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A Slotted Transmission with Collision Avoidance for LoRa Networks

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Abstract

Despite that the LoRa technology has its salient features such as long transmission range and low power consumption, it suffers from data collision and signal suppression. The signal suppression problem not only degrades reliability in data transmission, but also tends to incur the unfairness such that a receiver demodulates only the strongest one of multiple received signals. To tackle this problem, the proposed approach tries to avoid the situation that multiple nodes send data simultaneously. It allows every node to transmit data only at the boundary of transmission slots and uses both random delay slots and the listen-before-talk (LBT) mechanism for collision avoidance. It is proven by experiments that the proposed approach, named ST/CA, achieves high reliability and fairness against the variation of traffic loads compared with LoRaWAN.

Keywords: LoRa protocol; slotted transmission; collision avoidance; capture effect; listen-before-talk.

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1. Introduction

Recently, a lot of research and development activities on the LoRa technology have been made in academia and industry [1-4]. One of the reasons is that the LoRa technology enables a long range and low power data transmission. Among the solutions for the LoRa MAC layer, LoRaWAN which simply employs the principle of Aloha [5] in data transmission has been adopted successfully for many IoT applications such as smart monitoring, asset tracking, healthcare systems, etc. However, due to the random nature of data transmission, the LoRaWAN protocol has some limitations. First, data transmission suffers from a high collision rate due to lengthy packet *time-on-air* (*ToA*). This becomes severer with the increase of traffic load. Second, nodes experience the lack of fairness in data transmission due to both capture effect and imperfect orthogonality that allow a receiver to receive only the strongest signal [6].

Some studies tried to overcome the limitations of the LoRa technology or addressed the improvements of network scalability. In [7], the authors claim that given the constraint of a *packet delivery ratio* (PDR) greater than 0.9, LoRaWAN can support maximum 120 nodes when every node is required to transmit a packet of 20 bytes per 16.7 minutes. Such low performance is not sufficient for many IoT applications. In [8, 9], it was shown that PDR decreased significantly with increasing the number of nodes. The use of the higher spreading factors (SFs) makes the performance even worse due to the lengthier packet ToA and the longer transmission range. Some others [6, 10] studied collision behavior and the capture effect in data transmission with varying transmission parameters such as spreading factor, signal strength, and relative shifted time between packets. In [10], the authors examined the impact of interfering nodes on the nodes that transmit normal signals. They showed that a receiver could receive normal signals correctly against the interfering signals that have the same signal strength as the normal signals, if the two signals take some offset between their start times. Similarly, in [6], it was shown that a signal-to-interference noise of 0 dB is sufficient to exploit the capture effect if the normal and interfering signals use the same SF. Furthermore, due to the imperfect orthogonality of different SFs, they found out that only the strongest signal is received correctly unless the two signals have the difference of signal strengths under a certain threshold. Therefore, signal suppression can occur quite frequently in LoRa networks.

In satellite communication, it was proven that the Slotted Aloha protocol [5] could largely improve throughput in data transmission over the pure Aloha one. However, just a few approaches using a slotted transmission were proposed so far. Authors in [11] tried to regulate the communication of LoRa networks by allowing data transmission only at the boundaries of time slots. This approach alleviates the possibility of collision to some extent; it may not work effectively in real network deployment if the traffic is not sufficiently low since a downlink message can easily collide with uplink data. The on-demand LoRa protocol [12] uses two different TDMA strategies, called Unicast and Broadcast TDMA. Each node includes a wake-up radio that enables a low-energy listening state. A gateway (GW) sends a beacon message to a clusterhead so that the clusterhead can schedule the data transmission of its member(s) without collision. Although this approach improves reliability, the clusterhead may suffer from high energy consumption since it has to remain in listening mode. Meanwhile, the authors in [13] introduce a concurrent transmission technique, named *offset*-CT, to improve the reliability of data transmission in which two or more nodes transmit data concurrently within the same transmission slot, but with different time offsets. However, every data transmission involves data flooding, thus consuming high energy.

This paper introduces a slotted transmission with collision avoidance (ST/CA) that can improve the fairness as well as the reliability in data transmission. The protocol is structured by repeating frame periods, each of which has downlink and uplink sections. Nodes transmit data at the boundaries of transmission slots during the uplink section. This approach decreases the probability of data collision since it reduces the vulnerable period of the transmitted packet by half compared with the pure Aloha approach. Furthermore, since the signals generated by different nodes may experience different signal attenuations due to path loss and shadowing or distance, signal suppression can occur frequently. To deal with this problem, nodes need to avoid concurrent transmission. Thus, every node uses a random delay and the listen-before-talk (LBT) mechanism per a transmission slot. The ST/CA protocol was experimented on a testbed using a single channel gateway and twenty end nodes. It is shown that the protocol significantly outperforms LoRaWAN in terms of PDR under various traffic loads and reduces the signal suppression problem, thereby achieving high fairness.

The paper is organized as follows. Section 2 gives research background, and Section 3 describes the proposed protocol. Experiment are given in Section 4, followed by concluding remarks in Section 5.

2. Background

2.1. Network Model

A considered LoRa network consists of a number of end nodes, gateways, and a network server. All end nodes are connected directly to gateways that are wired to a server. The network operates on unlicensed sub-GHz RF bands where the nodes are required to comply with the medium access regulation.

2.2. Motivation

The signals generated by different nodes may experience the different degrees of signal attenuation due to path loss and shadowing. LoRaWAN handles this problem by having the nodes use different SFs. However, this approach suffers from a signal suppression problem due to the characteristics of the LoRa technology [6, 14].

The signal suppression comes from two sources: One is capture effect by which a node demodulates only the strongest one when it receives multiple signals concurrently with the same SF, and another is imperfect orthogonality by which a node cannot receive multiple signals with different SFs simultaneously. These two phenomena occur frequently due to the small range of the signal-to-interference ratio (SIR) protection value [6], thereby degrading the fairness and reliability of data transmission among the end nodes.

To overcome the signal suppression by imperfect orthogonality, one distinct channel can be assigned to the nodes using the same SF. However, this can incur another signal suppression by the capture effect among the nodes using the same channel and SF. To avoid collision, the simple Slotted Aloha protocol may not be sufficient since the vulnerable period of a LoRa packet is relatively long due to the lengthy packet ToA. Since LoRa nodes are able to identify whether a channel is busy or idle even though the signal is below the noise floor, the collision avoidance mechanism has to be designed carefully.

3. Protocol design

3.1. Protocol structure

The protocol structure consists of the repeating frame periods where each frame period is divided into a *downlink period* (DL) and an *uplink period* (UL) as illustrated in Fig. 1. Once the system starts, GW broadcasts a beacon message to start the operation of system at the time of *StartOP*. The beacon message can include network information (network ID, frame period, etc.), time synchronization information, and downlink data. Upon receiving a beacon message, every node performs time synchronization and goes to sleep until it receives a data transmission request. A node transmits data to GW according to a data transmission protocol during the UL period.

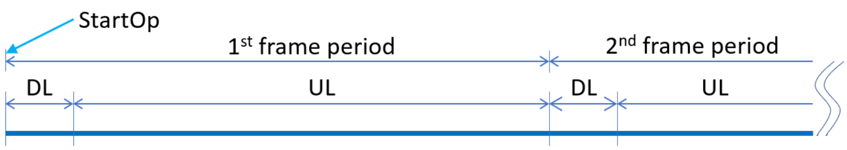


Figure 1. Protocol structure

3.2. Slotted Transmission with Collision Avoidance

In this section, the proposed protocol is described formally. First, the slotted transmission mechanism is explained in detail, and then is followed by the collision avoidance mechanism. For the slotted transmission, the uplink period is divided into a number of data slots so that every sending node can send data at the boundary of data slot. Since two or more nodes can choose the same data slot, they have to compete to acquire the channel with an additional random delay. A node senses the channel using the Channel Activity Detection (CAD) method to find if the channel is idle or not. If the channel is busy, it defers the current transmission to the later slot.

3.2.1. Slotted Transmission

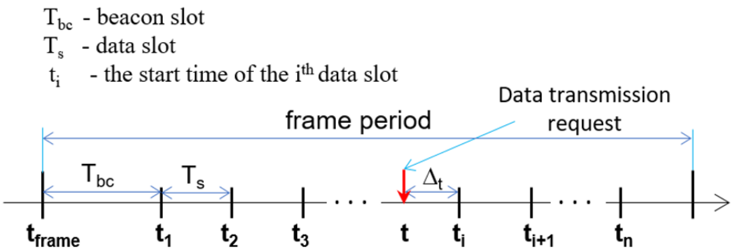


Figure 2. Slotted data transmission within one frame period

Upon receiving a beacon message, every node performs time synchronization to determine the start time of the current frame period, t_{frame}. Starting with t_{frame}, the frame period can be divided into *n data slots* logically as follows:

$$n = \left\lfloor \frac{FP - T_{bc}}{T_s} \right\rfloor \tag{1}$$

where *FP* indicates the frame period, T_{bc} and T_s indicate the length of beacon slot and data slot, respectively. Fig. 2 illustrates a frame period structure that consists of one beacon slot and *n* data slots.

Upon receiving data transmission request at time *t*, a node can calculate a current slot number, *curSlotNum* as follows:

$$curSlotNum = \left\lceil \frac{t - (t_{frame} + T_{bc})}{T_s} \right\rceil \tag{2}$$

Then, the transmission start time, *txStartTime* is given as follows:

$$txStartTime = t_{frame} + T_{bc} + curSlotNum \times T_s \tag{3}$$

Based on (3), if a node wakes up at time *t*, it sets a timer to *txStartTime* to start data transmission. For example, in Fig. 2, *txStartTime* = t_i.

3.2.2. Collision Avoidance

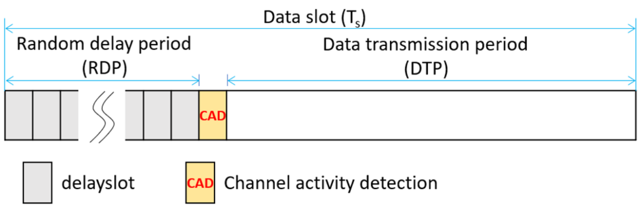


Figure 3. Structure of a data slot

Assuming that data arrives with the Poisson distribution, multiple nodes can compete for data transmission at the same data slot, thus incurring collision or capture effect. To deal with this problem, we introduce the notion of a *delay slot* (*delayslot*) such that if two nodes take some delay before transmission by the difference of at least one *delayslot*, they can avoid collision. One data slot includes a *random delay period (RDP)* and a *data transmission period* (*DTP*). To transmit a data packet at the selected data slot using spreading factor *q* (SF_q), a node generates time delay by using the following random delay function, *rdelay(q)*:

$$rdelay(q) = rand(0, MaxDelayCnt) \times delayslot(q) \quad (4)$$

where *delayslot(q)* indicates the length of a delay slot when SF_q is used, and *MaxDelayCnt* indicates the maximum number of *delayslot*(q)'s as an integer constant.

Fig. 3 illustrates the structure of a single data slot. Every node ready for data transmission waits for *rdelay*(q) and then senses the channel by using the CAD mode. If the channel is busy, it goes to sleep until the beginning of the next data slot to try again. For example, consider Fig. 4 in which two competing senders 1 and 2 generate random numbers 3 and 5, respectively. Then, sender 1 wins the channel and transmits the data packet to a gateway while sender 2 defers its transmission until the next data slot, thereby avoiding concurrent transmission. A transmitted packet can be laid over multiple data slots if its size is longer than a data slot size. In this case, the transmitted packet will not be interfered by other data transmissions if competing nodes can detect channel busy correctly.

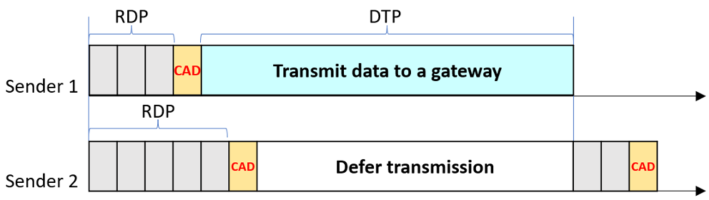


Figure 4. Example of collision avoidance mechanism

In fact, LoRa nodes are expected to suffer from well-known hidden terminal problem which affects negatively on the network's performance. In [15], the authors tried to exploit the request-to-send and clear-to-send (RTS/CTS) handshaking mechanism to alleviate the hidden terminal problem. However, this mechanism requires the gateway to send CTS whenever an end node is about to send data. These additional control messages cause higher energy consumption for end nodes, it also greatly increases the downlink traffic in the gateway side, thus violating LoRa duty cycle limitations. Therefore, this mechanism is impractical in LoRa networks where a gateway is associated with a high number of end nodes. In ST/CA, if hidden senders happen to select the same data slot and transmit data concurrently, the gateway can receive one packet with better signal strength by the capure effect.

3.3. Determination of Key Parameter values

A node checks the channel status by using the CAD mode which is designed to detect a LoRa signal with the best possible power efficiency. The CAD duration varies depending on the spreading factor; it is approximately equal to two LoRa symbol duration [16]. A symbol duration on SF_q, $T_{sym}(q)$, can be calculated as follows:

$$T_{sym}(q) = \frac{2^q}{BW} \quad (5)$$

where BW is the channel bandwidth.

The parameter *delayslot*(q) is set to the CAD duration when SF_q is used since if *delayslot*(q) is shorter than the CAD duration, a node might not be able to sense a signal from its competitors in case they have the part of a CAD time overlapped. According to [3], a node can detect the channel status with high detection probability while the preamble part of the packet is transmitted. Therefore, to improve the reliability of CAD checking, the longest delay time generated by the *rdelay(q)* function should be less than the packet's preamble duration, $T_{preamble}(q)$, as follows:

$$\max rdelay(q) < T_{preamble}(q) \quad (6)$$

We need to calculate the duration of the preamble part for each SF to determine the appropriate value of *MaxDelayCnt* in (4) such that the condition in (6) is satisfied. Table 1 shows the detail calculation. Note that in the last column, the maximum value of *rdelay(q)* is calculated when *MaxDelayCnt*=6. With this value, the maximum random delay time is always less than the preamble duration of any SF, thereby satisfying condition in (6).

Table 1. Calculation of preamble time and maximum rdelay(q), q=7..12 (MaxRandCnt = 6)

q	T_{sym} (ms)	CAD time [16] (T_{sym})	Delayslot (ms)	$T_{preamble}$ (ms)	Max. rdelay(q) (ms)
7	1.024	1.92	1.97	12.54	11.82
8	2.048	1.79	3.67	25.09	22.02
9	4.096	1.75	7.17	50.18	43.02
10	8.192	1.77	14.50	100.35	94.62
11	16.384	1.81	29.66	200.70	177.96
12	32.768	1.86	60.95	401.41	365.70

BW = 125kHz, CR = 4/5, preprogrammed preamble = 8 symbols

4. Experiment

In this section, the ST/CA protocol is compared with the LoRaWAN protocol in various traffic load scenarios.

4.1. Experimental Setup

The testbed was constructed with one GW and twenty nodes using STM32 microcontroller and SX1276 radio chip. It is believed that the use of one channel is sufficient to examine the advantages of the protocols comparatively. Two spreading factors, SF7 and SF10, are used in the testbed. The key parameters and values are shown in Table 2.

Table 2. Experimental parameters and values

Parameter	Value	Parameter	Value
SF	SF7 and SF10	#channels	1
Code rate	4/5	Frame period	25.7s
Preamble	8 symbols	Beacon slot size	500ms
Tx power	4 dBm	Data slot size	SF-dependent

4.2. Experiment Results

4.2.1. Dependability to Traffic Load

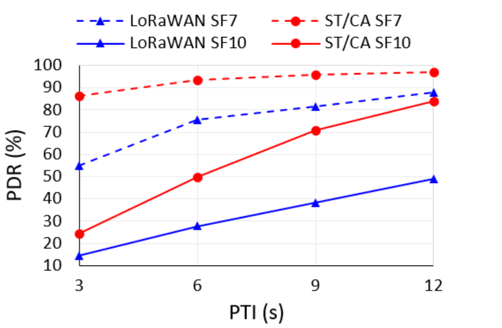


Figure 5. PDRs with varying packet transmission interval (PTI)

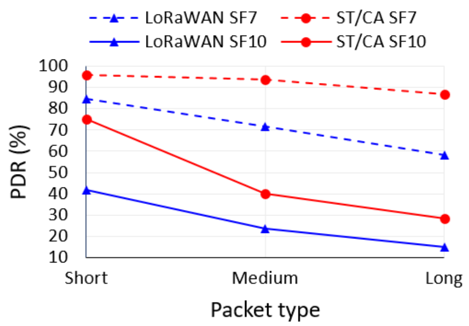


Figure 6. PDRs with various packet sizes while PTI is fixed to 10s

In fact, the PDR depends rather on the traffic load generated by varying the number of participating nodes than that generated by varying the transmission parameters of every single node. However, due to the limited number of available nodes, we could not maintain a testbed such that the number of nodes varies. Instead, we compared the

PDRs of ST/CA and LoRaWAN while changing traffic load by varying three parameters: spreading factors, packet transmission interval, and packet size.

In this experiment, to examine the effectiveness of our collision avoidance mechanism, all nodes were placed close to the gateway within the distance of 5 meters in the testbed. This enables all nodes to identify the channel busy correctly. Then, two scenarios are defined as follows. In Scenario I, traffic load is changed by varying the *packet transmission interval* (*PTI)* from 3 s to 12 s while the packet size is fixed to 25 bytes. In Scenario II, *PTI* is fixed to 10 s, and three different packet sizes are used as *short* (25 bytes), *medium* (70 bytes), and *long* (130 bytes). The short packet is fitted within a single data slot; however, the medium and long packets are laid across two and three consecutive data slots, respectively. The maximum number of attempts in data transmission is fixed to 4.

Fig. 5 compares PDRs using Scenario I. It shows that ST/CA far outperforms LoRaWAN overall. With SF10 and *PTI* = 3 s, ST/CA improves LoRaWAN by 66 % in PDR. As *PTI* increases (or traffic load decreases) to 12 s, ST/CA shows more improvement up to 71 % over LoRaWAN. When SF7 is used, both protocols show much higher PDRs due to the lower traffic load. ST/CA shows PDR of over 95 % overall and as PTI decreases down to 3 s, it still sustains PDR over 86 % while LoRaWAN shows the fast decrease of PDR resulting in 55 %.

Fig. 6 compares the PDRs of the two protocols with Scenario II. It can be observed that the graph pattern of PDRs are almost similar to those with Scenario I. This is because the use of long packets corresponds to the higher traffic. It also shows that ST/CA improves PDR considerably over LoRaWAN regardless of the packet sizes.

4.2.2. Examination on Capture Effect

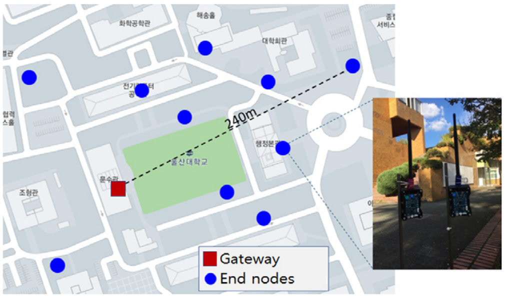
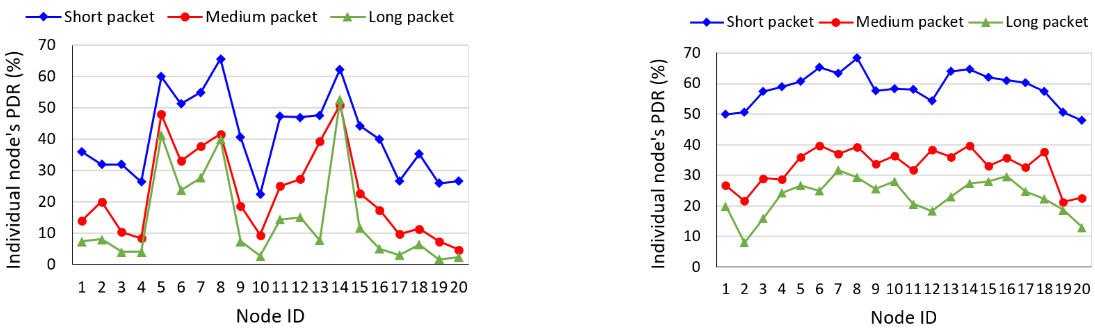


Figure 7. The testbed deployed in the University of Ulsan



(a) LoRaWAN (b) ST/CA

Figure 8. The dependability of the protocols to the signal suppression problem when retransmission is not allowed

In this section, the capture effect was examined when the nodes are deployed randomly in the university campus as shown in Fig. 7. The GW, denoted as a red rectangular, was installed at a position of 8 meters above ground, while the pairs of two end nodes, denoted as a blue circle, were placed in ten selected positions that have different distances to the gateway. The transmission links between the nodes and GW were checked beforehand to make sure that every node can communicate with GW by using either SF7 or SF10. In this experiment, we used the same experimental parameters as Scenario II in the previous section. However, we reduced the maximum number of attempts in packet transmission from 4 to 1. This allows us to examine the fairness of ST/CA in the situation that retransmission is severely constrained. The experimental results are shown in Fig. 8.

Fig. 8 shows how well ST/CA can handle the signal suppression problem compared with LoRaWAN. To better examine the effect of signal suppression, each node was allowed to transmit a packet only once. In Fig. 8-(a), different nodes achieve a lot different levels of PDRs, depending on where they are deployed in the campus. Some nodes such as 3, 4, 10, 17, 19, 20 show extremely low PDRs compared to other nodes. However, with ST/CA shown in Fig. 8-(b), most of nodes except for node 2 show the PDRs close to the average of them, thereby achieving quite good fairness in data transmission. Note that in this experiment, the average PDRs of ST/CA with three packet types are read as 58.6 %, 32.8 %, and 23.0 %. It is far lower than that obtained with Scenario II. This is because the experiment did not allow retransmission.

5. Conclusion

A new slotted LoRa protocol, named ST/CA, was proposed to improve the reliability and the fairness in data transmission by reducing the possibility of signal suppression. To tackle signal suppression, ST/CA addresses the problem of capture effect and imperfect orthogonality in the LoRa technology by making use of multiple channels and slotted transmission. By experiment, it was verified that ST/CA significantly improves the reliability and the fairness in data transmission over LoRaWAN.

6. Acknowledgements

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