Characteristics of LoRaWAN with Energy Detection Based Carrier Sense

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***Abstract*—This study investigates the characteristics of a long range wide area network (LoRaWAN) utilizing an energy detection based carrier sense. The authors have theoretically and numerically analyzed the energy detection based carrier sense and its characteristics in Sub-GHz band low-power wide-area networks (LPWANs), and numerically studied that the optimal carrier sense level depends on the packet length in networks. In previous studies, although LoRa signals were assumed to be LPWA signals, they were based on the assumption that all packets in a network have the same spreading factor and length. Since packets with different spreading factor are roughly orthogonal to each other, these evaluations are important in environments where several packets of different lengths are mixed. Therefore, in this study, characteristics of LoRaWAN utilizing the energy detection based carrier sense are discussed. The evaluation results show the roughly orthogonality of spreading factors changes the optimal carrier sense level in LoRaWAN.**

***Index Terms*—LPWA, LoRaWAN, energy detection based carrier sense, spreading factors.**

I. Introduction

Low power wide area networks (LPWANs) [1] are expected to be the wireless communication infrastructure for Internet of Things (IoT) systems, such as industrial applications [2] and environmental monitoring [3]. The LPWA technology enables energy efficient long distance communication at low data rates. In Japan, LPWA technology, such as long range wide area network (LoRaWAN) [4], SigFox [5], and wireless smart utility network (Wi-SUN) [6] is available in the Sub-GHz band under regulation, that is, the ARIB STD-T108 [7]. For Sub-GHz band use in Japan, a carrier sense [8] is required for coexistence with passive tag systems, depending on the duty-cycle or transmit power of the end-device. The signal detection technology [9] required to achieve carrier sense, such as peak detection, energy detection [10], and cyclostationary detection [11]. The signal detection problem for carrier sense involves determining the presence or absence of a detected signal from a signal contains only noise or both noise and a detected signal. It can be considered a binary hypothesis testing problem.

The carrier sense level in ARIB STD-T108 is defined as the instantaneous signal power of one channel at the feeding point of an end device; thus, it can be realized by utilizing peak detection. Peak detection is the simplest signal detection technique in which the maximum power is detected within a given signal detection period; however, it cannot achieve low signal detection levels owing to the noise effect. Concretely, signals with a power close to the noise power cannot be detected by utilizing peak detection. In addition to the purpose of spectrum sharing with existing systems, carrier sense is a technology that allows end devices to autonomously avoid interference and is a promising technology for the improvement of network characteristics; however, peak detection based carrier sense can no longer improve these characteristics because of the reasons given above.

The authors have theoretically and numerically analyzed the energy detection based carrier sense in Sub-GHz band LPWANs and its characteristics [12]. In the energy detection based carrier sense, a carrier sense level lower than the noise power is possible by utilizing energy detection as a signal detection technique. Furthermore, the authors have analyzed that the length of packets transmitted by end devices determines the optimal carrier sense level in LPWAN with the energy detection based carrier sense. However, previous studies assumed that all packet lengths in an LPWAN are equal. In addition, the results were based on the assumption of LoRaWAN where all spreading factors of end devices are considered the same. This study investigates the characteristics of the LoRaWAN with the energy detection based carrier sense.

II. System Model

A. Energy Detection Based Carrier Sense in LPWAN

Numerous theories and problems are have been established and considered under the assumption that the length of the target signal is infinite. However, the length of the packet is finite in an actual carrier sense environment. Since the target signal with a finite length is captured with a finite carrier sense period, blank periods are generated during the part of the carrier sense period. This degrades the accuracy of carrier sense when energy detection is employed as a signal detection scheme in carrier sense. In [12], the characteristics of the energy detection based carrier sense are analyzed by considering the finite length of the packet. In addition, the optimal carrier sense level for the best packet delivery ratio depends on the length of packet [12].

We let T_{P} and T_{CS} denote the length of packet and carrier sense period, respectively. The carrier sense success probability P_{CS} of the energy detection based carrier sense is given by the following equation [12],

$$P_{\text{CS}} = \frac{1}{T_{\text{P}} + T_{\text{CS}}} \left[2 \sum_{n=1}^{\min(T_{\text{P}}, T_{\text{CS}})} P_{\text{D,A}}(n) + \left(|T_{\text{P}} - T_{\text{CS}}| + 1 \right) P_{\text{D,A}} \left\{ \min\left(T_{\text{P}}, T_{\text{CS}}\right) \right\} \right], \quad (1)$$

where $\min(X, Y)$ is the function that return the minimum value of X and Y. $P_{\text{D,A}}(n)$ is the probability of signal detection when the arrival signal length takes finite values. $P_{\text{D,A}}(T_{\text{P}})$ is given by

$$P_{\text{D,A}}(T_{\text{P}}) = Q \left\{ \left(\frac{P_{\text{CS,mW}}}{\sigma_v^2 + \min\left(1, \frac{T_{\text{P}}}{T_{\text{CS}}}\right) \sigma_w^2} - 1 \right) \sqrt{2 T_{\text{CS}} BW} \right\}, \quad (2)$$

where $Q(z)$, $P_{\text{CS,mW}}$, σ_v^2, σ_w^2 and BW are $Q(z) = \frac{1}{\sqrt{2}} \int_z^\infty e^{-t^2/2} dt$, threshold for signal detection in milliwatts, variance of noise at the end device, variance of arrived interference, and channel bandwidth, respectively. Threshold for signal detection can be written by,

$$P_{\text{CS,mW}} = \sigma_v^2 \left\{ \frac{Q^{-1}\left(\overline{P_{\text{FA}}}\right)}{\sqrt{2 T_{\text{CS}} / BW}} + 1 \right\}, \quad (3)$$

where $\overline{P_{\text{FA}}}$ and $Q^{-1}(\cdot)$ are the target false alarm probability and inverse function of $Q(\cdot)$, respectively. An example of eq. (1) for different carrier sense levels with actual LPWAN parameters is shown in Fig. 1 according to which the channel bandwidth, noise figure (NF), arrived packet lengths (T_{TOA}), and received signal power of the arrived signal (P_{RX}) are $BW = 200$ kHz, $NF = 6$ dB, $T_{\text{TOA}} = 51.5, 153.9, 329.7$ ms, and $P_{\text{RX}} = -125$ dBm, respectively. The probability of signal detection deteriorates with a decrease in packet length and the range of carrier sense levels that provide good performance is also narrow. In addition, a lengthy carrier sense period causes the detection of even non-collision packets, resulting in lost packet transmission opportunities at the end device and consequently degraded packet delivery ratio characteristics [12].

The performances of the energy detection based carrier sense are limited by the accuracy of noise power estimation. The phenomenon is called SNR Wall [13]. To avoid the performance degradation due to the phenomenon, the noise power must be estimated using a sufficient period because thermal changes, which are the most influential factor in noise power changes, are very slow [14]. Although the arrived interference signal during the estimation degrades the accuracy of noise power estimation, the effect of interference avoidance owing to the energy detection based carrier sense outweighs the effect of noise power accuracy degradation due to the interference [12].

B. LoRaWAN

This study considers a LoRaWAN with the energy detection based carrier sense. The LoRaWAN is composed of N_{ED} end

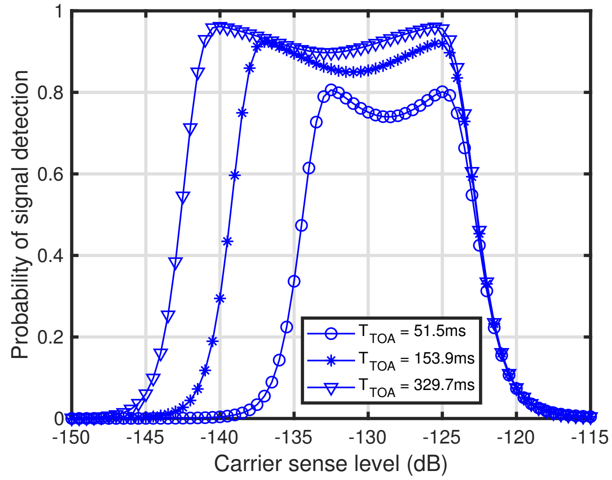

Fig. 1. Probability of signal detection for different carrier sense level. $BW = 200$ kHz, $NF = 6$ dB, $T_{\text{TOA}} = 51.5, 153.9, 329.7$ ms, and $P_{\text{RX}} = -125$ dBm.

devices and a gateway located at the center of communication area. The end devices transmit the observed data and the gateway collects data from end devices. Chirp spread spectrum based LoRa modulation is characterized by six types of spreading factors $SF \in \{7, \cdots, 12\}$ that are roughly orthogonal to each other [15]. This orthogonality leads roughly avoids collisions between packets with different spreading factors. In Japan, unlicensed LPWA communication operates in 920MHz frequency band, which is an ISM frequency band [7]. In Japanese regulations [7], a peak detection based carrier sense is required depending on the transmit power, transmission period and duty cycle to avoid interference with coexisting passive tag systems. For example, a carrier sense period above 5 ms is required when the transmit power, transmission time and duty cycle are reach 20 mW, 4 s and no limitation, respectively.

III. Characteristics of LoRaWAN with Energy Detection Based Carrier Sense

A. Experimental setup

The experimental parameters utilized in the study are listed in Table I. The path loss exponents between the gateway and each end device and between end devices are 2.7 and 3.3, respectively, in an area with $R = 1500$ m, comprising 200 end devices and a gateway located at the center of the area. We set the transmit power, carrier frequency, channel bandwidth, noise figure, average packet transmission interval, maximum number of transmission trials, number of channels utilized, and target false alarm probability are 13 dBm, 920 MHz, 200 kHz, 6 dB, 450 s (Poisson distribution), 3 times, 1 and 0.0001, respectively.

This section discusses the characteristics of LoRaWAN with the energy detection based carrier sense where several packets with different lengths and spreading factors are mixed. The seven types of LoRa signal utilized in the evaluation are listed in Table II according to which spreading factors and

TABLE I
EXPERIMENTAL PARAMETERS

Description	Variable	Numerical value(s)
p.d.f for sensor placement	-	Uniform distribution
Number of end devices	-	200
Path loss exponent end device $\rightarrow$ gateway	-	2.7
Path loss exponent end device $\leftrightarrow$ end device		3.3
Radius of area	R	1500 m
Transmit power	-	13 dBm
Carrier frequency	-	920 MHz
Channel bandwidth	BW	200 kHz
Noise figure	NF	6 dB
Average transmission interval	-	450 s / 1 packet
Maximum number of trial for transmission	-	3
Number of channels utilized	-	1
Target false alarm probability	$\overline{P_{\mathrm{FA}}}$	0.0001
Capture effect	-	Figs. 2 and 3

TABLE II
FIVE TYPES OF LORA SIGNALS IN NUMERICAL EXAMPLES

Parameter	Spreading factor	Packet length
LoRa1	7	51.5 ms
LoRa2	7	153.9 ms
LoRa3	10	329.7 ms
LoRa4	10	821.2 ms
LoRa5	7	821.2 ms
LoRa6	7	1 ms $\sim$ 1 s
LoRa7	10	1 ms $\sim$ 1 s

payload lengths of 7 and 10, 1 byte and 50 byte, respectively, are chosen.

The signal power to interference ratio (SIR) and signal power to noise ratio (SNR) characteristics of the capture effect are shown in Figs. 2 and 3. The spreading factors for the desired signals in Figs. 2 and 3 correspond to $SF = 7$ and $SF = 10$, respectively. These curves are obtained through computer simulations from a bit error rate of less than 10^{-5} by changing the SIR and SNR. In addition, the spreading factors of the interference signal in both figures are $SF = 7, 10$. Several curves with different spreading factors and power ratios for the desired and interference signals are shown in both figures. Each curve divides the plot area into two areas: right-upper and left-lower areas. The right-upper and left-lower areas represent packet transmission success and failure, respectively. Note that only two spreading factors are employed in this study to avoid complications and focus on the characteristics owing to the difference in spreading factors.

B. Evaluation I, same spreading factor and different packet length

First, the evaluation results of the LoRaWAN with mixed packets of LoRa1 and LoRa2 are presented; that is, the same spreading factor $SF = 7$ and different packet lengths 51.5 and 153.9 ms. Fig. 4 shows a packet delivery ratio for different carrier sense level in the end devices. In Fig. 4, the following five characteristics are evaluated.

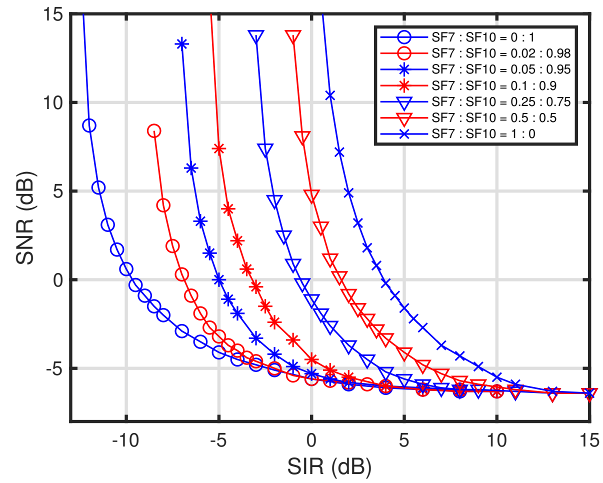

Fig. 2. SIR-SNR characteristics of capture effect when desired signal and interference signals are LoRa signals with $SF = 7$ and $SF = 7, 10$, respectively.

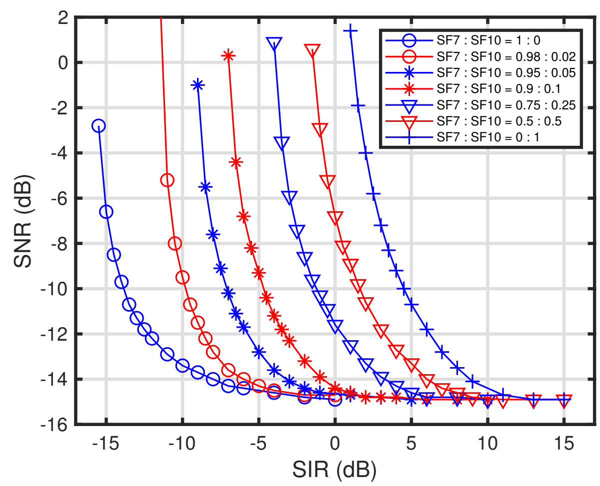

Fig. 3. SIR-SNR characteristics of capture effect when desired signal and interference signals are LoRa signals with $SF = 10$ and $SF = 7, 10$, respectively.

- Averaged characteristic for LoRa1 and LoRa2 in the mixed network.
- Characteristic of LoRa1 in the mixed network.
- Characteristic of LoRa2 in the mixed network.
- Characteristic of LoRa1 in the LoRa1 alone network.
- Characteristic of LoRa2 in the LoRa2 alone network.

As shown in Fig. 4, the optimal carrier sense level of LoRa1 in the mixed network is lower than that in the LoRa1 alone network. Furthermore, the optimal carrier sense level of LoRa2 in the mixed network is higher than that in the LoRa2 alone network. The optimal carrier sense levels are high and low for networks with short and long packet lengths, respectively. This is a fundamental characteristic of the LPWAN with the energy detection based carrier sense [12], and this characteristic can be observed in the results. In Fig. 5, a packet delivery ratio for different carrier sense levels compared with LoRa3 and LoRa4,

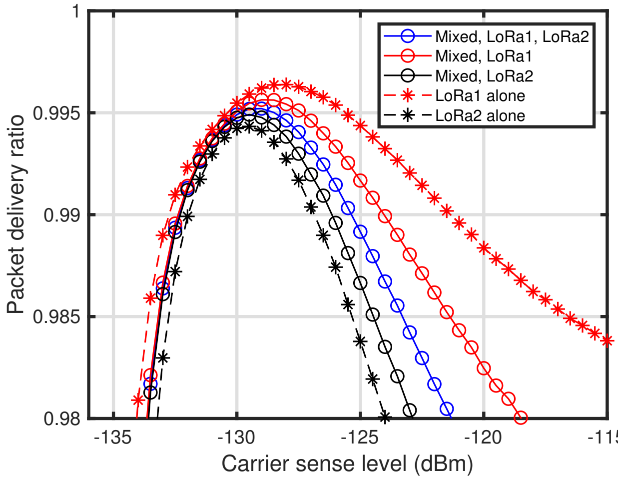

Fig. 4. Packet delivery ratio for different carrier sense level in the LoRaWAN with mixed packets of LoRa 1 ($SF = 7$, 51.5 ms) and LoRa 2 ($SF = 7$, 153.9 ms) listed in Table II.

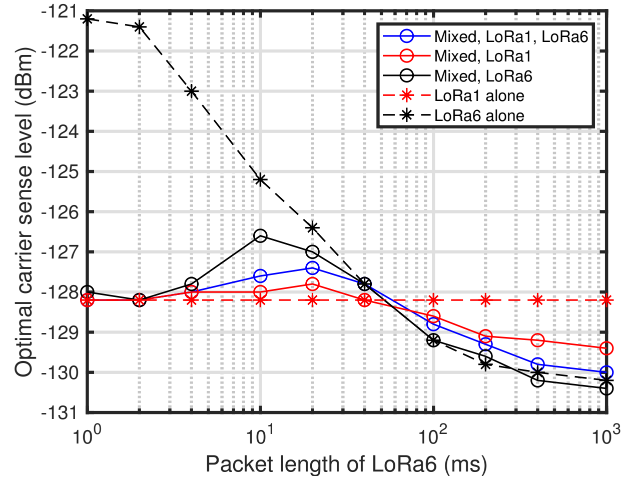

Fig. 6. Optimal carrier sense level for the network mixed with the LoRa1 ($SF = 7$, 51.5 ms) and LoRa6 ($SF = 7$, 1 ms $\sim$ 1 s).

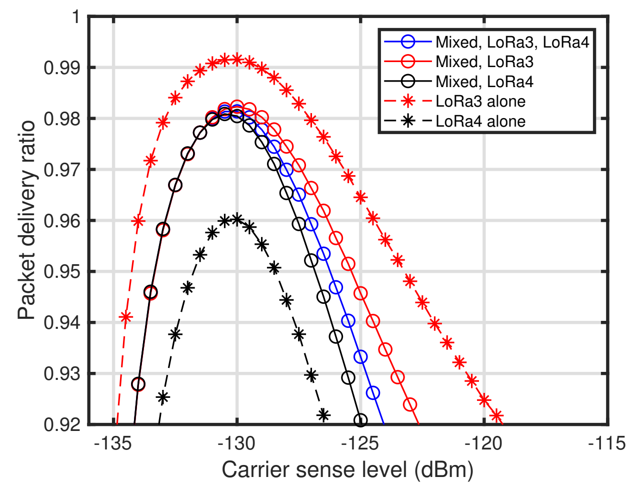

Fig. 5. Packet delivery ratio for different carrier sense level in the LoRaWAN with mixed packets of LoRa 3 ($SF = 10$, 329.7 ms) and LoRa 4 ($SF = 10$, 821.2 ms) listed in Table II.

where the same spreading factor $SF = 10$ and different packet lengths 329.7 ms and 821.2 ms. The characteristics in Fig. 5 exhibited a tendency similar to those in Fig. 4.

A network with two mixed LoRa communications (LoRa1 and LoRa6) is employed to clearly demonstrate these characteristics. For different packet lengths of LoRa6, the packet delivery ratio in the mixed network is shown in Fig. 6. As shown in Fig. 6, It can be seen the similar tendency as the characteristics shown in Figs. 4 and 5.

C. Evaluation II, different spreading factor and different packet length

Here, we present the evaluation results for the two networks: The LoRaWAN with mixed packets of LoRa1 ($SF = 7$, 51.5 ms) and LoRa4 ($SF = 10$, 821.2 ms) along with the network with mixed packets of LoRa1 ($SF = 7$, 51.5 ms) and LoRa5 ($SF = 7$, 821.2 ms). The two networks only differed in terms of the spreading factor of the packet with a length of 821.2 ms. The evaluation results for both networks are shown in Figs. 7 and 8. The characteristics of LoRa2 in Fig. 4 are replaced by LoRa4 or LoRa5 are shown in these figures. Note that the packet lengths of LoRa4 and LoRa5 are the same and the difference between LoRa4 and LoRa5 is spreading factor.

Compared with the characteristics shown in Figs. 7 and 8, the characteristics of the mixed networks shown in Fig. 7 are superior to those shown in Fig. 8. This results from the roughly orthogonal spreading factors. Furthermore, the optimal carrier sense level of LoRa1 in the mixed network shown in Fig. 7 is higher than that shown in Fig. 8. We employ a network with two mixed LoRa communications for proper demonstration. One is LoRa1 and the other is LoRa7 with a spreading factor $SF = 10$ and a packet length from 1 ms to 1 s. Fig. 9 shows the optimal carrier sense levels for different packet lengths in the network. Unlike Fig. 6, the characteristics of LoRa7 in the mixed network (black solid line with circle) and the LoRa7 alone network (black dashed line with asterisk) are almost similar. This results from the roughly orthogonal spreading factors.

IV. Conclusion

This study investigated the characteristics of the LoRaWAN with the energy detection based carrier sense. In the energy detection based carrier sense, the length of the packet and the spreading factors in the LoRaWAN depended on the optimal carrier sense level for the optimal packet delivery ratio. To reveal the characteristics in this context, the performance of the LoRaWAN with the energy detection based carrier sense was numerically evaluated. The evaluation results showed that the roughly orthogonality of spreading factors changes the optimal carrier sense level in LoRaWAN.

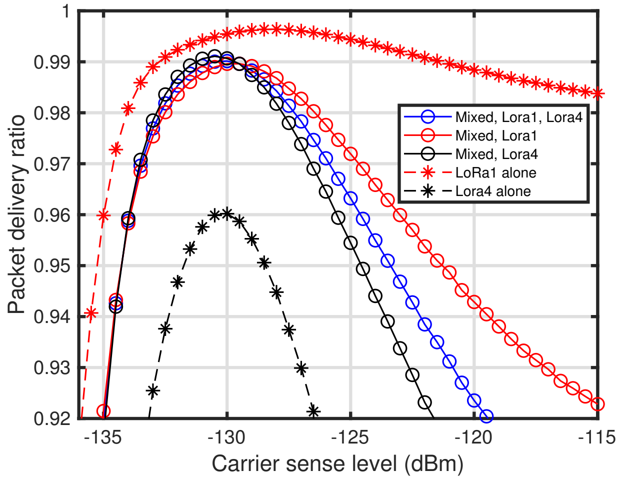

Fig. 7. Packet delivery ratio for different carrier sense level in the LoRaWAN with mixed packets of LoRa1 ($SF = 7$, 51.5 ms) and LoRa4 ($SF = 10$, 821.2 ms) listed in Table II.

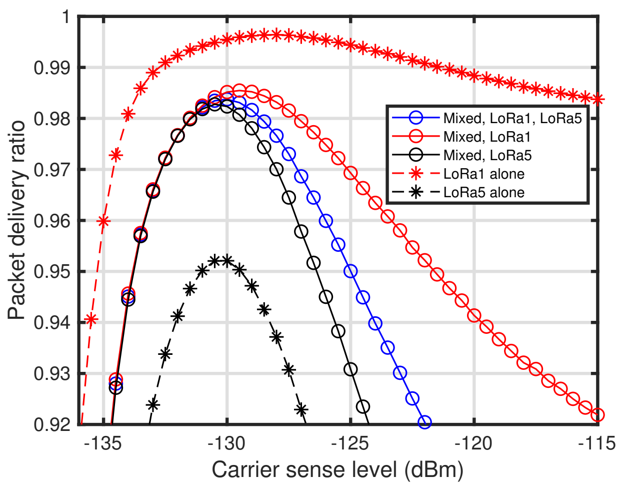

Fig. 8. Packet delivery ratio for different carrier sense level in the network with mixed packets of LoRa1 ($SF = 7$, 51.5 ms) and LoRa5 ($SF = 7$, 821.2 ms) listed in Table II.

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References

[1] U. Raza, P. Kulkami, and M. Sooriyabandara, "Low Power Wide Area Networks: An Overview," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 855–873, Secondquater 2017.

[2] M. Shahid, A. Ahmed, P. Zhibo, R. Ammar, T. K. Fung, and R. Jonathan, "Massive Internet of Things for Industrial Applications: Addressing Wireless IoT Connectivity Challenges and Ecosystem Fragmentation," *IEEE Industrial Electronics Magazine*, vol. 11, pp. 28–33, Jan. 2017.

[3] R. Mattia, F. Paolo, F. Alessandra, and S. Emiliano, "Evaluation of the IoT LoRaWAN Solution for Distributed Measurement Applications," *IEEE Transactions on Instrumentation and Measurement*, vol. 66, pp. 3340–3349, Dec. 2017.

[4] https://lora-alliance.org/.

[5] https://www.sigfox.com/en.

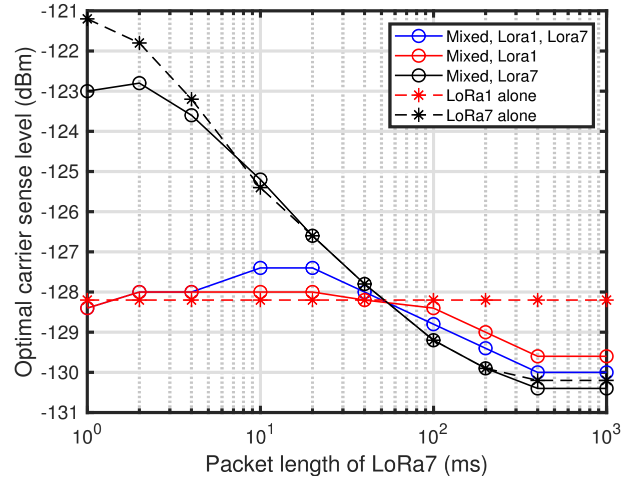

Fig. 9. Optimal carrier sense level for the network mixed with LoRa1 ($SF = 7$, 51.5 ms) and LoRa7 ($SF = 10$, 1 ms $\sim$ 1 s).

[6] P. Beecher, "Comparing IoT Networks at A Glance," Wi-SUN Alliance, White Paper, Dec. 2017, accessed: May 28, 2021. [Online]. Available:https://www.wi-sun.org/wp-content/uploads/Wi-SUN-Alliance-Comparing_IoT_Networks-r1.pdf.

[7] ARIB STD-T108, v. 1.2, Jan. 2018. (*in Japanese*).

[8] L. Kleinrock and F. Tobagi, "Packet Switching in Radio Channels: Part I - Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics," *IEEE Transactions on Communications*, vol. 23, no. 12, pp. 1400–1416, 1975.

[9] S. M. Kay, *Fundamentals of Statistical Signal Processing: Detection Theory*. Prentice Hall, 1998.

[10] H. Urkowitz, "Energy Detection of Unknown Deterministic Signals," *Proc. of the IEEE*, vol. 55, no. 4, pp. 523–531, 1967.

[11] W. Gardner, "Exploitation of Spectral Redundancy in Cyclostationary Signals," *IEEE Signal Processing Magazine*, vol. 8, no. 2, pp. 14–36, 1991.

[12] S. Narieda and T. Fujii, "Energy Detection Based Carrier Sense in LPWAN," *IEEE Access*, doi:10.1109/ACCESS.2023.3299219.

[13] R. Tandra and A. Sahai, "SNR Walls for Signal Detection," *IEEE Journal of Selected Topics in Signal Processing*, vol. 2, no. 1, pp. 4–17, 2008.

[14] A. Mariani, A. Giorgetti, and M. Chiani, "Effects of Noise Power Estimation on Energy Detection for Cognitive Radio Applications," *IEEE Transactions on Communications*, vol. 59, no. 12, pp. 3410–3420, 2011.

[15] A. Waret, M. Kaneko, A. Guitton, and N. E. Rachkidy, "LoRa Throughput Analysis with Imperfect Spreading Factor Orthogonality," *IEEE Wireless Commun. Lett.*, vol. 8, no. 2, pp. 408–411, Apr. 2019.