Transmission Timing Control Using ACK Signal in LoRaWAN

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***Abstract*—Long range wide area network (LoRaWAN) enables low-power and long-range communication suitable for wireless sensor networks (WSNs). Since LoRaWAN is a decentralized network, packet collision may occur if multiple nodes send data packets simultaneously. It is necessary to adjust the node's transmission interval properly to avoid such packet collisions. This paper proposes a transmission interval control strategy that takes advantage of an acknowledgment (ACK) signal from a gateway (GW) to each node. Instead of transmitting a controlling signal, the GW selects one of two receiving windows for ACK packet transmission to indicate 0 or 1. Thus, it does not incur any overhead. The proposed method adaptively changes the transmission interval of each LoRaWAN node by utilizing the ACK signal returned from the GW. The proposed method uses a simple prediction method that is computationally simple and can provide good properties even when there are constraints on the systems associated with observing gentle changes, such as environmental monitoring. Computer simulation results show that the proposed method can reduce the number of transmitted packets while achieving the same observation accuracy level as conventional methods.**

I. Introduction

Internet-of-things (IoT) and machine-to-machine (M2M) communication enable various devices to communicate with each other [1]. The number of nodes connected to the Internet is predicted to reach 50 billion by 2020 [2]. IoT exhibits various challenges, such as low-power consumption, low node cost, and simple network architecture. Existing cellular networks and wireless local area networks (WLAN) are mainly designed for high-speed communications of Mbps to Gbps over a range of several hundred meters. These networks are not suitable for low-rate communication from a large number of nodes installed over a vast area. Low power wide area (LPWA) has been attracting attention as a solution to these problems (Fig. 1) [3]. The long-term evolution for machine-type communication (LTE-M) and narrowband-IoT (NB-IoT) enable low-rate communication based on the LTE communication standards in the licensed band.

Long range wide area network (LoRaWAN), which is one of the LPWA standards, adopts the chirp spread spectrum (CSS) modulation as the physical (PHY) layer technology. LoRaWAN realizes low-power consumption communication over long distances by adaptively changing the spreading factor (SF). A pure ALOHA protocol [4], which is a simple random access method, is applied to the MAC layer. In LoRaWAN, three classes are defined for the MAC layer, namely, Class A, Class B, and Class C. Class A must be implemented

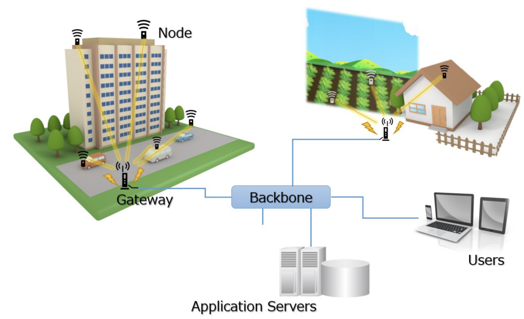

Fig. 1. In LoRaWAN architecture, nodes communicate to the network server through gateways.

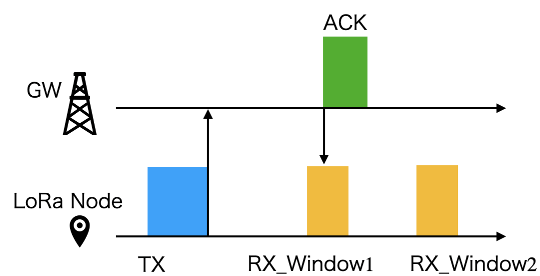

Fig. 2. LoRaWAN protocol on Class A.

in a node, and communication is always initiated from the node. Class A nodes send uplink (UL) packets to a gateway (GW) using the pure ALOHA protocol. It then receives the downlink (DL) packets by opening the two receiving windows at the predetermined receive timing, thus reducing the power consumption as shown in Fig. 2.

Since LPWA should satisfy a duty interval restriction, Duty Cycle (DC), LoRaWAN is suitable for collecting information that is not urgent and does not require a large amount of data. However, packet collisions frequently occur because multiple nodes may send packets simultaneously when the number of nodes in the network increases. This leads to a decrease in the throughput of the entire network. Due to its simple mechanism and node capability, a complicated scheduling mechanism is not suitable for LoRaWAN.

This paper proposes a transmission interval control method to avoid packet collision while preserving the quality of information. If the transmission interval is short, many mea-

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surement data can be obtained at the risk of high packet collision probability. On the other hand, if the transmission interval is long, the packet collision probability is reduced by sacrificing measurement data accuracy. Thus, it is necessary to adjust the transmission interval based on both the network condition and the measurement accuracy. However, it is not possible to introduce additional functions to LoRaWAN. The proposed method takes advantage of the fact that an acknowledgment (ACK) signal is transmitted from the GW to each node *in one of two receiving windows*. Instead of transmitting a controlling signal, the GW selects one of two receiving windows for ACK packet transmission to indicate either "0" or "1". Since the proposed method does not incur any overhead, it is compatible with LoRaWAN standards. Computer simulations' results show that the proposed method can reduce the number of packet transmissions while balancing information collection and packet collision accuracy even with the influence of DC in the system that does not change significantly, such as environmental monitoring. Furthermore, we show that good properties can be obtained even with simple prediction methods that require little computation, rather than computationally intensive methods such as ML methods.

The remainder of this paper is organized as follows. Sect. II describes the system model considered in this paper. Sect. III explains the proposed method. The results from the computer simulations and discussions are provided in Sect. IV. The conclusions of the paper are provided in Sect. V.

II. System Model

A. Network Model

One GW is located at the center of a communication area of $L \times L$ [km^2], and N LoRaWAN nodes are randomly and uniformly within the area. LoRaWAN node $n \in \{0, 1, \cdots, N-1\}$ randomly selects one of K frequency channels and transmits data packets to the GW at a predetermined interval while satisfying the DC restriction. After finishing one packet transmission, each node waits for the following time duration before transmitting the next packet:

$$T_{\rm wait} = \frac{1-G}{G} T_{\rm pckt}, \tag{1}$$

where $G \in (0, 1]$ is the DC and $T_{\rm pckt}$ is the packet length [s].

Each transmitted packet shall be considered successfully received at the GW if the signal-to-noise power ratio (SNR) and the signal-to-interference power ratio (SIR) are above the reception threshold $\Gamma_{\rm SNR}$ and $\Gamma_{\rm SIR}$, which are provided in Table I. Based on [5], if there are several packets are transmitted on the same frequency channel simultaneously, the GW is able to capture one of them if its SIR is higher than 6 dB.

B. Channel Model

For the propagation model between a LoRaWAN node and the GW, we adopt the Cost231 Walfisch Ikegami pathloss model [8] and spatially correlated shadowing loss [9]. The pathloss is given as

TABLE I
SNR threshold and SIR threshold

SF	Threshold $\Gamma_{\rm SNR}$ [dB] [6]	Threshold $\Gamma_{\rm SIR}$ [dB] [7]
7	-6	-11
8	-9	-13
9	-12.5	-16
10	-15	-19
11	-17.5	-22
12	-20	-24

$$L_{\rm GW}(d) = L_0(d) + L_{\rm rts} + L_{\rm ms}(d), \tag{2}$$

where $L_0(d)$, $L_{\rm rts}$ and $L_{\rm ms}(d)$ are loss in the free space, loss by diffraction and scattering from rooftop to street and loss due the multi-screen diffraction, respectively. Each loss is given by

$$\begin{cases} L_0(d) = 32.4 + 20\log d + 20\log f_{\rm c} \\ L_{\rm rts} = -16.9 - 10\log W + 10\log f_{\rm c} + 0.01 \\ L_{\rm ms}(d) = L_{\rm bsh} + k_a + 18\log d + k_f \log f_{\rm c} + 9\log B \\ L_{\rm bsh} = -18\log(1 + (h_{\rm GW} - h_{\rm ED})), \end{cases} \tag{3}$$

where $h_{\rm GW}$ [m] is height of the GW's antenna, $h_{\rm ED}$ [m] is height of the ED antenna and $f_{\rm c}$ [MHz] is the carrier frequency. The distance between buildings is B [m], the width of the street is W [m] and shadowing gain is $L_{\rm bsh}$. The factor k_a and k_f are given by:

$$\begin{cases} k_a = 54 + 0.8(h_{\rm GW} - h_{\rm ED}) \\ k_f = -4 + 0.7(f_{\rm c}/925 - 1). \end{cases} \tag{4}$$

We take into account the interference from other nodes while receiving the ACK signal. For the propagation model between LoRaWAN nodes, we adopt pathloss $L_{\rm ED}$ and shadowing loss η and is given as

$$L_{\rm ED} = 10\alpha \log_{10}(r) + \beta + 10\gamma \log_{10}(f_{\rm c}) + \eta, \tag{5}$$

where r [m] is the distance between LoRaWAN nodes, σ [dB] is the standard deviation of a zero-mean Gaussian random variable and $\eta \sim \mathcal{N}(0, \sigma^2)$. Propagation parameters α, β, and γ are the coefficients for distance, offset, and frequency loss component, respectively [10].

III. Proposed Method

This paper assumes that the node n observes analog data $d_n(t)$, such as room temperature, at every Δ_0 [sec]. Then, the node n converts $d_n(t)$ into observed data $d_{{\rm obs},n}(t)$. Without loss of generality, we omit index n in the following explanation for simplicity.

Each node transmits the observed data $d_{\rm obs}(t)$ to the GW at specific time instances, i.e., $t \in \{\cdots, t[m-1], t[m], t[m+1], \cdots\}$, where $t[m]$ is the time instance when the mth data packet is transmitted from node to the GW. Let $\mathcal{T} = \{\Delta_0, \Delta_1, \cdots, \Delta_{S-1}\}$ denote the set of transmission intervals. Each node selects one of transmission intervals. Let $\Delta[m] \in \mathcal{T}$

denote the transmission interval between the $(m-1)$th data packet and the mth data packet, i.e.,

$$\Delta[m] \triangleq t[m] - t[m-1], \tag{6}$$

or equivalently

$$t[m] = t[0] + \sum_{m'=1}^{m} \Delta[m']. \tag{7}$$

A. Data Prediction

Upon receiving $d_{\rm rec}[m-1] \triangleq d_{\rm obs}(t[m-1])$ from the node, the GW predicts the observed data that will be transmitted by the mth data packet by a simple exponential smoothing method [11] as (Fig. 3 (a))

$$\tilde{d}[m] = \alpha \cdot d_{\rm rec}[m-1] + (1-\alpha) \cdot \tilde{d}[m-1], \tag{8}$$

where $\alpha \in (0,1)$ is the smoothing constant.

After receiving data $d_{\rm rec}[m]$, the GW calculates normalized error $v[m]$ between $d_{\rm rec}[m]$ and $\tilde{d}[m]$ as

$$v[m] = \left| \frac{d_{\rm rec}[m] - \tilde{d}[m]}{d_{\rm rec}[m]} \right|. \tag{9}$$

A sufficiently small value of $v[m]$ indicates that the time series $\{d_{\rm rec}[m]\}$ are changing slowly, and hence even with longer transmission intervals $\Delta[m] \geq \Delta[m-1]$ can accurately track it. On the other hand, a large value of $v[m]$ indicates that $\{d_{\rm rec}[m]\}$ is changing fast, and hence it is necessary to shorten the transmission interval to track the change of $\{d_{\rm rec}[m]\}$. Thus, the proposed algorithm adjusts $\Delta[m+1]$ based on $v[m]$.

B. Transmission Interval Update

The ratio between two consecutive relative errors $v[m-1]$ and $v[m]$ is calculated as

$$c[m] = \frac{v[m]}{v[m-1]}, \tag{10}$$

If $c[m]$ is small, the normalized error becomes smaller, therefore it is easy to predict the trend of information. On the other hand, if $c[m]$ is large, the normalized error becomes larger. Thus, it is necessary to shorten the transmission interval to receive more data. The GW compares $c[m]$ with threshold values $\Gamma_{\rm low}$ and $\Gamma_{\rm high}$, and decides whether the current transmission interval is sufficient or not. Threshold values $\Gamma_{\rm low}$ and $\Gamma_{\rm high}$ are updated once the GW receives a data packet.

The update steps are as follows:

1) Initialize $\mathcal{W} = \{\underbrace{0, 0, \cdots, 0}_{R}\}$.
2) Once the GW receives data $d_{\rm rec}[m]$, calculate $c[m]$ based on Eq. (10).
3) Divide continuous value $c[m]$ by step size ϵ to obtain index r as

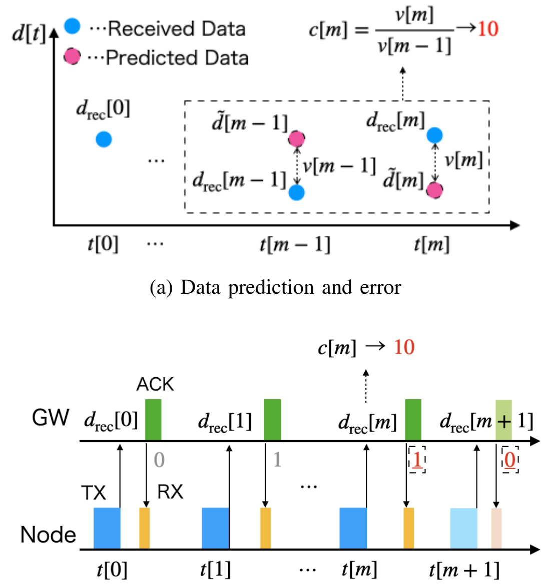
$$r = \left\lfloor \frac{c[m]}{\epsilon} \right\rfloor, \tag{11}$$

where $\lfloor x \rfloor$ returns the largest integer smaller than or equal to x.

4) Update $\mathcal{W}[r] = \mathcal{W}[r] + 1$.

TABLE II
THRESHOLD SETTING

ACK	Manipulation	Threshold
00	Longer	$c \leq \Gamma_{\rm low}$
01	Keep	$\Gamma_{\rm low} < c \leq \Gamma_{\rm high}$
10	Shorter	$\Gamma_{\rm high} < c$



(a) Data prediction and error

(b) Transmission interval update using ACK signal

Fig. 3. Schematic diagram of transmission interval update.

5) Obtain subset $\tilde{\mathcal{W}} = \{\mathcal{W}[\pi_0], \mathcal{W}[\pi_1], \cdots, \mathcal{W}[\pi_{M-1}]\} \subseteq \mathcal{W}$ such that $\mathcal{W}[\pi_0] \geq \mathcal{W}[\pi_1] \geq \cdots \geq \mathcal{W}[\pi_{M-1}] \geq \cdots \mathcal{W}[\pi_{R-1}]$. M is a parameter.
6) Set $\Gamma_{\rm low} = \epsilon \times r_{\rm min}$ and $\Gamma_{\rm high} = \epsilon \times r_{\rm max}$ with

$$\begin{cases} r_{\rm min} = \displaystyle\mathop{\arg\min}_{r' \in \{0,1,\cdots,M-1\}} \mathcal{W}[\pi_{r'}] \\ r_{\rm max} = \displaystyle\mathop{\arg\max}_{r' \in \{0,1,\cdots,M-1\}} \mathcal{W}[\pi_{r'}] \end{cases}. \tag{12}$$

The rationale behind this threshold setting is as follows.

If $c[m]$ is close to the other values collected in the past, the prediction is likely to be accurate. On the other hand, if the values are significantly different, error $v[m]$ is large. The latter means that the prediction is no longer accurate because the received data may have a sudden change. These received values are defined as outliers. Therefore, we set range $[\Gamma_{\rm low}, \Gamma_{\rm high}]$ to show close values, and whether $c[m]$ is included in this range or not can determine whether the prediction is accurate.

C. Interpolation of Missing Data

Each node observes analog data at every Δ_0 [sec]. However, if transmission interval $T[m]$ is longer than Δ_0, the node does not transmit some observed data to the GW. Furthermore, the GW may not be able to receive the observed data due to packet collision. These lost data are obtained by cubic spline interpolation [12].

TABLE III
SIMULATION PARAMETERS

Simulation area, $L \times L$	1×1 [km^2]
Number of LoRaWAN nodes, N	100
Transmit power P_t	13 [dBm]
Carrier frequency, f_c	920 [MHz]
Bandwidth B	125 [kHz]
Number of frequency channels, K	1
Spreading factor, SF	7
Propagation coefficient, α	4.0
Propagation offset, β	9.5
Propagation coefficient of frequency loss, γ	4.5
Noise power spectrum density,	-174 [dBm/Hz]
Dwell time,	400 [ms]
Duty cycle, G	0.1
Payload size	7 [Byte]
Measurement time interval, Δ_0	1 [min]
Step size, ϵ	0.01
Number of samples for threshold setting, M	2, 3, 4, 5

D. Transmission Interval Update using ACK Signal

Figure 3 (b) shows the schematic diagram of a interval update. After the LoRaWAN node sends the mth packet to the GW, the node will open *two receiving windows* at the specified receiving timing to receive an ACK packet from the GW. The GW utilizes this feature to inform the node of transmission interval $\Delta[m+1]$. The ACK signal in the first receiving window represents 0. The ACK signal in the second receiving window represents 1. Table II shows the assignment of the ACK and the threshold settings for each transmission interval update.

IV. COMPUTER SIMULATION

A. Simulation Parameters and Performance Metrics

This section provides computer simulations' results to verify the performance of the proposed method. Table III shows the simulation parameters. Transmit power P_t, carrier frequency f_c and bandwidth B are set to $13\,[\mathrm{dBm}]$, $920\,[\mathrm{MHz}]$ and $125\,[\mathrm{kHz}]$, respectively. A single channel is considered and all nodes use the same SF. Each node obtains observed data at every $\Delta_0 = 1$ [min]. Then, each node periodically transmits packets at constant intervals according to transmission cycle $T[m] \in \mathcal{T}$. The packets are sent while observing the duty cycle $G = 1\,[\%]$ and dwell time $T_{\mathrm{dwell}} = 400\,[\mathrm{ms}]$. We assume that there is no retransmission in case of packet failure. The propagation parameters used in the pathloss L_{ED} are set to $\alpha = 4.0, \beta = 10.2, \gamma = 2.36$ and $\sigma = 7.60$, respectively.

Six types of transmission intervals are used. The conventional method periodically transmits the observed data at every $\Delta_1 = 4$ [min], $\Delta_2 = 8$ [min], $\Delta_3 = 16$ [min], or $\Delta_4 = 32$ [min]. The proposed method adjusts the transmission interval, as explained in Sect. III starting with either Δ_1 or Δ_4. We refer to them as "Proposed 1" and "Proposed 2", respectively.

Figure 4 shows the example of the information observed by the sensor nodes. The observed information is different for each sensor location.

For performance evaluation, the three metrics are considered; packet reduction rate (PRR), packet delivery rate (PDR), and error rate (ER). The nodes failed to pass the threshold Γ_{SNR} are excluded from the simulation evaluation.

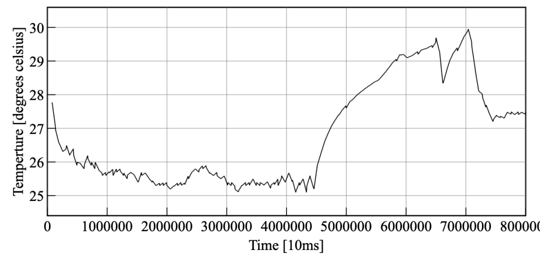


Fig. 4. Example of observed data series.

a) PRR: PRR defines how much the proposed method can reduce the number of transmitted packets from the number of packets sent by interval Δ_1, which is defined as

$$\mathrm{PRR} = \frac{\Sigma_{n=0}^{N-1} Q_{\Delta_1,n} - \Sigma_{n=0}^{N-1} Q'_n}{\Sigma_{n=0}^{N-1} Q_{\Delta_1,n}}, \tag{13}$$

where $Q_{\Delta_1,n}$ denotes the number of packets sent from LoRaWAN node n with Δ_1, Q'_n denotes number of packets sent from node n with the proposed method.

b) PDR: PDR is defined as

$$\mathrm{PDR} = \frac{\Sigma_{n=0}^{N-1} P_n}{\Sigma_{n=0}^{N-1} Q_n}, \tag{14}$$

where P_n denotes the number of successfully received packets from node n and Q_n denotes the number of packets generated by node n.

c) ER: ER is instantaneous value, which is defined as

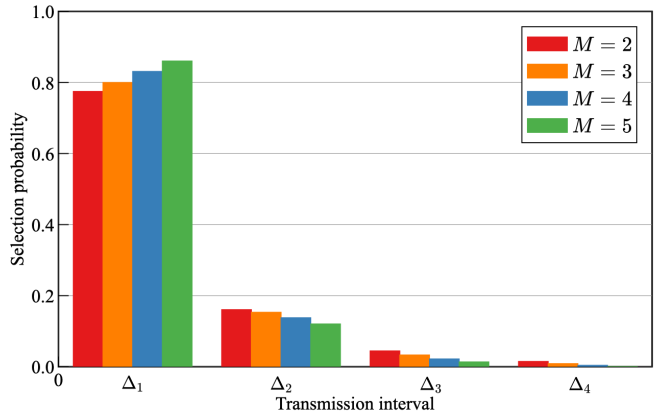
$$\mathrm{ER} = \left| \frac{d_{\mathrm{ip},n} - d_{\mathrm{obs},n}}{d_{\mathrm{obs},n}} \right| \tag{15}$$

where $d_{\mathrm{ip},n}$ denotes interpolated data of node n.

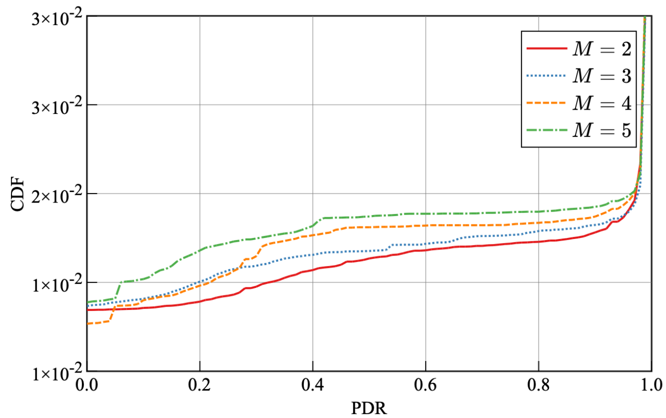
B. Simulation Results

Firstly, the impact of M on the performance of the proposed method (Proposed 1) is evaluated. Figure 5 (a) shows the probability of selecting different transmission intervals with M as a parameter. As the figure shows that Δ_1 is selected more as M increases. This is due to the fact that the range between the maximum and the minimum, i.e., Γ_{high} and Γ_{low}, becomes wider and the number of outlier targets becomes smaller, which results in less frequent control of the interval. Figure 5 (b) shows the cumulative distribution function (CDF) of PDR. The PDR performance improves as M becomes smaller. Figure 5 shows that a smaller M allows for more delicate cycle adjustment, which results in improved PDR performance. Thus, in the following, we set $M = 2$.

Figure 6 shows the performance comparison between the proposed method and the conventional fixed transmission interval methods. As Figure 6 (a) shows that the proposed method can reduce the number of transmitted packets compared to the conventional method with Δ_1. Proposed 1 can reduce packets about 50% and Proposed 2 can reduce packets

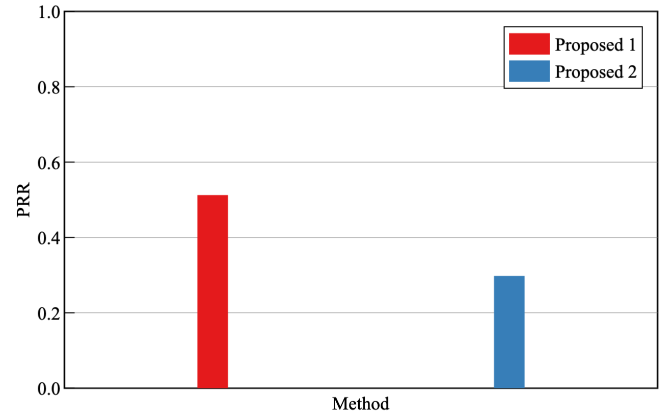


(a) Selection probability of each transmission interval.

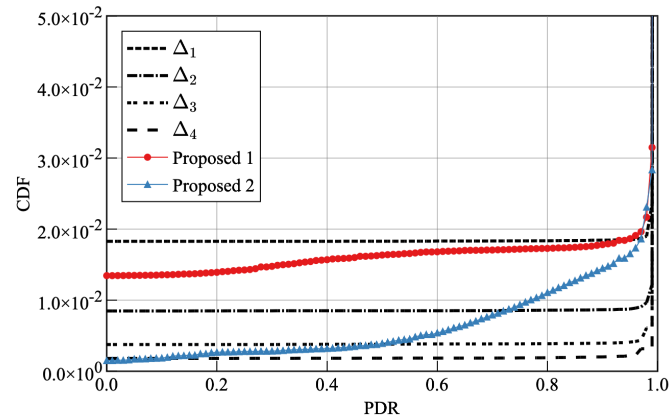


(b) PDR performance.

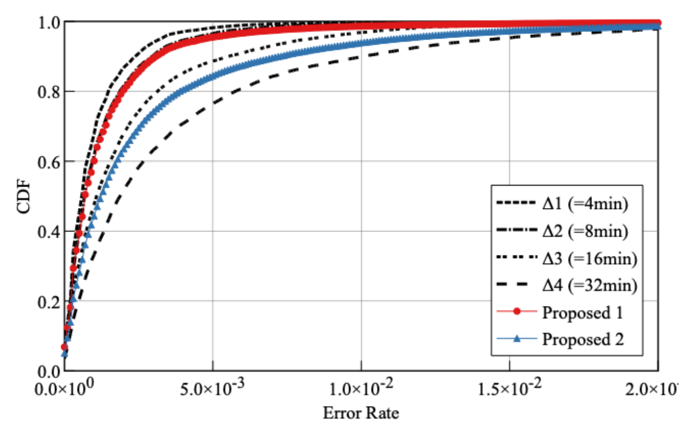
Fig. 5. Impact of M (Proposed 1).



(a) PRR



(b) PDR



(c) ER

Fig. 6. Simulation results.

about 70%. Therefore, the proposed method is expected to be effective in reducing packet collisions. The actual reduction of packet collisions will be confirmed by evaluating the PDR performance.

As can be seen from Fig. 6 (b), the PDR performance of the proposed method can be improved compared to the conventional method. Proposed 1 can reduce the ratio of $\mathrm{PDR} = 0.0$ about 25% compared to the conventional method with Δ_1. This is due to the fact that the proposed method can adaptively change the transmission interval on the received data. When the data change is smooth, the transmission cycle is extended and the number of transmitted packets is reduced compared to the conventional method. Therefore, the packet collision probability can be reduced.

Figure 6 (c) shows that there is a tradeoff between PDR and ER. Since the conventional method with Δ_1 provides the best ER performance as it allows each terminal to send the observed data frequently. However, as Fig. 6 (c) shows that the proposed method can provide close to the best performance obtained by the conventional method with Δ_1 while reducing the number of transmitted packets.

V. Conclusion

This paper proposed an adaptive transmission interval control method to avoid packet loss caused by packet collision in LoRaWAN. The proposed method takes advantage of an ACK signal transmitted from the GW to each node using one of two ACK receiving windows. By assigning 0 and 1 to each

ACK receiving window, the GW can inform each node of the information to control the transmission interval. The computer simulations' results have shown that the proposed method can reduce the number of transmitted packets up to 70% and achieve a similar reception accuracy as the conventional method with the shortest transmission interval.

Acknowledgment

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