

# Energy efficient slotted synchronization approach in LoRaWAN

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## ABSTRACT

In recent years, long-range wide-area networks (LoRaWAN) have gained much attention as low-power wide-area networks. LoRaWAN uses ALOHA as the medium access control protocol, where the end devices transmit data randomly and retransmit it up to eight times if collisions occur. ALOHA is not energy efficient and works perfectly for a smaller network. Several techniques, including the use of synchronization and scheduling schemes, to deal with the limitations imposed by ALOHA in LoRaWAN have been reported in the literature. However, the existing synchronization and scheduling algorithms transmit synchronization messages randomly using one super frame with fixed time slots that accommodate devices using different spreading factors, which limit the LoRaWAN network's scalability. This work proposes a slotted synchronization mechanism for transmitting synchronization requests to the gateway. The performance of the slotted synchronization was evaluated through simulation using packet delivery ratio (PDR) and energy efficiency as the performance parameters. The results indicate that when the number of devices in the network increases, a time-slotted synchronization consumes less energy, on average, by about 0.2 mAh. The use of a slotted synchronization can improve the energy efficiency of the end devices as collisions are completely avoided, achieving a PDR of 100%.

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## 1. INTRODUCTION

Long-range wide-area network (LoRaWAN) is a one-hop network that consists of end devices connected to the gateway using chirp spread spectrum (CSS) modulation [1]–[9]. Several studies suggest that LoRaWAN consists of three types of end devices, namely Class A, B, and C [10]–[15]. However, Class A devices are more energy efficient as they spend most of their time in sleep mode and become active whenever they have data to transmit [16]. LoRaWAN uses Pure ALOHA as the default media access control (MAC) protocol [17]–[25]. The random nature of ALOHA may negatively affect the energy utilization of Class A devices due to collisions, especially in denser networks [26].

Several methods, including slotted Aloha [27]–[29] carrier sense multiple access (CSMA) [30], [31], TDMA [32], scheduling schemes [33], and the design of new protocols, such as LoRa multi-communication (LMC) protocol [34] have been proposed to address the limitations of ALOHA in LoRaWAN. Scheduling schemes significantly reduce collisions, but to prevent clock drift-induced collisions, end devices must synchronize before transmitting data to the gateway. Most of the reported synchronization

algorithms, including absolute or relative synchronization [35], posteriori synchronization [36], lightweight scheduling schemes [17], fine-grained synchronization [33], TSCH-like scheduling [37], [38] use a random synchronization approach to synchronize end devices and the gateway. Random synchronization can result in collisions, requiring the EDs to utilize their limited power to re-transmit packets that the gateway will never receive. In a less dense network, the effect of unsynchronized devices can be neglected, but not in denser networks. In order to alleviate the problems associated with the random transmission of synchronization requests, a slotted synchronization has been proposed in this work. In slotted synchronization, the EDs are slotted to transmit synchronization requests to the gateway using device IDs. An optimal transmission interval and slot length have been defined to alleviate the issue of duty cycle limitation and the half-duplex nature of the gateway.

The performance of the slotted synchronization, in transmitting synchronization requests in the LoRaWAN network was evaluated and compared with the random approach. Three performance parameters, including packet delivery ratio (PDR), synchronized devices, and energy efficiency, were used. The use of less energy in the time-slotted synchronization was attained by switching the devices to sleep mode while waiting for their time slot to transmit without any collisions (i.e., PDR of 100%). However, the average synchronization time in the slotted synchronization increases with the increase in the number of devices because devices have to wait and transmit in the assigned time slot. The rest of the paper is organized as follows: the various methods, assumptions, and the proposed algorithm have been presented under Section 2. The performance evaluation of the proposed algorithm is presented in Section 3, followed by a conclusion in Section 4.

## 2. METHOD

To achieve the study's objective, we analyzed two transmission approaches, slotted and random, using Network Simulator 3 (NS3). The random synchronization approach was adopted from a work by [12]. The simulation of the two algorithms was carried out by varying the number of devices while recording the time and energy consumed to synchronize all devices in each transmission round.

### 2.1. Simulation setup and assumptions

The gateway clock is considered to have minimum or negligible drift as it is always wall-powered and hence used as a reference clock. The synchronization time interval was set to 30 minutes, and the spreading factors were assigned based on the log-distance propagation model. In-band synchronization was considered, in which the same channel was used for synchronization. Due to the fact that communication happens in the 868 MHz band, both gateways and end devices had to comply with a duty cycle limit of 1%. Therefore, every device in a sub-band must be off for a duration  $T_{off}$ , resulting in the cycle duration presented in (1).

$$\text{Cycle duration} = T_{oA} + T_{rcw} + T_{off} \quad (1)$$

Where  $T_{rcw}$  is the time for the EDs receive windows? The other parameters used during simulation are summarized in Table 1. These parameters were chosen for easier and fair comparison because they have been used to evaluate the performance of the random synchronization approach.

### 2.2. Performance parameters

We evaluated the performance of the two synchronization approaches using energy efficiency in terms of energy consumed, the number of successfully synchronized devices, and packet delivery ratio (PDR). The nodes were randomly distributed in a uniform disc of different radius  $R = 1 \text{ km}$  and  $R = 10 \text{ km}$ . We chose the number of devices to reflect the maximum capacity of a single LoRaWAN gateway architecture. Each device is assumed to transmit one packet in each transmission period, making the total number of packets equal the total number of devices in the network. The evaluation was based on two extreme cases with a small number of devices and a large number of devices in the short and long ranges, respectively.

Synchronization algorithms work by exchanging messages between devices and the node with the master clock. In LoRaWAN. The gateway clock is considered a master clock because it is connected to the grid and up-to-date with the network time. However, the design of most existing synchronization algorithms aims to achieve high accuracy and energy efficiency. To meet the energy-efficient requirements, the sensors wake up periodically but only transmit when an event is detected because most of the energy is consumed during data transmission.

Table 1. Simulation parameters

Parameter	Value
Synchronization payload	36 B
Slot length	1 s
Number of EDs (N)	Up to 900 devices
Duty cycle	1%
SFs	7-12
Gt	6 ms

### 2.3. Proposed algorithm

In slotted synchronization, the devices transmit synchronization requests in a slotted manner using device ID as presented in (2). The synchronization request is a confirmed packet with the acknowledgement bit set to high. The end device will initiate a receive window to obtain the time offset (4) information, which it will use to update the device clock using (3), and to determine the time slot index for data transmission. The end device will switch to sleep mode after synchronization to wait for the data transmission time slot. The resulting flow chart for the slotted synchronization approach, which is an application running on the end device, is presented in Algorithm 1.

$$T_{NextSlot} = TriggerTime + (ToA_{pkt} + G_t)N_{id} \quad (2)$$

Where  $N_{id}$  is the network identity number,  $G_t$  is the guard time and  $TriggerTime$  is the transmission interval.

$$T_{Current} = T_{GW} + (T_{RGt} - T_{XED}) \quad (3)$$

$$T_{RGt} - T_{XED} = Time\ Offset \quad (4)$$

Where  $T_{Current}$  is the updated end device time,  $T_{GW}$  is the time stamp at the gateway,  $T_{RGt}$  is the time for receiving the gateway time at the end device and  $T_{XED}$  is the time when the end device transmits the synchronization request. The devices in the LoRaWAN network must adhere to the duty cycle limitation presented in (5) which are region specific.

$$T_{off} = ToA(d^{-1} - 1) \quad (5)$$

Therefore adhering to the duty cycle, the maximum number of transmission cycles per node per minute is  $60dS_l^{-1}$  where  $d$  is duty cycle and  $S_l$  is the time slot length.

The requirements for the slotted synchronization algorithm are summarized in Table 2. The slot length defined in (6) depends on the time on air of a SF,  $ToA_{SF}$ , the time for the ED to update its clock,  $T_{ED}$  and the duty cycle limitation of the band used. The slot length is made large enough to accommodate the half duplex nature of the gateway in which the gateway cannot listen to the uplink transmission while replying to a synchronization request at the same time. Therefore, the slot length included the time for the two receive windows,  $RX_1$  and  $RX_2$  of an ED and the off time,  $T_{off}$  in order to allow the gateway to finish serving one device before starting serving another device.

$$S_l = ToA_{SF} + RX_1 + RX_2 + T_{ED} + T_{off} \quad (6)$$

In the slotted synchronization algorithm, the end device, at their time slot, sends a synchronization request of 21 B, which is a confirmed packet, to the gateway. The synchronization request packets include the current time reading of the end device. During the transmission process, the times for the end device to complete the transmission and the gateway to receive the packet are recorded. The gateway time is added as the header to the packet and then forwarded to the network server. The network server then sends an acknowledgment consisting of the gateway time to the end device during the first or second receive window. The acknowledgement packet sent from the network server also consists of the time slot for the end device to transmit the data packet. The assignment of the time slots is done following the algorithm presented in Algorithm 1. Therefore, the EDs are forced to sleep after updating their local clock while waiting for their scheduled time slot to start data packet transmission.

A single time slot is allotted to each individual device, and it is presumed that the amount of data collected is the same for all of the devices. The synchronization request is only sent once during each transmission round. If a device is unable to synchronize, it will not transmit during that cycle and will be required to wait until the subsequent transmission round.

Table 2. Requirements for the synchronization algorithm in LoRaWAN

Parameter	Value
Slot length	$To_{SF} + RX_1 + RX_2 + T_{off}$
Duty cycle	Region specific depending on the band used
Synchronization period	Should be low to avoid battery drainage
Synchronization payload	Must be small enough to avoid long time on air

**Algorithm 1.** Slotted synchronization algorithm**Require:**  $T_{trigger}$ ,  $N_{id}$ ,  $n_{preamble}$ ,  $R_{symbol}$ ,  $PL$ ,  $SF$ ,  $H$ ,  $DE$ ,  $CR$ ,  $T_G$ **Ensure:** Updated ED clock

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if  $T = T_{trigger}$  then
  Activate ED
  Calc  $a = n_{pre} + 4.25$ 
  Calc  $b = \frac{1}{R_{sym}}$ 
  Calc  $c = \frac{8PL - 4SF + 28 + 16CRC - 20H}{4(SF - 2DE)}$ 
  Calc  $d = CR + 4$ 
  Calc  $To_{Apkt} = a \times b + [8 + \max(\text{ceil}(c \times d, 0) \times b)]$  Calculate  $T_{next}$ 
   $= T_{trigger} + (To_{Apkt} + T_G)N_{id}$ 
  Calculate  $\Delta = T_{xD} - T_{gt}$ 
  if  $T = T_{next}$  then
    Sleep to wait for Slot
     $T_{next} \leftarrow T_{next} - 1$ 
  else
    Transmit
    Open RX1
    if ACK is received then
      if  $\Delta = 0$  then ... (i)
       $T_{upd} = T_{curr}$ 
    else
      if  $\Delta > 0$  then
         $T_{upd} = T_{curr} - \Delta$ 
      else
        if  $\Delta < 0$  then
           $T_{upd} = T_{curr} + \Delta$  ... (viii)
    else
      Open RX2
      if ACK is received then
        Repeat steps (i) to (viii)
      else
        Synch failed!
        Go to sleep to wait for  $T_{trigger}$ 
  End ALL

```

**3. RESULTS AND DISCUSSION**

In this section, the performance results of the proposed slotted synchronization algorithm in comparison to the random synchronization approach is presented in details. Through random transmission, the proposed slotted synchronization method allows for large-scale device synchronization. With smaller networks, packet re-transmission is worse, using more energy and slowing down the network.

**3.1. Synchronized devices**

Successfully synchronized devices for  $R=1$  km as shown in Figure 1. All scenarios, as shown in Figures 1(a) and (b), demonstrate the possibility of synchronizing a large number of devices using the proposed slotted synchronization approach. All devices managed to synchronize in a slotted synchronization approach for a 12 EDs network uniformly distributed in an area of of  $R = 1$  km (see Figure 1(a)). This signifies reduced interference or collision in the slotted transmission approach. On the other hand, all packets managed to synchronize with less than nine EDs in the network using a random transmission approach. When the number of devices increased from nine to 12, the SR for the random transmission approach decreased from 66% to 8.33%. As demonstrated in Figure 1(b), increasing the number of devices to 900 devices maintained the higher SR and PDR in the slotted synchronization approach, where all devices synchronized successfully. However, the number of EDs that managed to synchronize in the random synchronization approach significantly decreased.

We observe a drop in the SR for both synchronization approaches when we increase the propagation range to 5 km, the theoretical maximum propagation range in urban scenarios (Figure 2). However, the SR for the slotted synchronization approach is higher than that of the random approach by about 22% and 33% when the number of devices increases from nine to 12 devices, respectively, as shown in Figure 2(a). A large number of transmitted packets is observed in the random synchronization approach when the number of EDs is six, possibly due to the fact that some of the EDs use more than one transmission attempt to deliver the packet to the gateway, but the acknowledgment is never received at the EDs, resulting in the synchronization failure.

By increasing the number of devices to the maximum theoretical number that can be supported by the gateway, the PDR for the slotted synchronization approach decreases by 13% when the number of devices increases from 500 to 900, as shown in Figure 2(b). However, the synchronization drops from about 2.1% to 1% when the number of devices increases from 100 to 900 in the random synchronization approach. The decrease in the PDR and SR may be due to the increased propagation range and the use of higher spreading factors, which do not guarantee the delivery of the packets due to longer ToA.

The decrease in synchronization ratio is the result of transmitting confirmed packets in the LoRaWAN network, which is inefficient in dense networks with a single gateway architecture. Another reason for synchronization failure is the half-duplex property of gateways, whereby if, at a certain time, an uplink transmission is scheduled for an end node, the gateway has to listen to this transmission and cannot simultaneously reply to synchronization requests even when happening in a different channel.

### 3.2. Packet delivery rate

A large number of packets are transmitted (Figure 3), attaining a maximum packet transmission rate (PTR) of about 200% when random transmission is used due to the re-transmission attempts. Packet re-transmission is observed to be more severe when the number of devices connected to the network increases in a smaller network of 12 EDs (see Figure 3(a)). Increasing the number of devices to 900 EDs decreases the number of packets transmitted by the random synchronization due to the random nature of the transmission, as seen in Figure 3(b). This means that some of the devices will never transmit any packet while others will transmit more than one packet in order to synchronize in both smaller (12 EDs) and denser (900 EDs) networks.

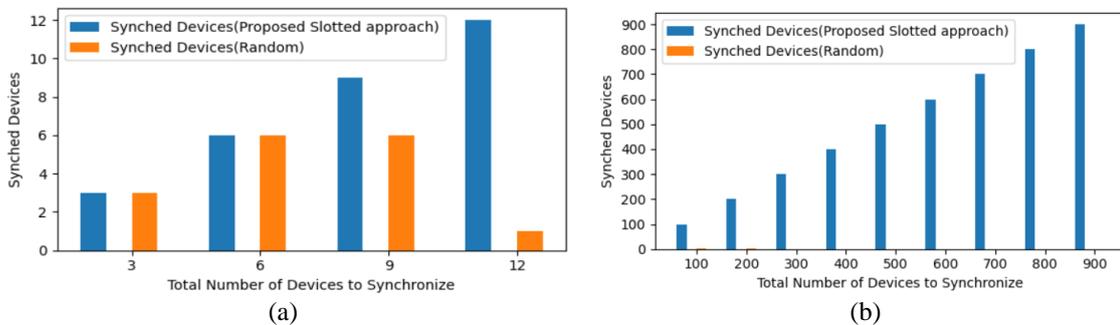


Figure 1. Successfully synchronized devices for R=1 km (a) N=12 and (b) N=900

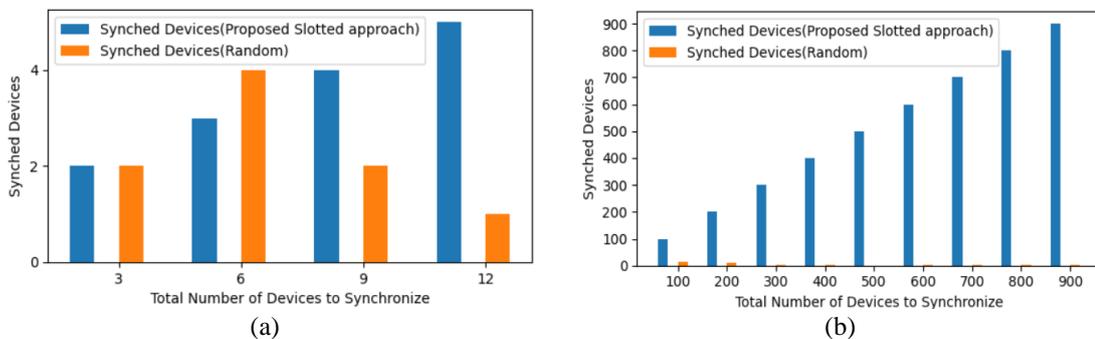


Figure 2. Successfully synchronized devices for R=5 km (a) N=12 and (b) N=900

Increasing the propagation range to 5 km shows in Figure 4, a significant drop in PTR of about 33% in a smaller network ( $N = 12$  EDs). This shows that a maximum of 8 packets are transmitted in a 5 km range as opposed to a maximum of 12 packets transmitted in a 1 km propagation range for both random and the proposed slotted synchronization approaches. This is only noticeable in a smaller network ( $N = 12$ ), as shown in Figure 4(a). Most of the packets are successfully transmitted using the proposed slotted synchronization approach in a network of 900 EDs distributed in a 5 km coverage radius network, as depicted in Figure 4(b). In the random transmission approach, the packet transmission rate (PTR) dropped from 25% to about 2% when the number of EDs increased from 100 to 300, respectively. The PTR is maintained constant regardless of the number of EDs in the network, as shown in Figure 4(b). Generally, there are fewer collisions in the slotted synchronization approach when compared to the random approach in a network when devices are more concentrated near the gateway ( $R=1$  km). The achieved synchronization ratio for the random synchronization approach was about 1.3%, which is equivalent to synchronizing 5 out of 300 devices before reaching the maximum re-transmission limit of eight. The decrease in synchronization ratio for the proposed slotted synchronization is the result of transmitting confirmed packets in the LoRaWAN network, which is inefficient in dense networks with a single gateway architecture. Another reason for synchronization failure is the half-duplex property of the LoRaWAN gateways, which cannot simultaneously listen and reply to synchronization requests even when happening in a different channel.

### 3.3. Energy consumption

Energy consumed for  $R=1$  km as shown in Figure 5. The energy consumed by both synchronization schemes when there are a small number of devices in the network is higher by about 0.5 J in the random synchronization approach, as presented in Figure 5(a). This may be due to the fact that all devices are striving to synchronize at the beginning, and this number decreases as other EDs get synchronized. Some of the devices will never synchronize after reaching the maximum transmission limit.

In both non-slotted and slotted transmission cases, we observe constant energy consumption after most devices have successfully synchronized or stop transmitting the synchronization request messages. On average, 4 J is consumed to synchronize less than 20 devices if a random synchronization approach is used, while about 3 J is consumed using slotted synchronization.

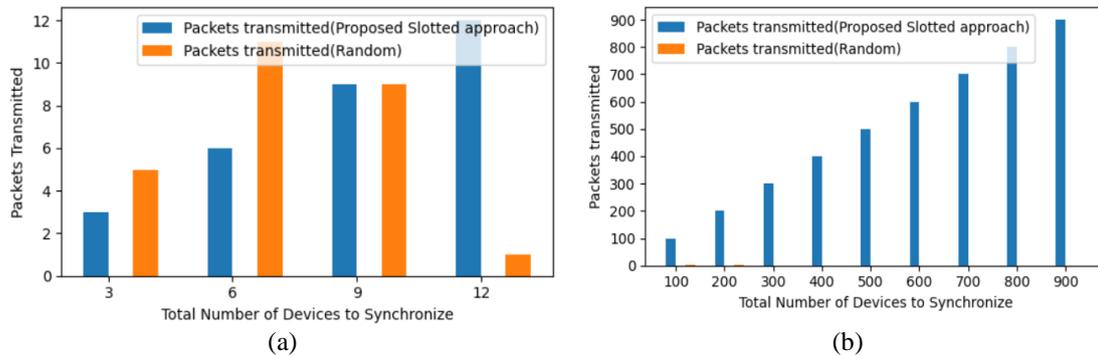


Figure 3. Total number of packets transmitted for  $R=1$  km (a)  $N=12$  and (b)  $N=900$

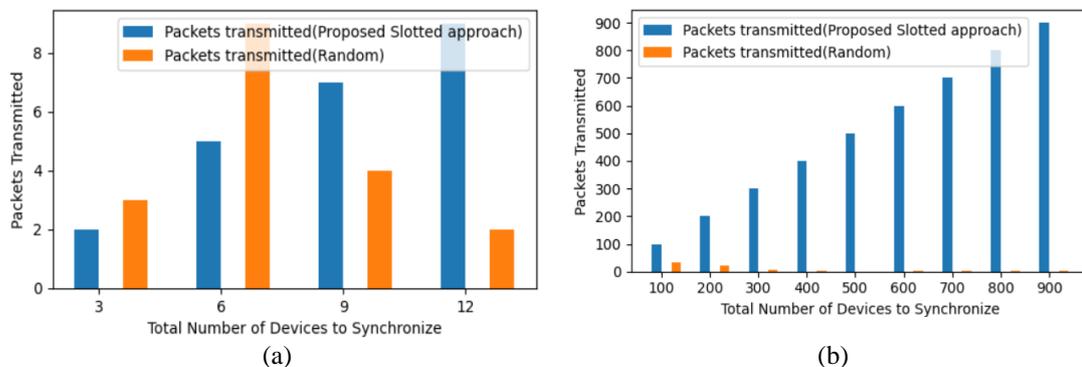


Figure 4. Total number of packets transmitted for  $R=5$  km (a)  $N=12$  and (b)  $N=900$

Increasing the number of devices from 10 EDs to 900 EDs increases the energy consumption of both the random and the proposed slotted synchronization approaches to 3.5 J and 3.25 J, respectively, as shown in Figure 5(b). The average energy consumption for the random synchronization approach was only 0.25 J higher than that of the proposed slotted synchronization. This is possibly due to the shorter propagation range that makes most of the EDs use the lower SF, which guarantees data delivery.

Energy consumed for R=5 km as shown in Figure 6. Increasing the range to 5 km, which is the maximum theoretical range for single-gateway LoRaWAN network architecture in an urban area, the energy consumed by the random synchronization approach increases significantly to about 20 J, while the energy consumption of the proposed slotted synchronization approach is constantly low at about 4 J, as shown in Figure 6(a). The increase in energy for the random synchronization approach might be due to some of the EDs using the maximum eighty retransmission trials to transmit packets that were never received at the network server, while others attempted less than the maximum transmission trials to synchronize.

Increasing the number of devices to 900 maintains the energy consumption by the proposed slotted synchronization algorithm at a constant value of 3 J, while the energy consumption by the random synchronization algorithm is also constant at about 7 J, except when the number of EDs in the network is 100. The average energy consumption by random synchronization when the number of EDs is 100 is a maximum of about 16 J, as shown in Figure 6(b).

Energy consumed in various ranges as shown in Figure 7. Fixing the number of devices to 12 EDs while varying the propagation range shows a significant increase of about 3 J in the energy consumption for the random synchronization approach as the range increases from 1 km to 5 km, as shown in Figure 7(a). On the other hand, the energy consumed by the slotted synchronization approach increases from about 3 J to 3.5 J when the range increases from 1 km to 5 km, respectively. The increase in energy consumption for the random synchronization approach could be a result of some EDs in the network transmitting the same data packet more than once.

Increasing the number of EDs to 900 creates a fair distribution of the SF to the EDs, resulting in reduced collisions, which decreases the retransmission trials. The effect of decreased retransmissions decreases the energy consumption for the random synchronization approach, as shown in Figure 7(b). The end device consumes energy based on the duration of the synchronization phase and the number of synchronization phases. In the slotted transmission approach, energy savings were achieved by spending less time in the synchronization phase and reducing the number of synchronization phases (i.e., one synchronization phase in each data transmission phase).

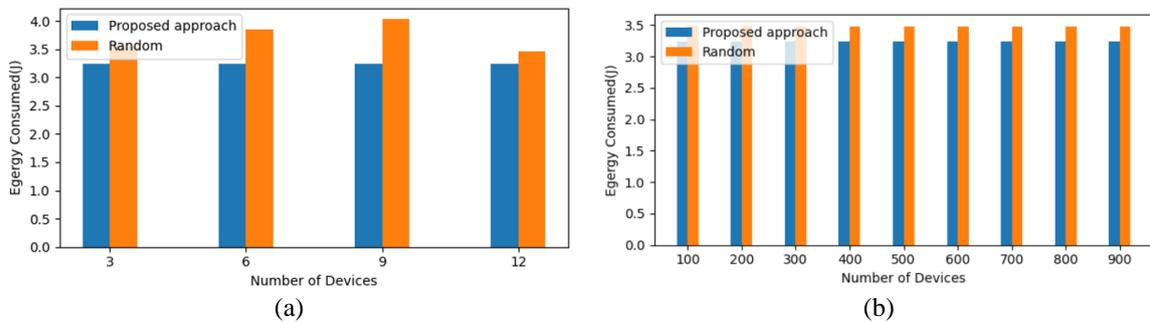


Figure 5. Energy consumed for R=1 km (a) N=12 and (b) N=900

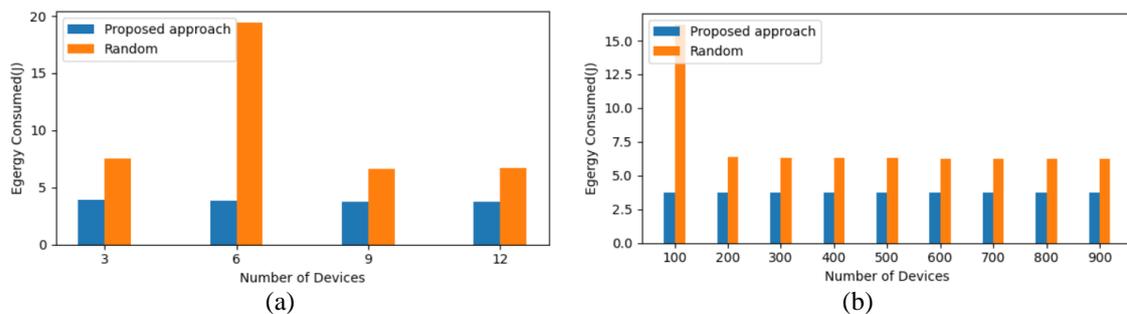


Figure 6. Energy consumed for R=5 km (a) N=12 and (b) N=900

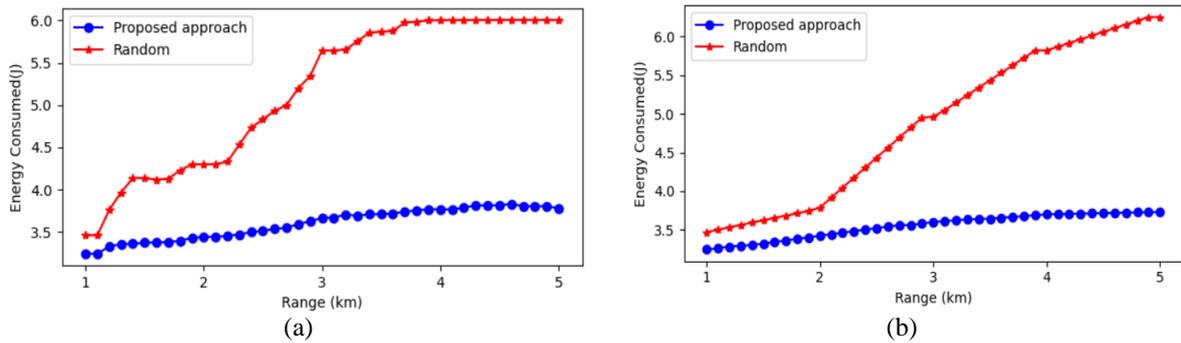


Figure 7. Energy consumed in various ranges (a) N=12 and (b) N=900

#### 4. CONCLUSION

Time-scheduling algorithms are better solutions to improve LoRaWAN network scalability. However, the EDs must synchronize before transmitting in their scheduled time slots. The use of a random approach to transmit synchronization requests causes significant collisions, which affect the packet delivery ratio and energy efficiency of battery-powered devices. In this work, a slotted synchronization approach has been proposed to synchronize LoRaWAN EDs, which have a unique operation when compared to other wireless devices. The use of the proposed slotted synchronization approach reduces collisions significantly. The synchronization time in slotted synchronization is longer than in the random synchronization approach, making it applicable to applications that are not time-sensitive. An innovation slotting scheme that minimizes unfair waiting time for devices with large device IDs is recommended as future work. Testing of the slotted synchronization approach in a complicated network architecture with more than one LoRaWAN gateway can also be considered future work.

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