Application of Nonlinerar Oscillator Desynchronization Phenomena to Collision Avoidance in LoRa and its Experimental Evaluation

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***Abstract*— With the widespread use of IoT, the adoption of LPWA technology operating in the sub-GHz band, such as LoRa, is increasing. However, as the number of connected devices grows, packet collisions become a significant issue in traditional communication methods. To address this issue, an autonomous decentralized collision avoidance technique using nonlinear oscillators has been proposed. Previous studies have confirmed its effectiveness in high-density communication environments through simulations and experiments with Wi-SUN. In this study, we apply this collision avoidance approach based on nonlinear oscillators to a LoRa system. We implement the proposed method on LoRa device and evaluate its effectiveness using 50 real devices. The experimental results demonstrate that this approach significantly reduces packet collisions in the LoRa network, even in high-density environments.**

Keywords IoT, LoRa, TDMA, nonlinear oscillator, collision avoidance, synchronization

I. Introduction

Long Range (LoRa) is one of Low Power Wide Area (LPWA) systems that enable long-distance communication with low power consumption and is widely used in the Internet of Things (IoT)[1]-[3]. Its advantages, such as extended communication range and low power consumption, are particularly beneficial for applications like sensor data collection and monitoring in remote areas[4][5]. With the increasing adoption of IoT devices, the number of devices using LoRa is expected to grow significantly in the future[6][7]. However, as the number of devices increases and they share the same wireless channel, communication collisions are likely to occur more frequently, severely impacting communication stability and efficiency. Therefore, it is essential to develop technologies that ensure stable communication while avoiding collisions, especially in large-scale IoT networks using LoRa[8].

One example of collision avoidance in centralized management is Time Division Multiple Access (TDMA) [9]. TDMA is a multiplexing scheme in which a gateway allocates timeslots to each device, enabling efficient communication. However, in IoT systems with an increasing number of devices, it is necessary to minimize control signals as much as possible to achieve low power consumption.

An example of an autonomous decentralized protocol used in wireless communication systems is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)[8]. This protocol uses random backoff time to avoid collisions. However, as the number of devices increases, the backoff time have to be also increased, limiting the time available for data transmission. As a result, in environments with a large number of IoT devices, efficient communication like that achieved with TDMA becomes difficult.

Decentralized collision avoidance approaches, such as “Desync-TDMA” [10] and “PCO-D” [11] have also been proposed. These methods adjust phase differences with adjacent nodes in the phase space based on desynchronization theory to avoid collision. When nonlinear oscillators are interconnected, they can exhibit synchronization or anti-phase synchronization phenomena. A representative model describing the behavior of such nonlinear oscillators is the Kuramoto model. By applying anti-phase synchronization from this model, phases are made to diverge, thereby enabling collision avoidance. However, the conventional methods proposed in Refs. [10] and [11] require sharing information within the network, such as the number of devices. In IoT environments, where the number of devices fluctuates frequently, it takes time to distribute each node's information across the network and to grasp the overall network information, making this process challenging. Furthermore, IoT devices often remain in a sleep mode for extended lifetime by conserving power, which make it difficult to efficiently share network information during these sleep periods. Therefore, these conventional methods are not suitable, particularly for IoT networks that require scalability and low power consumption.

On the other hand, Osada et al. proposed a decentralized collision avoidance method that applies the desynchronization phenomenon using intermittent coupling of nonlinear oscillators[12]. The key feature of this method is that it does not require detailed network information, enabling each device to autonomously achieve desynchronization. This improves scalability and flexibility in IoT environments while effectively suppressing collision occurrences.

In this study, the proposed decentralized collision avoidance method based on the anti-phase synchronization phenomena of nonlinear oscillators is applied to a large-scale LoRa network, and its ability to ensure stable communication is demonstrated through experimental validation. 50 devices are developed using commercially available LoRa modules and microcontrollers, while a single receiver device is created by combining a LoRa module with a Raspberry Pi. In this environment, both standard LoRa communication and the proposed method are implemented and their performances are analyzed based on the experimental results.

II. COLLISION AVOIDANCE METHOD USING DESYNCHRONIZATION

A. *Kuramoto model with inhibitory coupling*

The Kuramoto model [13] is a well-known model that explains how nonlinear oscillators synchronize through interactions. In this model, the phase θ_i of the i th oscillator is described by the following equation:

$$\frac{d\theta_i}{dt} = \omega_i + \frac{K}{N}\sum_{j=1}^{N}\sin(\theta_j - \theta_i) \tag{1}$$

where, K represents the coupling strength. When K is positive, the interaction between oscillators promotes synchronization. On the other hand, if K is negative, the coupling becomes repulsive, driving the oscillators to desynchronize by acting in opposite phases. By introducing this repulsive coupling, oscillators can achieve desynchronization, which helps avoid collisions at specific timings. This property serves as a fundamental principle for collision avoidance.

B. *Kuramoto model considering intermittent communication for IoT devices*

For IoT devices, low power consumption is critical, and continuous communication is impractical due to battery life limitations. Therefore, the model needs to be modified to allow intermittent coupling between devices. The modify equation is described as:

$$\frac{d\theta_i}{dt} = \begin{cases} \omega_i + \frac{K}{N}\sum_{j=1}^{N}\sin(\theta_j - \theta_i) & \text{if} -r\pi \le \theta_i < r\pi \\ \omega_i & \text{otherwise} \end{cases} \tag{2}$$

where, r is the coupling period ratio, ranging from 0 to 1. However, this model may fail to achieve desynchronization. For example, consider a situation where four oscillators are divide into two groups position on opposite sides of the phase space (e.g., their phases relative to one oscillator are 0,π,π/3,4π/3). In this case, the following
holds:

$$\frac{K}{N}\sum_{j=1}^{N}\sin(\theta_j - \theta_i) = 0 \tag{3}$$

As a result, the oscillators stop repelling each other. To address this, we limit the coupling to only the closest oscillator in phase space. This modification reduces the listening window, eliminating the need to identify all oscillators. The updated equation is:

$$\frac{d\theta_i}{dt} = \begin{cases} \omega_i + K\,sin(\theta_j - \theta_i) & \text{if} -r\pi \le \theta_i < r\pi \\ \omega_i & \text{otherwise} \end{cases} \tag{4}$$

Here, j refers to the nearest neighbor node of i, where: $j = \text{argmin}(|\theta_i - \theta_j|),\ (j|1 \le j \le N, j \ne i, -r\pi \le \theta_j < r\pi)$.

C. *Model modification for practical application*

To implement this model on real IoT devices, the continuous-time Kuramoto model must be converted into a discrete-time system that can run on a device's CPU or chip. The modified discrete-time model is given by:

$$\theta_i(t_{n+1}) = \begin{cases} \theta_i(t_n) + \omega + K\Delta t\sin(\theta_j - \theta_i) & \text{if} -r\pi \le \theta_i < r\pi \\ \theta_i(t_n) + \omega & \text{otherwise} \end{cases} \tag{5}$$

Here, j refers to the nearest neighbor node of i, where: $j = \text{argmin}(|\theta_i - \theta_j|)(j|1 \le j \le N, j \ne i, -r\pi \le \theta_j < r\pi)$.
Δt is the time step for computation. The i th node transmits a packet when θ_i=0. During the listening period, each device can receive signals from others, determine the phase distance using the receive timing, and select the closest device to calculate the phase difference.

III. APPLICATION OF AUTONOMOUS DECENTRALIZED COLLISION AVOIDANCE METHOD TO LORA

We apply the decentralized collision avoidance method based on the anti-phase synchronization of nonlinear oscillators to LoRa communication system. LoRa supports long-distance communication with low power consumption. It is suitable for building large-scale networks that connect low-power IoT devices. However, as the number of devices increases, packet collisions are likely to occur more frequently, potentially reducing the efficiency of data transmission and reception. Traditional collision avoidance methods are primarily centralized, leading to challenges such as increased power consumption due to control signal exchanges and limitations in network scalability. This study addresses these issues by applying a decentralized method base on the desynchronization phenomenon of nonlinear oscillators to LoRa, enhancing the feasibility of large-scale LoRa networks.

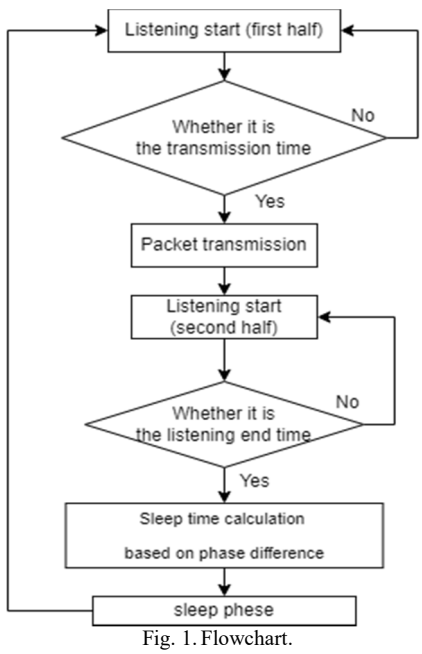

Fig. 1. Flowchart.

To implement this method in LoRa, a microcontroller is programmed according to the flowchart shown in Fig. 1. Specifically, when determining sleep durations, Eq. (5) is applied. This equation allows each device to autonomously adjust its sleep duration and synchronize its transmission timing in an out-of-phase manner. Devices wake up at regular intervals, receive signals from their surroundings to update phase information, and calculate the next sleep duration based on Eq. (5). Through this process, communication timing among devices is evenly distributed, achieving decentralized collision avoidance.

IV. Implementation on LoRa Device

To implement a decentralized collision avoidance method using the desynchronization phenomenon of nonlinear oscillators on actual devices, we develop terminal devices that combine a microcontroller with a LoRa module. Specifically, we use the LoRa module ES920LR [14] and the ESP32-WROOM-32E [15] microcontroller. This combination enable the development of terminal devices with low power consumption and high-performance communication capabilities. As shown in Figs. 2-5, 50 such terminal devices are created to simulate a large-scale network environment, allowing detailed evaluation of the proposed method's effectiveness and communication performance.

Additionally, a receiver system is developed using a Raspberry Pi 4 [16] and a LoRa module. This receiver communicates with the terminal devices via LoRa, collecting and analyzing the data transmitted by each terminal. This setup enables us to measure the communication performance of the terminal devices equipped with the proposed method, including metrics such as communication conditions and collision rates.

(a)terminal device (b) receiver device

Fig. 2. image of devices.

Fig. 3. terminal device by ES920LR(red) and ESP32(blue).

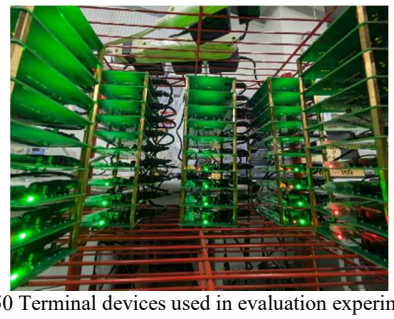

Fig. 4. 50 Terminal devices used in evaluation experiments.

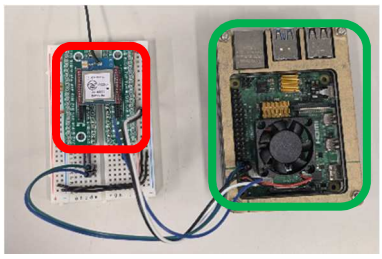

Fig. 5. Receiver device by ES920LR(red) and Raspberry Pi(green).

V. Experiments and Results

In the experiment, we evaluate the effectiveness of the proposed decentralized collision avoidance method by broadcasting transmissions from each device and recording the sender's device ID and reception time at the receiver. The settings for all devices are standardized as follows, Transmission interval is 30s, Number of Transmission is 200, Center of frequency is 920.4MHz,Bandwidth is 500kHz, Spreading Factor (SF) is 7,Transmission data length is 1 Byte, coupling strength (K) is 0.015, coupling period ratio (r) is 0.015 ,respectively.

First, measurements are conducted using 15 devices. The results are shown in Fig. 6, where the horizontal axis represents elapsed time, and the vertical axis represents phase differences between devices. The results demonstrate that phase differences became uniform over time, achieving desynchronization, by the proposed method. In contrast, standard LoRa communication show no change in phase differences over time, maintaining an uneven state. These findings confirm that the proposed method autonomously adjusts transmission timing among devices and effectively avoids collisions.

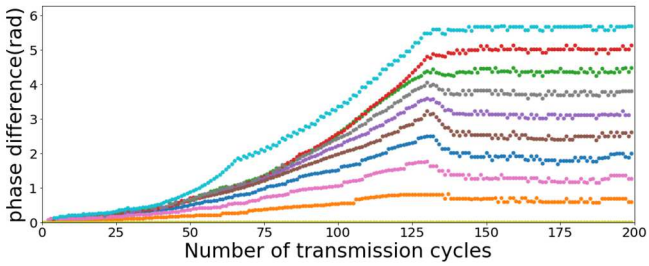

Fig. 6. Desynchronization (Static).

Next, the number of devices is varied, starting with 7, followed by 13, and then 9, to confirm the performance of the proposed method under the conditions where the number of devices dynamically changes. The results are shown in Fig. 7, where the horizontal axis represents elapsed time, and the vertical axis represents the phase of each device. Regardless of changes in the number of devices, the proposed method achieved evenly spaced phases after a certain period, confirming desynchronization again. On the other hand, with standard LoRa communication, phase differences remained unchanged regardless of the number of devices, indicating no collision avoidance. These results demonstrate that the proposed method can autonomously adapt to changes in the number of devices.

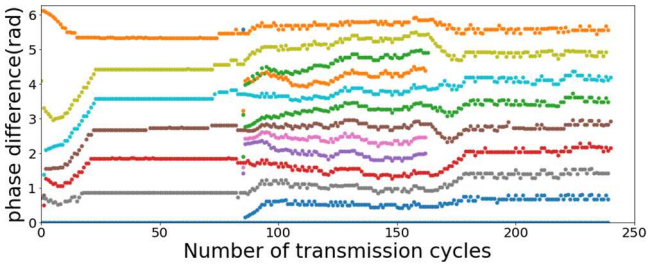

Fig. 7. Desynchronization (Dynamic).

Finally, collision rates are measured while varying the number of devices. The results are shown in Fig. 8, where the horizontal axis represents the number of devices, and the vertical axis represents the collision rate. In this measurement, the transmission timing of all devices is synchronized.

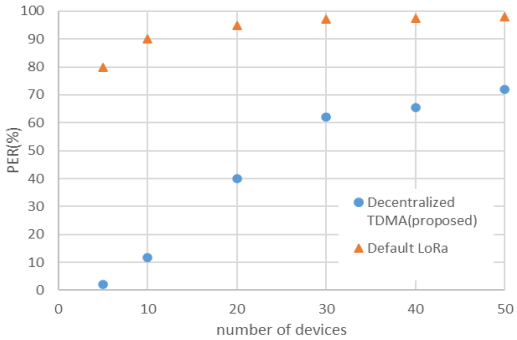

Fig. 8. Relationship between Per and number of devices.

From the results, the Default LoRa showed a very high collision rate regardless of the number of devices. This is believed to be due to the fact that only carrier sensing was performed without any phase adjustment, resulting in packet collisions. On the other hand, the proposed method consistently demonstrated a lower collision rate compared to default LoRa. Particularly when the number of devices is small, the proposed method effectively reduce the collision rate, proving its effectiveness. However, since the collision rate increased when the number of devices was large, further optimization of coupling strength and coupling functions will be pursued in the future to reduce the collision rate and enhance the method's capability to handle a larger number of devices.

VI. CONCLUSION

In this study, we implemented an autonomous decentralized collision avoidance method based on the anti-phase synchronization phenomenon of nonlinear oscillators in LoRa communications, aiming to reduce packet collisions in large-scale LoRa networks. We developed 50 device units using commercially available LoRa modules and microcontrollers and conducted actual experiments. The results confirmed that the proposed method reduces the collision rate compared to the conventional LoRa communication system. This demonstrates that the proposed method is effective in a large-scale LoRa environment and has the potential to achieve stable communication. In particular, the method does not require detailed network information, making it suitable for the low-power IoT networks, as it can autonomously avoid collisions.

As future work, we aim to optimize model parameters such as the coupling function and coupling strength to further reduce the collision rate. In addition, the adaptability of the method to an increasing number of devices and changes in network topology should be verified. Furthermore, we plan to assess the reliability and practicality of the proposed method through long-term operational tests in a real-world environment, contributing to the overall performance improvement of IoT systems using LoRa communications. Through these efforts, we expect to enable the realization of a low-power and highly efficient large-scale IoT network.

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