Indirect Notification of Interference Status Through Resource Mapping in LoRaWAN

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***Abstract*—The worldwide adoption of Long Range Wide Area Network (LoRaWAN) is rapidly accelerating alongside the development of the Internet of Things (IoT), owing to its capability for long-range communication with low power consumption. Since LoRaWAN operates in the unlicensed sub-GHz band, effective frequency sharing with other systems and interference avoidance are crucial for improving communication quality. This paper proposes a method to indirectly notify the Gateway (GW) of frequency channel interference conditions without incurring additional overhead. This indirect notification is achieved by strategically mapping the transmission of uplink packets to account for high interference around the node. Specifically, the proposed mapper notifies the interference-affected channel by dynamically determining the resource search order based on the packet counter. Consequently, the GW can estimate the interference-affected channel by referencing the mapping rule. Numerical calculations demonstrate the estimable characteristics at GW. Furthermore, computer simulations demonstrate that the proposed method improves throughput in LoRaWAN systems compared to existing methods.**

***Index Terms*—LoRaWAN, Radio Resource Allocation, Index Mapper**

I. Introduction

The rapid development of the Internet of Things (IoT) has accelerated the proliferation of Wireless Sensor Networks (WSNs) with wireless communication capabilities [1]. WSN nodes are typically designed to be compact, cost-effective, and energy-efficient. In this context, Low Power Wide Area Network (LPWAN), which achieves long-range communication with low power consumption, has gained significant attention [2], [3].

The Long Range Wide Area Network (LoRaWAN), which is one of the leading LPWAN standards, is attracting significant attention and is being widely deployed owing to its use of unlicensed bands and low deployment costs [3], [4]. In LPWAN using unlicensed frequency bands, frequency sharing with other systems necessitates that Gate-Ways (GWs) and nodes limit their transmission time per interval, a constraint known as Duty-Cycle (DC). Furthermore, for the same reason, implementing Carrier Sense (CS) for a specified period is mandatory before packet transmission to confirm channel availability. However, when the communication area is wide-range, as is characteristic of LoRaWAN, this leads to the well-known hidden node problem [5].

The Packet-Level Index Modulation (PLIM) proposed in [6] improves throughput by indexing the frequency channel and transmission timing of the packets, while considering DC constraints. Moreover, Channel Activity Detection-based PLIM (CAD-PLIM) was proposed in [7]. This method provides multiple opportunities for backoff and packet transmission when CS detects packet transmission from another node. Nevertheless, packet collisions persist at the GW between nodes that cannot detect each other's transmissions via CS. To address this issue, [8] proposes a method for assigning orthogonal frequency resources to such hidden nodes. Specifically, the GW estimates which other nodes' transmissions a node detected via CS and subsequently backed off, thereby enabling the GW to recognize the radio environment. A major drawback of this approach, however, is that the GW requires a prolonged observation period to accurately recognize the radio environment. Consequently, an effective mechanism is needed for nodes to indirectly notify the GW of frequency channels with high interference without incurring additional overhead.

In this context, a method was proposed in [9] that allows nodes to indirectly notify the GW of channel status in Up-Link (UL) communication without overhead. This method utilizes a portion of the payload bit sequence transmitted in packets as the PLIM bit sequence to indicate interference-affected channels. A dedicated mapper establishes unique resources for interference-affected channels and the PLIM bit sequence. However, this method is limited to notifying a maximum of two interference-affected channels. Furthermore, as the number of interference-affected channels increases, the number of available channels decreases, resulting in a reduction in the possible values for the PLIM bit. This inevitably leads to the occurrence of unassigned, extra resources.

This paper proposes an interference notification method capable of notifying up to $K-1$ interference-affected channels. The proposed method enables the indirect notification of interference-affected channels to the GW by designing a mapper that uniquely determines resources based on the packet counter included in the packet header. Our computer simulation results demonstrate that the proposed method improves throughput in LoRaWAN systems compared to the conventional PLIM [6].

The remainder of this paper is structured as follows. Section 2 describes the system model, Section 3 reviews PLIM which is

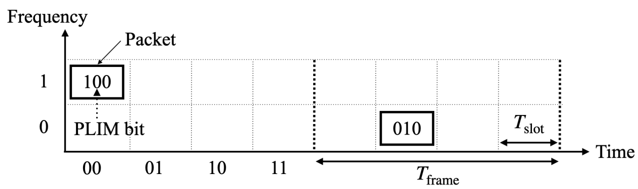

Fig. 1: Overview of PLIM $(K = 2, Q = 4)$ [7]

the conventional method [6], and Section 4 details the proposed method. Section 5 presents the estimation of the interference-affected channel through numerical calculations, and Section 6 presents an evaluation based on computer simulation results. Section 7 concludes this paper.

II. System Model

This paper assumes a LoRaWAN system featuring a single GW centrally located within a circular communication area of radius R [m]. Within this area, M nodes are spatially distributed according to a Poisson Point Process (PPP). Each node generates and transmits a packet to the GW every T_{frm} [sec]. The term *interference-affected channel* is used throughout this paper to refer to a frequency channel experiencing high interference. Also, it is assumed that each node is aware of the current interference-affected channel(s).

A. Clock Drift

Generally, the low cost of LoRaWAN nodes inherently leads to individual clock drift in each device. However, because the actual clock drift includes probabilistic fluctuations, the GW cannot precisely know the true clock drift value for any given node. Therefore, the GW tries to synchronize the time by estimating the drift value using historical packet reception logs. Consequently, a correction error invariably exists between the estimated value and the true value.

B. Packet Reception at GW

The success of packet reception at the GW is determined based on the received SNR and the received Signal-to-Interference Ratio (SIR), while considering the capture effect. Specifically, if the GW receives only one packet, it is considered to be successfully received if its received SNR exceeds the threshold value [10]. In the case of overlapping reception of multiple packets at the GW, reception success is judged for the packet that arrived first. This determination is based on the received SNR and SIR of the first packet; all other overlapping packets are considered lost [11].

III. Packet-Level Index Modulation (PLIM)

PLIM was proposed as a type of index modulation to improve the throughput of LoRaWAN systems [6]. By treating the combination of the frequency channel and the packet transmission timing as an index, PLIM conveys additional data bits implicitly. This approach increases throughput while complying with DC constraints. Figure 1 illustrates an overview of the scheme.

We consider a scenario typical of WSNs, where M nodes periodically generate data and transmit it to the GW. Without loss of generality, we focus on the communication between a representative node and the GW over K frequency channels. The node generates a data packet every frame length T_{f} [sec]. This frame is equally divided into Q time slots, each with a duration of T_{slot} [sec].

Each node is identified by a unique device address $\mathbf{B}_{\mathrm{addr}}$, and each packet carries a packet counter $\mathbf{B}_{\mathrm{pcnt}}$. The node generates an information bit sequence $\mathbf{B} = (b_0, b_1, \ldots, b_{B-1})$, where $b_i \in \{0, 1\}$. This sequence is divided into a PLIM bit sequence $\mathbf{B}_{\mathrm{plim}}$ of length B_{plim} and a payload bit sequence $\mathbf{B}_{\mathrm{pl}}$ of length B_{pl}, such that $B = B_{\mathrm{plim}} + B_{\mathrm{pl}}$. The payload $\mathbf{B}_{\mathrm{pl}}$ is transmitted using standard LoRaWAN processing. Further, it transmits the generated data packet at frequency channel $k \in \mathcal{K} = \{0, 1, \ldots, K-1\}$ and time slot $q \in \mathcal{Q} = \{0, 1, \ldots, Q-1\}$, which are determined by

$$(k, q) = \mathcal{F}_{\mathrm{plim}}(\mathbf{B}_{\mathrm{plim}}), \tag{1}$$

where $\mathcal{F}_{\mathrm{plim}}$ denotes an arbitrary index mapper.

Once the GW receives a packet on frequency channel $\tilde{k} \in \mathcal{K}$, it estimates time slot $\tilde{q} \in \mathcal{Q}$ [12]. The combination of the estimated frequency channel and time slots, $(\tilde{k}, \tilde{q})$, are input to the index de-mapper $\mathcal{F}_{\mathrm{plim}}^{-1}$, which demodulates the PLIM bit sequence $\tilde{\mathbf{B}}_{\mathrm{plim}} \in \{0, 1\}^{B_{\mathrm{plim}} \times 1}$ as

$$\tilde{\mathbf{B}}_{\mathrm{plim}} = \mathcal{F}_{\mathrm{plim}}^{-1}(\tilde{k}, \tilde{q}). \tag{2}$$

IV. Proposed Methods

The paper proposes an overhead-free method for indirectly notifying a LoRaWAN GW of channels frequently affected by interference. As mentioned previously in this paper, these channels are call *interference-affected channel* and are recognized by each node. The key idea is to design an index mapper that maps the packet counter and the node's locally known interference-affected channel set to a specific time–frequency resource selection order; the GW can then infer which channel(s) the node is avoiding by reversing the shared mapping rule from the observed resource and header packet counter. The proposed method enables indirect notification of interference-affected channels by transmitting UL packets, allowing notification of up to $K - 1$ interference-affected channels.

A. Definitions

Let us consider a system where K frequency channels and Q time slots are used. The set of all frequency channels is denoted as $\mathcal{K} = \{0, 1, 2, \cdots, K-1\}$, and the set of time slots as $\mathcal{Q} = \{0, 1, 2, \cdots, Q-1\}$. Thus, the total number of resources is $N_{\mathrm{res}} = K \times Q$. The transmitted code X is calculated as

$$X = \mathrm{mod}(D_{\mathrm{addr}} + D_{\mathrm{pcnt}}, N_{\mathrm{res}}), \tag{3}$$

where D_{addr} and D_{pcnt} are the decimal values of the bit sequences of the device address and packet counter, respectively. To represent the available state of each frequency channel, a binary variable a_k is introduced for each $k \in \mathcal{K}$, where $a_k = 1$

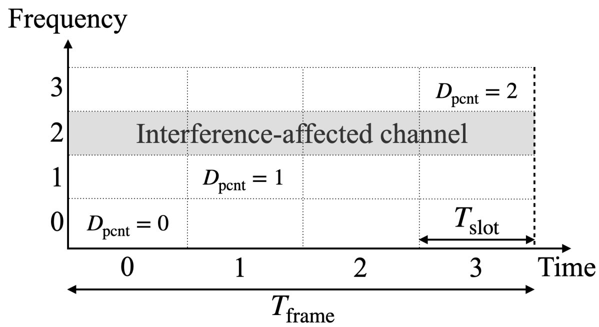

Fig. 2: Resource allocation using packet counters $(K = 4, Q = 4)$

indicates that channel k is available, and $a_k = 0$ indicates that channel k should be avoided.

$$a_k = \begin{cases} 1, & \text{if frequency channel } k \text{ is available,} \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Using these variables, the set of available channels is represented as $\mathcal{K}_a = \{k \in \mathcal{K} \mid a_k = 1\}$ and the set of interference-affected channels is $\mathcal{K}_b = \{k \mid a_k = 0\}, |\mathcal{K}_b| \leq K - 1$. The interference pattern, which is the sum of all combinations of interference-affected channels, can be expressed as follows:

$$\mathcal{P} = \{\mathcal{K}_b \subseteq \mathcal{K} \mid \mathcal{K}_b \neq \mathcal{K}\}. \tag{5}$$

Pattern with all frequency channels should be avoided is omitted, because there is no channel available for the node to transmit. Therefore, the total number of patterns is $P = |\mathcal{P}| = 2^K - 1$. Consequently, the condition $N_{\rm res} \geq P$ must be satisfied to assign a unique resource to each interference pattern. If this condition is not fulfilled, it becomes impossible to uniquely assign patterns to some interference-affected channels.

Finally, the node transmits the data packet using the frequency channel k and a time slot q. The combination of frequency channel and time slot is defined as the transmission resource index (k, q) (hereafter called resource).

B. Index Mapper

The operation of the index mapper $\mathcal{F}$ performs allocation based on a dynamic cycle of the resource allocation decision order, determined by the packet counter $D_{\rm pcnt}$ and the stringency of the interference-affected channel constraints. Fig. 2 shows this situation for the case where the interference-affected channel is $\mathcal{K}_{\rm b} = 2$. First, for the purpose of prioritizing patterns with strict resource allocation constraints, the elements of the interference pattern set $\mathcal{P}$ are sorted in order of increasing available channel count $|\mathcal{K}_{\rm a}|$, indexed by i. Next, the available channels $\mathcal{K}_a$ are checked in order of this i to determine whether they can be allocated to the resource (k, q). This check prioritizes frequency channel k over time slot q because the frequency channel allocation must be unbiased. The indices of frequency channel k and time slot q start from zero and increase in ascending order. These indices cyclically repeat within their respective ranges. Consequently, patterns with fewer degrees of freedom are prioritized for resource allocation. Thus, the initial indices of frequency channel k and time slot q for allocation are respectively given by

$$k_{\rm start} = \mathrm{mod}\left(D_{\rm pcnt} + i + k,\, |\mathcal{K}_a|\right), \tag{6}$$

$$q_{\rm start} = \mathrm{mod}\left(D_{\rm pcnt} + i + q,\, Q\right). \tag{7}$$

Using the initial indices, the frequency channel $k^\star$ and time slot $q^\star$ are determined for packet transmission.

C. Estimation of Interference-affected Channel

GW estimates the set of interference-affected channel(s) based on the received resource and the packet counter. GW computes all possible channel patterns in reverse, up to a maximum of $2^K - 1$ possibilities, using a common mapper shared with the node. Specifically, GW calculates a hypothetical estimated resource (k', q') from the available channels and packet counters for each pattern. If (k', q') matches the resource actually received, it is estimated that the available channel was used for transmission from the node. This mapping is a one-to-one relationship; therefore, for any given pair of a received resource and a packet counter, only one pattern exists that satisfies this condition. Thus, provided GW successfully receives packets, it can uniquely estimate the interference-affected channel condition around the node.

V. Numerical Calculation Results

A. Calculations Parameters and Evaluation Metrics

Even with a limited number of frequency channels and time slots $(K = 4, Q = 4)$, the proposed method effectively distinguishes multiple interference-affected channels while maintaining unique and collision-free (k, q) mappings. This suggests that implicit signaling based on resource allocation is feasible even in resource-constrained environments, where explicit notification would otherwise incur significant overhead. We focus on transmission symbols X in which only the packet counter $D_{\rm pcnt}$ is varied, while the device address $D_{\rm addr}$ is fixed to 0.

B. Estimation Results

Table I presents simulation results that illustrate how the transmission resource (k, q) varies according to the interference-affected channel(s). $K_{\rm a}$ and $\hat{K}_{\rm a}$ show available channels and estimated available channels. As defined in (4), there are represented in binary format, where 1 denotes an available channel and 0 denotes an interference-affected channel. The examples for $D_{\rm pcnt} = 1$ and $D_{\rm pcnt} = 3$ demonstrate that the resulting resource allocation changes depending on the interference-affected channels, even for the same packet counter. Since $D_{\rm pcnt}$ is mapped to different resources based on the specific configuration of interference-affected channels, the GW can infer the local interference environment of the node by comparing the received resource (k, q) with the packet counter extracted from the header. This confirms that even with a fixed $D_{\rm pcnt}$, the resulting resource *changes* depending on the interference-affected channel. Consequently, implicit interference status notification is achieved without any additional signaling.

TABLE I: Estimated interference-affected channel ($D_{\rm pcnt} = 1, 3$)

$D_{\rm pcnt}$	$K_{\rm a}$	(k, q)	$\hat{K}_{\rm a}$
1	$[1, 1, 1, 1]$	$(1, 0)$	$[1, 1, 1, 1]$
1	$[1, 0, 1, 1]$	$(3, 0)$	$[1, 0, 1, 1]$
1	$[1, 1, 0, 0]$	$(1, 4)$	$[1, 1, 0, 0]$
3	$[1, 1, 1, 1]$	$(3, 0)$	$[1, 1, 1, 0]$
3	$[1, 0, 1, 1]$	$(2, 1)$	$[1, 0, 1, 1]$
3	$[1, 1, 0, 0]$	$(1, 3)$	$[1, 1, 0, 0]$

TABLE II: Simulation Parameters

Parameters	Values
Area radius R	500 [m]
Carrier frequency $f_{\rm c}$	923.2 [MHz]
Bandwidth BW	125 [kHz]
Transmit power P_t	13 [dBm]
Number of nodes M	{200, 400, ..., 1000}
Total number of frequency channels K	4
Total number of time slots Q	4
UL packet generation cycle $T_{\rm frm}$	2 [min]
SF SF_m	7
Payload size	160 [bit]
Shadowing standard deviation	3.48 [dB]
Correlation distance $d_{\rm cor}$	50 [m]
Noise power spectral density σ^2	-174 [dBm/Hz]
Noise figure NF	10 [dB]

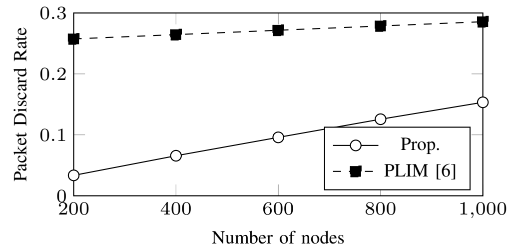

Fig. 3: Packet Discard Rate

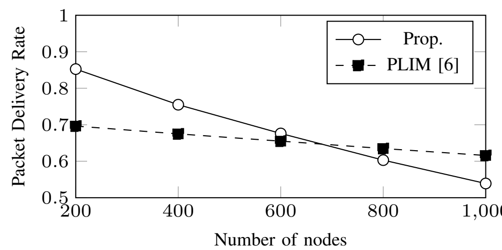

Fig. 4: Packet Delivery Rate

C. *Superior Resource Efficiency*

For the case of $K = 4$, if the conventional PLIM scheme [6] is used to notify the interference-affected channels, 4 bits of information are required. Since 4 bits correspond to $2^4 = 16$ unique combinations, this implies that $Q = 16$ time slots would be consumed just to convey this status. On the other hand, if explicit notification is used to avoid such resource consumption, it inevitably incurs additional communication overhead. In contrast, the proposed method only requires that the condition $N_{\rm res} \geq P$ be satisfied to assign a unique resource to each interference pattern. Therefore, with $K = 4$, the proposed method operates successfully with only $Q = 4$, reducing the required number of time slots by up to 75%. More importantly, the proposed scheme achieves this notification indirectly by embedding the interference information into the resource mapping of the standard UL data packet. Consequently, it enables the notification of channel status without increasing the number of time slots like conventional PLIM, nor incurring packet overhead like explicit notification.

VI. Computer Simulation Results

A. *Simulation Parameters and Evaluation Metrics*

The effectiveness of the proposed method is confirmed by comparing it with PLIM [6]. Table II shows the primary simulation parameters [13]. Simulation time is 72 [hour]. The normalized clock drift for node m was generated based on [12]. The mean μ_m and variance σ_m are determined by uniformly selecting the values within the ranges $[-1.91\times10^{-3}, 0.28\times10^{-3}]$ and $[9.59 \times 10^{-11}, 3.19 \times 10^{-10}]$, respectively [12].

In the simulation, 10% of the M nodes are treated as interference nodes. These interference nodes transmit packets only on one specific frequency channel. PLIM is configured to always perform discard when transmitting on the frequency channel used by the interference node.

The propagation path assumes a non-line-of-sight (NLoS) environment in urban areas and considers the effects of path loss and shadowing. When the distance is given as d_m [m] between node m and the GW, the path loss $P_{\rm Loss}(d_m)$ [dB] at node m is given by the following [14]:

$$P_{\rm Loss}(d_m) = 10\alpha \log_{10}(d_m) + \beta + 10\eta \log_{10}(f_{\rm c}), \quad (8)$$

where $f_{\rm c}$ denotes the carrier frequency [MHz], α, β, and η represent the propagation coefficient, propagation loss offset, and carrier coefficient, respectively. In this simulation, as the model assumes an urban setting, we employ $\alpha = 4.0$, $\beta = 9.5$, and $\eta = 4.5$ [11]. The received signal power $P_{{\rm r},m}$ [dBm] at GW for a packet transmitted by node m is given by

$$P_{{\rm r},m} = P_{\rm t} - P_{\rm Loss}(d_m) - \psi, \quad (9)$$

where $P_{\rm t}$ [dBm] represents the transmit power, and ψ [dB] is a log-normally distributed shadowing having spatial correlation.

The evaluation metrics employed are packet discard rate, packet delivery rate (PDR), packet collision rate, and throughput. The packet discard rate shows the rate of packets discarded when CS determines the channel is busy and transmission is canceled. The PDR is defined as the number of packets successfully received by the GW relative to the total number of packets generated by the node. Throughput is defined as the number of bits successfully received at GW per unit time. In this simulation, it is defined as the number of bits received per minute [bit/min]. Successful transmission and reception means that packets discarded at GW due to collisions, packets discarded at node due to loss, and packets at GW falling below the SNR and SIR thresholds are excluded.

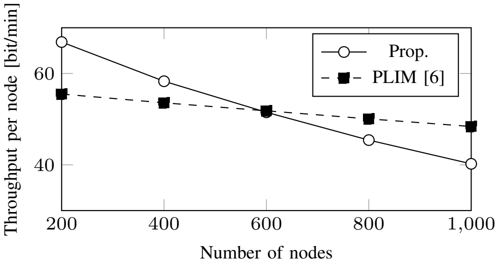

Fig. 5: Throughput per node

B. PDR

As shown in Fig. 3, the packet discard rate of the proposed method is significantly lower than that of PLIM. PLIM randomly selects from all four channels; however, if an interference-affected channel is selected, packets are invariably discarded. Consequently, the discard rate never falls below approximately 25% and shows a slight increase with the number of nodes. In contrast, the proposed method maintains a packet discard rate of nearly 0% because it avoids the interference-affected channel in advance. Meanwhile, as shown in Fig. 4, the proposed method achieves a higher PDR than PLIM in low-density environments. However, as the number of nodes increases, the PDR of the proposed method decreases sharply, falling below that of PLIM in high-density environments. This performance degradation is attributed to the proposed method utilizing only three available channels. The reduction in the number of available channels increases the node density per channel, leading to a rise in packet collision rate. Consequently, even when channels are determined to be available by CS, frequent packet collisions at the GW prevent correct packet reception, leading to the observed PDR performane.

C. Throughput

Figure 5 shows the average per-node throughput. The trend mirrors that of the PDR. In low-density environments, the proposed method achieves higher throughput than PLIM because PLIM inherently suffers from packet discards on the interference-affected channels, whereas the proposed method utilizes all packets for transmission.

However, as node density increases, the throughput of the proposed method decreases sharply and eventually falls below that of PLIM. This reversal results from channel load concentration in the proposed method, which leads to frequent packet collisions. Conversely, PLIM effectively reduces traffic load via packet discarding, thereby alleviating congestion and sustaining performance in high-density scenarios.

Notably, the throughput reversal at $M = 600$ precedes the PDR reversal at $M = 700$. This discrepancy is attributed to the *PLIM bits*. Since PLIM conveys additional information via channel indices, the effective information content per packet is larger. Consequently, throughput calculations based on total received bits confer a numerical advantage to PLIM even when its PDR is lower than that of the proposed method.

In conclusion, the proposed method enhances channel utilization efficiency by avoiding interference-affected channels, significantly improving system throughput in low-to-medium density environments.

VII. Summary

This paper proposed an indirect interference notification method for LoRaWAN. The proposed method enables the notification of the interference-affected channel around a node to the GW without additional overhead by utilizing resource selection in UL packet transmission. Furthermore, the proposed method reduces the number of time slots required for interference notification compared to the conventional PLIM, thereby improving resource efficiency. Moreover, computer simulations demonstrate that in low-to-medium density environments, the proposed method achieves a lower PDR and higher throughput than those of PLIM.

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