5
868 (EUR)	868-868.6	ASK*PSS	250	12.5
		O-QPSK*DSSS	100	25
IEEE 802.15.4a-2007 2450	2400-2483.5	DQPSK → DQCSK *CSS	250 / 1000	166.667 / 166.667
UWB sub-Ghz	250-750	BPM-BPSK	110/850	0.12/0.98(Mhz)
UWB low	3244-4742		6810	7.80(Mhz)
UWB high	5944-10234		27240	15.60(Mhz)
IEEE 802.15.4c-2009 780 (China)	779-787	O-QPSK	250	62.5
		MPSK	250	62.5
IEEE 802.15.4d-2009 950 (Japan)	950-956	2GFSK	100	100
		BPSK *DSSS	20	20
IEEE 802.15.4f-2012 433	433.05-434.79	MSK	31.25/100/250	31.25/100/250
2450	2400-2483		250	250
LRP UWB	6289.6-9185.6	PPM	31.25	31.25
		OOK	250/1000	250/1000
IEEE 802.15.4g-2012 **IEEE 802.15.4v-2017** **IEEE 802.15.4x-2019** **SUN**	169.400-169.475	2FSK	2.4 / 4.8	2.4/4.8
169 (EUR)		4FSK	9.6	4.8
450 (US)	450-470	2FSK	4.8	4.8
		4FSK	9.6	4.8
470 (China)	470-510	2FSK	10/20/50/100	10/2050/100
		~~4FSK~~ 2FSK	~~200~~ 150	~~100~~ 150
		O-QPSK	6.25-50	1.56-12.5
		OFDM(Opt. 4)	Table III	N/A
780 (China)	779-787	2FSK	10/20/50/100	10/20/50/100
		4FSK	200	100
		O-QPSK	31.25-500 6.25-50	7.8125-125 1.56-12.5
		OFDM	Table III	N/A
863 (EUR)	863-870	2FSK	10/20/50/100	10/20/50/100
		~~4FSK~~ 2FSK	~~200~~ 150	~~100~~ 150
		OFDM (Opt. 4)	Table III	N/A
867 (Singapore)	866-869	2FSK	10/20/50/100 150/200/300	10/20/50/100 150/200/300
		OFDM (Opt. 3,4)	Table III	N/A
		O-QPSK	6.25-50	1.56-12.5
870 (EUR)	870-876	2FSK	10/20 50/100/150	10/20 50/100/150
		OFDM (Opt. 4)	Table III	N/A
		O-QPSK	6.25-50	1.56-12.5
896 (US)	896-901	2FSK	10/20/40	10/20/40
901 (US)	901-902	2FSK	10/20/40	10/20/40

TABLE I a
(Continued) IEEE 802.15.4 PHY evolution.

PHY Band Name	**Frequencies (MHz)**	**Modulation - Spread Spectrum**	**Bit-Rate (kb/s)**	**Symbol Rate (ksym/s)**
915-a (Mexico/US)	902-928	2FSK	10/20 150/200/300	10/20 150/200/300
915-b (Brazil)	902-907.5	OFDM (Opt. 1-4)	Table III	N/A
	915-928	O-QPSK	31.25-500	7.8125-125
915-c (AU/NZ)	915-928		6.25-50	1.56-12.5
915-d (EUR)	915-921	2FSK	10/20 150/200/300	10/20 150/200/300
915-e (Philipines)	915-918 902-907.5	OFDM (Opt. 3,4)(Opt. 1-4)	Table III	N/A
		O-QPSK	6.25-50	1.56-12.5
915 (US)	902-928	2FSK	10/20 50/100/200	10/20 50/100/200
917 (Korea)	917-923.5	O-QPSK	31.25-500 6.25-50	7.8125-125 1.56-12.5
		OFDM(Opt. 1-4)	Table III	N/A
919 (Malaysia)	919-923	2FSK	10/20 150/200/300	10/20 150/200/300
		OFDM (Opt. 1-4)	Table III	N/A
		O-QPSK	6.25-50	1.56-12.5
920 (Japan)	920-928	2FSK	50/100/200	50/100/200
		4FSK	400	200
		O-QPSK	6.25-50	1.5625-12.5
		OFDM	Table III	N/A
920-a (China)	920.5-924.5	2FSK	10/20 50/100/150	10/20 50/100/150
		OFDM (Opt.4)(Opt. 1-4)	Table III	N/A
920-b (H.K, Sing. Thailand,Vietnam)	920-925	O-QPSK	6.25-50	1.56-12.5
928 (US)	928-960	2FSK	10/20/40	10/20/40
950 (Japan)	950-958	2FSK	10/20 50/100/200	10/20 50/100/200
		4FSK	400	200
		O-QPSK	6.25-50	1.5625-12.5
		OFDM	Table III	N/A
1427 (US)	1427-1518	2FSK	10/20/40	10/20/40
2450 (World Wide)	2400-2483	2FSK	50/150/200	50/150/200
		O-QPSK	31.25-500	7.8125-125
		OFDM	Table III	N/A
IEEE 802.15.4j-2013 2380	2360-2400	O-QPSK *DSSS	250	62.5
IEEE 802.15.4k-2013 **LECIM** 169	169.400-169.475	2FSK/P-FSK 2GFSK/P-GFSK	25/12.5	25/12.5
433	433.050-434.790	2FSK/P-FSK 2GFSK/P-GFSK	37.5/25/ 12.5	37.5/25/ 12.5
470	470-510	2FSK/P-FSK 2GFSK/P-GFSK	37.5/25/ 12.5	37.5/25/ 12.5
780	779-787			
863	863-870	BPSK/O-QPSK	Table II	-
915	902-928			
922	915-928			
917	917.1-963.5			
920	920-928			
921	921-928			
2450	2400-2483.5	BPSK/O-QPSK	Table II	-

TABLE I b
(Continued) IEEE 802.15.4 PHY evolution.

PHY Band Name	**Frequencies (MHz)**	**Modulation - Spread Spectrum**	**Bit-Rate (kb/s)**	**Symbol Rate (ksym/s)**
IEEE 802.15.4m-2014 **TVWS**		2FSK	50/100/200/300	50/100/200/300
CH.2 (US/Canada)	54-60	4FSK	400	200
CH.5-6 (US/Canada)	76-88	OFDM (BPSK)	390.625/1562.5	N/A
CH.7-13 (US/Canada)	174-216	OFDM (QPSK)	781.250/3125	
CH.14-20 (US/Canada)	470-512	OFDM (16-QAM)	1562.5/6250	
CH.21-36 (US/Canada)	512-608	NB-OFDM (BPSK)	156/234	
CH.38-51 (US/Canada)	614-698	NB-OFDM (QAM)	312/468	
CH.21-60 (UK/Europe)	470-790	NB-OFDM (16-QAM)	624/936	
(others)	790-862	NB-OFDM (64-QAM)	936/1404/1638	
IEEE 802.15.4p-2014 **RCC**		GMSK	9.6/19.2	9.6/19.2
161	160.170-161.580	C4FM	9.6/19.2/38.4	4.8/9.6/19.2
216	216-217	QPSK	16/32	8/16
217	217-220	Pi/4 DQPSK	16/32/36	8/16/18
220	220-222			
450	450-470			
770	769-775			
800	799-805			
806	806-821			
	851-866			
896	896-901			
	935-940			
915	902-928	GMSK	9.6/19.2	9.6/19.2
		C4FM	9.6/19.2/38.4	4.8/9.6/19.2
		QPSK	16/32	8/16
		Pi/4 DQPSK	16/32/36	8/16/18
		DPSK*DSSS	[24]	-
		BPSK*DSSS	40	40
928	928-960	GMSK	9.6/19.2	9.6/19.2
		C4FM	9.6/19.2/38.4	4.8/9.6/19.2
		QPSK	16/32	8/16
		Pi/4 DQPSK	16/32/36	8/16/18
2450	2400-2483.5	BPSK*DSSS	40	40
4965	4940-4990	DPSK*DSSS	[24]	-
		BPSK*DSSS	40	40
5800	5725-5850	DPSK*DSSS	[24]	-
		BPSK*DSSS	40	40
IEEE 802.15.4q-2016 169	169.400-169.475	RS-GFSK	(4.8,9.6)	4.8
			(9.6,19.2)	9.6
433	433.050-434.790	RS-GFSK	(4.8,9.6)	4.8
			(9.6,19.2)	9.6
			(50,100)	50
		TASK	202.38/101.19 75.89/31.62	-
450	450-470	RS-GFSK	(4.8,9.6)	4.8
			(9.6,19.2)	9.6
			(50,100)	50
			(150,300)	150
			(500,1000)	500
			250	250
			1000	1000

TABLE I c
(Continued) IEEE 802.15.4 PHY evolution.

PHY Band Name	**Frequencies (MHz)**	**Modulation - Spread Spectrum**	**Bit-Rate (kb/s)**	**Symbol Rate (ksym/s)**
470	470-510	RS-GFSK	(9.6,19.2)	9.6
			(50,100)	50
			(150,300)	150
			(500,1000)	500
			250	250
			1000	1000
		TASK	202.38/101.19 75.89/31.62	-
780	779-787	RS-GFSK	(50,100)	50
			(150,300)	150
			(500,1000)	500
			250	250
		TASK	485.71/242.85 182.14/75.89	-
863	863-876	RS-FSK	(50,100)	50
			(150,300)	150
			(500,1000)	500
			1000	1000
			500	500
		TASK	485.71/242.85 182.14/75.89	-
896	896-901	RS-GFSK	(4.8,9.6)	4.8
			(9.6,19.2)	9.6
			(50,100)	50
901	901-902	RS-GFSK	(4.8,9.6)	9.6
			(9.6,19.2)	9.6
915	902-928	RS-GFSK	(50,100)	50
			(150,300)	150
			(500,1000)	500
			250	250
			1000	1000
		TASK	485.71/242.85 182.14/75.89	-
918	915-921	RS-GFSK		
917	917-923.5	RS-GFSK	(50,100)	50
			(150,300)	150
			250	250
928	928-960	RS-GFSK	(4.8,9.6)	4.8
			(9.6,19.2)	9.6
1427	1427-1518			
2450	2400-2483.5	RS-GFSK	(50,100)	50
			(150,300)	150
			(500,1000)	500
			250	250
			1000	1000
		TASK	809.5/404.76 303.57/126.48	-
IEEE 802.15.4n-2016 195 (China)	174-216	2GFSK	50/100/200	50/100/200
416 (China)	407-425			
619 (China)	608-630	O-QPSK	250/500	62.5/125
IEEE 802.15.4u-2016		2FSK	10/20	10/20
866 (India)	865-867		50/100/150	50/100/150
		OFDM (Opt. 4)	Table III	N/A
		O-QPSK	6.25-50	1.56-12.5
IEEE 802.15.4t-2017 2450	2400-2483.5	MSK	2000	250

TABLE II
IEEE 802.15.4k LECIM BPSK and O-QPSK data rates (kbps).

Spreading Factor	**Modulation Rate (ksym/s)**				
	200	**400**	**600**	**800**	**1000**
16	6.25 / 12.5 kbps	12.5 / 25 kbps	18.75 / 37.5 kbps	25 / 50 kbps	31.25 / 62.5 kbps
32	3.125 / 6.25 kbps	6.25 / 12.5 kbps	9.375 / 18.75 kbps	12.5 / 25 kbps	15.625 / 31.25 kbps
64	1.5625 / 3.125 kbps	3.125 / 6.25 kbps	4.6875 / 9.375 kbps	6.25 / 12.5 kbps	7.8125 / 15.625 kbps
128	0.7813 / 1.5625 kbps	1.5625 / 3.125 kbps	2.3438 / 4.6875 kbps	3.125 / 6.25 kbps	3.9063 / 7.8125 kbps
256	0.3906 / 0.7813 kbps	0.7813 / 1.5625 kbps	1.1719 / 2.3438 kbps	1.5625 / 3.125 kbps	1.9531 / 3.9063 kbps
512	0.1953 / 0.3906 kbps	0.3906 / 0.7813 kbps	0.5859 / 1.1719 kbps	0.7813 / 1.5625 kbps	0.9766 / 1.9531 kbps
1024	0.0977 / 0.1953 kbps	0.1953 / 0.3906 kbps	0.293 / 0.5859 kbps	0.3906 / 0.7813 kbps	0.4883 / 0.9766 kbps
2048	0.0488 / 0.0977 kbps	0.0977 / 0.1953 kbps	0.1465 / 0.293 kbps	0.1953 / 0.3906 kbps	0.2441 / 0.4883 kbps
4096	0.0244 / 0.0488 kbps	0.0488 / 0.0977 kbps	0.0732 / 0.1465 kbps	0.0977 / 0.1953 kbps	0.1221 / 0.2441 kbps
8192	0.0122 / 0.0244 kbps	0.0244 / 0.0488 kbps	0.0366 / 0.0732 kbps	0.0488 / 0.0977 kbps	0.061 / 0.1221 kbps
16384	0.0061 / 0.0122 kbps	0.0122 / 0.0244 kbps	0.0183 / 0.0366 kbps	0.0244 / 0.0488 kbps	0.0305 / 0.061 kbps
32768	0.0031 / 0.0061 kbps	0.0061 / 0.0122 kbps	0.0092 / 0.0183 kbps	0.0122 / 0.0244 kbps	0.0153 / 0.0305 kbps

TABLE III
OFDM datarates according to the MCS and option selected.

	option 1	**option 2**	**option 3**	**option 4**
MCS 0 BPSK (*Fq. Rep.)	100 kbps	50 kbps	25 kbps	12.5 kbps
MCS 1 BPSK (*Fq. Rep.)	200 kbps	100 kbps	50 kbps	25 kbps
MCS 2 QPSK (*Fq. Rep.)	400 kbps	200 kbps	100 kbps	50 kbps
MCS 3 QPSK	800 kbps	400 kbps	200 kbps	100 kbps
MCS 4 QPSK	1200 kbps	600 kbps	300 kbps	150 kbps
MCS 5 16-QAM	1600 kbps	800 kbps	400 kbps	200 kbps
MCS 6 16-QAM	2400 kbps	1200 kbps	600 kbps	300 kbps

REFERENCES

[1] "IEEE standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks specific requirements part 15.4: Wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (lr-wpans)," *IEEE Std 802.15.4-2003*, pp. 1–670, 2003.

[2] A. G. Ramonet and T. Noguchi, "Ieee 802.15.4 historical evolution and trends," in *2019 21st International Conference on Advanced Communication Technology (ICACT)*, Feb 2019, pp. 351–359.

[3] *NXP ZigBee 3.0 Stack User Guide*.

[4] "IEEE standard for information technology– local and metropolitan area networks– specific requirements– part 15.4: Wireless medium access control (mac) and physical layer (phy) specifications for low rate wireless personal area networks (wpans)," *IEEE Std 802.15.4-2006 (Revision of IEEE Std 802.15.4-2003)*, pp. 1–320, Sept 2006.

[5] "IEEE standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirement part 15.4: Wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (wpans)," *IEEE Std 802.15.4a-2007 (Amendment to IEEE Std 802.15.4-2006)*, pp. 1–203, 2007.

[6] "IEEE standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks-specific requirements part 15.4: Wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (wpans) amendment 2: Alternative physical layer extension to support one or more of the chinese 314-316 mhz, 430-434 mhz, and 779-787 mhz bands," *IEEE Std 802.15.4c-2009 (Amendment to IEEE Std 802.15.4-2006)*, pp. 1–21, April 2009.

[7] "IEEE standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks-specific requirements part 15.4: Wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (wpans) amendment 3: Alternative physical layer extension to support the japanese 950 mhz bands," *IEEE Std 802.15.4d-2009 (Amendment to IEEE Std 802.15.4-2006)*, pp. 1–27, April 2009.

[8] "IEEE standard for local and metropolitan area networks–part 15.4: Low-rate wireless personal area networks (lr-wpans)," *IEEE Std 802.15.4-2011 (Revision of IEEE Std 802.15.4-2006)*, pp. 1–314, Sept 2011.

[9] "IEEE standard for local and metropolitan area networks–part 15.4: Low-rate wireless personal area networks (lr-wpans) amendment 1: Mac sublayer," *IEEE Std 802.15.4e-2012 (Amendment to IEEE Std 802.15.4-2011)*, pp. 1–225, April 2012.

[10] H. Kurunathan, R. Severino, A. Koubaa, and E. Tovar, "IEEE 802.15.4e in a nutshell: Survey and performance evaluation," *IEEE Communications Surveys Tutorials*, vol. 20, no. 3, pp. 1989–2010, thirdquarter 2018.

[11] *Identification cards - Contactless integrated circuit cards - Proximity cards*, ISO 14 443-1, 2008.

[12] "IEEE standard for local and metropolitan area networks– part 15.4: Low-rate wireless personal area networks (lr-wpans) amendment 2: Active radio frequency identification (rfid) system physical layer (phy)," *IEEE Std 802.15.4f-2012 (Amendment to IEEE Std 802.15.4-2011)*, pp. 1–72, April 2012.

[13] "IEEE standard for local and metropolitan area networks–part 15.4: Low-rate wireless personal area networks (lr-wpans) amendment 3: Physical layer (phy) specifications for low-data-rate, wireless, smart metering utility networks," *IEEE Std 802.15.4g-2012 (Amendment to IEEE Std 802.15.4-2011)*, pp. 1–252, April 2012.

[14] Y. Kabalci, "A survey on smart metering and smart grid communication," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 302 – 318, 2016.

[15] *Anritsu MS2830A Signal Analyzer Product Introduction*.

[16] J. Muoz, T. Chang, X. Vilajosana, and T. Watteyne, "Evaluation of ieee802.15.4g for environmental observations," *Sensors*, vol. 18, no. 10, 2018. [Online]. Available: http://www.mdpi.com/1424-8220/18/10/3468

[17] J. Muoz, E. Riou, X. Vilajosana, P. Muhlethaler, and T. Watteyne, "Overview of ieee802.15.4g ofdm and its applicability to smart building applications," in *2018 Wireless Days (WD)*, April 2018, pp. 123–130.

[18] "IEEE standard for local and metropolitan area networks - part 15.4: Low-rate wireless personal area networks (lr-wpans) amendment 4: Alternative physical layer extension to support medical body area network (mban) services operating in the 2360 mhz - 2400 mhz band," *IEEE Std 802.15.4j-2013 (Amendment to IEEE Std 802.15.4-2011 as amended by IEEE Std 802.15.4e-2012, IEEE Std 802.15.4f-2012, and IEEE Std 802.15.4g-2012)*, pp. 1–24, Feb 2013.

[19] "IEEE standard for local and metropolitan area networks– part 15.4: Low-rate wireless personal area networks (lr-wpans)–amendment 5: Physical layer specifications for low energy, critical infrastructure monitoring networks." *IEEE Std 802.15.4k-2013 (Amendment to IEEE Std 802.15.4-2011 as amended by IEEE Std 802.15.4e-2012, IEEE Std 802.15.4f-2012, IEEE Std 802.15.4g-2012, and IEEE Std 802.15.4j-2013)*, pp. 1–149, Aug 2013.

[20] B. G. Gebremedhin, J. Haapola, and J. Iinatti, "Performance evaluation of ieee 802.15.4k priority channel access with dsss phy," in *Proceedings of European Wireless 2015; 21th European Wireless Conference*, May 2015, pp. 1–6.

[21] "Ieee standard for local and metropolitan area networks - part 15.4: Low-rate wireless personal area networks (lr-wpans) - amendment 6:

Tv white space between 54 mhz and 862 mhz physical layer," *IEEE Std 802.15.4m-2014 (Amendment to IEEE Std 802.15.4-2011 as amended by IEEE Std 802.15.4e-2012, IEEE Std 802.15.4f-2012, IEEE Std 802.15.4g-2012, IEEE Std 802.15.4j-2013, and IEEE Std 802.15.4k-2013)*, pp. 1–118, April 2014.

[22] T. Shimomura, T. Oyama, and H. Seki, "Analysis of tv white space availability in japan," in *2012 IEEE Vehicular Technology Conference (VTC Fall)*, Sep. 2012, pp. 1–5.

[23] C. Sum, M. Zhou, L. Lu, F. Kojima, and H. Harada, "Performance and coexistence analysis of multiple ieee 802 wpan/wlan/wran systems operating in tv white space," in *2014 IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN)*, April 2014, pp. 145–148.

[24] "Ieee standard for local and metropolitan area networks - part 15.4: Low-rate wireless personal area networks (lr-wpans) - amendment 7: Physical layer for rail communications and control (rcc)," *IEEE Std 802.15.4p-2014 (Amendment to IEEE Std 802.15.4-2011 as amended by IEEE Std 802.15.4e-2012, IEEE Std 802.15.4f-2012, IEEE Std 802.15.4g-2012, IEEE Std 802.15.4j-2013, IEEE Std 802.15.4k-2013, and IEEE Std 802.15.4m-2014)*, pp. 1–45, May 2014.

[25] "IEEE standard for low-rate wireless networks," *IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011)*, pp. 1–709, April 2016.

[26] "IEEE standard for low-rate wireless networks – amendment 1: Physical layer utilizing china medical bands," *IEEE Std 802.15.4n-2016 (Amendment to IEEE Std 802.15.4-2015)*, pp. 1–27, April 2016.

[27] "IEEE standard for low-rate wireless networks –amendment 2: Ultra-low power physical layer," *IEEE Std 802.15.4q-2016 (Amendment to IEEE Std 802.15.4-2015 as amended by IEEE Std 802.15.4n-2016)*, pp. 1–52, April 2016.

[28] "IEEE standard for low-rate wireless networks–amendment 3: Use of the 865 mhz to 867 mhz band in india," *IEEE Std 802.15.4u-2016 (Amendment to IEEE Std 802.15.4-2015 as amended by IEEE Std 802.15.4n-2016 and IEEE Std 802.15.4q-2016)*, pp. 1–18, Feb 2017.

[29] "IEEE standard for low-rate wireless networks–amendment 4: Higher rate (2 mb/s) physical (phy) layer," *IEEE Std 802.15.4t-2017 (Amendment to IEEE Std 802.15.4-2015 as amended by IEEE Std 802.15.4n-2016, IEEE Std 802.15.4q-2016, and IEEE Std 802.15.4u-2016*, pp. 1–25, April 2017.

[30] "IEEE standard for low-rate wireless networks - amendment 5: Enabling/updating the use of regional sub-ghz bands," *IEEE Std 802.15.4v-2017 (Amendment to IEEE Std 802.15.4-2015, as amended by IEEE Std 802.15.4n-2016, IEEE Std 802.15.4q-2016, IEEE Std 802.15.4u-2016, and IEEE Std 802.15.4t-2017)*, pp. 1–35, June 2017.

[31] "Ieee standard for low-rate wireless networks amendment 6: Enabling spectrum resource measurement capability," *IEEE Std 802.15.4s-2018 (Amendment to IEEE Std 802.15.4-2015 as amended by IEEE Std 802.15.4n-2016, IEEE Std 802.15.4q-2016, IEEE Std 802.15.4u-2016, IEEE Std 802.15.4t-2017, IEEE Std 802.15.4v-2017, and IEEE Std 802.15.4-2015/Cor 1-2018)*, pp. 1–51, June 2018.

[32] "Ieee standard for low-rate wireless networks - amendment 7: Defining enhancements to the smart utility network (sun) physical layers (phys) supporting up to 2.4 mb/s data rates," *IEEE Std 802.15.4x-2019 (Amendment to IEEE 802.15.4-2015 as amended by IEEE 802.15.4n-2016, IEEE 802.15.4q-2016, IEEE 802.15.4u-2016, IEEE 802.15.4t-2017, IEEE 802.15.4v-2017, IEEE 802.15.4s-2018, and IEEE 802.15.4-2015/Cor. 1-2018)*, pp. 1–30, April 2019.

[33] J. Zheng and M. J. Lee, "A comprehensive performance study of ieee 802.15. 4," *Sensor network operations*, vol. 4, pp. 218–237, 2006.

[34] A. Boulis, "Castalia userś manual v3.2," *NICTA*, 2011.

[35] Nsam, "Ns-3 discrete event simulator," http://www.nsnam.org, accessed Jan. 07. 2017.

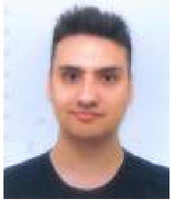
[36] P. Jurčík and A. Koubâa, "The ieee 802.15.4 opnet simulation model:reference guide v2.0," *IPP-HURRAY Technical Report, HURRAY-TR-070509*, 2007.

[37] A. Cunha, A. Koubaa, R. Severino, and M. Alves, "Open-zb: an open-source implementation of the ieee 802.15.4/zigbee protocol stack on tinyos," in *2007 IEEE International Conference on Mobile Adhoc and Sensor Systems*, Oct 2007, pp. 1–12.

[38] J. Flora and P. Bonnet, "Never mind the standard here is the tinyos 802.15. 4 stack," *University of Copenhagen, Technical Report*, vol. 6, no. 10, 2006.

[39] J.-H. Hauer, "Tkn15. 4: An ieee 802.15. 4 mac implementation for tinyos," 2009.

[40] Zigbee Alliance, "Zigbee 3.0," https://www.zigbee.org/, accessed May. 15. 2019.



Alberto Gallegos Received his B.E. degree in computer science from Guadalajara University, Jalisco, Mexico in 2005. He later received his M.S. and PH.D. degrees in Engineering from Ritsumeikan University, Shiga, Japan in 2014 and 2018 respectively. He joined the College of Information Science and Engineering at Ritsumeikan University in 2018, where he is currently Assistant Professor. His current research interests include but are not limited to Wireless Sensor Networks and routing protocols.

Taku Noguchi Received his B.E., M.E. and Ph.D. degrees in communications engineering from Osaka University, Osaka, Japan in 2000, 2002 and 2004, respectively. He joined College of Information Science and Engineering at Ritsumeikan University in 2004, where he is currently a Professor. His research interests include performance analysis and the design of computer networks and wireless networks. He is a member of IEEE, IEICE and IPSJ.