Characteristics of Transmit Power Allocation for Poor Conditioned End Devices in LPWAN with Peak Detection Based Carrier Sense

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***Abstract*—This paper investigates characteristics of transmit power allocation technique in low-power wide-area networks (LPWANs) with a carrier sense. Traditionally, we have studied the performance improvement technique for the end devices with high path loss to the gateway in the LPWAN. The technique can improve the performance of such end devices by allocating the transmit power so as to provide the benefit of the capture effect for all end devices. However, the effectiveness of the technique in the LPWAN with the carrier sense has never been verified. In Japan, wireless transceivers in sub-GHz band shall execute the carrier sense based on peak detection before transmitting a packet, and the performance must be verified. Numerical examples are provided to analysis the characteristics of the conventional technique in the LPWAN with the carrier sense based on peak detection.**

I. Introduction

Low-power wide-area networks (LPWANs) [1] are unprecedented wireless technologies to realize the concept of Internet of Things (IoT). Since low-power wide-area (LPWA) technologies enables long range communications and low energy consumptions, the technologies are expected as the communication infrastructure for IoT systems, e.g. environmental monitoring [2], and so on. Several LPWA technologies have been developed, such as long range (LoRa) with a chirp spread spectrum (CSS) modulation [3] and wireless smart utility network (Wi-SUN) with multi-rate frequency shift keying [4], and these can build a private or local network in an unlicensed band, for example, sub-GHz band can be used for the communication in Japan [5].

The LPWAN with a wide communication area occurs a large difference in the received signal strength indicator (RSSI) from each end device at the gateway. This causes a deterioration of the communication quality at the end devices with high path loss to the gateway, that is, poor conditions, and this phenomenon is called the capture effect [6], [7]. To overcome this problem, authors have studied the technique to take advantage of the effect of the capture effect to improve the performance of such end devices [8]. However, although the effectiveness of the technique for the LPWAN with a pure ALOHA [9] has been verified, it has never been verified for the LPWAN with carrier sense. In Japan, wireless communications operated in sub-GHz band shall execute the carrier sense, and the carrier sense level is defined as the instantaneous received signal power of one channel at the feed point of the end device [5]. Peak detection can detect the instantaneous power, and therefore, the performance in the LPWAN with a carrier sense based on peak detection must be verified. In this paper, we investigate characteristics of the conventional technique [8] in the LPWAN with the carrier sense based on peak detection.

II. Preliminary Notion

A. System Model

In this paper, we assume the LPWAN model based on LoRaWAN which employs a pure ALOHA [9] is employed as the medium access control schemes, and we assume that the LoRa signals with only one spreading factor are assumed as the LPWA signals. The LPWAN model contains K end devices and one gateway located in the center of the communication area with a radius R m, and each end device transmits own data to the gateway without acknowledgment according to a Poisson process with rate $1/T_{\rm TX}$ where $T_{\rm TX}$ is an average transmission period. In Japanese regulations for sub-GHz band communications [5], each end device must execute the carrier sense based on peak detection for the communication without the limits of the transmission power and duty cycle, and therefore, we assume that each end device executes the carrier sense with a level $P_{\rm CS,level}$ dBm, a period $T_{\rm CS,time}$ ms and a retransmission time $T_{\rm RE}$. The RSSI $P_{{\rm RX},i}$ at the ith end device can be written as

$$P_{{\rm RX},i} = P_{{\rm TX},i} - L_i, \tag{1}$$

where $P_{{\rm TX},i}$ and L_i are the transmit power at the ith end device and the path loss between the gateway and the ith end device, respectively, and furthermore, $P_{{\rm RX},i}$ and $P_{{\rm TX},i}$ are in decibel milliwatts and L_i is in decibel. A simple propagation model is assumed in this paper, and it is given by [10]

$$L_i = -10\log_{10}\left(d_i^{\alpha} f_{\rm c}^2 \times 10^{-2.8}\right), \tag{2}$$

where d_i, α and $f_{\rm c}$ are the distance between the gateway and the ith end device, the path loss exponent, and the carrier frequency, respectively. We assume that all the end devices are in descending order of path loss, that is, $L_1 \leq L_2 \leq \cdots \leq$

$L_{K-1} \leq L_K$. Furthermore, we let γ_i denote the SNR at the ith end device in decibel. It can be written as [11]

$$\gamma_i = P_{\text{RX},i} + 174 - 10\log_{10}(BW) - NF, \tag{3}$$

where BW and NF are the channel bandwidth and noise figure in decibel, respectively, and we let $P_{\text{capture}}(\gamma_i)$ denote the SIR threshold in decibel where the capture effect at the ith receive signal. $P_{\text{capture}}(\gamma_i)$ is defined to represent the characteristics of the LoRa signal that the resistance to interference increases as the SNR increases.

Based on what has been shown in previous, we describe the packet reception probability from the ith end device $F_{\text{PRP},i}$ at any packet sending opportunity, and it can be written as

$$F_{\text{PRP},i} = \left(1 - \frac{1}{T_{\text{TX}}}\right)^{2T_{\text{TOA}}(N_i - 1)}, \tag{4}$$

where N_i is the number of end devices that can cause the packet collision with the ith end device, and N_i is given by

$$N_i = \sum_{k=1,k\neq i}^{K} I\left[P_{\text{capture}}(\gamma_i) > (P_{\text{RX},i} - P_{\text{RX},k})\right], \vee I\left[P_{\text{CS,level}} < (P_{\text{TX},i} - \Theta_{i,k})\right], \tag{5}$$

where $I[\cdot]$ and $\Theta_{i,k}$ are the indicator function and the path loss between the ith end device and the kth end device, respectively, and $\Theta_{i,k}$ is given by

$$\Theta_{i,k} = -10\log_{10}\left(d_{i,k}^{\beta} f_{\text{c}}^2 \times 10^{-2.8}\right), \tag{6}$$

where β and $d_{i,k}$ are path loss exponent between each end device and the distance between the ith end device and the kth end device, respectively. In eq. (5), the first indicator function represents whether the packet from the ith end device can overcome the simultaneously transmitted packet from the kth end device, and the second indicator function represents whether the carrier sense at the ith end device can detect the LPWA signal from the kth end device. Note that the second indicator function in eq. (5) is not needed for the no carrier sense case.

B. Conventional Techniques

In this subsection, we describe the conventional transmit power allocation techniques [8] which can adopt to a pure ALOHA based LPWAN, to clearly show the problem in the technique. The purpose of the conventional technique is to improve the performance of uplink communication for M poor conditioned end device by appropriately allocating transmit power to all the end devices. Note that the poor condition indicates that low RSSI from end devices at the gateway due to long distance, buildings around the end device, and so on. In the conventional technique, two types of transmit power sets, i.e., set A and set B, are calculated and allocated to each end device alternately in time, in order to effectively take the benefit of capture effect to the performance improvement of end devices. We let $P_{\text{TX},A,i}$, $P_{\text{TX},B,i}$, $N_{A,i}$ and $N_{B,i}$ are transmit power for ith end device in sets A and B, the number of interferences at the ith device in sets A and B, respectively. The conventional technique determines $P_{\text{TX},A,i}$ and $P_{\text{TX},B,i}$ so as to satisfy the following optimization problem,

$$\underset{P_{\text{TX},A,i},P_{\text{TX},B,i},\forall i}{\text{minimize}} \quad \text{E}\left[N_{A,i} + N_{B,i}\right], \tag{7}$$

$$\underset{P_{\text{TX},A,i},P_{\text{TX},B,i},\forall i}{\text{minimize}} \quad \text{Var}\left[N_{A,i} + N_{B,i}\right] \tag{8}$$

$P_{\text{TX},A,i}$ and $P_{\text{TX},B,i}$ satisfying eqs. (7) and (8) as suboptimal solutions are given by

$$P_{\text{TX},A,i} = P_{\text{TX,max}} \tag{9}$$

$$P_{\text{RX},A,i} = P_{\text{TX},A,i} - L_i \tag{10}$$

$$P_{\text{TX},B,i} = \begin{cases} P_{\text{TX},A,i} & i = 1, \cdots, M, \\ \overline{P}_i + L_i & i = M+1, \cdots, K \end{cases} \tag{11}$$

$$P_{\text{RX},B,i} = P_{\text{TX},B,i} - L_i \tag{12}$$

$$\overline{P}_i = \begin{cases} \widetilde{P}_i & \widetilde{P}_K \geq P_{\text{LB}} \\ P_{\text{LB}}\widetilde{P}_i/\widetilde{P}_K & \widetilde{P}_K < P_{\text{LB}} \end{cases} \tag{13}$$

$$\widetilde{P}_i = P_{\text{RX},B,1} - \sum_{k=M+1}^{i} P_{\text{capture}}(\gamma_k) \tag{14}$$

where $P_{\text{TX,max}}$, $P_{\text{RX},A,i}$, $P_{\text{RX},B,i}$ and P_{LB} are a maximum transmit power, the RSSI from the ith end device in set A, the RSSI from the ith end device in set B, and lower bound of the RSSI, respectively, and $P_{\text{LB}} = P_{\text{S}} + \Delta P$ where P_{S} and ΔP are sensitivity and the margin of the RSSI, respectively. As shown in eqs (9) and (11), in the conventional techniques, the transmit power is allocated so that the RSSI from the end devices arranged in descending/ascending order of path loss have a difference, and if possible, only $P_{\text{capture}}(\gamma_i)$ is different. As a result, $P_{\text{TX},B,i}$ may fall below the sensitivity for the LPWAN with massive end devices. In order to avoid this, the minimum RSSI is aligned with the sensitivity using eq. (13) so as not to break the order of $P_{\text{RX},B,i}$.

III. Numerical Examples Based Analyses

In this section, we provide numerical examples based analysis results for the effect of the carrier sense based on peak detection on the performance of the conventional technique [8] in the LPWAN with the carrier sense. The parameters for the numerical examples are listed in Table I, and the numerical examples are obtained by computer simulations based on the parameters. In the numerical examples, the performances of the end devices with following two techniques are compared: i) the conventional technique with the carrier sense based on peak detection and ii) the conventional technique. Fig. 1 shows the performance of a packet delivery ratio for different number of end devices. As shown in Fig. 1, the peak detection based carrier sense can improve the performance of the end devices with the conventional technique. However, in the conventional technique with the carrier sense, the performance of the end devices in the poor condition is inferior to that in the other condition. Furthermore, Fig. 2 show the performance of the packet delivery ratio for different radius of communication area. It can be seen that the performance of the end devices in

TABLE I
PARAMETER SETUP

Description	Variable	Numerical value(s)
Distribution for placement of end devices	-	uniform distribution
Number of end device	K	Max. 400
Path loss exponent	α	2.7 (suburban)
Path loss exponent	β	3.3
Ratio of K to be improved	η	0.1
Max. transmit power	$P_{\text{TX,max}}$	13 dBm
Min. transmit power	$P_{\text{TX,min}}$	-1 dBm
Carrier frequency	f_c	920 MHz
Average transmission period	T_{TX}	450 sec
Retransmission time	T_{RE}	3
Carrier sense level	$P_{\text{CS,level}}$	-105 dBm
Carrier sense period	$T_{\text{CS,time}}$	0.128 ms
Bandwidth	BW	125 kHz
Spreading Factor	SF	10
Payload length	-	20 Bytes
Programmed preamble	-	8 symbols
Coding rate (Hamming code)	-	4/5
Time on Air ($SF = 10$)	T_{TOA}	370.7 ms
Sensitivity ($SF = 10$)	P_{S}	-132 dBm
Margin of RSSI	ΔP	5 dB
Noise figure at end devices	NF	6 dB
Number of channels used	-	1
Model of capture effect	-	Model shown in [8]
Simulation period	-	336 hours

the poor conditions is deteriorated as the radius increases. The reason for these results is that packets from the end devices excepted for in the poor conditions cannot be detected by the carrier sense from the end devices in the poor conditions frequently found at the edge of the communication area.

IV. CONCLUSION

In Japanese regulations [5], the end devices in sub-GHz band shall execute the carrier sense based on peak detection before transmitting a packet. In this paper, we studied the characteristics of the conventional transmit power allocation technique [8] in the LPWAN with the carrier sense based on peak detection. Numerical examples were provided to analysis the characteristics of the conventional technique in the LPWAN with the carrier sense based on peak detection. The results showed that the performance of the end devices in the poor conditions is limited owing to the range of the carrier sense based on peak detection.

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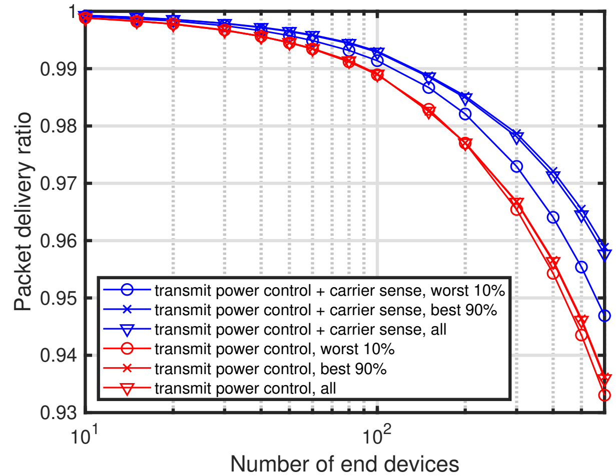

Fig. 1. Performance of packet delivery ratio for different number of end devices. $R = 600$ m.

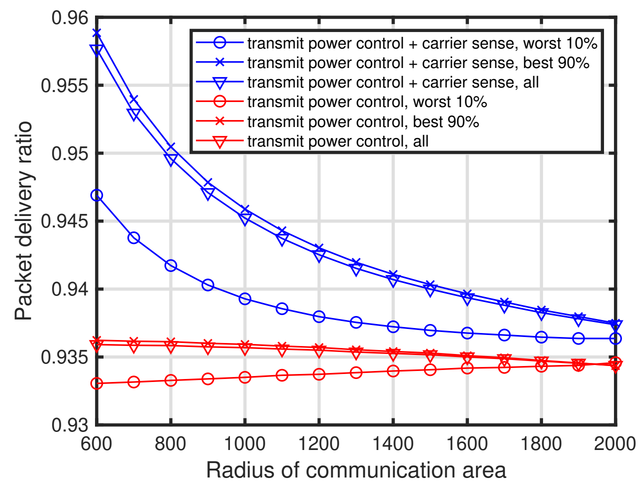

Fig. 2. Performance of packet delivery ratio for different radius of communication areas. $K = 600$.

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