LBT-based Resource Allocation Methods Utilizing Periodicity of Traffic in LPWAN

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***Abstract*—Low-power wide-area networks (LPWANs) have recently attracted much attention from both industry and academia. In some LPWAN applications, periodic uplink (UL) traffic dominates the network traffic. Since LPWANs adopt simple asynchronous random access protocols, continuous packet collisions may occur in the periodic UL traffic. Therefore, this paper proposes an autonomous distributed resource allocation method that utilizes carrier sense (CS) and UL traffic periodicity. A node detects the downlink (DL) signal to another node via CS and selects wireless resources to avoid packet collisions. Computer simulation results show that the proposed method can improve the packet delivery rate (PDR) performance by up to about 26% and 9% compared to ALOHA and listen-before-talk (LBT) based method, respectively.**

***Index Terms*—Wireless sensor networks, LPWA, LoRaWAN, Resource allocation, Periodic traffic**

I. Introduction

The Internet-of-things (IoT), connecting various devices to the Internet, is rapidly spreading due to the miniaturization and long-life operation with low power consumption of wireless devices. In particular, wireless sensor networks (WSNs), which employ sensor nodes capable of wireless communication to gather information, are anticipated to find industrial applications due to high flexibility and independence from the need for physical cable wiring [1], [2]. Among the WSN standards, low power wide area network (LPWAN), which can accommodate many sensor nodes and enable long-distance communication over up to several kilometers, is rapidly gaining popularity [3]. Generally, sensor nodes are deployed in a specific area to sense the surrounding environment and periodically transmit the observation data to an information aggregation station such as a gateway (GW) in industrial applications such as smart cities and smart agriculture. As a result, periodic uplink (UL) traffic dominates the network traffic [4]–[6]. In general, a simple asynchronous random access protocol, such as the ALOHA, is adopted for UL in LPWANs. However, with the ALOHA protocol, packet collisions occur more frequently as the number of sensor nodes in the network increases. In particular, when periodic UL traffic dominates, continuous packet collisions may occur depending on the combination of transmission cycles between nodes. Therefore, packet collision avoidance is essential for LPWANs with periodic UL communication.

Various packet collision avoidance methods have been proposed for LPWANs [7]–[9]. In [7], [8], a listen-before-talk (LBT) method based on carrier sense (CS) is considered to be applied to LPWANs. The LBT scheme changes transmission timing based on the CS result. When a node detects the signal by CS, the node can avoid radio resource conflict by probabilistically backoff the transmission timing. However, packet collisions frequently occur in LPWANs with large communication areas due to the hidden node problem. In addition, communication quality is generally inferior compared to centralized control schemes because less information is available for resource allocation. We have proposed a centralized packet collision avoidance method for periodic UL traffic in [9]. In this method, the GW allocates wireless resources that can avoid packet collisions based on the transmission cycle information and transmission timing, and then the GW informs each node of the assigned resource through the downlink (DL). Compared to the ALOHA protocol, this method has been shown to improve communication quality significantly. However, centralized resource allocation may become difficult to apply as the number of nodes increases because the overhead of DL transmission for control becomes large. Therefore it is necessary to provide a resource allocation technique for packet collision avoidance that can be applied to LPWANs with a large number of nodes.

Given such a background, This paper proposes an autonomous distributed resource allocation method that utilizes the CS and UL traffic periodicity. In [9], the GW has to decide the resources used by all nodes. On the other hand, in the proposed method, the GW only needs to transmit the DL without control information to nodes that satisfy specific conditions. In the proposed method, each node detects hidden nodes based on DL signals from the GW to cope with the hidden node problem. Since the DL signal from the GW generally reaches all nodes, the DL signal to the hidden node is more likely to be detected by the CS. If a node detectes a DL signal by the CS, the node may be able to avoid packet collisions with hidden nodes by changing the wireless resources to be used. In this paper, we evaluate a system that assumes LoRaWAN, which is a kind of LPWAN standard. Computer simulations show that the proposed method can improve the packet delivery rate (PDR) by up to about 26% and 9% compared to the conventional method using ALOHA and LBT-based methods, respectively. The main contribution of this paper is to reduce packet collisions caused by the hidden node problem without any control signal to the node.

The remainder of this paper is organized as follows. Section II describes the LoRaWAN-based system model. The proposed method is presented in Sect. III. Section IV provides computer simulation results. Section V concludes the paper.

II. System Model

This paper considers a network comprising I LoRaWAN nodes ($\mathcal{I} = \{1, \cdots, i, \cdots, I\}$) and a single GW. Each node chooses one of K orthogonal frequency channels ($\mathcal{K} = \{1, \cdots, k, \cdots, K\}$) for packet transmission. Both the nodes and GW operate in a half-duplex communication mode.

A. Packet Transmission in LoRaWAN

The LoRaWAN adopts LoRa modulation based on CSS modulation at the physical layer. In LoRa modulation, time duration of one symbol $T_i^{\mathrm{s}}(S_i)$ [sec] varies with spreading factor (SF) S_i. The symbol length for a spreading factor $S_i \in \mathcal{S}$ is determined by

$$T_i^{\mathrm{s}}(S_i) = 2^{S_i}/W, \tag{1}$$

where W [Hz] is the frequency bandwidth. Since the number of bits that can be transmitted per symbol is S_i, number of symbols per packet $N_i^{\mathrm{s}}(S_i)$ can be calculated as

$$N_i^{\mathrm{s}}(S_i) = O_{\mathrm{sym}} + \left\lceil \frac{B^{\mathrm{data}}/R}{S_i} \right\rceil, \tag{2}$$

where O_{sym} is the number of overhead symbols required for one packet transmission, B^{data} [bit] is packet data size, R is the coding rate, and $\lceil x \rceil$ is the ceiling function of x. Therefore, the time-on-air (ToA) per packet for node i, denoted as T_i^{ToA} [sec], is expressed as

$$T_i^{\mathrm{ToA}} = T_i^{\mathrm{s}}(S_i) \times N_i^{\mathrm{s}}(S_i). \tag{3}$$

B. LoRaWAN Node

Node i is assumed to observe its surrounding environment at a predetermined cycle of G_i^{p} [min] and transmit the observation results to the GW. This paper assumes that each node can store observation data in the payload without delay between the observation timing and UL packet generation timing. The UL packet generation cycle, G_i^{p}, is randomly and uniformly selected from range $[1, G_{\max}^{\mathrm{p}}]$ with $G_{\max}^{\mathrm{p}}$ [min] being the maximum UL packet generation cycle. A UL packet containing packet counter m is transmitted to the GW using SF $S_i \in \mathcal{S}$ and frequency channel $k_i \in \mathcal{K}$.

All UL packets are transmitted as an unconfirmed message, which does not require an acknowledgement (ACK) from the GW. Note that UL packets are transmitted after the CS process, as described later. Node i waits for T^{w} [sec] after transmitting a packet, then opens a receive window. Opening the receive window enables the node to receive a DL packet from the GW. This paper assumes that the receive window opens for a duration equal to T_i^{ToA}, and DL packets transmitted from the GW during the receive window are ideally received.

C. GW

In this paper, the GW successfully received a UL packet if its signal-to-noise power ratio (SNR) is above threshold value Γ^{SNR}. Furthemore, this paper considers the capture effect. Even in the case of packet collision, the GW can sucessfully reeives the UL packet first received among colliding packets if it satisifies both SNR and signal-to-interference power ratio (SIR) thresholds [10], [11].

When the GW successfully receives a packet from node i, the GW may transmit a DL packet to node i with same SF S_i and frequency channel k_i as node i. The frequency of DL packet transmission is significantly influenced by the number of nodes in the system, necessitating careful consideration of the Duty cycle (DC) constraint. To satisfy the DC constraint, after transmitting a DL packet on frequency channel k_i, the GW stops DL packet transmission on frequency channel k_i for a duration of $T_{k_i}^{\mathrm{DC}}$ [sec]. If DL packet transmission timing exceeds the reception window period of a node by DC constraint, the GW discards the DL packet. The waiting time, $T_{k_i}^{\mathrm{DC}}$, is expressed as

$$T_{k_i}^{\mathrm{DC}} = \left(\frac{1 - D_{\mathrm{c}}}{D_{\mathrm{c}}} \right) T_i^{\mathrm{ToA}}(S_i), \tag{4}$$

where $D_{\mathrm{c}} \in (0, 1]$ is the DC.

D. CSMA-x

This subsection describes the brief operation of CSMA-x [7], which forms the basis of the proposed method. In this paper, each node performs CS and backoff based on CSMA-x. Prior to UL packet transmission, node i performes CS for a duration of T^{CS} [msec]. During T^{CS}, if observed power value P_i^{CS} [dBm] by CS is less than or equal to CS threshold Γ^{CS} [dBm], the node transmits the packet immediately after T^{CS} elapses. On the other hand, if P_i^{CS} [dBm] exceeds Γ^{CS} [dBm], node i judges frequency channel k_i is in use and initiates a backoff procedure. Backoff waiting time $T_{\mathrm{back}}^{\mathrm{cs}}$ [sec] for the m-th packet is expressed as

$$T_{\mathrm{back}}^{\mathrm{cs}} = \mathcal{U}'\left(1, 2^{n_{\min}^{\mathrm{CS}} + n_{\mathrm{r}}^{\mathrm{CS}}}\right), \tag{5}$$

where $\mathcal{U}'(a, b)$ is a function that uniformly randomly generates values in the range $[a, b]$, $n_{\min}^{\mathrm{CS}}$ is the minimum backoff exponent, and $n_{\mathrm{r}}^{\mathrm{CS}}$ indicates the backoff count for the m-th packet. Backoff procedure occurs until $n_{\min}^{\mathrm{CS}} + n_{\mathrm{r}}^{\mathrm{CS}} \leq N_{\max}^{\mathrm{CS}}$, where $N_{\max}^{\mathrm{CS}}$ is the maximum backoff exponent.

III. Proposed Scheme

In LoRaWAN with a wide communication area, the hidden node problem may arise in CSMA-x, where the UL signal cannot be detected by CS. Therefore, this paper proposes a distributed resource allocation method that utilizes both CS and traffic periodicity. The proposed method tries hidden node detection using DL signals from the GW to alleviate the hidden node problem. The rationale behind the proposed method is that *node i can detect DL signals transmitted to a node that is the hidden node from the viewpoint of node i.* Once node i detects DL signals transmitted to hidden nodes, node i switches to another frequency channel to avoid packet collisions.

A. Overview of Proposed Method

Firstly, we explain transmission timing control for the nodes that can CS each other. Since the UL packet transmission is periodic, for example, two nodes that can CS each other

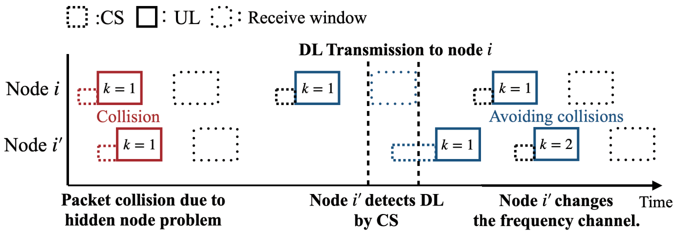

Fig. 1. Overview of proposed method

and whose UL packet transmission timing overlaps with each other must perform backoff processing every UL packet transmission. Therefore, we introduce a transmission offset T_i^{off} at node i to efficiently avoid transmission timing overlap between such nodes. Next, we explain how to allocate resources to avoid packet collisions between hidden nodes. *Since DL signals from the GW generally reach all nodes, it is highly likely that node i can detect DL signal to its hidden node i'.* In the proposed method, node i executes CS in its own receive window timing of the mth UL packet, and we define it as *receive window timing CS*. If node i detects a DL signal that is not intended to node i by receive window timing CS, it presumes that another node transmitted a UL packet at the timing of mth UL packet transmission of node i. Therefore, as shown in Fig. 1, if node i detects a DL signal by the receive window timing CS, node i tries to avoid packet collision by changing frequency channel k_i. However, in order to transmit a DL signal to node i', the UL packet of node i' must be successfully received. Hence, when continuous collisions occur due to the hidden node problem and the periodicity of UL traffic, it is necessary to temporarily change the transmission timing of node i so that the GW can receive the UL packets of node i'. Thus, the proposed method introduces a transmission timing change probability p^{t} at each node to change the transmission timing probabilistically.

The flow of the proposed method is summarized below.

1) A node autonomously determines the transmission timing offset to avoid packet collisions with neighboring nodes.
2) A node temporarily avoids consecutive packet collisions using transmission timing change probability p^{t}.
3) The GW transmits a DL signal to the node whose UL packet has been successfully received.
4) When a node detects a DL signal intended to the other node from the GW by the receive window timing CS, the node autonomously changes the frequency channel.

B. Transmission Timing Offset

To avoid transmission timing overlap with node i's neighbors, node i determines transmission timing offset T_i^{off}. When node i receives a DL packet from the GW corresponding to its own mth successful UL packet reception, node i determines T_i^{off} as

$$T_i^{\mathrm{off}} = T_{i,m}^{\mathrm{back}} - T_{i,m}^{\mathrm{g}} - T^{\mathrm{CS}}, \tag{6}$$

where $T_{i,m}^{\mathrm{back}}$ [sec] is the CS processing end time, including backoff processing time for the mth packet and $T_{i,m}^{\mathrm{g}}$ [sec] is the time when the mth UL packet is generated. Therefore, CS start time $T_{i,m+1}^{\mathrm{CS}}$ [sec] for the $m+1$th packet at node i can be expressed as

$$T_{i,m+1}^{\mathrm{CS}} = T_{i,m+1}^{\mathrm{g}} + T_i^{\mathrm{off}}. \tag{7}$$

When the frequency channel is changed as described below, node i sets $T_i^{\mathrm{off}} = 0$ and performs the above process again.

C. Transmission Timing Change Probability

All nodes are pre-assigned a transmission timing change probability p^{t}. Each node temporarily changes the packet transmission timing with probability p^{t}. Here, the packet counter notation is set to m' for the mth packet whose transmission timing is changed with p^{t}. Since the transmission timing of UL packets depends on the result of CS execution, the temporary transmission timing start time is expressed by changing the CS start time. The m'th packet CS start time, $T_{i,m'}^{\mathrm{CS}}$, is expressed as

$$T_{i,m'}^{\mathrm{CS}} = T_{i,m}^{\mathrm{CS}} + T^{\mathrm{CS}} + T_i^{\mathrm{ToA}} + 2T^{\mathrm{w}}. \tag{8}$$

After $T_{i,m'}^{\mathrm{CS}}$, node i performs CSMA-x operation. When a DL packet for the m'th UL packet is received, T_i^{off} is not calculated.

D. Receive Window Timing CS

Node i executes receive window timing CS in addition to the CS of CSMA-x when it becomes m'th packet with p^{t}. The start time of receive window timing CS, $T_{i,m'}^{\mathrm{RWCS}}$, is expressed as

$$T_{i,m'}^{\mathrm{RWCS}} = T_{i,m}^{\mathrm{CS}} + T^{\mathrm{CS}} + T_i^{\mathrm{ToA}} + T^{\mathrm{w}}. \tag{9}$$

The timing of the DL packet to node i transmission may be delayed within the receive window duration of node i due to DC constraints at the GW. Therefore, the receive window timing CS duration is set to the same length as T_i^{ToA} and is longer than T^{CS}. Equation (9) allows node i to perform CS at the time of DL signal transmission for the UL packet of another node that has overlapped with the mth packet transmission timing of node i.

CS detects the presence of a signal solely based on the power value in frequency channel k_i. Thus, it is difficult for node i to judge whether or not the detected signal is a DL signal from the GW by the CS only. Thus, DL signal detection is performed by comparing the DL packet received power P_i^{RDL} [dBm] and P_i^{CS} observed by the receive window timing CS. The indicator function taking P_i^{RDL} and P_i^{CS} as arguments is expressed as

$$f(P_i^{\mathrm{CS}}, P_i^{\mathrm{RDL}}) = \begin{cases} 1 & \text{if } \mathrm{round}(P_i^{\mathrm{CS}}) = \mathrm{round}(P_i^{\mathrm{RDL}}) \\ 0 & \text{otherwise} \end{cases}, \tag{10}$$

where $\mathrm{round}(x)$ denotes a function that rounds x to the nearest integer value. Equation (10) being 1 indicates that the signal detected by the receive window timing CS is the DL signal from the GW.

TABLE I
SIMULATION PARAMETERS

Simulation area radius, R	300 [m]
Simulation time	2880 [min]
Number of LoRaWAN nodes, I	1000
Transmit power, P_t	13 [dBm]
Carrier frequency, f_c	923 [MHz]
Bandwidth, W	125 [kHz]
Number of frequency channels, K	$\{2, 4, 8\}$
SF, $\mathcal{S}$	7
SNR threshold, Γ^{SNR}	-7.5 [dB]
SIR threshold, Γ^{SIR}	6 [dB]
Coding rate, R	4/7
Duty cycle, D_c	0.01
Noise power spectrum density, N_0	-174 [dBm/Hz]
α, β, η	$4.0, 9.5, 4.5$
Overhead symbol, O_{sym}	20.25
Packet data size, B_{data}	160 [bits]
$G^{\mathrm{p}}_{\max}$	5 [min]
CS threshold, Γ^{CS}	-110 [dBm]
CS duration, T^{cs}	5 [msec]
$n^{\mathrm{CS}}_{\min}, n^{\mathrm{CS}}_{\max}$	$1, 3$
T^{w}	1 [sec]
Transmission timing change probability p^{t}	0.05

E. Target Node for DL Transmission

When the GW successfully receives a UL packet from node i, the GW can know packet counter m based on the information included in the packet header. Therefore, the GW can estimate number of lost packets $\hat{N}_i^{\mathrm{loss}}(j)$ between the $j-1$th and the jth successful receptions from node i. Due to DC constraints and half-duplex communication mode, it is inefficient for the GW to transmit DL packets to all UL packets of all nodes. In addition, it is important to reallocate wireless resources to nodes causing continuous packet collisions due to the hidden node problem. Thus, based on $\hat{N}_i^{\mathrm{loss}}(j)$, The GW transmits DL packets to the nodes suffering from continuous packet collisions. The GW transmits DL packets to node i, satisfying

$$\hat{N}_i^{\mathrm{loss}}(j) \geq 2. \tag{11}$$

F. Frequency Channel Selection

When node i detects a DL signal for another node based on (10), node i changes frequency channel k_i. Here, $\mathcal{K}'_i \subseteq \mathcal{K}$ is defined as the set of frequency channels already used by node i. Node i randomly selects a frequency channel from among the available frequency channels, excluding already used frequency channels. Therefore, the allocation of a new frequency channel $k_i{}^\star$ satisfies

$$k_i{}^\star \in \mathcal{K} \setminus \mathcal{K}'. \tag{12}$$

If $\mathcal{K} \setminus \mathcal{K}' = \emptyset$, then node i resets $\mathcal{K}' = \emptyset$.

IV. SIMULATION AND RESULTS

The nodes are distributed randomly and uniformly within a circular communication area with a radius of R [m], centered around the GW. This paper adopts a simple channel model to evaluate the impact on communication quality through resource allocation without loss of generality. The received power at the GW from node $i \in \mathcal{I}$ is expressed as

$$P_i^{\mathrm{r}} = P^{\mathrm{t}} - P^{\mathrm{Loss}}(d_i), \tag{13}$$

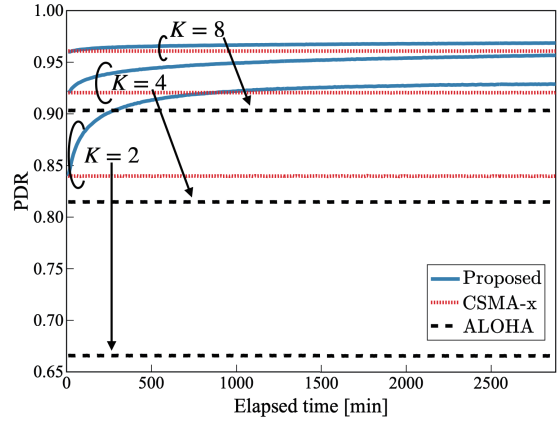

Fig. 2. PDR performance.

where P^{t} [dBm] is the transmit power common to the nodes and GW, $P^{\mathrm{Loss}}(d_i)$ [dB] is the path loss component, and d_i [km] is the physical distance between node i and the GW. The path loss component assumes an urban environment with non-line-of-sight (NLoS) conditions. From [12], path loss component $P_{\mathrm{Loss}}(d_i)$ [dB] is expressed as

$$P_{\mathrm{Loss}}(d_i) = 10\alpha \log_{10} d_i + \beta + 10\eta \log_{10} f_\mathrm{c}, \tag{14}$$

where propagation parameters α, β, and η are the path loss coefficient, offset, and frequency loss component, respectively, and f_c [MHz] is the carrier frequency. Assuming a reciprocal channel between the UL and DL channel, the received signal power at node i from the GW is assumed to be equal to P_i^{r}.

A. Simulation Parameters

In the simulation, $R = 300$ [m] is set so that the DL signal can be detected by the CS anywhere in the communication area. The system parameters are listed in Tables I, which follow the Japanese parameter configuration AS923 [13].

B. Performance Metrics

Since the proposed method performs sequentially, it is necessary to evaluate the time variation of the communication quality of the system. Thus, in this paper, we evaluate the PDR at fixed cycles. We define a *cycle* as 10 [min], which is indexed by $c \in \{1, \cdots, c, \cdots, C\}$. The PDR during the cth observation period is expressed as

$$\mathrm{PDR} \triangleq \frac{\sum_{i=1}^{I} N_{i,c}^{\mathrm{s}}}{\sum_{i=1}^{I} N_{i,c}^{\mathrm{t}}}, \tag{15}$$

where N_c^{s} is the number of UL packets of node i successfully received by the GW and N_c^{t} is the total number of packets transmitted by node i during the cth cycle, respectively. The PDR of each node is also evaluated. The PDR of node i from the start to the end of the system is expressed as

$$\mathrm{PDR}_i \triangleq \frac{\sum_{c=1}^{C} N_{i,c}^{\mathrm{s}}}{\sum_{c=1}^{C} N_{i,c}^{\mathrm{t}}}, \tag{16}$$

To evaluate the effects of continuous packet collisions and transmission timing offset, we define the UL packet reception

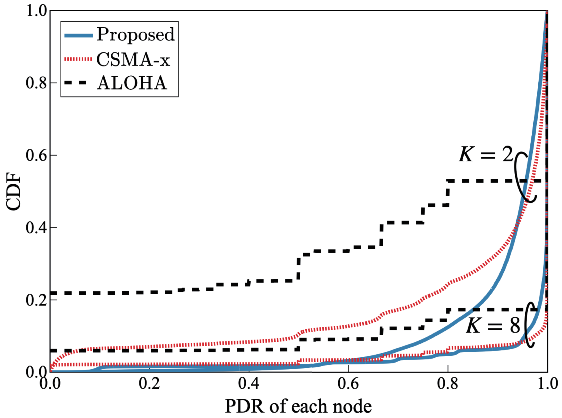

Fig. 3. CDF of the PDR for each node.

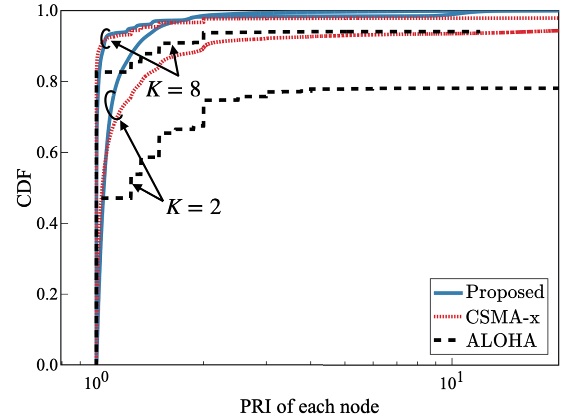

Fig. 4. CDF of PRI.

interval (PRI) from node i at the GW. The normalized UL PRI for node i is expressed as

$$\mathrm{PRI}_i \triangleq \frac{1}{J_i - 1} \sum_{j=1}^{J_i} \left(\frac{T_{i,j}^{\mathrm{R}} - T_{i,j-1}^{\mathrm{R}}}{G_i^{\mathrm{P}}} \right), \tag{17}$$

where J_i is the count of UL packets of node i successfully received at the GW and $T_{i,j}^{\mathrm{R}}$ [sec] is the reception time of the jth packet at the GW.

C. Numerical Results

To check the effectiveness of the proposed method, we also evaluate the performance of ALOHA in the LoRaWAN standard and CSMA-x in Section II-D. Fig. 2 shows the performance of the PDR defined by (15). From Fig. 2, the proposed method improves the PDR performance as time elapses. This is because the transmission timing offset and frequency channel changes by receive window timing CS can avoid packet collisions caused by the hidden node. When $K = 2$, the proposed method can improve PDR by up to approximately 26% and 9% compared to ALOHA and CSMA-x, respectively. Fig. 3 shows the cumulative distribution function (CDF) performance of the PDR_i. From Fig. 3, the proposed method shows that the proposed method can reduce the ratio of nodes with low PDR compared to ALOHA and CSMA-x. Therefore, compared to CSMA-x, the proposed method improves the PDR fairness between nodes while improving the entire system PDR.

Fig. 4 shows the CDF performance of PRI for each node. From Fig. 4, the proposed method increases the ratio of nodes with low PRI compared to ALOHA and CSMA-x, even though transmission delays are caused by transmission timing offset and temporary changes in transmission timing. This is because the packet generation cycle is much larger than the transmission delay caused by the proposed method, so the effect of avoiding continuous packet collisions is significant.

V. Conclusion

This paper proposed a distributed resource allocation method that utilizes both CS and the periodicity of traffic in LPWANs. By utilizing the periodicity of UL traffic, nodes perform DL detection using receive window timing CS to avoid packet collisions caused by the hidden node. Computer simulation results have shown that the proposed method can improve the PDR performance by up to about 26% and 9% compared to ALOHA and CSMA-x, respectively.

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