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# Transmission Timing And Synchronization Control For Energy Efficient Multi-Hop LoRaWAN

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**Abstract:** LoRaWAN, each node transmits packets autonomously, so packet collisions occur when multiple nodes transmit packets at the same time and frequency. However, the clocks of inexpensive LPWAN nodes are generally not highly accurate, and synchronization errors can occur between devices over time. In addition, in single-hop LoRaWAN, it is not possible to achieve high data rates and a wide communication range at the same time. By using multi-hop communication, it is possible to achieve a wide communication range while maintaining a high data rate. However, LoRaWAN multi-hop communication suffers from the hidden node problem, throughput degradation due to the inability to transmit and receive packets simultaneously, and power consumption due to the need to constantly open the receive window. This paper proposes an autonomous distributed adaptive resource allocation method to solve the above problems. Specifically, we show that by assigning packet transmission slot decisions based on LoRaWAN packet information, the transmitting and receiving sides can share transmission and reception locations, avoid packet collisions, and reduce power consumption by avoiding unnecessary opening of reception windows

**Keywords:** Transmission Timing, Synchronization Control, Energy Efficiency, Multi-Hop LoRaWAN, Wireless Communication

## INTRODUCTION

LoRaWAN (Long Range Wide Area Network) is a widely adopted low-power, wide-area network (LPWAN) technology, designed for long-range communication with minimal energy consumption. It has gained significant attention in IoT (Internet of Things) applications, where devices need to communicate over long distances while maintaining energy efficiency. However, as IoT networks scale and involve multiple devices, managing transmission timing and synchronization becomes crucial for optimizing network performance and ensuring reliable communication. In multi hop LoRaWAN networks, data is relayed through intermediate devices, creating a more complex environment than a simple point-to-point communication. Effective synchronization and transmission timing control are necessary to avoid collisions, reduce energy consumption, and improve the overall network throughput. As devices in such networks are often battery-powered, optimizing energy usage while ensuring synchronized communication is essential.This paper explores the challenges and solutions related to transmission timing and synchronization control in multi-hop LoRaWAN networks. It focuses on strategies to enhance energy efficiency, minimize interference, and maintain accurate synchronization across multiple hops. By addressing these factors, the proposed approach aims to optimize the performance of large-scale LoRaWAN deployments, ensuring reliable and energy-efficient operation for a wide range of IoT applications.

## METHODOLOGY

### A. Dataset

The Transmission Timing and Synchronization Control for EnergyEfficient Multi-Hop LoRaWAN dataset is designed to capture critical factors affecting the performance and energy efficiency of multi-hop communication in LoRaWAN networks. This dataset includes data collected from multiple nodes operating as end devices, relays, or gateways within

  

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a LoRaWAN infrastructure. It provides comprehensive insights into transmission timing, synchronization accuracy, and energy consumption for each hop in a multi-hop communication.

### B. Preprocessing

In LoRaWAN communication, multi-hop communication is a method to achieve simultaneous high data rate and long-range communication [9]. A GW, multi-hop communication can maintain a high data rate while achieving a wide communication area. This makes it difficult for LoRaWAN to adopt resource allocation methods that require strict time synchronization. Additionally, the overhead for the network, such as control signals, increases for synchronization the hidden node problem, in which packet collisions occur due to simultaneous transmissions from nodes outside the CS range. Specifically, in the case of multi-hop communication from the transmitter to relay 1, relay 2, and GW in the order, the transmission of relay 2 cannot be detected by the transmitter, and packets transmitted by the transmitter and relay 2 may collide. In addition to packet collisions, LoRaWAN nodes cannot transmit and receive packets simultaneously due to halfduplex communication, resulting in a decrease in overall system throughput compared to single-hop communication. To improve throughput, it is necessary to relay packets frequently, but this requires a lot of power for the relay. In addition, the receiver side does not know when a packet will arrive, so the receive window must always be open, which causes a battery consumption problem due to relaying. Furthermore, signals for synchronization can only be sent to one hop ahead in the communication range at a time, and synchronization with two or more hops ahead requires additional time overhead. This paper proposes an autonomous decentralizedadaptive resource allocation method to solve the above problems of conventional multi-hop LoRaWAN. The proposed method dynamically allocates resources for packets to be transmitted to achieve high interference tolerance and to apply to a larger number of systems. Specifically, packet transmission slots are allocated using the index of the hop order and the packet counter of the transmitting node in the header of the LoRaWAN packet [10]. This allows the receiver and transmitter sides to share the time and frequency of packets to be transmitted, avoiding packet collisions and reducing power consumption without opening unnecessary receive windows.

## SYSTEM MODEL

### A. Transmission and Reception Processes

This paper assumes a multi-hop communication system consisting of M devices ( M = {0, ...,m,...,M −1}) where data packets are transmitted from a transmitter (m = 0) to a GW (m = M − 1) through M − 2 relays (m ∈ {1, 2, . . . M − 2}). Each device is assigned an index m ∈ M that determines the order of hops, and these indices are assumed to be known among the devices. The transmitter sequentially transmits Npckt packets of a fixed time length T pckt [sec]. The ith packet (i ∈ I = {0, . . . , Npckt − 1}) contains a packet counter Dpcnt i = i. The relays and GW ("receiving devices mr ∈ M\{0})") will be in the standby state with the receive windows of all frequency channels ("all receive windows") opened until reception of the first packet from the transmitter and their previous relay ("transmitting devices mt ∈ M \ { M −1}"). The relays are able to transmit a packet after receiving the packet from its previous transmitting device with a smaller index than its own. As shown in Fig. 1, the system divides the continuous time into multiple frames of frame time length T frame [sec], which is further split into *Q* time slots of *T* slot [sec]. The start time of the *g*th frame is denoted by *t* f g rame the system uses *K* frequency channels.

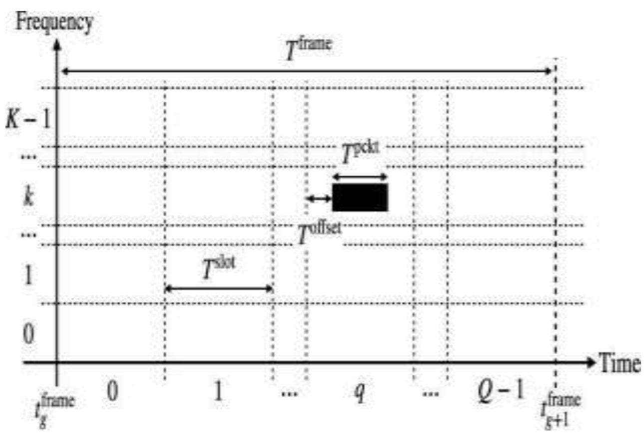

Fig. 1 Composition of packet transmission/reception frames

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Each transmitter selects one of the combinations of time slot and frequency channel, i.e., *radio resource*. Thus, the number of available resources within a frame is $Q \times K$. LoRaWAN nodes generally operates in a half-duplex mode, which means that transmission and reception cannot be performed simultaneously. Therefore, for example, the transmission timing of a transmitter ($m = 0$) and a relay ($m = 1$) must be different. In this paper, the nodes with even index $m$ for each node are assumed to transmit on even-numbered frames, and the nodes with odd indexes are assumed to transmit on odd-numbered frames, alternately. In a transmission frame, each node transmits a packet in one slot within the frame. The packets are transmitted with an offset time $T$ offset [sec] from the starting time in the slot. Conversely, the non- transmitting frame is the receiving frame, and the packet is received.

### B. Clock Drift

Since the clocks of inexpensive LPWAN devices are generally not highly accurate, time deviations occur between devices when there is no external input such as global positioning system (GPS). Such time discrepancy accumulates over time. This paper defines the clock drift as the relative time deviation of device $m$ ∈ M\{ 0 } from device $m$ = 0. The clock drift accumulated during a certain period. For example, during the period $T$frame[sec] at device $m$, $T$m frame [sec], is given by $T$ frame = $T$ frame + ∫ T f r a m e 0 m Δ$T$ d ($t$)$dt$, (1) m where Δ $T$ m d represents the normalized clock drift of device $m$ normalized by unit time and Δ$T$ d ∼ mN ( $\mu$ , $\sigma$ )m wit2hm m N( $\mu$ m, $\sigma$ 2 ) representing a Gaussian distribution with mean $\sigma$ 2 m $\mu$m and variance [11]. Similarly, $T$ slot , $T$ offset,and $T$ pckt are set to $T$m slot ,$T$m offset ,and $T$m pckt , taking into account the clock drift at device $m$. When $m$ = 0, Δ $T$ d m= 0 due to the clock drift as the relative time deviation of device $m$ ∈ M\{ 0 } from device $m$ = 0.

## PROPOSED SYSTEM

### A. Overview

This subsection describes the flow of the proposed method. The transmitter sets the start time as the start time of the 0th frame, $t$ frame 0 [sec], and transmits subsequent packets according to the packet transmission procedure described in Sect. III-B at an even number of frames.

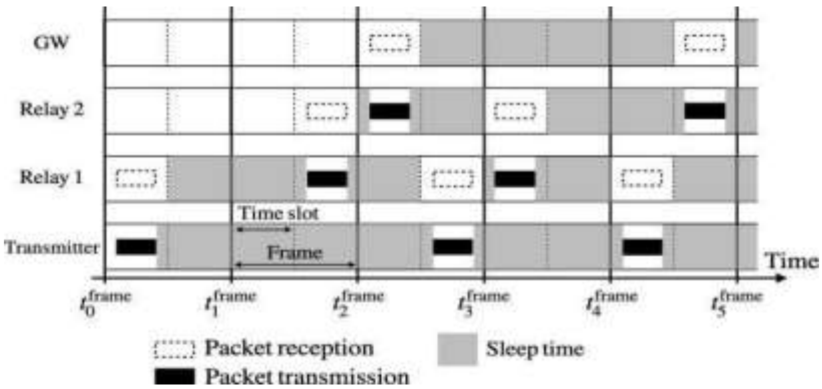


Fig. 2. Proposed scheme when each device is synchronized ( $K$ = 1, $Q$ = 2)

Once a relay receives a data packet, it calculates the frame time to relay packet and to receive subsequent packets according to the procedure in Sect. III-C. By doing this, the time for transmission and reception has been calculated, the sleep time is set according to the procedure in Sect. III-D. Packet transmission is performed along the same way as the transmitter along the procedure in Sect. III-B. Figure 2 shows an example of the proposed scheme when each device is synchronized and number of time slots is $Q$ = 2. In this case, transmitter $m$ = 0 and relay $m$ = 2 transmit in the same even frames, but in different time slots by following the procedure in Section III-B. Thus, relay $m$ = 1 can receive packets from transmitter $m$ = 0 without the interference from relay $m$ = 2. After receiving a packet, the GW calculates the frame time to receive subsequent packets according to the packet reception procedure described in Section III-C.

As mentioned above, devices are subject to time deviations due to clock drift. Therefore, this paper proposes a synchronization algorithm at each device based on the information in the header of the LoRaWAN packet in a distributed manner. When a device receives the first packet, it carries out initial synchronization as described in Section III-C1, and performs sequential synchronization as in Section III-C2. This compensates for time deviations due to clock drift and enables a transmission/reception method that avoids packet collisions.

 

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### B. Packet transmission procedure

Transmitting device *mt* ∈ M \ { *M* − 1 } determines time slot *q* and frequency channel *k* in which it transmits the *D*pcnt i th packet as follows. *q*(*mt*, *D*pcnt) = mod(*f*q(*mt*, *D*pcnt), *Q*), i i *k*(*mt*, *D*p cnt p cnt i ) = mod(*f*k(*mt*, *D*i ),*K*) wheremod(·,·) is the remainder operation, *f* q(*mt*, *D* p cnt i ) and *f* k(*m* t, *D*pcnt i ) is an arbitrary function uniquely determined by index *mt* of the transmitting device and the packet counter *D* p cnt . *D* p cnt can be obtained by receiving packet,*mt* and Eqs. (2) and (3) are known by all the devices, and the transmission resources can be shared among all devices. This paper designs functions *f* q(*mt*, *D*pcnt ) and *f* k(*mt*, *D*pcnt) for collision avoidance only. The packet transmission start time, *t*m tx t ,j [sec], is expressed as follows: *t* tx = *t* txframe + *q*(*mt* , *D* p cnt ) × *T* slot + *T* offset , mt ,i mt ,i i mt mt (4) t where transmission frame start time *t* ˜m , txframe i [sec] is obtained by (6) in case of relay. The transmitter calculates *t*m tx ,i with t its own clock from the start time of the 0th frame *t* frame 0 .

### C. Packet reception procedure

Suppose that receiving device *mr* ∈ M\{ 0 } receives a packet *D*pcnt fromi transmittingr device *mt* = *mr* − 1 at time *t* rm ec , v i [sec] for the first time, r r it sets the synchronization time as *t* sm ync = *t* rm ec , v i . Then, the start time of the *g*-th frame *t*˜g frame [sec] is calculated as *t*˜ fra me = *t* sync − *T* offset − *q*(*mr* − 1, *D* p cnt ) × *T* slot g mr mr i mr +( *g* − 2· *D* p cnt − *mr* + 1) × *T* frame . (5) i mr i r For a relay, start time *t*˜txfrmame,i of the frame transmitting received packet *D*pcnt is calculated as *t*˜ txframe ˜ = *t* frame . mr ,i mr +2 i (6) Receiving device *mr* ∈ M\{ 0 } calculates the starttime of j the receiving slot for next packet *D*pcnt (*j* > *i*) as *t*˜rxSlot = *t*˜frame mr ,j mr−1+ 2 j + *q*(*mr* − 1,*D* p cnt ) × *T* slot . (7) j mr .Receiving device *mr* ∈ M\{ 0} updatesthe synchronization r r time to *t* sm ync = *t*m rec , v j once it receives the second or later packet *D* j p cnt (*j* > *i*) at time *t* recv mr ,j[sec]. Then, based on the updated synchronization time *t* sync mr , it uses (5) ∼ (7) to update *t* ˜ frame g [sec], *t*˜m txframe r ,j , and *t*˜rxSlot mr,l (*l* > *j*).

### D. Sleep time control

Each device reduces its power consumption by switching to sleep during periods when it is not transmitting orreceiving. Receiving device *m* ∈r M\{ 0 } enters the sleep state and closes all receive windows as soon as the first packet is received from the transmitting device *mt* ∈ M \ { *M* − 1}. Then, at *t*˜mtx ,[isec], which is derived using Eq. (4), the device comes out sleep, forwards the packet, and switchs back into sleep. Then, at *t*˜mrx , S i lot [sec], which is derived using Eq. ((7)), the Receiving device releases sleep for *T* [sec] and waits to receive packets. Sleep and transmission/reception are repeated in the same manner. When the second and subsequent packets are received, due to clock drift, the start time of packet reception *t*˜recv =mr ,j (2) (3) m ,j m r r *t*˜rxSlot + *T* offset [sec] assumed by the receiving device andthe recv r actual start time of reception *t*m ,j [sec] are different. In order to receive packets with consideration of this time discrepancy, the receiving device wakes up from sleep at the start time *t*˜mrx , S i lot [sec] of the receive slot and waits for the reception of packets in the entire receive slot.

TABLE I SIMULATION PARAMETERS

| Parameters | Values |
|---|---|
| Number of devices $M$ | 4 |
| Frame length $T^{frame}$ | 2.825 [sec] |
| Packet length $T^{pckt}$ | {72,123, 226}[msec] |
| Number of frequency channels $K$ | 4 |
| Number of time slots $Q$ | 2 ∼ 40 |
| Duty cycle $\Delta_{DC}$ | 0.01 |
| Mean $[\mu_{min}, \mu_{max}]$ | $[-1.91\times 10^{-3}, 0.28\times 10^{-3}]$ |
| Variance $[\mu_{min}, \mu_{max}]$ | $[9.59\times 10^{-11}, 3.19\times 10^{-10}]$ |
| Power consumption (transmission) $W_{tx}$ | $99\times 10^{-3}$[W] |
| Power consumption (reception) $W_{rx}$ | $18.15\times 10^{-3}$ [W] |
| Power consumption (sleep) $W_{slp}$ | $2.97\times 10^{-6}$ [W] |

## RESULTS AND DISCUSSION

The performance of the proposed method is evaluated using computer simulations. Table I shows the simulation parameters. The frame length, *T* frame [sec], is determined so that it satisfies duty cycle ΔDC for each frequency channel at each transmitting device as

$T_{frame} = T_{pckt} / (2K \cdot \Delta_{DC})$

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Since $T$ pckt [sec] depends on bandwidth $W$ and spreading factor $SF$ , $W$ = 125 [kHz] and spreading factor $SF$ = {7, 8, 9}= {72, 123, 226} [msec] are used for calculating $T$ pckt [sec] [12].The offset time, $T$ offset [sec], is set to $T$ offset = ($T$ slot − $T$ pckt)/2 to transmit a data packet at the center of the time slot. Mean $\mu$m r and variance $\sigma$m 2 r used for the clock drift value of each node are determined from uniform random numbers taking the range [$\mu$min, $\mu$max] and [$\sigma$m 2 in ,$\sigma$2 max ] of the minimum and maximum values obtained from experimental evaluation [11]. The arbitrary function used i i in the proposed method is $f$ q($m$t, $D$pcnt) = $f$ k($m$t,$D$pc nt) = $m$t +$D$p i c nt . This paper does not consider any retransmissions. Power consumption $W$tx , $W$rx , $W$slp are determined based on the parameters of 920 MHz band radio module [12]. If multiple packets are transmitted simultaneously at the same frequency channel and can be received by a receiving node, we assume that the packets lost, i.e., no capture effect is taken into account. If a receiving node can receive a packet during the estimated receive slot, it is considered that the packet reception is unsuccessful.

### A. PDR

Figure 3 shows the packet delivery rate (PDR) performance as a function of elapsed time. Number of time slots $Q$ is set to 2, which is the minimum number for the proposed method to operate. The PDR is determined by 1 − $N$ fail u($t$)/$N$p ckt u ($t$) where $N$ u pckt($t$) denotes the total number of packets transmitted by the transmitter up to a certain time $t$. $N$u ($t$) fail denotes the total number of packets cannot be received by the GW until a certain time $t$. The PDR performance with the proposed sequential synchronization (clock drift compensation) is denoted as "w/ comp." and the case without sequential synchronization is denoted as "w/o comp". By using the proposed sequential synchronization method, the PDRperformance can be 1 regardless of $SF$ . On the other hand, the PDR performance begins to deteriorates after a certain period of time. This is becuase of the accumulated clock drift, which prevents packets from fitting into the expected receive slots at the receiving device, resulting in a drop in PDR.

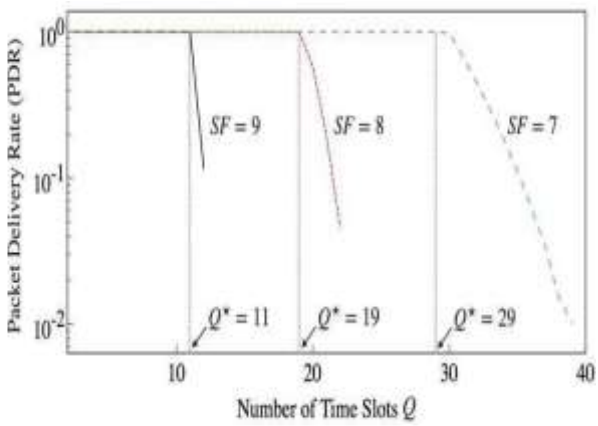


Fig. 3. PDR performance as a funtion of elapsedtime performance

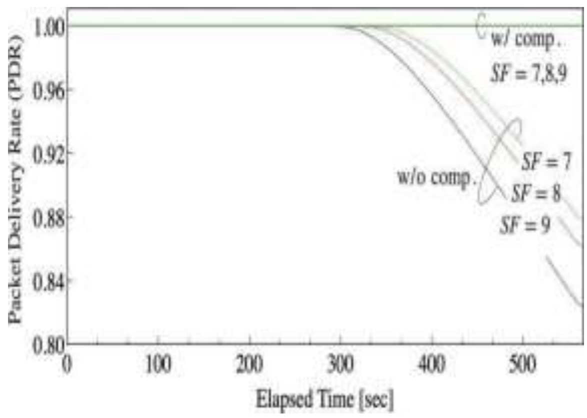


Fig. 4. The impact of number of time slots $Q$ on PDR

In addition, the PDR begins to drop earlier when the $SF$ is large, i.e., when $T$ pckt [sec] is large, because it is more susceptible to the effects of clock drift. Next, the effect of the number of time slots $Q$ on the PDR performance of the proposed method is shown in Fig 4. The PDR is determined by $N$ s u uc/$N$pckt where $N$pckt denotes the total number of packets transmitted and $N$ u suc denotes the number of packets successfully received by the GW. Increasing number of time slots $Q$ leads to more sleep time, but it shortens time slot length $T$ slot[sec] and time offset length $T$ offset within that slot, which makes it impossible to absorb the effect of clock drift. In LoRa, the larger $SF$ becomes, the longer $T$ pckt [sec] becomes. Thus, the larger $SF$ , the system becomes more susceptible to clock drift and the PDR performance starts to drop earlier. In particular, for the considered simulation parameters, $SF$ = 9 can keep PDR of 1 up to $Q\star$ = 11,$SF$ = 8 up to $Q\star$ = 19, and $SF$ = 7 up to $Q\star$ = 29. If $Q$ is increased beyond these values, the clock drift value cannot be absorbed and the PDR will start to drop.

### B. The power consumption

Finally, this section provides the power saving effect of the proposed method. Since relays do not know the reception timing of the data packetin multi-hop communication, it is necessary to keep the receive window open at all times so that it can receive the data packet. Thus, the scenario when the relays always open the receive window is considered for comparison. On the other hand, the relay can estimate the packet transmission time from its corresponding transmitter, so it can reduce power consumption by switching to sleep mode.

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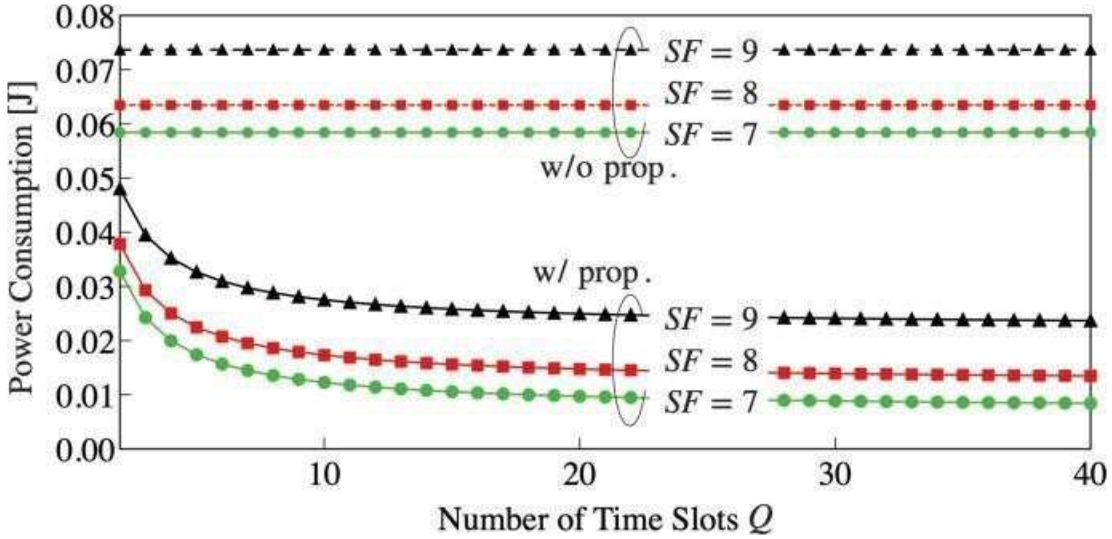

Fig. 5. The power consumption for the number of time slots $Q$

First, the power consumption of a transmission frame $J_{tx}$ can be calculated as $J_{tx} = W_{slp} \times (T_{frame} - T_{pckt}) + W_{tx} \times T_{pckt}$ , where each relay becomes sleep mode except for packet transmission $T_{pckt}$ [sec] during a transmission frame. This value is same for both the proposal and comparison method. The comparison method always keeps the receive win- dow open during the entire reception frame, so, the power consumption during the reception frame of the comparison method, $J_{rx,conv}$, is expressed as follows $J_{rxconv} = W_{rx} \times T_{frame}$ The power consumption during the reception frame of the proposed method, $J_{rx,prop}$, is calculated as $J_{rx,prop} = W_{slp} \times (T_{frame} - T_{slot}) + W_{rx} \times T_{slot}$.

(11) The power consumption required to forward one packet at each relay for the comparison method, $J_{conv}$, and that for the proposed method, $J_{prop}$ , are respectively calculated by $J_{conv} = J_{tx} + J_{rx,conv}$, $J_{prop} = J_{tx} + J_{rx,prop}$. (12a) (12b) The power consumption required to forward one packet at each relay for the number of time slots $Q$ is shown inFig 5. The comparison method is denoted as “w/o prop.” and the proposed method as “w/ prop.”, and the evaluation is performed at each spreading factor $SF$ . “w/o prop.” requires a constant amount of power consumption regardless of the number of time slots, because the receive window must always be open in the reception frame (10). However, the smaller $SF$ is, the shorter the packet transmission time $T_{pckt}$ [sec] is, the smaller power consumption $J_{tx}$ of the transmission frame becomes, and overall power consumption $J_{conv}$ is smaller. On the other hand, “w/ prop.”, time slot length $T_{slot}$ [sec] can be reduced by increasing the number of time slots $Q$, and power consumption of the received frame $J_{rx,prop}$ is reduced. This means that the larger the number of time slots $Q$ is, the lower the overall power consumption $J_{prop}$ becomes. However, Fig.(4)shows that if number of time slots $Q$ is increased to a certain number, packets with a time length $T_{pckt}$ [sec] cannot be received within time slot length $T_{slot}$ [sec], resulting in a significant decrease in PDR. In other words, there is a limit to the amount of power consumption that can be reduced while maintaining a high PDR in a system using the proposed method. Therefore, the power consumption $J_{prop}$ (Fig. 5) when the number of time slots $Q$ with PDR of 1 in Fig. 4 is the performance limit of the system. Considering these limits, especially for the present simulation parameters, the proposed scheme reduces the energy consumption by about 84.7% (at $Q^\star = 29$) for $SF = 7$, 76.5% (at $Q^\star = 19$) for $SF = 8$, 63.3% (at $Q^\star = 11$) for $SF = 9$, compared to the system without proposed scheme.

## CONCLUSION

This paper proposed an autonomous decentralized adaptive resource allocation method for LoRaWAN multi-hop communication using the information in the header of the LoRaWAN packet. In particular, the proposed method maps transmission resources using the index of the order of hops and the packet counter. The proposed method can share the transmission resources between the transmitting and receiving sides, avoiding packet collisions and eliminating the time wasted in opening the receive window. Future work includes the incorporation and evaluation of the proposed method using actual equipment.The Multi-Hop LoRaWAN with Transmission and Synchronization Control system presents a powerful and efficient solution for addressing the challenges faced by large-scale Internet of Things (IoT) networks. By extending the range, improving energy efficiency, and enhancing the reliability of communication, this system enables effective deployment across diverse industries, including smart agriculture, industrial automation, smart cities, and healthcare. The integration of multi-hop communication with synchronization

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control not only ensures consistent data delivery even in remote or infrastructure-limited areas but also optimizes energy consumption, which is critical for battery-powered IoT device.

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