

Out-of-Band Synchronization for Slotted LoRaWAN Using Periodic External Signals

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Abstract—Long-range wide-area network (LoRaWAN) is widely used for Internet-of-Things (IoT) applications, however its pure ALOHA medium access control (MAC) protocol suffers from packet collisions in dense networks. Although Slotted ALOHA (S-ALOHA) mitigates packet collisions by aligning transmissions with time slots, it requires strict node synchronization. This paper proposes a synchronization method utilizing an out-of-band periodic signal for slotted LoRaWAN. Each node independently determines slot boundaries based on the received signal power of the periodic external signal without data demodulation. Simulation results show that the proposed method reduces the packet error rate (PER) and enhances throughput. For $N = 500$ nodes under spreading factor of $SF = 8$, the proposed method reduces the average PER to 12.4%, significantly outperforming conventional listen before talk (17.0%) and pure ALOHA (18.0%).

Index Terms—LoRaWAN, slotted ALOHA, out-of-band synchronization, LPWAN, 5G NR

I. INTRODUCTION

WITH the recent development of Internet-of-Things (IoT), IoT applications connecting various nodes have become increasingly diverse [1]. Particularly in areas such as environmental monitoring and facility surveillance, it is common to deploy numerous battery-powered sensor nodes over a wide area that can operate without a continuous power supply [2]. Since such systems require long-term operation and wide communication coverage, low-power wide-area networks (LPWANs) have attracted significant attention [3]. Among LPWAN standards, long-range wide area network (LoRaWAN), which can be deployed at a low cost due to its use of unlicensed bands, has been widely adopted as one of the representative LPWAN technologies and allows users to construct networks flexibly [4]. The physical layer of LoRaWAN adopts chirp spread spectrum (CSS) modulation, achieving long-range communication and high interference robustness [1]. Most LoRaWAN deployments are designed for low-cost IoT nodes. For simplicity of implementation, the pure ALOHA protocol is generally adopted at the medium

access control (MAC) layer, where nodes perform uplink (UL) transmissions randomly [5], while the listen-before-talk (LBT) mechanism is mandatory in some countries and regions such as Japan due to local regulations. However, as the number of nodes increases, the probability of packet collision rises, severely degrading the PER and limiting the scalability of LoRaWAN [6]. Furthermore, in the unlicensed bands used by LoRaWAN, the transmission time of a node per unit time is strictly limited by duty-cycle (DC) constraint to ensure fair spectrum sharing with other systems [7].

To overcome packet collisions in pure ALOHA and improve the scalability of LoRaWAN, alternative access mechanisms such as LBT and Slotted ALOHA (S-ALOHA) have been proposed [2]. In LBT, packet collisions are avoided by performing carrier sense (CS) before transmission. However, packet collisions still occur due to simultaneous transmissions from hidden nodes that cannot detect each other's signals via CS [8]. In S-ALOHA, all nodes in the network are time-synchronized and transmit packets aligned with predetermined slot boundaries. This approach can significantly reduce the probability of packet collisions compared to pure ALOHA [9]. However, it requires strict time synchronization across all nodes to maintain slot alignment [10].

Time synchronization methods are broadly categorized into in-band and out-of-band synchronization [11]. In in-band synchronization, a gateway (GW) transmits synchronization information via downlink, which reduces the available opportunity of data transmission due to channel sharing and half-duplex constraints [12], [13]. Out-of-band synchronization approaches, such as global positioning system (GPS) and FM-RDS, avoid occupying frequency channels used for data transmission. Although GPS achieves high synchronization accuracy, it requires a dedicated receiver module, resulting in high hardware cost, high power consumption, and limited applicability in indoor or obstructed environments [14]. Meanwhile, FM-RDS offers lower power consumption but suffers from poor synchronization accuracy and still requires

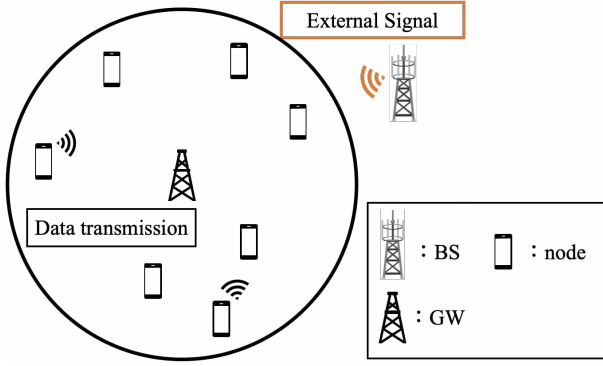


Fig. 1. Proposed system model under out-of-band synchronization.

additional hardware [11]. To address the challenge of time synchronization in S-ALOHA, this paper proposes an out-of-band synchronization method for slotted LoRaWAN. In the proposed method, each node determines its slot boundaries based on received power thresholding of the periodic external signal, without any data demodulation. This eliminates the need for a complex receiver capable of demodulating the external signal, thereby achieving both low hardware cost and low power consumption, which are essential for battery-powered IoT nodes.

The remainder of this paper is organized as follows. Section II describes the system model, Section III details the proposed method, Section IV presents the simulation setup, Section V discusses the simulation results, and Section VI concludes the paper.

II. SYSTEM MODEL

This paper considers a star-topology LoRaWAN network, as illustrated in Fig. 1. The system consists of a single GW and N battery-powered sensor nodes randomly and uniformly distributed within a circular area of radius R [m] centered at the GW. Each node generates UL data packets according to a Poisson process with an average arrival rate of λ [packet/sec]. In addition to the LoRaWAN entities, a base station (BS) of an external system such as a 5G cellular network is located at a distance of d_{BS} [m] from the GW, and periodically broadcasts a periodic external signal in a frequency band separate from that used by LoRaWAN. In the proposed system, this periodic external signal is utilized by the nodes as a synchronization signal to achieve out-of-band synchronization.

III. PROPOSED SLOTTED LORAWAN WITH OUT-OF-BAND PERIODIC EXTERNAL SIGNAL

This section details the proposed slotted LoRaWAN method utilizing a periodic external signal. The proposed method consists of two primary processes: (i) periodic out-of-band signal detection at each node, and (ii) slot boundary determination based on the captured timing to align packet transmissions. In the following, Section III-A describes the signal detection and power-saving mechanisms, and Section III-B details the slot boundary aligning and transmission scheduling.

A. Periodic External Signal Detection

In the proposed method, each node opens a receive window for a predefined duration to detect the periodic external signal by monitoring the instantaneous received power. The overall process of the proposed periodic external signal detection for out-of-band synchronization is illustrated in Fig. 2. The received baseband signal at the node, denoted as $r(t)$, is modeled as

$$r(t) = s(t) + n(t), \quad (1)$$

where $s(t)$ represents the periodic external signal and $n(t)$ represents the additive white Gaussian noise (AWGN). The instantaneous received power is obtained via square-law detection $|r(t)|^2$ and converted to the decibel scale, denoted as $P_{inst}(t)$ [dBm].

During the initial period of the receive window, T_{init} [sec], the node estimates the noise floor P_{noise} [dBm] to determine a detection threshold. The node estimates P_{noise} by calculating the median, ensuring robustness against the potential presence of the periodic external signal itself during T_{init} . The detection threshold P_{th} [dBm] is then defined as

$$P_{th} = P_{noise} + M_{det}, \quad (2)$$

where M_{det} [dB] is a fixed detection margin.

The node detects the period during which the received power exceeds the threshold P_{th} . To improve timing accuracy, the exact threshold-crossing time is calculated by linearly interpolating between consecutive sampling points. Finally, the falling edge crossing time, at which the instantaneous power falls below P_{th} , is recorded as the periodic external signal reception completion time t_{end} .

After the initial periodic external signal detection, the node estimates the expected arrival time of the k -th periodic signal, t_{pred}^k , based on the known transmission period of the external signal T_{sync} [sec]. The node performs intermittent reception by transitioning its state between Active and Sleep modes to reduce power consumption. Initially, the receiver operates in the Active state to perform continuous sampling until the first periodic external signal is successfully detected. After capturing the completion time of the first periodic external signal, t_{end} , the receiver transitions to the Sleep state to save power. Subsequently, the receiver is periodically activated to the Active state only during the active window W^k [sec], which is defined as

$$W^k = [t_{pred}^k - \Delta t_{win}/2, t_{pred}^k + \Delta t_{win}/2], \quad (3)$$

where Δt_{win} is the window duration. The receiver immediately returns to the Sleep state after the active window expires. This intermittent Active/Sleep operation significantly reduces the power consumption. If a node fails to detect the periodic external signal, it falls back to the conventional LBT-based asynchronous access.

B. Slot Boundary Determination

Let t_{sync}^i denote the synchronization signal reception completion time (i.e., the falling edge) within the initial receive

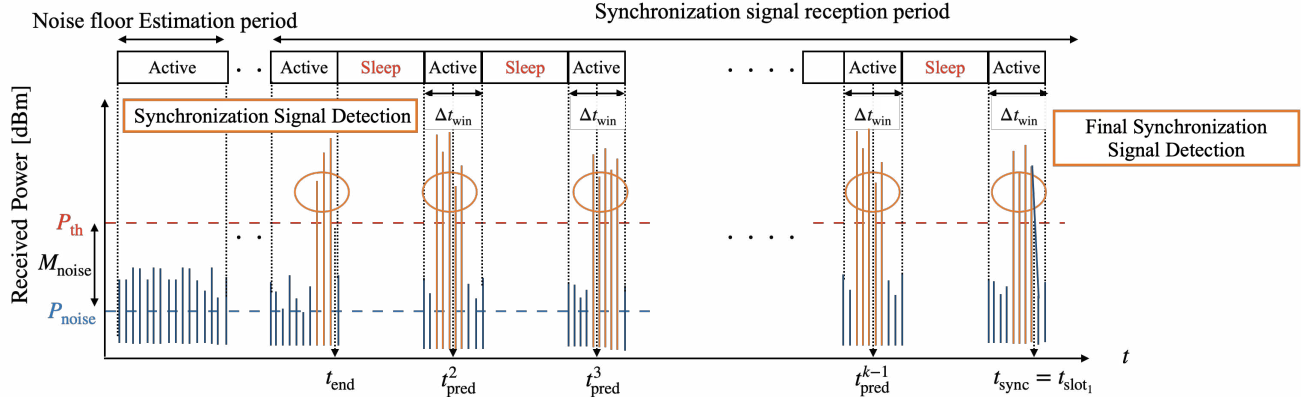


Fig. 2. Proposed synchronization signal detection process showing the initial noise floor estimation and the subsequent intermittent reception mechanism.

window for node i . This time is defined as the start time of the first data slot, denoted by $t_{\text{slot}_1^i}$ [sec]. Subsequently, node i establishes the following slot boundaries at intervals of the nominal slot duration T_{slot} [sec]. However, in practical deployments, the crystal oscillators of low-cost nodes generally suffer from hardware imperfections, causing clock drift. Letting $\Delta\epsilon^i$ be the clock drift rate of node i in parts per million (ppm), the actual k -th slot boundary $t_{\text{slot}_k^i}$ is given by

$$t_{\text{slot}_k^i} = t_{\text{sync}}^i + (k-1)T_{\text{slot}}(1 + \Delta\epsilon^i \times 10^{-6}). \quad (4)$$

Because $t_{\text{slot}_1^i}$ varies for each node depending on its activation time and propagation distance from the BS, the resulting slot boundaries are naturally distributed across nodes. Figure 3 illustrates an example of slot boundary setting in a two-node environment. Finally, to allow the LBT mechanism to effectively detect concurrent transmissions and avoid collisions among nodes with overlapping slot boundaries, each node adds a random offset to its slot boundary before performing CS. The actual transmission time $t_{\text{tx}}^{i,k}$ in the k -th slot is:

$$t_{\text{tx}}^{i,k} = t_{\text{slot}_k^i} + \delta^{i,k}, \quad \delta^{i,k} \sim U(0, T_{\text{offset}}), \quad (5)$$

where $\delta^{i,k}$ is a uniform random variable representing the offset delay within the maximum offset T_{offset} [sec]. Before the scheduled transmission time $t_{\text{tx}}^{i,k}$, node i performs CS using the LBT mechanism. If the channel is detected as idle, the node immediately transmits the packet. In contrast, if the channel is detected as busy, the node defers its transmission to the next slot to avoid packet collisions.

IV. SIMULATION RESULTS

A. Simulation Setup

The simulation parameters are listed in Table I. The radio propagation channel between the transmitters (BS, GW, and nodes) experiences pathloss and shadowing. The pathloss $P_{\text{Loss}}(d)$ at a distance d [m] is modeled using the log-distance pathloss model:

$$P_{\text{Loss}}(d) = P_{\text{Loss}}(d_0) + 10\alpha \log_{10}(d/d_0), \quad (6)$$

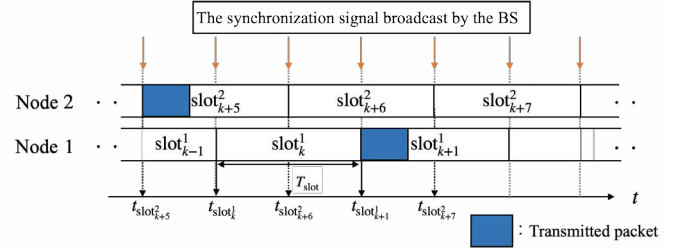


Fig. 3. Example of slot boundary setting based on synchronization signal reception for two nodes.

where $d_0 = 1$ m is the reference distance, α is the pathloss exponent, and $P_{\text{Loss}}(d_0)$ is the free-space pathloss at the reference distance, given by [7]

$$P_{\text{Loss}}(d_0) = 20 \log_{10}(f_c) - 147.55, \quad (7)$$

where f_c [Hz] is the carrier frequency. Shadowing is modeled as a zero-mean Gaussian random variable $X_\sigma \sim \mathcal{N}(0, \sigma^2)$ in decibels with a standard deviation of σ [dB].

Furthermore, assuming a uniform power spectral density for the orthogonal frequency division multiplexing (OFDM)-based periodic external signal, the anti-aliasing low-pass filter (LPF) reduces the received signal power P_s [dBm] by a factor of the bandwidth ratio $B_{\text{rx}}/B_{\text{tx}}$. Thus, P_s is expressed as

$$P_s = P_{\text{tx}} - P_{\text{Loss}}(d) - X_\sigma - 10 \log_{10}(B_{\text{tx}}/B_{\text{rx}}), \quad (8)$$

where P_{tx} [dBm] is the transmit power of the BS. The thermal noise power P_n [dBm] in the narrowband receiver is limited to B_{rx} due to the LPF and is given by

$$P_n = N_0 + 10 \log_{10}(B_{\text{rx}}) + NF, \quad (9)$$

where N_0 [dBm/Hz] is the thermal noise density and NF [dB] is the receiver noise figure.

For a realistic packet collision and interference evaluation, we employ a physical layer model based on the signal-to-interference-plus-noise ratio (SINR). This enables us to model co-channel interference and the capture effect, where a target packet can still be successfully demodulated at the GW if its

TABLE I
SIMULATION PARAMETERS

Parameters	Values
<i>Periodic External Signal</i>	
Signal carrier frequency	3.7 GHz
Signal bandwidth	1.905 MHz
Sampling rate at node	256 kHz
Signal duration	66.67 μ s
Signal transmit power	40 dBm
Detection margin M_{det}	15.0 dB
<i>Data Communication</i>	
Carrier frequency f_c	920 MHz
Node bandwidth W	125 kHz
Number of channels	8
Payload size	10 bytes
Node transmit power	13 dBm
Area radius R	1000 m
Pathloss exponent	2.7
Shadowing standard deviation σ	8.0 dB
Noise figure NF	6.0 dB
Noise power spectrum density N_0	-174 dBm/Hz
SINR capture threshold	6.0 dB
DC limit	1.0%
Maximum clock drift $\Delta\epsilon$	4 ppm
Maximum random offset T_{offset}	10 ms
LBT duration T_{LBT}	5 ms
LBT CS threshold	-80.0 dBm
Mean packet generation interval T_{interval}	30 s
Simulation duration T_{sim}	60 min
Spreading factor SF	8
Packet airtime (ToA)	72.2 ms
Slot duration T_{slot}	200 ms
Sync. signal interval T_{sync}	100 ms

received power sufficiently exceeds the cumulative power of concurrent interfering transmissions.

The proposed method is compared with two conventional schemes in terms of the average PER and system throughput:

- **Prop.:** The proposed slotted LoRaWAN method, which aligns transmission timing with slot boundaries. If a node fails to establish synchronization, it falls back to the conventional LBT-based asynchronous access.
- **Conv.-LBT:** A conventional asynchronous random access protocol where nodes perform CS for a duration of T_{LBT} before transmission.
- **Conv.-pure ALOHA:** A standard random access protocol without CS where nodes immediately transmit packets upon generation.

B. PER Performance

The PER is defined as the ratio of packets that fail to be successfully received at the GW to the total number of transmitted packets:

$$\text{PER} = 1 - N_{\text{success}}/N_{\text{tx}}, \quad (10)$$

where N_{tx} is the total number of transmitted packets and N_{success} is the number of packets successfully demodulated at the GW under the SINR-based capture model described above.

Figure 4 shows the PER performance of each method when the number of nodes N is varied from 100 to 1000 for $SF = 8$. The PER tends to increase as N increases, which is attributed to the higher probability of packet collisions caused by the

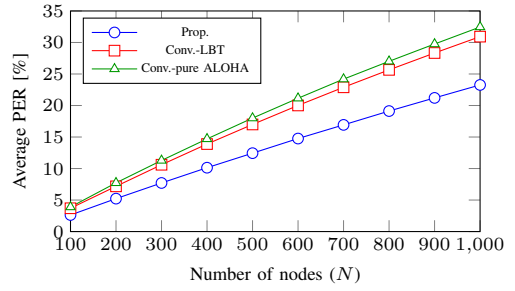


Fig. 4. Average PER comparison under $SF = 8$.

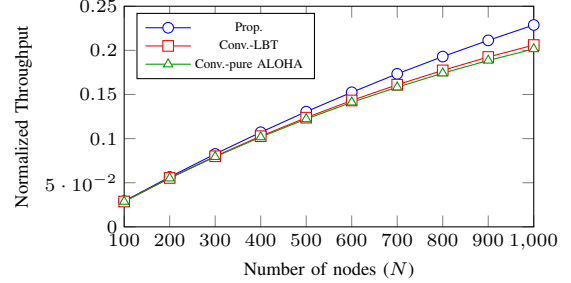


Fig. 5. Normalized throughput comparison under $SF = 8$.

increased overall traffic in all three methods. However, the Prop. achieves a lower PER than both the Conv.-LBT and Conv.-pure ALOHA methods across all evaluated numbers of nodes. This significant PER reduction inherently verifies that the nodes successfully detect the periodic external signals and accurately align their transmissions to the derived slot boundaries. In particular, when $N = 500$, the PER of the Prop., Conv.-LBT, and Conv.-pure ALOHA are approximately 12.4%, 17.0%, and 18.0%, respectively. This suggests that by out-of-band slotting, the Prop. effectively avoids simultaneous packet transmissions on the same frequency channel, thereby mitigating the probability of packet collision at the GW. Furthermore, Conv.-pure ALOHA exhibits the worst PER performance because it does not employ any CS mechanism, leading to frequent packet collisions. In contrast, while Conv.-LBT reduces packet collisions compared to pure ALOHA by deferring transmissions when the channel is busy, it still suffers from hidden node problems.

C. Throughput Performance

In addition to PER, the normalized throughput, which represents the effective data delivery capacity of the system, is evaluated.

Figure 5 shows the throughput performance of each method when the number of nodes N is varied from 100 to 1000 for $SF = 8$. It can be seen that the throughput of all three methods increases as the number of nodes increases, which is due to the larger total amount of traffic offered to the network. In the low node density region ($N \leq 300$), the throughput values of all three methods are almost identical. This is because

TABLE II
AVERAGE SYNCHRONIZATION SUCCESS RATE [%] UNDER DIFFERENT BS
DISPLACEMENTS d_{BS} AND NUMBER OF NODES N .

BS displacement d_{BS}	Number of nodes N				
	100	200	300	400	500
0 m	95.75	95.66	95.87	95.52	95.58
500 m	92.46	92.48	92.57	92.38	92.52
1000 m	84.01	84.08	84.00	83.88	83.87
1500 m	72.53	71.94	72.21	72.06	72.24
2000 m	59.50	59.01	59.13	59.19	59.10

packet collisions rarely occur under such light traffic conditions, allowing almost all packets to be successfully received. However, as the number of nodes N increases beyond 300, the throughput of the conventional methods begins to slow down due to severe channel congestion. In contrast, the Prop. maintains a steady growth, achieving higher throughput than the conventional methods in the high node density. Specifically, when $N = 1000$, the normalized throughput of the Prop., Conv.-LBT, and Conv.-pure ALOHA are approximately 0.229, 0.206, and 0.202, respectively. This improvement is achieved because the proposed method reduces packet collisions, thereby enhancing both communication reliability and network capacity under high node densities.

D. Effect of BS Position on System Performance

Table II and Fig. 6 show the impact of the BS displacement d_{BS} from the GW on the average synchronization success rate and the average PER under $SF = 8$, respectively. Across all evaluated node counts ($N = 100, 200, 300, 400, 500$), the average synchronization success rate decreases as d_{BS} increases from 0 m to 2000 m. This decline is because as the BS moves further away from the GW, the periodic external signals cannot be detected by distant nodes due to large attenuation. Consequently, as shown in Fig. 6, the average PER increases as d_{BS} increases from 0 m to 2000 m. This is because a lower synchronization rate increases the ratio of nodes falling back to asynchronous access, thereby elevating the probability of packet collisions. For instance, when $N = 500$, the PER rises from approximately 12.4% at $d_{BS} = 0$ m to 15.1% at $d_{BS} = 2000$ m. Even when nearly 40% of the nodes fail to synchronize at $d_{BS} = 2000$ m, the overall PER only increases by 2.6 percentage points compared to the co-located case ($d_{BS} = 0$ m). This implies that under a hybrid scenario where synchronized and asynchronous nodes coexist, slotting the synchronized majority (60%) effectively mitigates collisions. Consequently, the asynchronous minority can transmit their packets with a significantly reduced risk of colliding with other synchronized transmissions, confirming the high robustness of the proposed method against BS displacement.

V. CONCLUSION

This paper proposed an out-of-band synchronization method for slotted LoRaWAN utilizing periodic external signals. The proposed method enables the nodes to independently determine their slot boundaries based on the received power of a periodic external signal without requiring data demodulation.

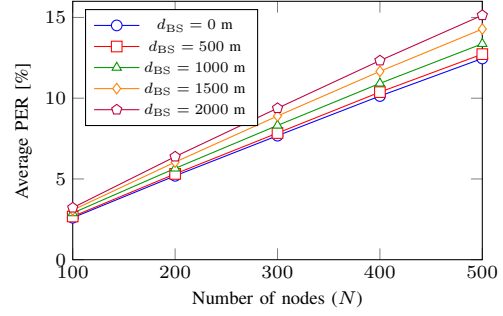


Fig. 6. Effect of BS displacement on Average PER ($SF = 8$).

In simulation, the proposed method reduces the average PER to 12.4% for $N = 500$ nodes, compared to 17.0% in conventional LBT and 18.0% in conventional pure ALOHA.

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