# Autonomous Decentralized Frequency Resource Allocation using ACK Signal in LoRaWAN

Kosuke Suzuki*, Naoki Aihara†, Koichi Adachi† and Satoshi Yamazaki*
* National Institute of Technology, Numazu College,
Numazu, Japan
† Advanced Wireless and Communication Research Center (AWCC), The University of Electro-Communications,
Chofu, Japan

***Abstract*—With the further development of the internet-of-things (IoT), numerous nodes are expected to be densely deployed. If multiple nodes simultaneously transmit packets on the same frequency channel, packet collision can occur at the gateway leading to packet loss. By transmitting an acknowledgment (ACK) signal to the node whose packet was correctly received by the gateway, the other nodes can initiate packet retransmission in order to resolve packet loss. However, ACK signal transmission is required from the gateway to all the nodes, increasing the gateway processing load and impacting the duty cycle (DC) restriction on the gateway. In this paper, we propose an autonomous decentralized frequency resource allocation scheme for LoRaWAN, aiming to reduce the number of packet collisions and the gateway processing load. We implement the proposed approach, and demonstrate its effectiveness through computer simulation and experimental evaluation.**

***Index Terms*—LoRaWAN, Frequency resource allocation, ACK, Confirmed packet**

## I. Introduction

In recent years, low-power wide-area (LPWA) that enables low-power consumption and wide-area communication for the internet-of-things (IoT) has been attracting attention [1], [2], [3]. Moreover, numerous nodes are expected be densely deployed with the further development of IoT. In such an environment, packets can collide, if multiple nodes simultaneously transmit packets to one gateway. Therefore, the gateway cannot receive the data correctly and the nodes cannot grasp the success or failure of packet transmission. To address this problem, a scheme called acknowledgment (ACK) transmission is available in which the gateway returns an ACK packet to the node after receiving the packet. The node that does not receive the ACK for the transmitted packet avoids packet loss by retransmitting the packet. However, the time required for transmitting an ACK will increase and the throughput will be degraded, if the gateway transmits an ACK each time a packet is received [4]. Furthermore, the duty cycle (DC), which is the time rate in which each node including the gateway can use the channel, is specified in the LPWA [1]. Therefore, the DC set for the gateway may be insufficient, if an ACK is transmitted frequently. For such problems, the impact of various downlink settings on the throughput has been evaluated through computer simulation for LoRaWAN [5], which is one of the LPWA standards [6], [7]. However, it has not been evaluated in an environment, where multiple nodes transmit packets at fixed time intervals. In addition, a scheme has been proposed in which packets that are originally intended to be received by one gateway are received by multiple gateways. It has been demonstrated that this scheme reduces the processing load of the gateway that originally receives it as well as packet loss in the entire gateway. However, this scheme does not change the processing load of the entire gateway.

In view of the above, in this paper, we propose a frequency resource allocation scheme in which each node decides the transmission frequency channel in an autonomous and decentralized manner. We consider an environment where multiple nodes transmit packets to a gateway at fixed time intervals. This scheme aims to simultaneously reduce the packet collision rate and processing load on the gateway. Specifically, we focus on unconfirmed packets that do not include an ACK transmission request and confirmed packets that include an ACK transmission request. We propose two schemes; in the first scheme, a node transmits a confirmed packet to a gateway periodically, and in the second scheme, a node transmits it probabilistically. If the node that transmits the confirmed packet does not receive an ACK signal, it is estimated that the transmitted packet is lost due to collision, and the frequency channel for the next transmission is randomly selected. The effectiveness of the proposed scheme is demonstrated through computer simulation and actual experimental evaluation.

The reminder of this paper is structured as follows: Section II outlines LoRaWAN, and section III describes the proposed scheme for frequency allocation using an ACK signal. Sections IV and V present the computer simulation and actual machine experimental results, respectively. Section VI summarizes the paper.

## II. Conventional LoRaWAN

### A. Overview

LoRaWAN [5] uses chirp spread spectrum (CSS) modulation in the physical (PHY) layer and the pure ALOHA scheme in the medium access control (MAC) layer [8]. Further, we describe two concepts related to this paper.

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*1) Class:* Three classes (class A, B, and C) are specified in the MAC layer. In class A used in this paper, two reception windows are formed immediately after an uplink transmission (node $\rightarrow$ gateway). After the window is setup, it receives the downlink (gateway $\rightarrow$ node). The uplink packet in class A includes five parts: the preamble, PHY header, header cyclic redundancy check (CRC), PHY payload (the first 3 bits are the MAC header), and CRC.

*2) Message type:* Message type is an identifier that represents the type of transmission packet included in the MAC header. In this paper, there are four related items: unconfirmed data up (UP), confirmed data up (CP), unconfirmed data down (ACK), and confirmed data down. For example, when UP is set as the message type, the gateway does not send an ACK even if the gateway successfully received a packet transmitted from a node. Similarly, when ACK is set, the node does not send an ACK, even if the gateway sends a packet to the node. On the other hand, when CP is set, the gateway sends an ACK, if the node sends a packet to the gateway.

Hereafter, a packet for which CP (UP) is set as the message type is referred to as the "CP (UP)".

### B. Time-sequence example

We assume an uplink environment in which two nodes transmit packets to a gateway at fixed time intervals. Fig. 1 depicts an example of the time sequence in the conventional LoRaWAN. Here, the activation at the start of communication is assumed to be activation by personalization (ABP) [5].

UP is first transmitted from node $j$ at time $t_1$ and frequency $f_1$, and it is assumed that the gateway successfully receives it. Now, the gateway does not transmit an ACK, and node $j$ does not judge the success or failure of packet transmission.

CP is then transmitted from node $j$ at time $t_2$ and frequency $f_1$, and it is assumed that the gateway successfully receives it. Now, the gateway transmits an ACK to node $j$, which judges that the packet is received successfully if it receives an ACK within $T_{\rm ack}$ [sec] after the end of packet transmission.

Further, CP is transmitted from node $j$ at time $t_3$ and frequency $f_1$, and UP is transmitted from node $i$ at time $t_4$ and frequency $f_1$; it is assumed that these packets collide and the gateway fails to receive both of them. Now, node $j$ judges that packet transmission has failed, if it does not receive an ACK within $T_{\rm ack}$ [sec] after the end of packet transmission. However, node $i$ does not judge the success or failure of packet transmission.

## III. Proposed Scheme

### A. System model

We assume an uplink environment in which $N$ nodes transmit packets to a gateway at fixed time intervals, as shown in Fig. 2. Each node transmits a packet at every time interval, $T_{\rm int}$ [sec]. In addition, node $n \in \{1, \cdots, N\}$ commences transmission at $T_{\rm s}(n)$ $(0 \leq T_{\rm s}(n) < T_{\rm int})$ and transmits the first packet.

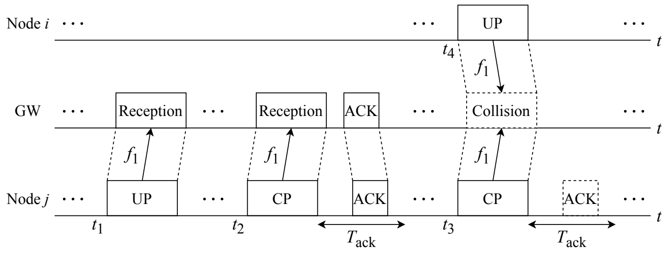



Fig. 1. Time-sequence example in conventional LoRaWAN

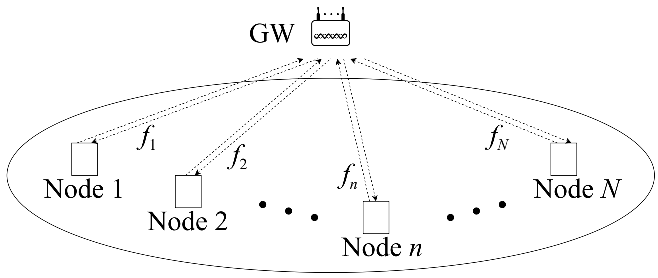



Fig. 2. System model

### B. Autonomous decentralized frequency resource allocation

Let us denote the transmission rate of CP by $R_{\rm cp}$, which is given by

$$R_{\rm cp} = N_{\rm cp}/(N_{\rm cp} + N_{\rm up}), \tag{1}$$

where $N_{\rm cp}$ and $N_{\rm up}$ are the number of CP and UP transmitted from a node, respectively. Then, the number of transmitted packets $L = 1/R_{\rm cp}$ is defined as one cycle. $R_{\rm cp}$ can be set arbitrarily under the constraint that $L$ is a natural number. The operation common to the two proposed schemes is described, after which each scheme is illustrated.

*Common operation:* Each node randomly selects the initial transmission frequency $f_n \in \mathcal{F}$. Further, either UP or CP is transmitted at a constant interval $T_{\rm int}$ according to each operation of the two proposed schemes described later. If each node does not receive an ACK from the gateway during CP transmission, it detects packet collision and randomly selects the next transmission frequency from $\mathcal{F} = \{1, \cdots, F\}$.

*Proposed scheme-1:* Before the commencement of communication ($t = 0$), a random variable $x$ (a natural number that satisfies $1 \leq x \leq L$ and follows a uniform distribution) is generated at the node. The CP is then transmitted $x$ times in one cycle; i.e., in one cycle, UP is first transmitted $x-1$ times, after which CP is transmitted once, and UP is transmitted $L-x$ times.

*Proposed scheme-2:* CP is transmitted with probability $R_{\rm cp}$ and UP is transmitted with probability $1 - R_{\rm cp}$. Specifically, before transmitting each packet, a random variable $y$ (which follows a uniform distribution, with a natural number satisfying $1 \leq y \leq L$) is generated in the node, and if $y = 1$ (For example, CP is transmitted, and if $y \neq 1$), UP is transmitted. This process is performed for all the transmitted packets in one cycle.

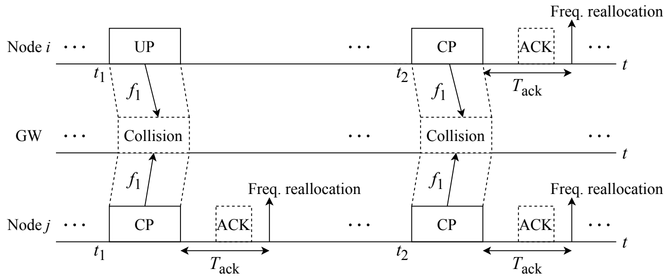



Fig. 3. Time-sequence example for the proposed scheme

As can be observed, proposed schemes- 1 and 2 both transmit CP once in a cycle. As mentioned in Sect. II-B, in conventional LoRaWAN operation, the transmission frequency is not changed, even if a collision occurs; however, in the proposed scheme, autonomous decentralized frequency resource allocation using ACK signals from the gateways is used.

### C. Time-sequence example

Fig. 3 displays an example of the time sequence for the operation of the proposed scheme, when two nodes $i$ and $j$ transmit packets to one gateway. In Fig. 3, $t_{k+1} = t_k + T_{\rm int}$ ($k$ : integer of 1 or more, $T_{\rm ack} < T_{\rm int}$).

UP is first transmitted from node $i$ and CP is transmitted from node $j$ simultaneously at time $t_1$ and frequency $f_1$, and it is assumed that these packets collide and the gateway fails to receive them. Now, since node $j$ does not received an ACK within $T_{\rm ack}$ [sec], it judges that packet transmission has failed and randomly selects the transmission frequency from $\mathcal{F} = \{1, \cdots, F\}$. However, node $i$ cannot judge the success or failure of packet transmission. Here, it is assumed that node $j$ selects transmission frequency $f_1$.

CP is then transmitted from nodes $i$ and $j$ simultaneously at time $t_2$ and frequency $f_1$, and it is assumed that these packets collide and the gateway fails to receive them. Now, since both nodes $i$ and $j$ do not receive an ACK within $T_{\rm ack}$ [sec], they judge that packet transmission has failed, and randomly select the transmission frequency from $\mathcal{F} = \{1, \cdots, F\}$.

## IV. Computer simulation

The system model depicted in Fig. 2 is applied, and the proposed schemes are evaluated through computer simulation. In this paper, for simplicity, we assume that there are no bit errors, radio wave propagation delays, and interference from other systems. Section IV-A performs basic evaluation in a multinode environment based on which Sect. IV-B evaluates the proposed scheme.

### A. Prior evaluation in conventional LoRaWAN

The maximum number of simultaneously transmitting nodes $N_{\rm col}$ is evaluated, applying the simulation specifications listed in Table I. Here, $N_{\rm col}$ is the maximum number of nodes that transmit simultaneously (the transmission packets overlap in time). Note that the number of frequency resources $F$ is 1 and the frequency does not change, even if packet collision occurs as described in Sect. III-B. Hence, the evaluation is based on the operation of the conventional LoRaWAN.

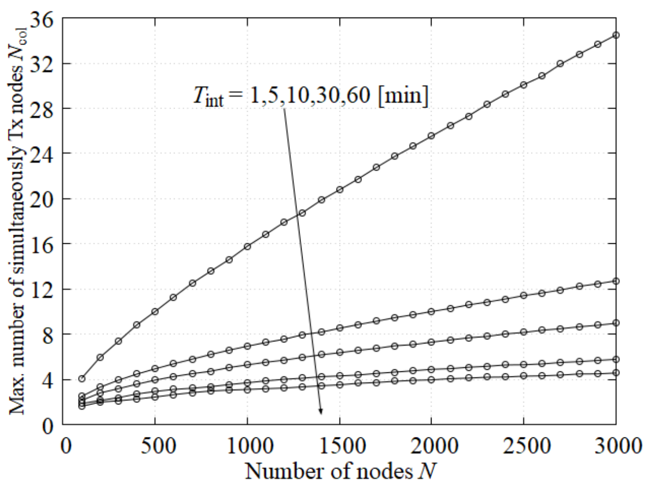



Fig. 4. Maximum number of simultaneously transmitting nodes $N_{\rm col}$ vs $N$

Fig. 4 shows the maximum number of simultaneously transmitting nodes $N_{\rm col}$ vs all the nodes $N$. It can be observed that when $T_{\rm int}$ is 5 [min] or more and $N$ is 1000 or less, $N_{\rm col}$ is at most eight. Hence, it can be considered effective in avoiding packet collisions between a limited number of nodes in an environment where many nodes simultaneously transmit packets at fixed time intervals. Based on the above result, while evaluating the proposed scheme in the next section, the total number of nodes is set to $N = 8$.

### B. Evaluation of the proposed scheme

Packet collision rate $R_{\rm col}$ defined by the following equation is evaluated, applying the simulation parameters in Table II:

$$R_{\rm col} = \sum_{n=1}^{N} \{N_{\rm tx}(n) - N_{\rm suc}(n)\} \Big/ \sum_{n=1}^{N} N_{\rm tx}(n), \qquad (2)$$

where $N_{\rm tx}(n)$ is the total number of transmitted packets of node $n$, and $N_{\rm suc}(n)$ is the total number of successfully transmitted packets of node $n$. Let $N_{\rm tx}(n) = 100$. In this paper, as multiple nodes simultaneously transmit packets at fixed time intervals, $T_{\rm s}(n)$ is the same for all the nodes. If packet collision occurs, the frequency is assigned according to Sect. III-B. The initial value of the transmission frequency $f_n$ is evaluated in two cases: a case where all the nodes take

TABLE I
Simulation parameters-1

| | |
|---|---|
| Number of nodes $N$ | 100, 200, $\cdots$ , 3000 |
| Number of frequency resources $F$ | 1 |
| Transmission interval $T_{\rm int}$ | 1, 5, 10, 30, 60 min |
| Protocol | Pure ALOHA |
| Spreading factor $SF$ | 10 |
| Payload size $l_{\rm p}$ | 11 byte |
| Number of trials $I$ | 100000 |

random values (RANDOM), and the other in which all the nodes take the same value (FIXED).

Here, the theoretical value of $R_{\mathrm{col}}$ in conventional LoRaWAN is expressed by the following equation. The derivation is omitted.

$$R_{\mathrm{col}} = \begin{cases} 1 & \text{(FIXED)} \\ 1 - \{(F-1)/F\}^{N-1} & \text{(RANDOM)}. \end{cases} \quad (3)$$

*1) Impact of the CP transmission rate:* Fig. 5 displays $R_{\mathrm{col}}$ vs $R_{\mathrm{cp}}$, when $N = 8$ and $F = 8$. Here, the conventional LoRaWAN result is also shown. In the conventional LoRaWAN, as mentioned in Sect. II-B, frequency allocation is not performed even when packet collision occurs. Therefore, packet collisions are repeated at the next packet transmission, and $R_{\mathrm{cp}}$ does not depend on $R_{\mathrm{col}}$, which is constant in the system model adopted in this paper described in Sect. III-A. In the case of FIXED, packet collision always occurs and $R_{\mathrm{col}} = 1$ because all the nodes transmit at the same frequency every time. In the case of RANDOM, different frequencies may be assigned to different nodes, and packet collisions are reduced. The simulation results indicate that $R_{\mathrm{col}}$ is approximately 0.6. Equation (3) gives $R_{\mathrm{col}} \simeq 0.607$, when $N = 8$ and $F = 8$, establishing the validity of the simulation results. On the other hand, in the two proposed schemes, CP transmission is decided according to $R_{\mathrm{cp}}$, after which the frequency resources are reassigned on the node-side depending on the presence of an ACK from the gateway. Therefore, $R_{\mathrm{col}}$ is reduced according to $R_{\mathrm{cp}}$.

Moreover, if $R_{\mathrm{cp}}$ is made small, the gateway load will reduce, but if it is too small, $R_{\mathrm{col}}$ will increase. Therefore, there is an optimal transmission rate $R_{\mathrm{opt}}$ in terms of the packet collision rate $R_{\mathrm{col}}$. In the case of proposed scheme-2 and RANDOM, $R_{\mathrm{opt}}$ was 0.5, in particular. Based on the above, it can be stated that the two proposed schemes can be flexibly selected according to the system requirements: reducing the number of packet collisions and reducing the gateway processing load.

Furthermore, proposed scheme-2 can reduce $R_{\mathrm{col}}$ compared to proposed scheme-1, regardless of $R_{\mathrm{cp}}$ and the initial value of transmission frequency $f_n$. In particular, $R_{\mathrm{col}}$ is the least in the case of proposed scheme-2 and RANDOM. This is because proposed scheme-1 has a fixed CP transmission timing within a cycle, and if the CPs collide, CP collisions will be repeated in the subsequent cycles. On the other hand, in proposed scheme-2, the packet collision rate was reduced because CP transmission was probabilistically determined for each packet in a cycle.

TABLE II
SIMULATION PARAMETERS-2

| | |
|---|---|
| Number of nodes $N$ | 2, 4, 6, 8, 10, 12, 14 |
| Number of frequency resources $F$ | 8 |
| Transmission interval $T_{\mathrm{int}}$ | 5 min |
| Protocol | Pure ALOHA |
| Spreading factor $SF$ | 10 |
| Payload size $l_{\mathrm{p}}$ | 11 byte |
| Number of transmission packets $N_{\mathrm{tx}}(n)$ | 100 |
| Number of trials $I$ | 100000 |

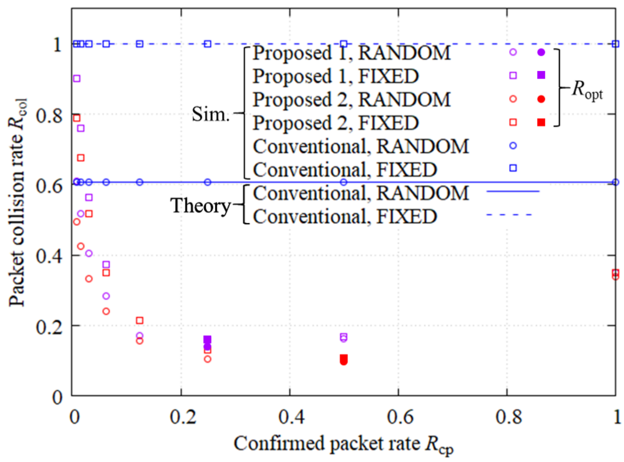



Fig. 5. $R_{\mathrm{col}}$ vs $R_{\mathrm{cp}}$ ($N = 8$ and $F = 8$)

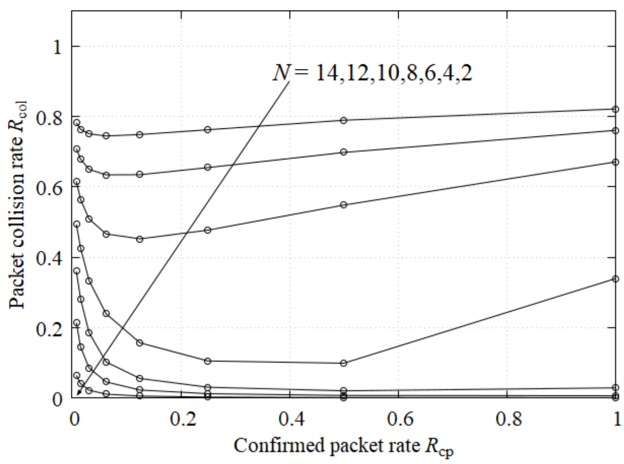


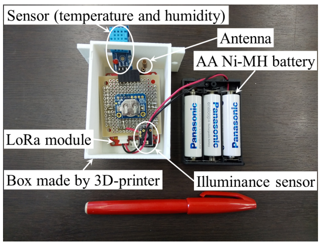

Fig. 6. Impact of the number of nodes $N$ (Proposed scheme-2, RANDOM, Simulation)

*2) Impact of the number of nodes:* Fig. 6 depicts $R_{\mathrm{col}}$ vs $R_{\mathrm{cp}}$, when using proposed scheme-2 and RANDOM. Here, we set $N = \{2, 4, 6, 8, 10, 12, 14\}$ and $F = 8$. If $N$ is decreased, $R_{\mathrm{col}}$ decreases. In particular, when $N$ is in the vicinity of 8–10, there is a sharp change in $R_{\mathrm{col}}$. Specifically, there is a difference of approximately 0.35 in $R_{\mathrm{opt}}$. This implies that if $N$ is less than or equal to $F$, all the packets may be successfully transmitted due to frequency resource allocation. However, if $N$ is greater than $F$, packet collision occurs at one frequency at least for each packet transmission, even if frequency resource allocation is performed.

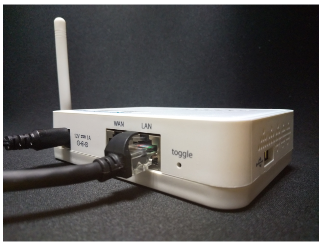
## V. EXPERIMENTAL EVALUATION

### A. Experimental system

Assuming the system model in Fig. 2, we evaluate the proposed scheme, applying the parameters in Table III. In this




(a) Developed LoRaWAN node



(b) LoRaWAN gateway [10]

Fig. 7. Experimental system

paper, we used a maximum of four nodes, and set the distance between each node and the gateway to 0.5 m, and conducted an indoor experiment.

*1) Node:* Based on the LoRaWAN-compatible IoT sensor module LoRa mini-JP [9], we designed and developed a sensor node using only commercially available sensors. We measured the temperature, humidity, and illuminance, and operated with three AA batteries. By storing a set of modules in a box constructed using a 3D printer, outdoor usage is possible; Fig. 7a shows its outline.

*2) Gateway:* The commercially available LoRaWAN gateway Dragino LG01 [10] was used; Fig. 7b depicts the overview. As the maximum number of simultaneous reception channels of this unit was 1, we prepared multiple units and operated them as a gateway capable of receiving multiple channels simultaneously.

### B. Experimental results

Fig. 8 shows $R_{\mathrm{col}}$ vs $R_{\mathrm{cp}}$, when $N = 4$ and $F = 4$. These results are in good agreement with the characteristics of the computer simulation depicted in Fig. 5. The superiority of the proposed scheme in actual experimental evaluation, i.e., reduction in the number of packet collisions and in the gateway processing load was established. $R_{\mathrm{col}}$ is lower than the simulation result regardless of $R_{\mathrm{cp}}$ because of the differences in the evaluation specifications and the capture effect at the time of packet collision in the real environment.

## VI. Conclusion

We proposed an autonomous decentralized frequency resource allocation scheme in which the nodes determine the transmission frequency by periodically and probabilistically transmitting confirmed packets containing ACK transmission requests for LoRaWAN. Through computer simulation and experimental evaluation, we confirmed that the proposed scheme can reduce the packet collision rate and the processing load on the gateway, simultaneously, and that it is advantageous compared to the conventional scheme. In particular, the reduction in the packet collision rate is maximum, when a confirmed packet is transmitted probabilistically and the initial transmission frequency is randomized. In this evaluation, the optimal transmission rate was 0.5 with respect to the packet collision rate. Future works include evaluation considering the radio wave propagation environment and the development of a frequency allocation method using carrier sense.

TABLE III
Experimental parameters

| | |
|---|---|
| Number of nodes $N$ | 2, 4 |
| Number of frequency resources $F$ | 4 |
| Transmission interval $T_{\mathrm{int}}$ | 5 min |
| Protocol | Pure ALOHA |
| Spreading factor $SF$ | 10 |
| Payload size $l_{\mathrm{p}}$ | 11 byte |
| Number of transmission packets $N_{\mathrm{tx}}(n)$ | 100 |
| Number of trials $I$ | 10 |

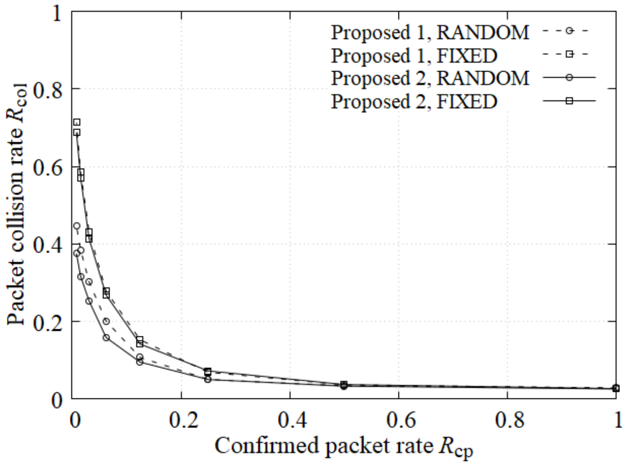



Fig. 8. Experimental results ($N = 4$ and $F = 4$)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