LoRaWAN Scheduling Mechanism for 6G-based LEO Satellite Communications

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***Abstract*—As the Internet of Things (IoT) is poised to become a global phenomenon, it is imperative to schedule the transmissions of IoT devices effectively and in a fair way. Leveraging Long Range (LoRa) technology, we can achieve transmissions that consume minimal power while covering vast distances, aligning with the requirements of IoT devices. However, the proximity of multiple devices within the same area often leads to packet interference and collisions. To address this, our study introduces a pioneering scheduling method utilizing a constellation of Low Earth Orbit (LEO) satellites to manage and streamline the transmission of data from End Devices (EDs). This method employs two LEO satellites: the first satellite assigns the sequence for EDs to dispatch their packets, and the second collects these packets in the predetermined sequence before forwarding them to the LoRa Network Server (LNS). For urgent (URG) communications, EDs can alert the first satellite, which then coordinates with the LNS to schedule these priority transmissions. The LNS generates a schedule that is relayed to the second satellite, informing EDs with URG packets of their specific transmission times and channels. This scheduling approach is designed to optimize channel usage effectively while accommodating the transmission of urgent data.**

***Index Terms*—6G, Internet of Things, LoRa, Scheduling mechanism, LEO satellites.**

I. Introduction

6G networks are poised to redefine the landscape with a vast network of IoT devices catering to a wide array of uses such as precision farming, land mapping and monitoring, asset tracking, and wildlife protection [1]. In this emerging ecosystem, LoRa technology stands out for its ability to facilitate long-distance communication essential for satellite interactions, which typically occur at distances starting from 500km above the Earth's surface. LoRa's unique chirp signal modulation sets it apart from other radio communication methods, offering superior battery efficiency—a critical factor for IoT devices where power constraints are significant [2]. Given the challenges of battery replacement in the scenarios mentioned, which may extend over months or even years, LoRa emerges as the premier radio technology capable of meeting these demanding requirements.

As IoT applications expand globally, the need for communication with the LNS [3], potentially situated on the opposite side of the globe, becomes crucial. This is where LEO satellites come into play, orbiting the Earth at altitudes ranging from approximately 200km to 2,000km [4]. LEO satellites are integral to various fields, including communications, military operations, and imaging, due to their numerous advantages. One significant benefit is their reduced propagation delay, which contributes to lower latency in communications. Additionally, their deployment is more cost-effective compared to geosynchronous satellites, as they operate at much lower altitudes, reducing both launch and operational costs.

A critical element in satellite communication is the period of satellite visibility. LEO satellites, known for their rapid orbit around the Earth, can complete multiple orbits daily. This necessitates that EDs time their transmissions to coincide with the periods when the satellite is visible overhead. To accommodate this, our approach includes scheduling the EDs' transmission times based on the orbital periods of satellites 1 and 2 utilized in our system. Utilizing the ALOHA protocol [5], which represents the most basic form of transmission, would lead to significantly inefficient channel use due to high rates of re-transmissions caused by collisions. Therefore, this method is generally unsuitable for our purposes. However, an exception has been made for the transmission of urgent packets using ALOHA, with the rationale for this decision detailed within our paper.

A. Motivation

Existing scheduling algorithms for IoT devices on LoRaWAN networks [6] mainly cater to ground-based devices. As IoT becomes ubiquitous, the expected surge in devices will likely cause packet collisions and power inefficiencies, especially critical for power-sensitive devices. This is compounded when EDs need to communicate with a remotely located LNS, necessitating satellite communication. However, satellite communication introduces complex scheduling challenges due to the dynamic nature of satellite availability and the need for precise timing of transmissions from multiple EDs, making traditional FIFO methods inadequate [7]. This paper highlights that satellite constellations can improve scheduling efficiency, ensuring optimal channel utilization and fairness. Traditional algorithms do not adequately address urgent transmissions, prioritize among competing transmissions, or adapt to topology changes. By focusing on these aspects, our approach aims to enhance satellite-based scheduling for LoRaWAN IoT networks. This paper explores these challenges in detail, proposing innovative approaches to improve scheduling efficiency and effectiveness in satellite-supported LoRaWAN networks.

II. System Architecture

We considered a LoRaWAN network [6] whose architecture is depicted in Fig. 1. In satellite-monitored networks, device transmissions should be timed based on the satellite's orbit period rather than their stochastic sensing of the environment. This is because devices, such as sensors in agricultural monitoring (e.g., temperature, humidity, and soil pH sensors), can only transmit data when the satellite is visible. Given the varying data update frequencies of these sensors—approximately every 2, 6, and 12 hours for temperature, humidity, and pH sensors, respectively—transmission schedules should align with the satellite's orbit, ensuring efficient data relay. For instance, if the satellite orbits every 1 hour and 15 minutes, sensor transmissions can be planned for when the satellite is next visible, optimizing data collection and transmission timings based on the satellite's orbit cycle.

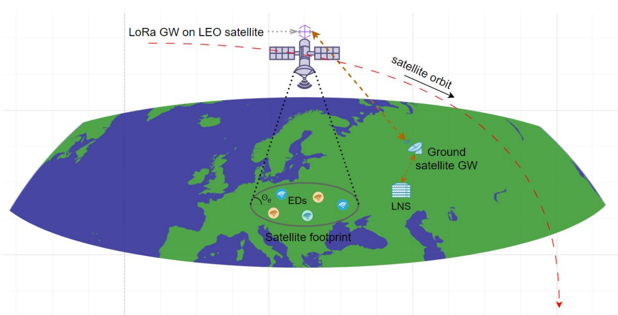

Fig. 1. LoRaWAN Network Architecture

We utilize two satellites for our network. The first satellite receives scheduling data from the LNS. During the initial joining phase, devices register via Over the Air Activation (OTAA) [8]. Once registered, the LNS gains insight into the network's topology and organizes transmission schedules accordingly. The service area is segmented into distinct zones, crucial for planning transmissions. As illustrated in Figure 1, the satellite oversees a specific coverage area, known as the satellite footprint, containing the EDs. It's important to note that although the coverage region may extend beyond the satellite's footprint, EDs can only transmit data when they are within this footprint. The second satellite collects data transmissions from the EDs based on the LNS's schedule. Equipped with a LoRa gateway, this satellite converts the received signals into IP packets, which are then relayed to a ground-based Satellite Gateway Receiver Dish. This dish forwards the packets to the LNS, enabling communication with EDs located far from the LNS and highlighting the significant advantage of satellite integration in extending network reach. During the initial network joining phase: 1) each ED sequentially joins the network by establishing a connection to the LNS through OTA registration, and 2) the LNS keeps a record in a table that includes each device's joining ID, the number of transactions (n_{tx}), and their designated zone (cut).

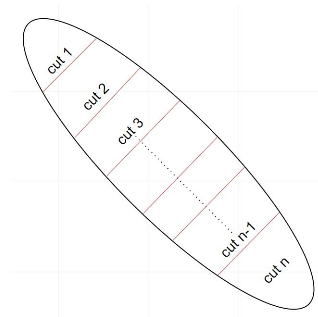

Fig. 2. Defining a Cut

A. Defining a Cut

We configure the area encompassing all the EDs as an ellipse. This ellipse will have a variable length but a width consistent with the satellite's footprint dimensions. The EDs on the Earth's surface will occupy this elliptical area, segmented into equally sized sections, or cuts. The overall length of the elliptical area will be proportional, being a multiple of the length of a single section.

Next, we compute the length of each cut. If T is the transmission time of one ED and assuming that every ED has the same transmission time, independent of the nature of transmission, we have,

$$Cut_{len} = T \times v_{sat} \tag{1}$$

where, Cut_{len} length of 1 cut in metres, v_{sat} is the velocity of the satellite. A guard time, T_{guard}, can be added to T, for adjusting the clock drifts that may occur. The primary reason for keeping width of the elliptical path (where end-devices are present) the same as the satellite footprint width is that the patch width is matched to the satellite footprint to prevent adjustments with each new ED entry or exit. Thus, it avoids areas outside the satellite signal reach and ensures effective communication without constant modification.

Task of satellite 1: The LNS will provide Satellite 1 with a schedule, detailing the specific times and channels for ED transmissions. As Satellite 1 approach a designated cut, it will broadcast beacons that include the identity of the ED scheduled for transmission and the designated channel for this activity. URG packets will be managed through URG channels. Given the periodicity of the satellite, EDs are aware of its approach timing and will dispatch Request to Send packets using an ALOHA protocol. If collision occurs, exponential back-off will be applied.

B. Satellite Tasks

Task of satellite 2: For EDs not transmitting URG packets, Satellite 1 will only receive transmissions from those EDs it has previously scheduled. Satellite 2's primary role is to broadcast beacons to EDs with urgent data packets to transmit, specifying the timing and channel for their URG packet transmission, utilizing the available urg_c Urgent channels. Upon Satellite 2's coverage encompassing an entire area, it will issue a beacon detailing the specific time and channel for EDs to send their urgent data packets.

The spacing between satellite 1 and satellite 2 is done in such a way, that satellite 1 sends all the urgent packet requests to LNS for scheduling them, and LNS after computing the schedule, sends it to satellite 2.

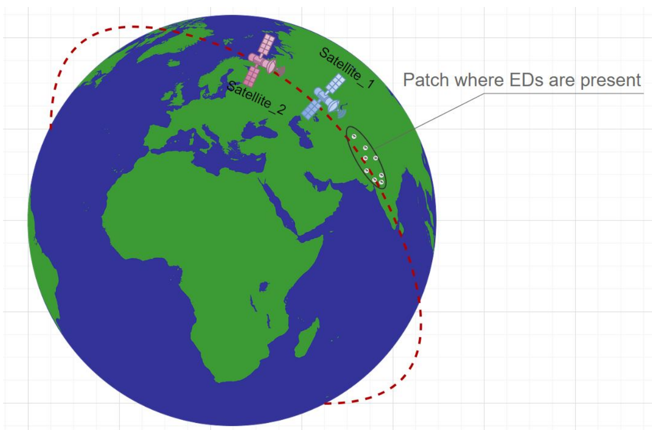

Fig. 3. System Model- Abstracted View

C. Timing Considerations

The EDs' timers are adjusted so that their designated time, t, coincides with Satellite 2's arrival at cut 1, aligning with the orbit period of the LEO satellite for that specific location. Additionally, guard times are essential to account for, as precise cutoffs are impractical due to inevitable clock drifts. Such drifts are particularly challenging in satellite operations, potentially influenced by various space phenomena like solar winds.

D. Dealing with URG packets and their scheduling

For URG packet transmission, the ALOHA protocol will be employed. The EDs that are within the satellite's coverage area will attempt to send packet transmission requests with a certain probability,p, specifically through a channel dedicated to URG packets. The initial satellite in contact will compile a queue of these transmission requests and forward this data to the LNS to coordinate the scheduling of URG packet transmissions by the EDs. Upon the approach of a second satellite, the LNS will have already established a schedule that ensures:

1) As soon as an ED enters the coverage area of the second satellite, it will receive a beacon through the URG channel from the satellite. This beacon will specify the timing for the ED's URG data packet transmission and suggest an available channel for use.
2) This process allows for efficient use of bandwidth; for example, a single ED might transmit during a specific time slot (cut 5), while four standard channels remain unused. Other EDs intending to send URG packets can utilize these available channels if they simultaneously fall within the satellite's footprint.
3) For non-URG packet transmissions, the LNS will schedule based on the transmission frequency of each packet type. For instance, Type A packets might be sent every 2 hours, Type B every 6 hours, and Type C every 12 hours, allowing the LNS to allocate channels based on these intervals.

The first satellite will issue a beacon that includes the order of reception and the available channel for use. If multiple EDs of the same type contend for transmission and channels are still available, the LNS will prioritize based on the number of transmissions (n_{tx}) each ED has made, favoring those with fewer transmissions. If a tie occurs, priority is then given based on the joining ID, with preference given to lower IDs. Following this decision, the LNS will update a table tracking each ED's transmission count (n_{tx}), their ID, and their current slot, thereby managing transmission priorities and channel allocation efficiently.

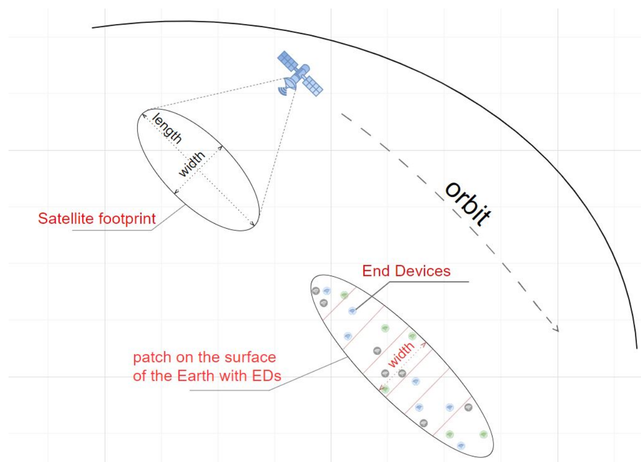

Fig. 4. Defining a Cut EDs and Sat Footprint

E. Dealing with topology changes

If a new ED enters the existing topology, then a new entry will be made in the table by appending it, and giving it ID = last ID + 1, count of n_{tx} = 0, and providing with the cut that it is present in. This information will be later used for the next scheduling, which it can be part of. There are three scheduling that need to be done at the LNS:

1) The first scheduling will be done by the LNS when all the EDs join the network
2) Scheduling needs to be done for the URG packets whose information will be sent by the satellite 1.
3) When the topology changes, a new scheduling needs to be done.

III. Proposed Work at LNS

The LNS executes three algorithms (Algorithm 1, Algorithm 2, and Algorithm 3) as described below. The three

Algorithm 1: DGS: DSME-GTS Scheduling

```
t = orb_p ;
for each cut_k ∈ cut_n do
    for i=0 to D-1 do
        if ((t%k_h orb_p ≠ 0) && (t%k_{h-1} orb_p ≠ 0)
          && ... && (t%k_{i+1} orb_p ≠ 0) &&
          (t%k_i orb_p == 0)) then
            type=i ;
        end
        if (count_of_ED_curr_cut_type_i ) > c then
            temp_tb_1 =
              sort(master_tb[cut_k][typ], no_of_trxs)
              ;
        end
        temp_tb_1 = select * from temp_tb_1 group
          by no_of_trxs order by id ;
        final_tb = select top c from temp_tb_1 ;
    end
    if (t%k_h orb_p == 0) then
        t = orb_p ;
    end
    else
        t = t + orb_p ;
    end
end
```

Algorithm 2: DGS: DSME-GTS Scheduling

```
Use URG channel to transmit request to Sat_1 ;
Sat_1 appends requests in its list, B;
After all the cuts are traversed in the satellite path, B
  is sent to the LNS for scheduling ;
Sort B in linear order ;
The LNS identifies the particular ED, channel and the
  timestamp for transmission to Sat_2 ;
Sat_2 transmit beacon with schedule information in
  URG channel_1 ;
```

Algorithm 3: DGS: DSME-GTS Scheduling

```
EDs appends the ID, cut and type that has to be
  transmitted to the LNS ;
Request to send beacon from ED to satellite 1 using
  URG channel ;
Beacon containing the schedule information (computed
  by LNS) is transmitted to the EDs by Sat_2 ;
```

algorithms execute at the LoRa Network Server. We assume $\mathcal{D}$ type of devices named A, B, C, etc. If the $orbit\_period$ of Sat_2 is orb_p hrs, then devices A.....Z will have to send times in multiples of orb_p like :

A will have sending time = $k_0$orb_p hrs
B will have sending time = $k_1$orb_p hrs
C will have sending time = $k_2$orb_p hrs

here note that :

$$k_0 < k_1 < k_2 ... \quad and \quad k_0 >= 1$$

Here, time t = orb_p. Also, we maintain a 2D list where every row corresponds to a cut. There are n number of cuts(cut_1, cut_2, ... cut_n).

The EDs are synchronized with the satellites, ensuring precise awareness of a satellite's arrival within their respective sectors. The LNS holds a detailed registry that includes information on each sector, the sector number, the ED identifier, and the channel number. As Satellite 1 traverses through each sector, acting as a beacon, it transmits every corresponding entry for that particular sector.

IV. Preliminary Experimental Results

For the experiments, we consider the length of a elliptical path to be equal to length of one cut multiplied by 100. We assume width of elliptical patch is equal to 2 kms. We consider 1000 EDs within the elliptical path, that are randomly deployed. Further, the cuts are equidistant from one another. In our Python based simulation, we have considered 5 channels and two urgent channels. We execute the proposed algorithms and measure the performance based on packet delivery ratio (PDR), power consumption, schedulability of the proposed mechanism, and latency of packet delivery.

A. Packet Delivery Ratio

PDR is a crucial metric in evaluating the reliability and performance of a network, particularly in wireless networks where packet loss due to interference, congestion, or other factors is common [9]. A higher PDR indicates better reliability and efficiency in data transmission, while a lower PDR suggests potential issues that may need to be addressed to improve network performance. From Fig. 5, it can be observed that PDR stabilizes around 90% as the number of EDs increases beyond 600. This shows that proposed scheduling mechanism is able to schedule transmissions of all the EDs. Loss of packets may be contributed to collisions or interference from other networks.

B. Power Consumption

One of the primary design goal of any scheduling mechanism is to have minimal overhead in terms of power consumption. Power consumption refers to the rate at which energy is used or the amount of energy used over a certain period of time. It can be observed from Fig. 6 that average power consumption slightly increases as the network is scaled up towards 1000 EDs. This is because although more number of devices are in contention for the transmission slots, the proposed scheduling mechanism is able to schedule the transmissions in a non-overlapping manner.

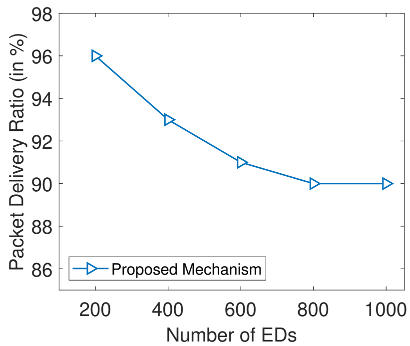

Fig. 5. Average Packet Delivery Ratio.

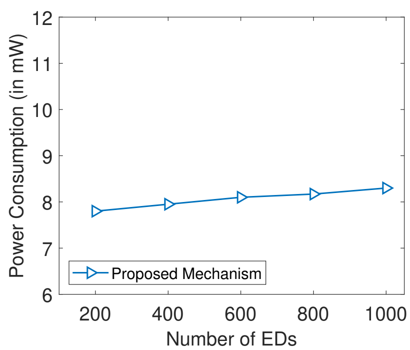

Fig. 6. Average Power Consumption.

C. Schedulability

The choice of a scheduling scheme also depends on its schedulability. A higher schedulability also reflects better channel utilization. The schedulability of the proposed mechanism is presented in 7. The scheme is able to schedule a high number of EDs.

D. Latency

Latency refers to the time delay between the initiation of a process and its completion. It is commonly used in the context of computer networks, where it represents the time it takes for a data packet to travel from the source to the destination.

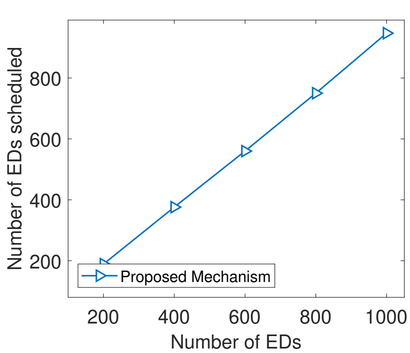

Fig. 7. Schedulability.

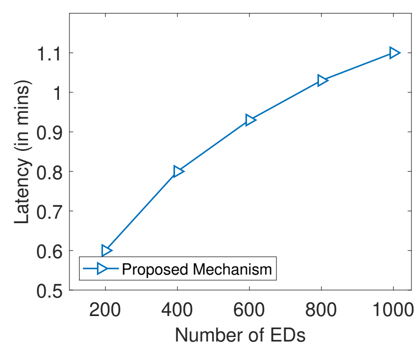

Fig. 8. Average Latency.

Latency can be affected by various factors such as the distance between the EDs and LEO satellites, and the speed of data transmission. Fig. 8 presents the latency of transmissions using the proposed mechanism.

V. Conclusion

The paper highlights the successful implementation and evaluation of the proposed LoRaWAN scheduling mechanism for 6G-based LEO satellite communications. Through innovative scheduling algorithms and the utilization of LEO satellites, the system effectively manages IoT device transmissions, optimizing channel usage and accommodating urgent data transmission. The paper demonstrates promising results in terms of packet delivery ratio, power consumption, schedulability, and latency, showcasing the efficiency and reliability of the proposed mechanism. Overall, the research contributes to enhancing satellite-based scheduling for LoRaWAN IoT networks, addressing challenges and improving scheduling effectiveness in satellite-supported communication systems.

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