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IEEE 802.15.4g Based Wi-SUN Communication Systems

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SUMMARY This paper summarizes Wi-SUN communication systems and their physical (PHY) layer and media access control (MAC) specifications. Firstly, the Wi-SUN communication systems are categorized into three. The key PHY and MAC standards, IEEE 802.15.4g and .4e, that configure the systems are explained, and fundamental transmission performances of the systems in the PHY layer and MAC layer are evaluated by computer simulations. Then, the Wi-SUN alliance and the Wi-SUN profiles that include IEEE 802.15.4g and .4e are explained. Finally, to understand the transmission performance of actual IEEE 802.15.4g Wi-SUN radio devices, PER performances under AWGN and multipath fading environments are measured by using IEEE 802.15.4g compliant and Wi-SUN alliance certified radio modules. This paper is an instruction paper for the beginners of the Wi-SUN based communications systems.

key words: *IEEE 802.15.4g, Wi-SUN, mobile communication, sensor network, smart utility network*

1. Introduction

There are increasing demands for Wireless Smart Utility Network (Wi-SUN) communication systems. In the systems, Electricity/Gas/Water meters equipping Smart Utility Network (SUN) radio devices can effectively and automatically relay the measurement data to data collection base station (BS) by a multi-hop operation. The BSs transfer their data to the cloud or data server in the intranet or the Internet by wireless Wide Area Networks (WANs) such as mobile communication systems or wired networks. Then the collected measurement big data is analyzed, and the results are transferred to the meters to control energy consumption in the house [1], [2].

The physical (PHY) layer specification of Wi-SUN is mainly based on IEEE 802.15.4g that defines an alternate physical layer specification for principally outdoor Low Data Rate Wireless Smart Metering Utility Network [3]. The Wi-SUN also includes additional specifications of media access control (MAC), adaptation, network and transport layers' protocols standardized by IEEE and IETF in order to support several applications. Currently, the technical specifications and interoperability test plans of Wi-SUN systems have been standardized by the Wi-SUN alliance [4] that is established in 2012 and includes more than 100 member companies [4]. The technical specification defined by Wi-SUN alliance is called Wi-SUN profile. One of the achievements of the Wi-SUN profile is the specification for the communication between radio devices in Japanese electricity smart meter and home energy management system (HEMS). All electricity companies in Japan have adopted the specification and the number of its subscribers is more than tens million in 2014. After the success, new application fields for the Wi-SUN are being considered. Agriculture, disaster prevention and intelligent transport systems have currently been proposed.

Considering new applications such as agriculture and disaster prevention, the coverage area should be as large as possible. The regulation in Japan for IEEE 802.15.4g based systems is the following. The operational frequency band is 920 MHz band and the maximum transmission power for license-exempt radio devices is 20 mW. In this case around 500 m of the transmission range is expected when an omnidirectional antenna is used. If the range needs to be expanded, the power can be raised to 250 mW by registering the radio device with the regulator. However, the power boost is not always good for the radio devices in the meters from the view point of power consumption of meters. And it is complicated to register too many radio devices for the meters to the regulator. The system configuration of Wi-SUN needs to be considered.

This paper summarizes the Wi-SUN communication systems and their PHY and MAC specifications. Firstly, three Wi-SUN communication systems are categorized into three in Sect. 2. The key standards to configure the Wi-SUN communication systems are explained in Sect. 3. They are IEEE 802.15.4g and .4e that are PHY and MAC layer standards, respectively and are evaluated by computer simulations. Then, the Wi-SUN alliance that standardizes, certifies and promotes their standards based systems and the Wi-SUN profiles that are technical specifications of the Wi-SUN based systems are described in Sect. 4. In Sect. 5 PER performances under AWGN and multipath fading environments are measured by using IEEE 802.15.4g compliant and Wi-SUN alliance certified radio modules to understand transmission performance of actual IEEE 802.15.4g Wi-SUN radio device. Section 6 concludes the paper. This paper becomes an instruction paper for the beginners of Wi-SUN based communications systems.

2. Wi-SUN Communication Systems

Figure 1 and Table 1 categorize the Wi-SUN communication

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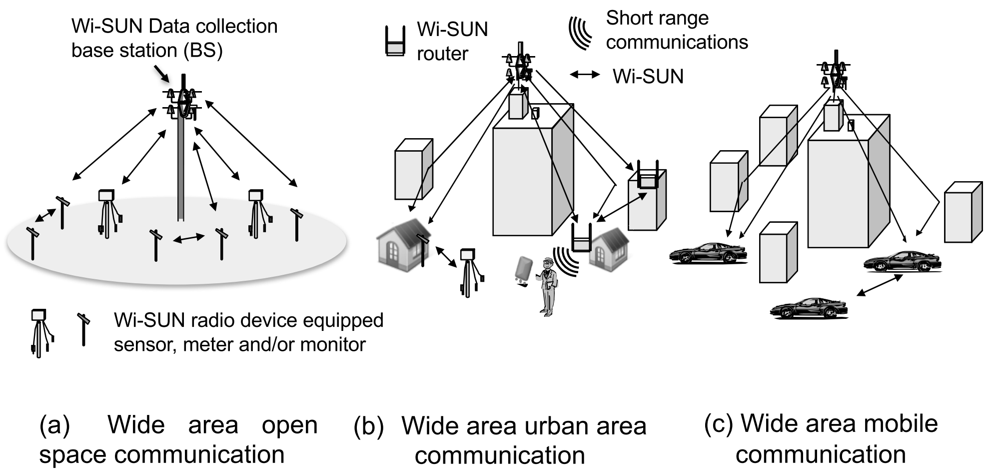

Fig. 1 Wi-SUN communication systems.

Table 1 Categories of Wi-SUN communication systems.

Category	(a) Wide area open space communication	(b) Wide area urban area communication	(c) Wide area mobile communication
Applications	• Sensor, meter and/or monitor network for Energy management, Agriculture, disaster prevention, animal husbandry, and so on	• Information distribution, digital signage to building and store • Sensing and monitoring for building and store (smart city) • Sensing and monitoring from smartphone via Wi-SUN router	• Collection of sensing data from vehicles such as car and bus • Control and management of vehicles
Frequency , Typical data rate	Sub-GHz bands (mainly 800-900 MHz bands), 50,100,150 kbps		
Transmission power	AP : 20 mW, 250 mW Terminal: 20 mW	AP : 20 mW, 250 mW Terminal, router: 20 mW	AP : 20 mW, 250 mW Terminal: 20 mW
Antenna configuration	AP TX: Compliant with regulation in each region AP RX: Multiple antennas. Diversity reception may be used. Terminal: Compliant with regulation in each region		
Antenna height	> 4 m		
Coverage area	1 km-5 km	100 m-2 km	100 m-2 km
Radio propagation	Line-of-sight	Non line-of-sight	Non line-of sight
Path-loss model	Okumura-Hata model	Walfisch-Ikegami model	Walfisch-Ikegami model
Fading model	Multipath fading	Multipath fading (e.g. GSM typical urban (TU) model)	
Terminal radio devices	Fixed installation	Basically fixed installation	Installation in vehicle Vehicle speed: 40-80 km/h
Multi-hop support	May be needed to extend its coverage area and/or to keep high reliability.		

systems into three [1]. Category (a) is an information sensing and monitoring system in the wide area open space environment. The category is based on fixed point-to-multipoint communication and its coverage area is 1–5 km. In Fig. 1, radio device in each sensor, meter or monitor communicates with the BS. If the devices cannot communicate with the BS directly, they may relay their data via other radio devices to the BS by multi-hop operation.

Figure 2 shows three configurations of BS. BS (i) is based on a Wi-SUN certified IEEE 802.15.4g module. The module may divide into two parts: transmission part and reception part. The reception part may have a function of diversity such as maximum ratio combining (MRC) diversity. BS (ii) is based on several Wi-SUN certified IEEE 802.15.4g modules. Some of them may be used only for diversity reception. BS (iii) is based on a software-defined radio that consists of multiband RF units for transmission and reception and a reconfigurable signal-processing unit (SPU).

Category (b) is an information sensing and monitoring system in wide area urban environment. BSs are equipped on the building and communicate with radio devices in the sensors, meters and/or monitors equipped with houses and/or shops by Wi-SUN. The communication is mainly non-line-of-sight and therefore the direct communication between BSs and the radio devices may not be available. In this case, we may use multi-hop operation between radio devices or via Wi-SUN routers shown in Fig. 3. The router is a bridge between Wi-SUN and short-range wireless (SRW) communication systems such as Wi-SUN, Bluetooth™, and NFC [1].

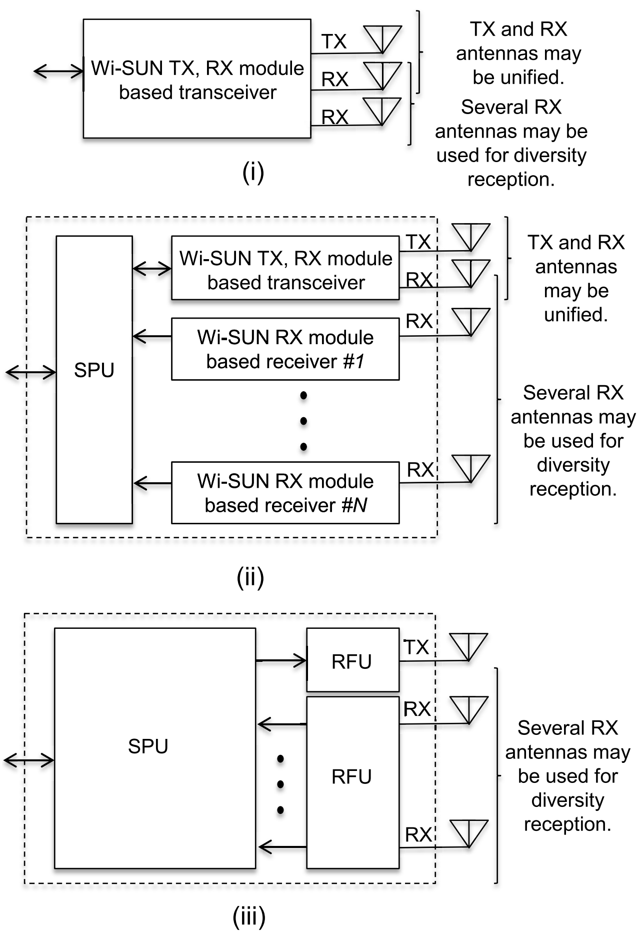

Fig. 2 Categories of BS.

Category (c) is an information sensing and monitoring system in the wide area mobile communication environment. BSs are equipped on the building, and communicate with radio devices in sensors and/or monitors equipped with vehicles such as car and bus. The feasibility challenge of the system is to add functions into Wi-SUN radio devices to receive the sensor, meter or monitor information in the mobile environment.

3. Key Standards to Realize Wi-SUN Communication Systems

Key standards to realize the Wi-SUN communication systems and achieve the configuration and requirements in Fig. 1 and Table 1 are IEEE 802.15.4g and .4e. They are PHY and MAC layer standards, respectively.

3.1 IEEE 802.15.4g

3.1.1 Overview [3]

IEEE 802.15.4g defines an amendment to IEEE 802.15.4. It addresses principally outdoor Low Data Rate Wireless Smart Metering Utility Network requirements. It defines an alternate PHY and only those MAC modifications needed to support its implementation [3]. IEEE 802.15.4g adopts three PHYs: multi-rate and multi-regional (MR-) FSK, MR-offset QPSK and MR-OFDM. In the PHYs, MR-FSK is most commercialized PHY. This paper focuses on MR-FSK. The MR-FSK supports multi-regional operation. Table 2 summarizes the operational frequency bands where more than 50 kbit/s data rate is available [3]. In the Table, modulation, bit rate, channel spacing, total number of channels and modulation index are also summarized. MR-FSK has two modes: mandatory transmission modes that shall be implemented in the radio devices and optional transmission modes as shown in Table 2. In Japan, 50 and 100 kbit/s are mandatory transmission rates by filtered FSK. The mean of "filtered FSK" is that FSK must be filtered to achieve regulation requirements of each region. In Japan GFSK shall be used as the filtered FSK to fulfill the requirements.

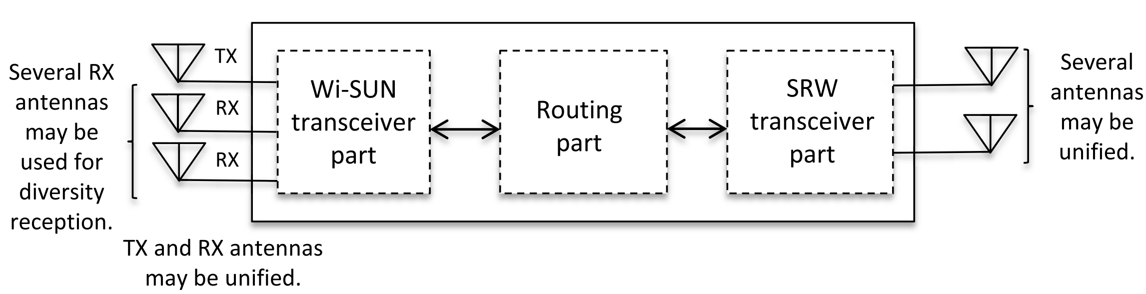

Fig. 3 Configuration of Wi-SUN router.

Table 2 IEEE 802.15.4g modulation and frequency related parameters.

Frequency band (MHz)	Modulation	Bit rate (kbps)	Channel Spacing (kHz)	Total Number of channels	Modulation index
470-510 (China)	Filtered 2FSK*	50	200	199	1.0
	Filtered 2FSK	100	400	99	1.0
	Filtered 4FSK	200	400	99	0.33
779-787 (China)	Filtered 2FSK*	50	200	39	1.0
	Filtered 2FSK	100	400	19	1.0
	Filtered 4FSK	200	400	19	0.33
863-870 (Europe)	Filtered 2FSK*	50	200	34	1.0
	Filtered 2FSK	100	400	17	1.0
	Filtered 4FSK	200	400	34	0.33
902-928 (US)	Filtered 2FSK*	50	200	129	1.0
	Filtered 2FSK	150	400	64	0.5
	Filtered 2FSK	200	400	64	0.5
917-923.5 (Korea)	Filtered 2FSK*	50	200	32	1.0
	Filtered 2FSK	150	400	16	0.5
	Filtered 2FSK	200	400	16	0.5
920-928 (Japan)	Filtered 2FSK*	50	200	38	1.0
	Filtered 2FSK*	100	400	18	1.0
	Filtered 2FSK	200	600	12	1.0
	Filtered 4FSK	400	600	12	0.33

* denotes mandatory transmission mode.

3.1.2 GFSK

GFSK is a filtered FSK. The transmission signal of FSK is formulated a

$$s(t) = \cos\{2\pi f_c t + \phi(t)\}, \tag{1}$$

where f_c and $\phi(t)$ are carrier frequency and phase, respectively. In the FSK the $\phi(t)$ is shifted by the input transmission data, $a_k = \{-1, 1\}$ as

$$\frac{1}{2\pi}\frac{d\phi(t)}{dt} = \frac{\Delta f}{2}\sum_k a_k g(t-kT), \tag{2}$$

$$\phi(t) = \pi\Delta f\int_{-\infty}^{t}\sum_k a_k g(u-kT)du, \tag{3}$$

where Δf and T are frequency deviation and symbol duration, respectively. $g(t-kT)$ is a pulse waveform shown expressed as

$$g(t-kT) = \begin{cases} 1, & (k-1)T \le t < kT \\ 0, & \text{otherwise} \end{cases}. \tag{4}$$

The phase difference between $\phi(kT)$ and $\phi((k-1)T)$ is described as

$$\phi(kT) - \phi((k-1)T) = \pi\Delta f T a_k = \pi m a_k, \tag{5}$$

where $m = \Delta f T$ is modulation index. Figure 4 shows transition and constellation of the modulated phase in the case of $m = 1$. When a_k is 1 or -1, the phase rotates with π positively or negatively, respectively.

GFSK is a FSK filtered by a Gaussian filter $h(t)$ which is expressed as

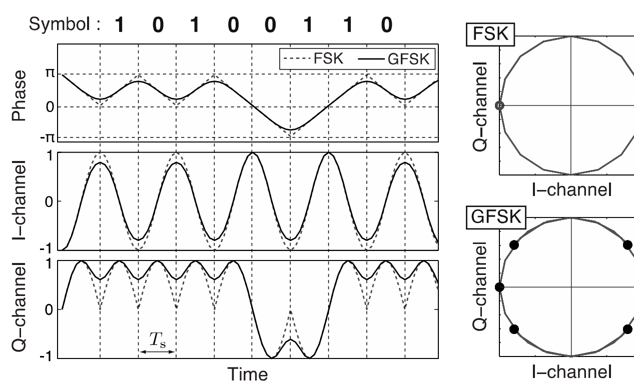

Fig. 4 Difference between FSK and GFSK.

$$h(t) = \frac{\sqrt{\pi}}{\alpha}e^{-\frac{\pi^2}{\alpha^2}t^2}, \tag{6}$$

where α is described as

$$\alpha = \sqrt{\frac{\ln 2}{2}}\frac{1}{BT}, \tag{7}$$

where B is bandwidth of the GFSK. The phase $\phi(t)$ in Eq. (3) is filtered by Eq. (6) as

$$\phi_2(t) = \int_{-\infty}^{+\infty} h(\tau)\phi(t-\tau)d\tau. \tag{8}$$

The constellation of the filtered and modulated phase $\phi_2(t)$ is also shown in Fig. 4 where $BT = 0.5$. The BER performances of FSK and GFSK by computer simulations are shown in Fig. 5.

3.1.3 Configuration of Transmitter

Figure 6 shows configuration of the physical layer convergence protocol data unit (PPDU) format of IEEE 802.15.4g MR-FSK. The MR-FSK PPDU consists of a synchronization header (SHR) including a preamble sequence for symbol timing synchronization and a start frame delimiter (SFD) sequence for frame start timing synchronization, a PHY header (PHR) including control information of the frame and PHY payload parts. The preamble sequence is alternate pattern with ‘0’ and ‘1’, e.g. ‘01010101’. The minimum and maximum length of the preamble sequence is regulated as 4 and 1000 octets, respectively [3]. Figure 7 shows four patterns of the SFD sequence [5]. The sequence is used to estimate frame start timing, to indicate the usage of forward error correction coding (FEC) and to know which FEC is used. Since two types of FECs are standardized and the FECs encode the PHR and PHY payload in Fig. 6, four types of SFD are standardized. The FECs are based on convolutional coding with constraint length of 4 and coding rate of 1/2. One is recursive and systematic code (RSC) encoder in Fig. 8 and the other is non-recursive and non-systematic code (NRNSC) in Fig. 9. The difference between them is that the encoded data by RSC encoder includes original transmitted data and the radio device without FEC decoder may receive the encoded data.

Figure 10 shows the configuration of PHR. When the entire packet is transmitted at a single data rate and using a single modulation scheme, the Mode Switch field is set to zero [3]. The FCS Type field indicates the length of the FCS field that is included in the PHY payload named as PSDU [3]. The Data Whitening (DW) field indicates whether data whitening for the PSDU is used upon transmission. The data whitening is to multiply PSDU by the nine stage pseudo-random (PN) sequence generated by the generator shown in Fig. 11. The Frame Length field indicates the total number of octets contained in the PSDU prior to FEC encoding [3].

Figure 12 and Table 3 show a reference modulator diagram [3] and the function of each block in the modulator,

	SFD value for coded (PHR+PSDU)	SFD value for uncoded (PHR+PSDU)
Mandatory SFD	0110111101001110	1001000001001110
Optional SFD	0110001100101101	0111101000001110

Fig. 7 SFD sequence.

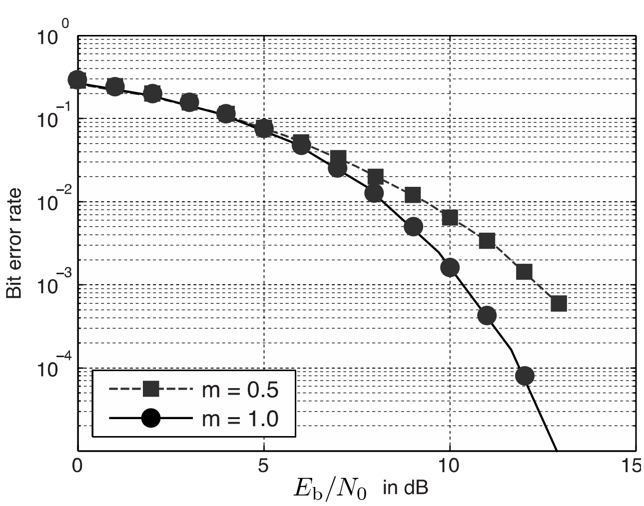

Fig. 5 BER performance of GFSK.

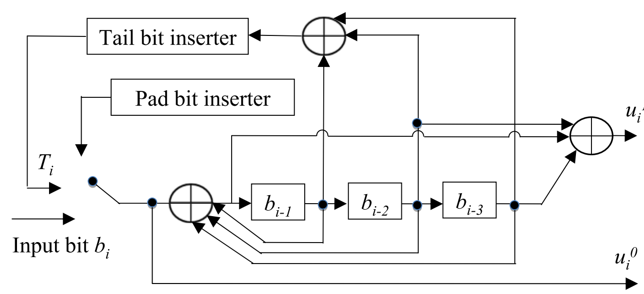

Fig. 8 Recursive and systematic code (RSC) encoder.

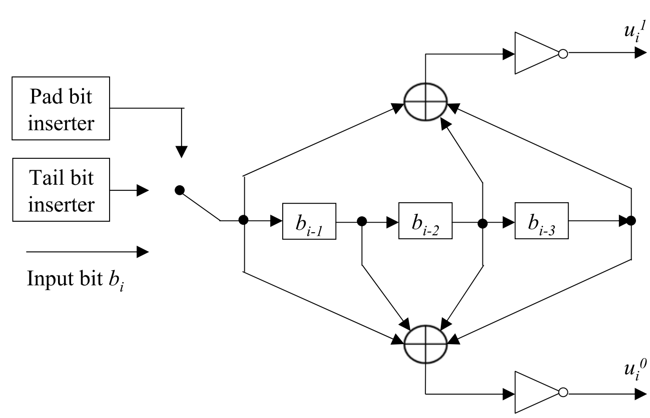

Fig. 9 Non-recursive and non-systematic code (NRNSC) encoder.

Octets	PHY dependent		2	Variable
PHR Layer	Preamble Sequence	Start Frame Delimiter	Frame Length /Reserved	PSDU
	SHR		PHR	PHY Payload

Fig. 6 PPDU format of IEEE 802.15.4g MR-FSK.

Bit string index	0	1	2	3	4	5-15
Field name	Mode Switch	Reserved		FCS Type	Data Whitening	Frame Length

Fig. 10 Configuration of PHR.

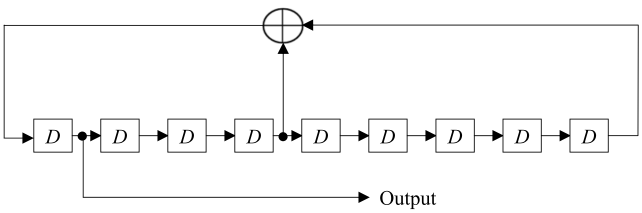

Fig. 11 Data whitening sequence generator.

Table 3 Functions of the blocks in the reference modulator.

Name of block	Function
SHR generation block	• Generate preamble sequence with the length requested • Select SFD sequence from Fig. 7 • Concatenate preamble sequence and SFD sequence
Forward error correction coder	• Encode input data by a convolutional coding scheme standardized by IEEE 802.15.4g
Data whitening encoder	• Multiply PSDU by the nine stage PN sequence standardized by IEEE 802.15.4g (randomization of PSDU)
Concatenator	• Concatenate SHR, PHR PSDU and make PPDU
GFSK modulator block	• Modulate PPDU by GFSK

respectively. After concatenation of SHR, PHR and PSDU, the PPDU is modulated by GFSK. The DW and FEC blocks may be used if needed.

3.1.4 Configuration of Receiver

Figure 13 and Table 4 show a reference demodulator diagram [3] and the function of each block in the demodulator, respectively. The carrier frequency offset (CFO) estimation and compensation scheme by using a moving average low-pass filter (LPF) and artificially designed frequency offset was proposed [6] and the scheme can compensate larger CFO ±30 ppm at 920 MHz.

The BER and PER performances of IEEE 802.15.4g GFSK in the AWGN and multipath fading environment are evaluated by computer simulations in Figs. 14 and 15, respectively. Tables 5 and 6 show the parameters used in the simulations and multipath channel model used in the simulation. COST207 GSM typical urban (TU) model is used as a multipath channel model as shown in Table 6. The required E_b/N_0 is determined as the one which satisfies PER<10% when the length of PSDU and symbol rate are set to 250 octets and 50 kbit/s and greater, respectively [3]. The required E_b/N_0 with and without FEC coding in AWGN are around 8 dB and 12 dB, respectively. In addition, the required E_b/N_0 with and without FEC coding in multipath

Table 4 Functions of the blocks in the reference demodulator.

Name of block	Function
CFO estimation & compensation block	• Estimate carrier frequency offset by using preamble sequence and compensate the offset
Symbol synchronization block	• Decide symbol synchronization point by using preamble sequence
GFSK demodulation block	• Demodulate RX GFSK data
Frame synchronization block	• Decide frame stating point by using SFD sequence
Data whitening Decoder block	• Decode data whitening and recover raw data transmitted
Forward error correction decoder	• Decode demodulated data by Viterbi decoding scheme

Table 5 Parameter used in the BER and PER evaluations.

Parameters	Value
Modulation	2-GFSK
Symbol rate	100 ksymbols/s
Modulation index	1.0
Gaussian filter BT	Tx: 0.5 , Rx: 0.7
Demodulation	Discriminator detection
Channel coding	RSC, K=4, R=1/2
Channel decoding	Viterbi algorithm (hard decision)
Packet size	Preamble: 15 Byte SFD: 2 Byte PHR: 2 Byte PHY payload: 250 Byte
Fading model	COST 207 GSM typical urban

Table 6 Multipath channel model used in the computer simulations.

Model name		Path 1	Path2	Path3	Path4	Path5	Path6
GSM Typical Urban	Delay time [us]	-0.2	0	0.3	1.4	2.1	4.8
	Relative power [dB]	-3	0	-2	-6	-8	-10

environment are around 23 dB and 27 dB, respectively.

3.2 IEEE 802.15.4e

3.2.1 Overview

IEEE 802.15.4e defines an amendment to enhance and add functionality to the IEEE 802.15.4$^{\text{TM}}$-2006 MAC. One of the functionalities is low energy (LE) consumption MAC [7], [8]. IEEE 802.15.4 and .4e MACs are categorized into two: synchronous and asynchronous. The synchronous MAC has two categories: beacon based and channel hopping based MACs. Moreover, there are three MACs in the asynchronous

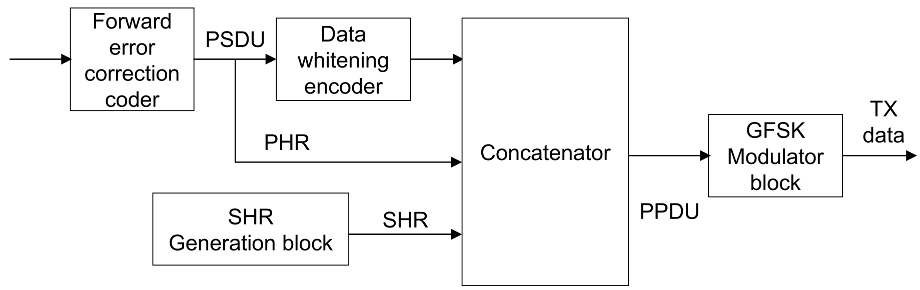

Fig. 12 MR-FSK reference modulator block diagram.

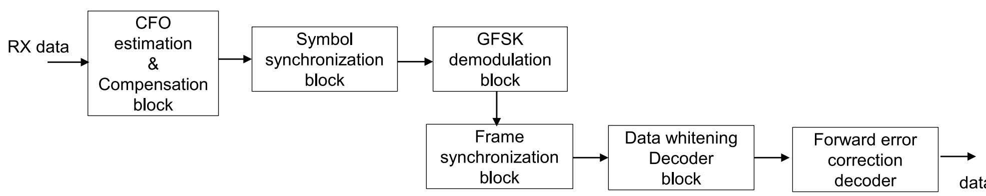

Fig. 13 MR-FSK reference demodulator block diagram.

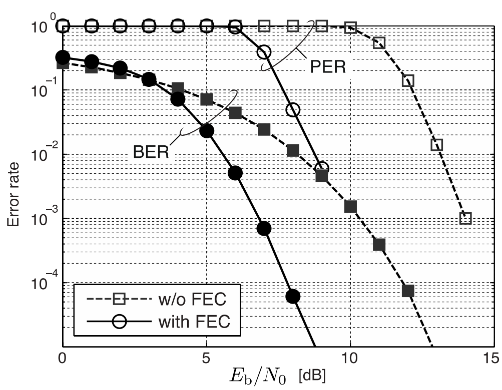

Fig. 14 BER and PER performances in AWGN.

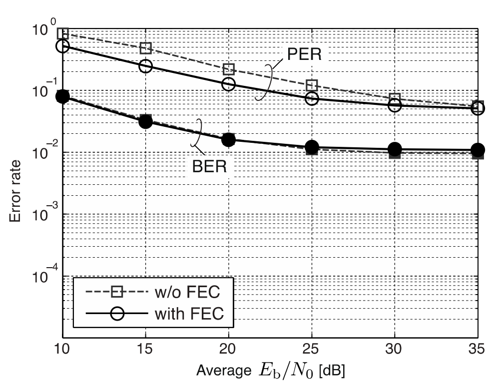

Fig. 15 BER and PER performances in multipath fading environment.

MAC: CSMA/CA, coordinated sampled listening (CSL) and receiver initiated transmission (RIT). In the three MACs, CSL and RIT are standardized by IEEE 802.15.4e as the LE operation MAC. This paper focuses on the asynchronous MAC.

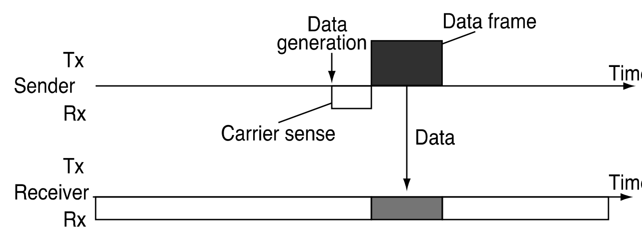

Fig. 16 CSMA protocol.

3.2.2 CSMA

Figure 16 shows the operation of the CSMA protocol. When a data generation occurs on a sender, the radio device performs a receiving action called carrier sense. When the device does not detect a carrier signal, the device transmits the data to the desired partner, i.e. the receiver. When the device detects a carrier signal, it suspends transmitting data, waits for a certain period of time decided randomly and then attempts retransmission.

3.2.3 CSL

Figure 17 shows the operation of the CSL protocol. Each radio device performs a periodical receiving action, called channel sampling, with a fixed interval, called the MAC CSL period. When a data generation occurs on a sender, the sender performs the continuous transmission of the wakeup sequence. The wakeup sequence is continuously transmitted for a duration exceeding the MAC CSL period. After the end of the wakeup sequence transmission, the sender transmits the generated data frame to the desired partner, i.e. the receiver.

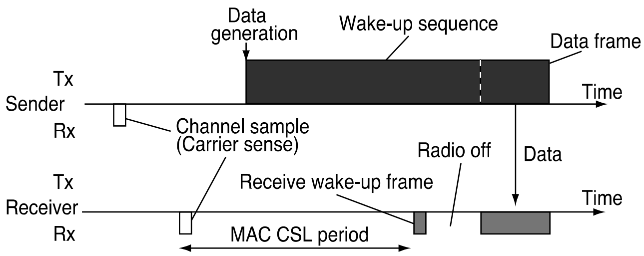

Fig. 17 CSL protocol.

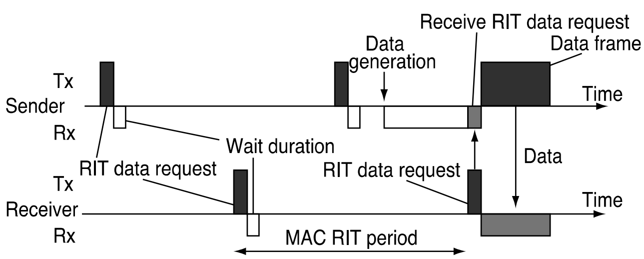

Fig. 18 RIT protocol.

3.2.4 RIT

Figure 18 shows the operation of the RIT protocol. In the RIT protocol, each radio device transmits an RIT data request frame with a fixed interval, called the MAC RIT period. Immediately after the RIT data request transmission, a short time listening called the MAC RIT data wait duration is performed. The RIT data request frame complies with the MAC header of IEEE 802.15.4 [7] and consists of several optional pieces of information, such as the destination network ID, destination address, network ID of the source, and source address.

When a data generation occurs on a sender, the sender firstly proceeds with the receiving action. After receiving the RIT data request frame from the desired receiver, the sender completes the data transmission process by sending the data frame to the receiver on reflex. This periodical wake-up and sleep behavior has advantages in high time utilization efficiency per a channel and power consumption, and the RIT protocol is appropriate for multi-hop Wi-SUN networks that have tolerances for delay. As an easy implementation RIT based MAC, the Feathery-RIT (F-RIT) protocol is proposed [9].

3.2.5 F-RIT

Figure 19 shows the operation of the F-RIT protocol [9]. Two important specifications have been implemented on the F-RIT protocol. The first is the compacted RIT data request frame, in which only a source ID is included. The second is to adopt pre-carrier sense (Pre-CS), which is performed before the transmission of the RIT data request frame. When a device (or a sender) detects a carrier signal in Pre-CS period, the device suspends transmitting the RIT data request until

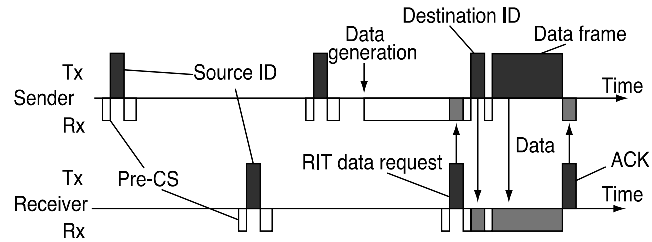

Fig. 19 F-RIT protocol.

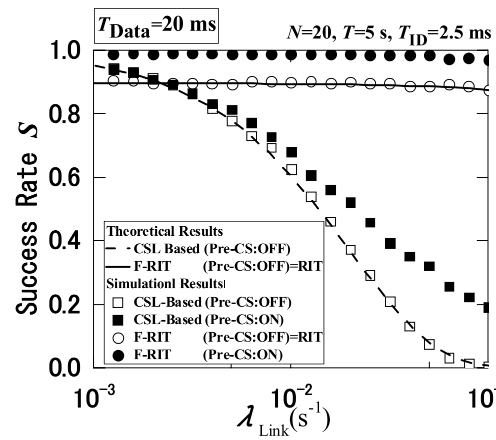

Fig. 20 Performance comparison between F-RIT and CSL-based MAC protocols.

Table 7 Parameters used in the MAC protocol evaluation.

Parameters	Value
MAC Types	F-RIT, CSL
Pre-CS	ON, OFF
Number of radio devices N	20
Repeat listen interval: T	5 s
Pre-CS and Wait duration time: T_{CS}	0.01 ms
ID transmission time: T_{ID}	2.5 ms
Data transmission time: T_{Data}	20 ms

the next periodical time, and does not attempt retransmission. The purposes of Pre-CS are to give a priority to a data frame and to reduce the receiving power consumption for searching a channel vacancy under radio interference. The RIT data request does not always need to transmit, but a data frame should be transmitted successfully.

Figure 20 shows comparison a result of success rate vs. communication link establishment requesting rate, λ_{Link} (s^{-1}) among CSL, RIT and F-RIT by computer simulations and theoretical calculations [9]. In the Figure, RIT is expressed as "F-RIT (Pre-CS: OFF)". Moreover, the Pre-CS is performed before transmitting a wake-up sequence in CSL. Table 7 summarizes parameters used in the simulation and theoretical calculations. In the simulation independent 10 pairs one-direction communications of radio devices are established and data generations randomly occurs in the pairs with Poisson distribution [9].

In the CSL-based protocol with or without CS, colli-

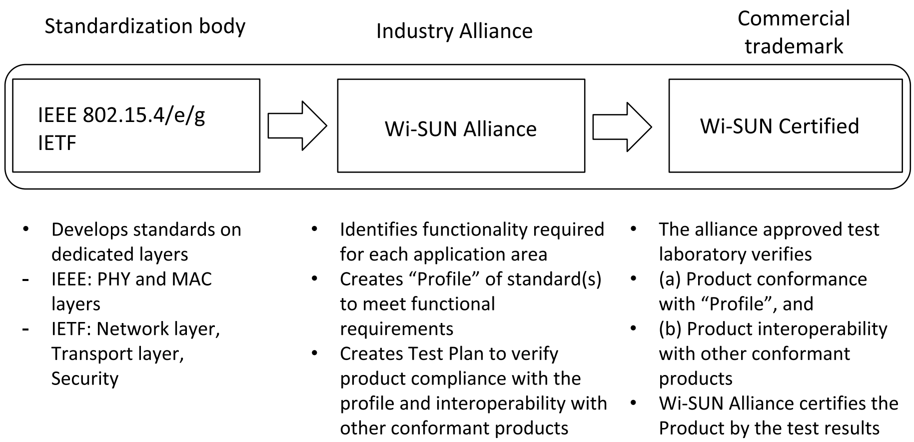

Fig. 21 Position and role of Wi-SUN alliance.

sions between wake-up frames from several radio devices increase as communication link establishment requesting rate increases. The success rate of CSL therefore decreases. In the F-RIT, collisions between RIT data requests are smaller than that between wake-up frames. The success rate of the F-RIT is better than that of CSL as λ_{Link} increases. However, if Pre-CS is not used, it is difficult to increase the rate because the collisions between data frames may occur. By using Pre-CS (namely F-RIT), RIT data request is not transmitted during the time transmitting RIT data frame between other devices and it means that new RIT data frame is also not transmitted. As a result, transmission success rate close to 100% is achieved by the F-RIT protocol.

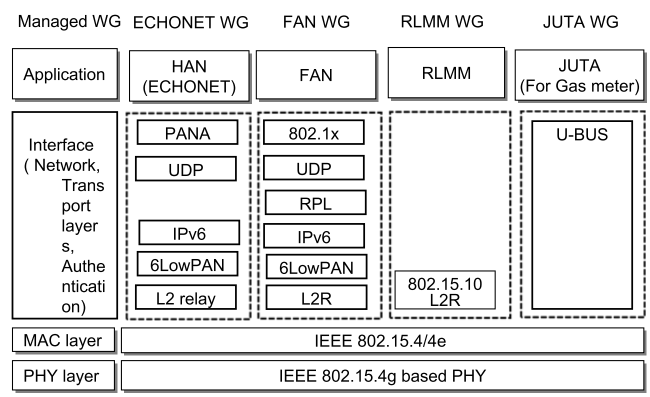

Fig. 22 Wi-SUN profiles.

4. Wi-SUN Profiles

4.1 Overview

IEEE 802.15.4, .4g, and .4e are standards that mainly define the specifications of PHY and MAC layers. On the other hand, most applications need more specifications of other layers such as network and transport layers and also require security and authentication protocols. However, some of the layers are defined by entities other than IEEE such as IETF. Therefore, an industry alliance that identifies functionality is required for each application area by combining several standards for several layers. The Wi-SUN alliance [4] was established in April 2012 in Tokyo and has been incorporated as a Not for Profit Organization in US since 2013. Figure 21 shows the position and role of the alliance and the relationship with Standardization bodies such as IEEE and IETF. The Wi-SUN alliance identifies functionality required for each application area and develops technical "Profile" that consists of several open standards to meet the functional requirements for the applications. Moreover, the alliance develops test plans to verify the compliance of products with the profile and interoperability with other conformant products. Then test laboratories to do the products compliance and interoperability tests are appointed by the alliance. Finally, the alliance certifies the products from the test results operated by the test laboratories. The certified products can use the name of Wi-SUN as commercial trademark.

4.2 Wi-SUN Profiles

Figure 22 summarizes the Wi-SUN profiles developed by working groups (WGs) in the Wi-SUN alliance. Currently four WGs develop the standards: ECHONET WG, FAN WG, RLMM WG, and JUTA WG. ECHONET WG develops specification to drive a Japanese official application profile for electricity energy management, ECHONET Lite. It is used for the communication between a smart electricity meter and HEMS. The Wi-SUN ECHONET profile is based on IEEE 802.15.4, .4g, .4e, 6LowPAN, IPv6, UDP, and PANA, as PHY, MAC, convergence layer, network layer, transport layer and authentication protocol, respectively. The ECHONET profile also includes two hops relay communication in datalink layer and supports communication between HEMS and radio devices set in the home electrical appliances.

FAN WG develops a profile for field area networks (FANs) that connects "field" devices into utility operations. The field devices include Advanced Metering Infrastructure (AMI) and electric utility Distribution Automation (DA) components such as meters, line sensors, capacitor banks, distributed energy resources, and distribution automation elements [9]. The FAN profile is based on IEEE 802.15.4, .4g and .4e, 6LowPAN, IPv6, and UDP. Additionally, some new functions are adopted: routing operation based on IETF RPL layer 3 routing and ANSITIA-4957.210 layer 2 routing (L2R) standardized by TIA TR-51 and IEEE 802.1x based security system.

RLMM WG develops a profile for resource limited monitoring and management (RLMM) systems such as agriculture and disaster prevention monitoring. The difference from FAN profile is that the RLMM profiles is based on non-IP based communication to reduce power consumption. Moreover, the profile supports L2R protocol standardized by IEEE 802.15.10. JUTA WG develops a specification to drive a Japanese official application profile for gas energy management, U-BUS. The Wi-SUN JUTA profile has defined mainly PHY, MAC and interfaces to support U-BUS Air in Japanese gas metering systems.

5. Experimental Transmission Performance by IEEE 802.15.4g Compliant Wi-SUN Module

To understand transmission performance of actual IEEE 802.15.4g Wi-SUN radio device, PER performances under AWGN and multipath fading environment are measured by using IEEE 802.15.4g compliant and Wi-SUN alliance certified radio modules as shown in Fig. 23. In the laboratory experiment, two radio modules and a fading emulator are used to measure the PER performances. Table 8 summaries parameters used in the experiment. One path Rayleigh fading and TU model shown in Table 6 are used as channel models for the fading emulator. Figures 24 and 25 show the PER performances in AWGN and multipath fading environment, respectively. To achieve 10% PER required by the standard, −102 dBm and −100 dBm are required for the transmission rate of 50 kbit/s and 100 kbit/s, respectively. In addition, it is impossible to meet 10% PER under the multipath fading environment with Doppler frequency of 34 Hz at 920 MHz. The Wi-SUN module however achieves 10% PER under one path and multipath fading environment with Doppler frequency of 0.4 Hz at 920 MHz. This means that the Wi-SUN radio devices are expected to achieve AMI and DA services in urban area where sensors are fixedly launched. However, 10% PER is not achievable in TU channel model when Doppler frequency is 34 Hz. New receiver architecture with diversity reception and IEEE 802.15.4g standardized FEC and its decoder must be designed to improve the PER performance in the wide area mobile communication systems shown in Fig. 1. That is one of future important works.

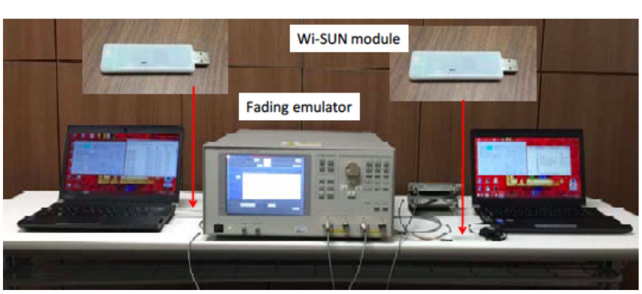

Fig. 23 Measurement setup.

Table 8 Parameter used in the experimental evaluations.

Compliant standard	IEEE 802.15.4g
Frequency band	920 MHz
Modulation	2-GFSK
Modulation index	1.0
Preamble length	15 octets
Payload size	250 octets
Transmission rate	100 kbps
Data whitening	Off
CRC	CRC-32
Coding	OFF
Fading model	1 path Rayleigh fading, COST207 GSM typical urban
Maximum Doppler freq.	34 Hz, 0.4 Hz

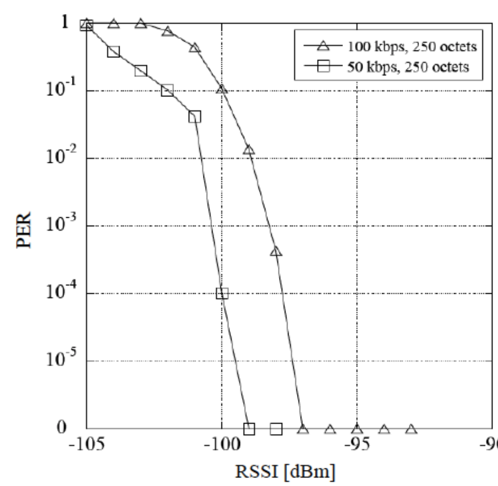

Fig. 24 PER experimental performance (AWGN).

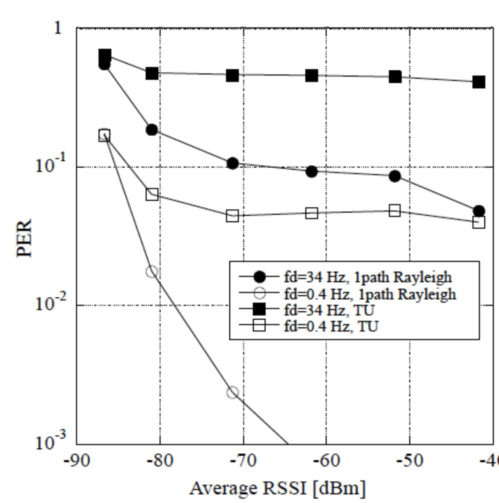

Fig. 25 PER experimental performance (fading).

6. Conclusions

This paper summarized the Wi-SUN communication systems and their PHY and MAC specifications. Firstly, three Wi-SUN communication systems were introduced. The key PHY and MAC standards, IEEE 802.15.4g and .4e, that configure the systems were explained, and their fundamental PHY and MAC transmission performances were evaluated mainly by computer simulations. Regarding MAC, transmission success rate close to 100% is achieved by the F-RIT protocol with Pre-CS when 10 pairs one-direction communications of radio devices are established in the same area. Then, the Wi-SUN alliance and the Wi-SUN profiles, ECHONET, FAN, RLMM and JUTA were explained. Then, to understand transmission performance of actual IEEE 802.15.4g Wi-SUN radio device, PER performances under AWGN and multipath fading environments were measured by using IEEE 802.15.4g compliant and Wi-SUN alliance certified radio modules. To achieve the 10% PER required by the standard, −102 dBm and −100 dBm are required for the transmission rate of 50 kbit/s and 100 kbit/s, respectively. In addition, the Wi-SUN module achieves 10% PER under one path and multipath fading environments with Doppler frequency of 0.4 Hz at 920 MHz. This paper became the instructive paper for the beginner of Wi-SUN based communications systems. As further studies, field measurements of the radio devices in the several application fields and transmission performance evaluations of PHY and MAC under multi-hop environments should be done. Also it should be done to design new receiver architecture which includes diversity reception and IEEE 802.15.4g standardized FEC and its decoder must be designed to improve the PER performance in the wide area mobile communication systems.

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References

[1] H. Harada, K. Mizutani, K. Mochizuki, and K. Obata, "IEEE802.15.4g based wide area and mobile Wi-SUN communication systems," Proc. WPMC 2015, pp.1–6, Dec. 2015.

[2] H. Harada, "Smart utility network: Overview and status of standardization," IEICE Technical Report, SR2010-48, Oct. 2010 (in Japanese).

[3] "IEEE Std 802.15.4g$^{\mathrm{TM}}$-2012," April 27, 2012.

[4] http:// www.wi-sun.org

[5] L. Lu, H. Harada, R. Funada, and C.-S. Sum, "Design of the start-frame-delimiter pair for 802.15 smart utility network system," IEICE Trans. Commun., vol.E96-B, no.3, pp.730–736, March 2013.

[6] K. Obata, K. Mizutani, and H. Harada, "Carrier frequency offset estimation scheme for IEEE 802.15.4g based wide area Wi-SUN," Proc. IEEE ICC 2016, pp.1–6, June 2016.

[7] "IEEE Std 802.15.4$^{\mathrm{TM}}$-2011," June 16, 2012.

[8] "IEEE Std 802.15.4e$^{\mathrm{TM}}$-2012," April 16, 2012.

[9] J. Fujiwara, R. Okumura, K. Mizutani, H. Harada, S. Tsuchiya, and T. Kawata, "Ultra-low power MAC protocol complied with RIT in IEEE 802.15.4e for wireless smart utility networks," Proc. IEEE PIMRC'16, pp.1–6, Sept. 2016.

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