Transmit Power Allocation Schemes for Performance Improvement of Poor Conditioned End Devices in LPWAN

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ABSTRACT This paper studies the performance improvement of end devices with a low received signal strength indicator, that is, the poor condition, in general low power wide area networks (LPWANs). To improve the performance, we discuss the transmit power allocation utilizing the benefit of the capture effect, which results in an advantage depending on the signal-to-noise ratio and signal-to-interference ratio at each end device. However, the benefit of the capture effect cannot be realized simultaneously in all end devices owing to its characteristics. To avoid performance degradation of the specific end devices that are unable to realize the benefit of the capture effect, we propose transmit power allocation schemes. In the proposed technique, two types of allocated transmit power, which are designed in conjunction with each other, are used alternately in time. Numerical examples validate the effectiveness of the proposed technique.

INDEX TERMS LPWAN, wireless sensor network, transmit power allocation, capture effect.

I. INTRODUCTION

Internet of Things (IoT) has been drastically spread in recent years. Massive number of IoT devices powered by batteries are deployed and equipped in factories and warehouses for logistics and quality control [1]–[3]. Furthermore, IoT devices are also used for health and wellness monitoring applications [4], smart city scenarios [5], and environmental monitoring in outfields [6], [7]. One of the technologies that support these IoT applications is wireless sensor networks (WSNs) that are constructed some gateways and a lot of end devices equipped with radio transceivers, and low power wide area networks (LPWANs) [8] are widely used as communication infrastructures for WSNs. Although the data rate of low power wide area (LPWA) communication technologies is low, the LPWN can accommodate a massive number of IoT devices deployed in geographically large areas, with low power connectivity, and offer low cost end devices. Several LPWA technologies operating in the sub-GHz band have been developed, such as long range (LoRa) [9], SigFox [10], wireless smart utility network (Wi-SUN) [11] and narrow band-IoT (NB-IoT) [12], and most of them, except for NB-IoT etc, can build a private/local network in an unlicensed band. These technologies employ several modulation schemes for narrowband communication channel in industrial, scientific, and medical (ISM) band, i.e., LoRa and Wi-SUN employ a chirp spread spectrum (CSS) modulation [13] and frequency shift keying (FSK) respectively, and further, SigFox employs differential binary phase shift keying (DBPSK) and Gaussian FSK as the modulation schemes in uplink and downlink communications, respectively.

In the LPWAN, a lot of end devices connect to the gateway in a wide communication area, which generates a large difference in the received signal strength indicator (RSSI) from each end device at the gateway. In particular, the difference is remarkable in the LPWA employing LoRa, which has a lower sensitivity than other LPWA technologies. In such a network, it is well known that uplink communication characteristics, such as the packet reception probability at the gateway from the end devices in the vicinity of the gateway tend to be satisfactory. The reason for this phenomenon can be attributed to the capture effect [14], [15], which states that even if some end devices simultaneously transmit packets that are non-orthogonal to each other, the packet from end devices with sufficiently high signal-to-noise ratio (SNR)
and signal-to-interference ratio (SIR) will not result in collision. Traditionally, the effect of the capture effect on the performance of wireless systems has been investigated [14]–[27]. The effects of the capture effect on ALOHA systems in several fading channels have been investigated [14], [15]. In [16], the throughput analysis of carrier sense multiple access networks in the presence of the capture effect was studied. Furthermore, the effects on the performance of wireless local area networks [17]–[19], code division multiple access networks [20], massive multi-input multi-output systems [21] and relay communications for cognitive radio networks [22] have been investigated. For LPWAN, the effect of the capture effect on the uplink communication characteristics for simultaneously received packets with different spreading factors in long range wide area network (LoRaWAN) was numerically and experimentally investigated [23]–[27]. Reference [24] also investigated the effect on the characteristics of SigFox networks.

The capture effect can contribute to the performance improvement of the end devices in the vicinity of the gateway, that is, the end devices in good condition because of the high RSSI values compared with the assumption that there is no capture effect; that is, the contribution is beneficial to the end devices. However, the end devices far from the gateway, that is, the end devices in poor conditions because of the low RSSI value, cannot benefit from the capture effect that improves the uplink communication characteristics. Consequently, the performance of the end devices in the poor condition is inferior to that of the end devices in the good condition. We consider that it is a truly wide area network by giving almost the same communication quality to all end devices, and therefore, the performance of the end devices in the poor conditions must also be improved. Traditionally, several techniques for the performance improvement of the end devices in LPWANs have been presented [28]–[37]. In [28], to minimize the collision probability, the transmit power and spreading factor allocation algorithm for the end devices in LoRaWAN was presented. In addition, for LoRaWAN, the spreading factor allocation to increase the throughput in LoRaWAN [29], the technique [29] based the spreading factor allocation considering on the capture effect [30], a fair and an unfair allocation algorithm for the spreading factor [31], the spreading factor and transmit power allocation technique for fair energy consumption at the end device [32], and the data rate and transmit power allocation technique for a fair collision rate [33], have been presented, respectively. In [34], a jointly optimization for the spreading factor and transmit power allocation in LoRaWAN has been proposed. Based on the pre-driven percentage of end devices allocated to all spreading factors, transmit power allocation techniques using Game theory have been proposed [35]–[37].

In this paper, we focus not only on LoRaWAN, but also on general LPWAN including Wi-SUN and so on, which do not have multiple spreading factors. These conventional techniques are for LoRaWAN and utilize the different in the spreading factor to allocate transmit power. In LoRaWAN, which can use multiple spreading factors, i.e., $SF = 7, \cdots, 12$ where $SF$ is a spreading factor, the SNR and SIR relationship among multiple spreading factors with imperfect orthogonality [25], [38] determines whether the benefits of the capture effect can be obtained. Furthermore, these relationships for the resistance to interference, are not equal for each spreading factor; for example, signals with higher spreading factors tend to be more resistant to interference with other spreading factors [25]–[27]. On the other hand, in the general LPWANs that have no multiple spreading factors, there is a difference in the performance between the end devices because the packet transmission success depends on the strength of the received signal power. Therefore, it cannot be directly adopted these conventional techniques to the general LPWANs that have no multiple spreading factors to improve the performance of the end devices in the poor condition, and the purpose of the technique proposed in this paper is to overcome this difficult problem.

This paper proposes transmit power allocation schemes for the performance improvement of the poor conditioned end devices in the general LPWAN. In the proposed technique, we utilize the benefit of the capture effect in the design of the allocated transmit power. The advantage of this is that the network performance can be improved only by controlling the transmit power of the end devices. Further, a simple algorithm to obtain the allocated transmit power can be developed using only the RSSI from all end devices on the gateway. Thus, although the performances of almost all end devices can be improved, it is difficult to improve the performance of the end devices in the poor condition. This is because the capture effect results in an advantage depending on the SNR and the SIR at each end device in terms of the uplink communication characteristics, such as, the packet reception probability, for the simultaneous reception of multiple packets. This causes a difference in the performance between the end devices, and therefore, it may drastically deteriorate the performance of end devices in the poor condition by utilizing the benefit of the capture effect as it is. To overcome this problem, we propose the transmit power allocation schemes in which two types of allocated transmit power are designed in conjunction with each other and allocated to the end devices alternately in time. By averaging the benefit of the capture effect on all end devices, the proposed technique can improve the performance of the end devices in the poor condition.

The main contribution is the development of the simple transmit power allocation technique for the performance improvement of the end devices in the poor condition, that is, low RSSI. To realize this technique, the transmit power allocation scheme in which two types of allocated transmit power, which are designed in conjunction with each other, are used alternately in time is proposed.

The remainder of this paper is organized as follows. In Section II, we show the fundamental system model of LPWAN. In Section III, we formulate the problem to be solved in this study and show the proposed transmit
power allocation schemes. Numerical examples are shown in Section IV. Finally, we conclude the paper in Section V.

II. PRELIMINARY NOTION

A. LPWAN MODEL

In this study, we consider LoRa with only one spreading factor as an example of the general LPWAN. The networks are composed of $K$ end devices and one gateway. All end devices are randomly deployed according to a homogeneous Poisson point process (PPP) with intensity $\lambda = \frac{K}{\pi R^2}$, where $R$ is a radius of the communication area and $K$ is the mean of Poisson random variable $K$. The gateway is located in the center of the area. The end device transmits the observed data, and the gateway collects the transmitted data from the end devices. Furthermore, each end device can control the transmit power by itself. We let $P_{RX,i}$ denote the RSSI at the gateway from the $i$th end device in decibel milliwatts. $P_{RX,i}$ can be written as

$$P_{RX,i} = P_{TX,i} - L_i,$$ (1)

where $P_{TX,i}$ and $L_i$ are the transmit power at the $i$th end device in decibel milliwatts and the path loss between the gateway and the $i$th end device in decibels, respectively. $L_i$ is given by [39]

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

where $d_i$, $\alpha$ and $f_c$ are the distance between the gateway and the $i$th end device, the path loss exponent, and the carrier frequency, respectively. In this paper, the simple propagation model shown in eq. (2) is assumed. This does not limit the employment of other propagation models or actual measured propagation results, as discussed later.

It is well known that a pure ALOHA [40] is one of the simple medium access control schemes, and this can construct a simple LPWAN where all the end devices can transmit their data to the gateway only once, without acknowledgment. This means that each end device cannot learn whether the own packet transmission is successful and the gateway can immediately collect the observed data obtained at each end device if the packet transmission is successful. In this paper, we employ the systems as the medium access control schemes because the retransmission mechanisms cause the wasting away valuable battery power [13] for WSNs. In the LPWAN, each end device generates and transmits a packet according to a Poisson process with rate $1/T_{TX}$ where $T_{TX}$ is the average transmission period. Additionally, $T_{TX} \ll T_{TOA}$ holds $T_{TX} \approx T_{TX} - T_{TOA}$ where $T_{TOA}$ is the length of the packet.

B. CAPTURE EFFECT

The capture effect affects the LPWA signals in their communications, which include not only LoRa but also other LPWA signals, i.e., Wi-SUN or SigFox. To mathematically represent the effect of the capture effect on the LPWA signals, some examples have been reported [25]–[27]. Reference [27] numerically showed that the SNR and SIR determine the degree of the capture effect. We let $\gamma_i$ denote the SNR at the $i$th end device in decibels. It can be written as [41]

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

where $BW$ and $NF$ are the channel bandwidth and noise figure in decibels, respectively. Fig. 1 shows an example of LoRa ($SF = 10$) SNR sensitivity thresholds as a function of the SIR for $BW = 125$ kHz and $NF = 6$ dB [41]. The curve shown in Fig. 1 is numerically obtained using computer simulation from the bit error rate (BER) characteristics satisfying less than $10^{-5}$ by changing the SNR and the SIR as shown in [27]. Fig. 1 shows the characteristics of the LoRa signal that the resistance to interference increases as the SNR increases. In Fig. 1, the region in the upper right of the blue line is defined as the packet transmission success whereas the region in the lower left of the blue line is defined as the packet collision. Although the curve is dealt with as a function of the SNR, we deal with the curve as a function of the SIR in this study. We let $P_{capture}(\gamma_i)$ denote the SIR threshold in decibels where the capture effect resuscitates the $i$th receive signal, and we consider $P_{capture}(\gamma_i)$ as a function of the SNR at the $i$th end device because it is necessary to describe the proposed technique shown in Sec. III. Note that although Fig. 1 is for LoRa, similar derivations should be investigated for other LPWA communications; for example, the reference [24] has also investigated this for the case of SigFox. These are not dealt with in this paper because we focus on the proposed technique to improve the performance of the end devices in the poor condition.

III. PROPOSED TRANSMIT POWER ALLOCATION SCHEMES

A. PRINCIPLE OF PROPOSED TECHNIQUE

First, we discuss the problems to be solved in this study. As mentioned previously, the packet transmission timing follows a Poisson process, and the packet reception probability
of the ith end device $F_{PRP,i}$ can be written as

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

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

$$N_i = \sum_{k=1, k \neq i}^{K} I\left[P_{\text{capture}}(\gamma_k) > (P_{RX,i} - P_{RX,k})\right],$$

where $I\left[\cdot\right]$ is the indicator function.

Fig. 2 shows an example of LPWAN, which includes one gateway and end devices. In Fig. 2, there are some end devices in the poor condition due to factors such as a long distance to the gateway and low height antenna at the end device. We focus on the improvement for the uplink communication characteristics by controlling the transmit power of all the end devices. We let $M$ denote the number of end devices in the poor condition which should be improved the performance, and $M = [\eta K]$ where $\eta$ is an arbitrary positive number to determine $M$ and $0 \leq \eta \leq 1$. In this paper, we attempt to improve the performance, that is, the packet reception probability, of $M$ end devices in the poor condition, while maintaining the performance of other end devices as much as possible. We apply the transmit power control that chooses the appropriate $P_{TX,i}$, $\forall i$ to solve both problems. As shown in eqs. (4) and (5), it can be seen that the maximization problem of $F_{PRP,i}$ reverts the minimization problem of $N_i$. Therefore, to improve the performance of the end devices in the poor condition and maintain the performance of the other end devices, all the $N_i$s must be minimized while also minimizing the variation of $N_i$s. Accordingly, two optimization problems to be solved simultaneously in this study can be written as

$$\min_{P_{TX,i}, \forall i} E\left[N_i\right],$$

$$\min_{P_{TX,i}, \forall i} \text{Var}\left[N_i\right].$$

Note that eq. (6) is used for the performance improvement of all end devices, whereas eq. (7) is used for the performance improvement of the end devices in the poor conditions. Next, we consider a solution that satisfies the two optimization problems shown in eqs. (6) and (7). Because $N_i$ depends on the magnitude relationship between each $P_{RX,i}$ as shown in eq. (5), for the minimization of $N_i$, $P_{RX,i}$ must be larger than $P_{RX,k} + P_{\text{capture}}(\gamma_k), k \neq i$. Furthermore, we deal with the two end devices case for simply description in the explanation only here. From these, the following equation is obtained,

$$P_{RX,i} > P_{RX,k} + P_{\text{capture}}(\gamma_k), \quad i \neq k.$$  (8)

We assume that all end devices are in descending order of path loss, that is $L_1 \geq L_2 \geq \cdots \geq L_{K-1} \geq L_K$, and from eq. (1), the relationship between $P_{RX,i}$ and $N_i$ can be written as

$$P_{RX,1} \leq \cdots \leq P_{RX,K} \Rightarrow N_1 \geq \cdots \geq N_K.$$  (9)

Note that $P_{RX,i-1} = P_{RX,i}$ holds for $N_{i-1} = N_i$ in eq. (9); however, $P_{RX,i-1} < P_{RX,i}$ does not hold for $N_{i-1} < N_i$ because of $P_{\text{capture}}(\gamma_i)$. From eqs. (8) and (9), we can obtain the following equation

$$P_{RX,1} \leq \cdots \leq P_{RX,K} \Rightarrow N_1 \leq \cdots \leq N_K.$$  (10)

To exploit the capture effect at the ith end device, $P_{RX,i}, \forall i$ must satisfy eq. (10). However, by satisfying eq. (10), the proper allocation of the transmit power cannot obtain a good solution for eq. (7), because of $P_{\text{capture}}(\gamma_i)$ and eq. (10), whereas it may obtain a good solution for eq. (6). This means that the performance of the end devices in the poor condition is clearly inferior to that of the end devices in the good condition. To obtain a good solution for eq. (7), the performance of all end devices are almost the same, that is, $N_1 = \cdots = N_K$. However, the benefit of the capture effect cannot be realized for all the end devices because all the $P_{RX,i}$s are the same or the differences between each $P_{RX,i}$ are smaller than $P_{\text{capture}}(\gamma_i)$. This implies that only a poor solution for eq. (7) can be obtained, in other words, this indicates that the performances of all the end devices are poor although the performances of the end devices in both conditions are the same. Therefore, it is difficult to obtain good solutions for the two optimization problems shown in eqs. (6) and (7).

The purpose of the proposed technique is to accomplish both objectives by utilizing the benefits of the capture effect. One is to improve the performance of the end devices in the poor condition and the other is to improve the performance of all the end devices as much as possible. For the objectives, we discuss the transmit power allocation schemes for the end devices in which two types of allocated transmit power sets are alternately in time employed to all the end devices to exploit the capture effect. We let $P_A$ and $P_B$ denote the allocated transmit power sets, called sets A and B, respectively. Furthermore, we let $N_{A,i}$ and $N_{B,i}$ denote the number of interferences at the ith end device in sets A and B, respectively. Although $N_{A,i}$ may or may not be equal to $N_{B,i}, \forall i$, we attempt to equalize the total number of interferences in sets A and B at each end device by employing both power sets alternately in time. This is so that all end devices can take the benefit of the capture effect. The two optimization problems defined in eqs. (6) and (7) can be rewritten as

$$\min_{P_{TX,i}, P_{TX,B}, \forall i} E\left[N_{A,i} + N_{B,i}\right].$$  (11)

$$\min_{P_{TX,i}, P_{TX,B}, \forall i} \text{Var}\left[N_{A,i} + N_{B,i}\right].$$  (12)
where \( P_{TX,i} \) and \( P_{TX,j} \) are the allocated transmit powers for the \( i \)th end device in sets A and set B, respectively. Furthermore, \( P_{TX,i} \in \mathcal{P}_A \) and \( P_{TX,j} \in \mathcal{P}_B \). The details of the design of both allocated transmit power are shown in a later subsection.

**B. OVERVIEW OF DESIGN**

As mentioned in the previous subsection, the objectives of the proposed transmit power allocation are to improve the performance of the end devices in the poor condition, as well as to improve the performance of all the end devices as much as possible. Furthermore, eqs. (11) and (12) show the formulated optimization problems for the allocated transmit power sets to achieve both objectives. However, \( N_i \), defined in eq. (5), includes the indicator function which is a nonlinear function that is difficult to deal with in the optimization problem. Furthermore, it is difficult to directly solve the optimization problems mathematically. Therefore, we attempt to find a solution to the optimization problems according to the following policy for the design of \( \mathcal{P}_A \) and \( \mathcal{P}_B \).

- In \( \mathcal{P}_A \), which is one of the two allocated transmit power sets, the proposed technique makes a difference to the RSSI from each end device as much as possible, to exploit the benefit of the capture effect. Thus, the following equation can be obtained,

\[
P_{RX,A,i} \geq P_{RX,A,i-1} + P_{\text{capture}}(\gamma_{i-1}),
\]

where \( P_{RX,A,i} \) is the RSSI from the \( i \)th end device in \( \mathcal{P}_A \), and the unit of \( P_{RX,A,i} \) is decibels. In the case where it is difficult to achieve the above equation, the proposed technique determines the allocated transmit power so that the following equation is achieved,

\[
P_{RX,A,i} \geq P_{RX,A,i-1}.
\]

- In \( \mathcal{P}_B \), unlike the case of \( \mathcal{P}_A \), the proposed technique allocates the transmit power to each end device to realize the reverse order of the RSSI magnitude of \( \mathcal{P}_A \), as shown in the following equation,

\[
P_{RX,B,i-1} \geq P_{RX,B,i} + P_{\text{capture}}(\gamma_i),
\]

where \( P_{RX,B,i} \) is the RSSI from the \( i \)th end device in \( \mathcal{P}_B \), and the unit of \( P_{RX,B,i} \) is decibels. Similar to the design of \( \mathcal{P}_A \), \( P_{RX,B,i} \) are determined as follows when it is difficult to achieve the above equation,

\[
P_{RX,B,i-1} \geq P_{RX,B,i}.
\]

According to the equations presented in the above policies and eq. (9), the following relationships can be obtained,

\[
P_{RX,A,1} \leq \cdots \leq P_{RX,A,K} \Rightarrow N_{A,1} \geq \cdots \geq N_{A,K},
\]

\[
P_{RX,B,1} \geq \cdots \geq P_{RX,B,K} \Rightarrow N_{B,1} \leq \cdots \leq N_{B,K}
\]

(17)

In eqs. (17) and (18), the order of \( N_{A,i} \) and \( N_{B,i} \) are the exact reverse orders. Concretely, \( N_{A,i} \) is the \( i \)th largest in all \( N_{A,i} \), whereas \( N_{B,i} \) is the \( K - i + 1 \)th largest in all \( N_{B,i} \), which makes the average order of all the number of interference equal. By satisfying the above relationships, we consider that the solution to the optimization problems shown in eqs. (11) and (12) is mostly satisfied. However, with the design, the transmit packet from each end device is susceptible to interference from other LPWANs. Therefore, it can be said that the proposed design of the allocated transmit power is a suboptimal solution for the optimization problem shown in eqs. (11) and (12). In the next subsection, we discuss the design of allocated transmit power sets according to the policy, as well as the interference tolerance.

**C. DESIGN OF ALLOCATED TRANSMIT POWER**

Fig. 3 shows an overview of the allocated transmit power of \( \mathcal{P}_A \) and \( \mathcal{P}_B \). In Fig. 3, \( P_{TX,max} \), \( P_{LB} \) and \( P_S \) are the maximum transmit power of the end device, lower bound of the RSSI to be designed and sensitivity, respectively. Note that \( P_{LB} = P_S + \Delta P \) where \( \Delta P \) is the margin of the RSSI. The state of symmetry of the two allocated transmit power sets \( \mathcal{P}_A \) and \( \mathcal{P}_B \), especially from the 1th to the \( M \)th end devices, can also be confirmed in Fig. 3. The design policy shown in previous subsection is illustrated in Fig. 3, and the details of the design are provided in this subsection.

First, we show the design of the allocated transmit power in \( \mathcal{P}_A \) for the end devices. In the design for \( \mathcal{P}_A \), the allocated transmit powers are determined first, and then the RSSIs from all the end devices are determined. In the proposed technique, all allocated transmit powers in \( \mathcal{P}_A \) are designed as

\[
P_{TX,A,i} = P_{TX,max} - L_i.
\]

(19)

The design cannot realize the benefit of the capture effect on the end devices because the difference between \( L_i \) and \( L_{i-1} \) is not necessarily greater than \( P_{\text{capture}}(\gamma_i) \), and the benefit of the capture effect cannot be given to the end devices. However, eq. (19) is important to design the allocated transmit power of the end device in the LPWANs. The reason for this is to combat the interference signals from other LPWANs operated in the same frequency band, while following the design policy shown in the previous subsection, as much as possible. The design can avoid the drastic deterioration of the performance of the end devices at least compared to end devices with the poor condition included in other LPWANs without transmit power control because the maximum transmit power is allocated to these end devices. The RSSI \( P_{RX,A,i} \) in \( \mathcal{P}_A \) is given by

\[
P_{RX,A,i} = P_{TX,A,i} - L_i.
\]

(20)

For all \( P_{RX,A,i} \) and \( N_{A,i} \), the following equations for \( \mathcal{P}_A \) and \( \mathcal{P}_B \) can be achieved,

\[
P_{RX,A,1} \leq P_{RX,A,2} \leq \cdots \leq P_{RX,A,K-1} \leq P_{RX,A,K} \]

\[
\Rightarrow N_{A,1} \geq N_{A,2} \geq \cdots \geq N_{A,K-1} \geq N_{A,K}.
\]

(21)

Note that \( P_{RX,A,i-1} = P_{RX,A,i} \) does not hold for \( N_{A,i-1} = N_{A,i} \) in eq. (21) because \( L_i \) and \( L_{i-1} \) may be equal, or there is no difference between them only in \( P_{\text{capture}}(\gamma_i) \).
Next, we show the design of the allocated transmit power in \( P_B \). Unlike the design in \( P_A \), the RSSIs from the end devices are determined first, and then, the allocated transmit powers are given in the design of \( P_B \). This is because the allocated transmit power in \( P_B \) must be designed in conjunction with that in \( P_A \) to exploit the capture effect on all the end devices. The RSSI \( P_{RX,B,i} \) in \( P_B \) is given by

\[
P_{RX,B,i} = \begin{cases} 
    P_{RX,A,i} & i = 1, \ldots, M, \\
    P_I & i = M + 1, \ldots, K,
\end{cases}
\]

where \( P_I \) is the allocated power for the \( i \)th end device in decibels (\( i = M + 1, \ldots, K \)) which is given by

\[
P_I = \begin{cases} 
    \bar{P}_I & P_{RX,B,K} \geq P_{LB}, \\
    P_{RX,B,K} & P_{RX,B,K} < P_{LB},
\end{cases} \quad i = M + 1, \ldots, K,
\]

(23)

\[
\bar{P}_I = P_{RX,B,M} - \sum_{k=M+1}^{i} P_{\text{capture}}(\gamma_k),
\]

(24)

Note that \( P_{RX,B,i}, i = 1, \ldots, M \) are the same as \( P_{RX,A,i}, i = 1, \ldots, M \) in eq. (22). The reason for the design is to combat the interference signals from other LPWANs as mentioned previously. As shown in eq. (23), \( P_I \) is divided into two cases, i.e., \( \bar{P}_I \geq P_{LB} \) and \( \bar{P}_I < P_{LB} \). When \( \bar{P}_I \geq P_{LB} \), the number of end devices is small, and the following equation can be obtained for all \( P_{RX,B,i} \)s and \( N_{B,i} \)s

\[
P_{RX,B,K} < \cdots < P_{RX,B,M+1} < P_{RX,B,1} \leq \cdots \leq P_{RX,B,M} \\
\Rightarrow N_{B,K} > \cdots > N_{B,M+1} > N_{B,1} \geq \cdots \geq N_{B,M}.
\]

(25)

Note that \( N_{B,K} > \cdots > N_{B,M+1} > N_{B,1} \) is achieved because the difference in \( P_{\text{capture}}(\gamma_k) \) is maintained between each \( P_{RX,B,i}, i = 1, M + 1, \ldots, K \) of each other. On the other hand, when \( \bar{P}_K < P_{LB} \), the number of end devices is large. In addition, \( \bar{P}_K \) is less than \( P_{LB} \) if the upper right side of eq. (23) is applied as it is, that is, the sensitivity with the RSSI margin by cumulating \( P_{\text{capture}}(\gamma_k) \). To prevent the end device communication failure owing to the low RSSI, an adjustment of the allocated transmit power is executed as shown in the bottom right side of eq. (23), and the following equation can be obtained

\[
P_{RX,B,K} < \cdots < P_{RX,B,M+1} < P_{RX,B,1} \leq \cdots \leq P_{RX,B,M} \Rightarrow N_{B,K} > \cdots \geq N_{B,M+1} \geq N_{B,1} \geq \cdots \geq N_{B,M}.
\]

(26)

Unlike the case in which \( \bar{P}_K \geq P_{LB} \), \( N_{B,i-1} \) may be equal to \( N_{B,i} \) for \( i = 1, M + 1, \ldots, K \), because the allocated transmit power is adjusted, and the difference in \( P_{\text{capture}}(\gamma_k) \) is not maintained between each \( P_{RX,B,i}, i = 1, M + 1, \ldots, K \). Note that \( P_{RX,B,i-1} = P_{RX,B,i} \) does not hold for \( N_{B,i-1} = N_{B,i} \) in eq. (26) as eqs. (21) and (9). The allocated transmit power \( P_{TX,B,i} \) which gives \( P_{RX,B,i} \) can be written as

\[
P_{TX,B,i} = P_{RX,B,i} + L_i.
\]

(27)

As shown in the above equations, the proposed technique does not require a complex algorithm, and the allocated transmit power can be obtained using eq. (19) for \( P_A \) and eqs. (22), (23), (24) and (27).

D. REALIZATION OF PROPOSED TECHNIQUE

In this subsection, we discuss a method for realization of the proposed technique. We assume that the gateway can learn the RSSI from each end device, and this assumption is reasonable because the gateway receives packets from all end devices. Therefore, the allocated transmit power can be computed at the gateway by sending a packet from each end device with pre-determined transmit power to the gateway once. After the computation, the gateway sends the computed allocated transmit power value to each end device. This also indicates that the proposed technique does not depend on the path loss model. The gateway computes \( P_{TX,B,i} \)s based on the path loss information \( L_i \)s and transmits the information of the computed transmit power to each end device. The LPWA module installed in the end device can control the transmit power in a fixed range from \( P_{TX,max} \) to \( P_{TX,min} \), where \( P_{TX,min} \) is the minimum transmit power controlled by the LPWA module. We assume that all end devices are equipped with a programmable attenuator [42], [43] to output a transmit power of less than \( P_{TX,min} \). The programmable attenuator is effective when the end device transmits its own packet. We let \( P_{\text{ATT},i} \) denote the attenuation value in decibels at the \( i \)th end device to realize the proposed technique. \( P_{\text{ATT},i} \) can be controlled by the programmable attenuator, and \( P_{\text{ATT},i} \) for the case where \( P_B \) is given by

\[
P_{\text{ATT},i} = \begin{cases} 
    0 & P_{TX,B,i} \geq P_{TX,min} \\
    P_{TX,min} - P_{TX,B,i} & P_{TX,B,i} < P_{TX,min}.
\end{cases}
\]

(28)
From these, the actual transmit power in $P_B$ can be represented as

$$P_{TX,B,i} = \begin{cases} P_{TX,B,i} & P_{TX,B,i} \geq P_{TX,min} \\ P_{TX,min} - P_{ATT,i} & P_{TX,B,i} < P_{TX,min}. \end{cases}$$  \hspace{1cm} (29)$$

E. DISCUSSION

The design for both sets of allocated transmit powers is shown in the previous subsection. As mentioned previously, both sets are alternately used and allocated in time to improve the performance of not only the end devices in the poor condition, but also other end devices. However, they do not completely follow the principle shown in Sec. III-A, which is evident from the relationship between eqs. (21), (25), and (26) that are not in the exact reverse order. Furthermore, as shown in eq. (20), the differences in each $P_{RX,A,i}$ are not equal to $P_{capture}(y)$ and do not follow this principle. As mentioned earlier in this section, the reason for this design is to combat the interference signals from other LPWANs.

The effect of the proposed design on the performance of all the end devices must be discussed. To discuss this, it is ideal that the performance of the proposed technique is analyzed based on the theoretically derived number of interferences $N_{A,i}$ and $N_{B,i}$, $\forall i$. However, it is difficult to derive them because $N_{A,i}$ and $N_{B,i}$ cannot be derived from the RSSI in some cases owing to the relationship between the number of interferences and the RSSI as shown in eqs. (21), (25) and (26). Consequently, the optimization problems shown in eqs. (11) and (12) cannot be directly solved theoretically. Therefore, they are numerically provided in the next section.

IV. NUMERICAL EXAMPLES

A. PARAMETER SETUP

To verify the proposed technique, we show some numerical examples in this section. All numerical examples shown in this paper were obtained by Monte-Carlo simulations using MATLAB 2021a. Table 1 lists the parameters for the numerical examples shown in this section. These parameters are mainly derived from the EU863-870 ISM band from document [44]. All end devices are uniformly deployed in the communication area with $R = 2000$ m. The path loss exponent between the end devices and the gateway is chosen as $\alpha = 2.7$ (suburban scenario) [45]. We set the ratio of the number of the end devices to be improved the performance as $\eta = 0.1$. Each end device transmits its own observation using $T_{TX} = 3600$ sec, $BW = 125$ kHz channel bandwidth and spreading factor $SF = 10$. Note that only one spreading factor was employed in the numerical examples to simulate the general LPWAN. We assume that the employment of SX1272 produced by Semtech [46], and we assume that the maximum and minimum transmit powers are $P_{TX,max} = 13$ dBm and $P_{TX,min} = -1$ dBm, respectively. The packet from the end devices has 20 byte payload data, 8 symbols from packet preambles, coding rate 4/5 (parity check), $P_S = -132$ dBm and $NF = 6$ dB [41]. Further, we chose $\Delta P = 5$ dB. We employ the time on air (ToA) of the packet as $T_{TOA} = 370.7$ ms which can be obtained by the Semtech LoRa Calculator [46]. We assume that all the end devices can use only one channel for their communications because we focus on the evaluation for the effect of the proposed technique, that is, the benefits of the capture effect, on the performance of the LPWAN. Further, we employ Fig. 1 as the model of the capture effect $P_{capture}(\cdot)$, as shown in the previous section. Simulation period in MATLAB for the numerical examples shown in this section is 336 hours and it is executed for 2000 patterns of randomly determined the placement of end device. The allocated transmit power in $P_{X}$ and $P_B$ are used in the first and second half of the period, respectively.

We also evaluated the performance of the proposed technique for the transmit power control errors and RSSI measurement errors. First, we demonstrate the transmit power control errors. As described in the previous section, the proposed technique can be established by assuming perfect transmit power control. However, inaccurate transmit power control may deteriorate the performance of the proposed technique because the benefit of the capture effect is not effectively realized in all end devices. Therefore, the effects of the inaccurate transmit power control on the performance of the proposed technique were numerically evaluated. We assume that the transmit power control error has a log-normal probability density function with a standard deviation $\sigma_{TX,E}$ dB. Concretely, the transmit power with control error can be represented as $\{P_{TX,A,i} + N(0, \sigma^2_{TX,E})\}$ dBm and $\{P_{TX,B,i} + N(0, \sigma^2_{TX,E})\}$ dBm, where $N(X, Y)$ is a Gaussian random variable with mean $X$ and variance $Y$. Next, we show the RSSI measurement errors. We assume that the estimate of the RSSI is obtained from the square of the root mean square of a received signal with AWGN and the known noise floor, and furthermore, we assume that the RSSI measurement error causes additive white Gaussian noise (AWGN) at the gateway. Concretely, the RSSI with the measurement error can be represented by adding the random variable, that is, $N(0, \sigma^2)$ to the received signal power where $\sigma$ is standard deviation, and $\sigma^2$ is in milliwatts, which is determined from the channel bandwidth, ToA, and known noise floor. Considering that the square of the noise signal follows a Chi-square distribution with degree of freedom 2, that is, the received signals and AWGN are complex signal, and the central limit theorem [47], $\sigma_v$ is given by

$$\sigma_v = \sqrt{\frac{4 \cdot 10^{-2} \{174 - 10 \log_{10}(BW) - NF\}/10}{2 T_{TOA} BW}}. \hspace{1cm} (30)$$

Furthermore, to practice the proposed technique, we provide the required characteristics of each end device, that is, the average current consumption and the average required attenuation value. The current consumption determines the lifetime of the end device and is defined in two operation modes: packet transmission and sleep. The exact current consumption of the LoRa module can be obtained from the Semtech LoRa Calculator [46], and therefore, we employ the average
TABLE 1. Parameter setup.

| Description                  | Variable     | Numerical value(s) |
|------------------------------|--------------|--------------------|
| Distribution for             | -            | homogeneous PPP    |
| placement of end devices     | K            | Max. 600           |
| Number of patterns for       | R            | 2000               |
| placement of end devices     | α            | 2.7 (suburban)     |
| Average number of end device | η            | 0.1                |
| Radius of area               | P_{TX,max}   | 13 dBm             |
| Path loss exponent           | P_{TX,min}   | -1.0 dBm           |
| Ratio of K to be improved    | f_c          | 868.1 MHz          |
| Max. transmit power          | T_{TX}       | 3600 sec           |
| Min. transmit power          | BW           | 125 kHz            |
| Carrier frequency            | SF           | 10                 |
| Spreading Factor             | Payload length| 20 Bytes          |
| Programmed preamble          | Coding rate  | 8 symbols          |
| (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  | N F          | 6 dB               |
| Number of channels used      | -            | 1                  |
| Model of capture effect      | P_{capture}  | Fig. 1             |
| Simulation period            | -            | 336 hours          |

current consumption of the end devices for the evaluation of the end device’s lifetime. For the parameters listed in Table 1, the current consumption for the packet transmission mode is 100 nA regardless of the transmit power. In this section, the performances of the end devices with following three techniques are compared: i) the proposed technique, ii) the case in which all the end devices transmit their packets with the maximum transmit power, and iii) the case in which the RSSI values from all the end devices at the gateway are the same. Note that the third case indicates that none of the end devices can exploit the benefit of the capture effect because all RSSIs are the same at the gateway. In other words, the last case is a poor solution to the optimization problem shown in eq. (11) whereas the last case is a good solution to the problem shown in eq. (12).

B. PERFORMANCE OF PROPOSED TECHNIQUE

Fig. 5 shows the performances of the packet reception probability in the propagation model with the shadowing component shown in the following equation,

\[ L_i = \log_{10} \left( 10^{\frac{P_{TX} + \Delta P - 10 \log_{10} d_f^2 \times 10^{-2.8}}{\sigma_X^2}} + X_0 \right), \]

where \( X_0 \) is the shadowing component following a normal distribution with 0 dB mean and a standard deviation of \( \sigma_X = 7.8 \text{ dB} \), which is the estimated value in [48]. Fig. 6 shows the performances. As shown in Fig. 6, the performances of the proposed technique are almost the same as that in Fig. 6. This is because the performance of the proposed technique depends on the accuracy of the measured RSSI. Fig. 7 shows the performance of the packet reception probability for the proposed technique with the RSSI measurement errors. As shown in Fig. 7, the RSSI measurement errors under the conditions listed in Table 1 do not affect the performance of the proposed technique. This is because the number of samples for the RSSI measurement, which corresponds to \( T_{TOA} \), is sufficiently long, i.e., the number of samples for the measurement is 92,500 based on the parameters listed in Table 1, i.e., the measurement error is given by \( \sigma_X^2 \approx 1.71 \times 10^{-28} \text{ mW} \) (or \(-277 \text{ dBm})\). Note that the length of the packet (\( T_{TOA} = 370.7 \text{ ms} \)) is long in the sense that it causes no RSSI measurement error, and the packet length is very short compared to the packets with a payload of 20 byte or more. Fig. 8 shows the performance of the packet reception probability for the proposed technique with the transmit power control errors and the RSSI measurement errors. In Fig. 8, the proposed technique is evaluated with the capture effect due to the equal RSSI at the gateway. From the above comparisons, we can say that the proposed technique can share the benefit of the capture effect to all the end devices, which helps achieve the performance improvement of the end devices. Furthermore, it is obvious that the performance of the proposed technique can be improved even if the number of the end devices does not completely realize the benefits of the capture effect, as shown in the right bottom side of eq. (23).
a maximum of $\sigma_{TX,E} = 3$ dB. The transmit power control errors and the RSSI measurement errors do not affect the performance of the proposed technique, and it can be seen that it can exploit the benefits of capture effect to all the end devices, even if a rough transmit power control at the end devices and the RSSI measurement errors.

Fig. 9 demonstrates the characteristic of the average current consumption of the end device for $P_{TX,max} = 13, 9, 1$ dBm. In [46], the average current consumption of the end devices with the proposed technique is less than that of the end devices with the maximum transmit power. This indicates that the energy consumption of the end devices with the proposed technique is less than those without transmit power control, and therefore, the proposed technique can achieve the energy-saving of the LPWAN. Fig. 10 shows the characteristic of the average maximum attenuation required for each end device in the proposed technique. The attenuation value increases as the number of the end devices increases and the attenuation of about 70 dB is required at the end device for the proposed technique. Finally, we show the reason attributed to the change in the characteristics at around $K = 20$ to $K = 40$ in Figs. 9 and 10. To investigate, we focused on the behavior of eq. (23) in the numerical examples because eq. (23) drastically changes the allocated transmit power when $P_K < P_{LB}$. Therefore, we investigate
the probability that it is executed the allocated transmit power adjustment represented by $\hat{P}_K < P_{LB}$ case in eq. (23). Fig. 11 shows the probability for different $K$. It can be seen that the depicted curve drastically changes at around from $K = 20$ to $K = 40$, and we believe that the behavior is the reason.

C. PERFORMANCE OF PROPOSED TECHNIQUE WITH INTERFERENCES FROM OTHER LPWANs

In this subsection, we discuss the performance evaluation of the proposed technique in an environment with interference from other LPWANs. Fig. 12 shows the performance of the packet reception probability in an interference environment. The performances of the proposed technique for $K = 200$ and different numbers of the interference are shown in Fig. 12. In Fig. 12, the interference sources, that is, the end devices belonging to other LPWANs, have the same communication parameters as the end devices with the three techniques shown in the previous subsection. The performance of the distant end devices with the proposed technique does not deteriorate significantly compared to the performance of the distant end devices with the maximum transmit power.

Fig. 13 shows the performance of the packet reception probability on the propagation model shown in eq. (31). Unlike the case of Figs. 5 and 6, the performances of the proposed technique in Fig. 13 are superior to that in Fig. 12. This is because the effect of interferences on the performance of the proposed technique is weakened by shadowing component. Further, we show the performance of the proposed technique with the transmit power control errors and the RSSI measurement errors in the interference environment in Fig. 14. In the figure, the performances for $\sigma_{TX,E} = 0$ dB and 3 dB and $K = 200$ are depicted. Similar to the results shown in Fig. 8, it can be seen that the transmit power control errors and the RSSI measurement errors do not affect the proposed technique in the interference environment.

D. NUMERICAL ANALYSES OF PROPOSED TRANSMIT POWER ALLOCATION SCHEME

In this subsection, we provide the evaluation results for the incompleteness of the transmit power control, in which $P_A$ and $P_B$ are not in the exact reverse order, among all the end devices in the proposed technique. First, we compare the
Similarly, we let $P_{TX,sym,A,i}$ and $P_{TX,sym,B,i}$ denote the allocated transmit power of the $i$th end device in $P_A$ and $P_B$ for the symmetrical power allocation case, respectively. Furthermore, we let $P_{RX,sym,A,i}$ and $P_{RX,sym,B,i}$ denote the RSSI from the $i$th end device in $P_A$ and $P_B$ for the symmetrical power allocation case, respectively. To achieve eqs. (17) and (18), $P_{TX,sym,A,i}$ and $P_{RX,sym,A,i}$ are designed in conjunction with each other. $P_{TX,sym,B,i}$ and $P_{RX,sym,B,i}$ can be obtained as follows:

$$P_{TX,sym,A,i} = P_{TX,max},$$

$$P_{RX,sym,A,i} = P_{TX,sym,A,i} - L_i$$

$$P_{TX,sym,A,i} = P_{RX,sym,A,i} + L_i, \quad i = 1, \cdots, K - 1$$

$$P_{RX,sym,A,i} = \begin{cases} \tilde{P}_{sym,A,i} & P_{RX,sym,A,i} \geq P_{LB}, \\ P_{LB} & P_{RX,sym,A,i} < P_{LB}, \end{cases}$$

$$i = 1, \cdots, K - 1$$

$$\tilde{P}_{sym,A,i} = P_{RX,sym,A} - \sum_{k=i+1}^{K} P_{capture}(\gamma_k).$$

Similarly, $P_{TX,sym,B,i}$ and $P_{RX,sym,B,i}$ can be obtained as follows:

$$P_{TX,sym,B,i} = P_{TX,max},$$

$$P_{RX,sym,B,i} = P_{TX,sym,B,i} - L_i$$

$$P_{TX,sym,B,i} = P_{RX,sym,B,i} + L_i, \quad i = 2, \cdots, K$$

$$P_{RX,sym,B,i} = \begin{cases} \tilde{P}_{sym,B,i} & P_{RX,sym,B,i} \geq P_{LB}, \\ P_{LB} & P_{RX,sym,B,i} < P_{LB}, \end{cases}$$

$$i = 2, \cdots, K$$

$$\tilde{P}_{sym,B,i} = P_{RX,sym,B} - \sum_{k=2}^{i} P_{capture}(\gamma_k).$$

where $\tilde{P}_{sym,A,i}$ and $\tilde{P}_{sym,B,i}$ are the power values in decibels for $P_A$ and $P_B$, respectively. Note that $P_{TX,sym,A,i}$, $P_{RX,sym,A,i}$, $P_{TX,sym,B,i}$ and $P_{RX,sym,B,i}$ are only used for the comparison with the proposed technique. Fig. 15 shows the performance of the packet reception probability for the proposed technique and the symmetrical power allocation case. As shown in Fig. 15, the both performances are almost the same, and it can be seen that the effect of the proposed technique, which is not in the exact reverse order, can be ignored. Furthermore, Fig. 16 shows the performance of the packet reception probabilities in the interferences environment. The performance of the proposed technique is superior to that of the symmetrical power allocation case. It can be seen that the proposed technique can obtain the resistance to interference.

We let $\mu(X, Y)$ denote a set of end devices consisting of XMth to YMth end devices. We divide the $M$ end devices into four sets: $\mu(0, 0.25)$, $\mu(0.25, 0.5)$, $\mu(0.5, 0.75)$ and $\mu(0.75, 1)$, and evaluated the performance of the end devices belonging to each set. Fig. 17 shows the performance of the packet reception probability for the proposed technique with different values of $\eta$ and $K = 200$. As shown in Fig. 17,
although the performances of end devices belonging to \( \mu(0.5, 0.75) \) and \( \mu(0.75, 1) \) are ameliorated as \( \eta \) increases, the performance of end devices belonging to \( \mu(0, 0.25) \) and \( \mu(0.25, 0.5) \) deteriorates as \( \eta \) increases. Although the incompleteness of the transmit power control affects the performance of the end devices belonging to the set at a long distance from the gateway, it does not significantly affect the performance of the proposed technique with a small \( \eta \).

V. CONCLUSION

This paper proposed simple transmit power allocation schemes for the performance improvement of the poor conditioned end devices in the general LPWAN. In the proposed schemes, two types of allocated transmit power were employed to distribute the benefit of the capture effect to all the end devices because the benefit cannot be realized in all the end devices simultaneously owing to its characteristic. These were designed in conjunction with each other and alternately used in time at each end device. The proposed technique can improve the performance of the end devices in the poor condition, and we showed that the proposed technique is robust in the transmit power control error and the interference from other LPWANs. In future work, the proposed technique will be extended to the general LPWAN constructed by the end devices with a carrier sense which must be employed in the Japanese Regulations for unlicensed sub-GHz band LPWA communications [49].

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