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MULTIPLE CHANNEL LoRa-TO-LEO SCHEDULING FOR DIRECT-TO-SATELLITE IOT

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Abstract - *As IoT applications expand rapidly, devices are increasingly being deployed in remote areas requiring satellite networks, particularly Low-Earth Orbit (LEO) satellites, to deliver global connectivity for use cases such as disaster response, precision agriculture, and environmental monitoring. A key challenge in direct-to-satellite (DtS)-IoT is enabling energy-efficient and spectrum-efficient multiple access. This paper introduces two novel scheduling methods for DtS-IoT networks, both derived from the LoRa to LEO satellite scheduling algorithm (SALSA), which allocates time slots on a first-come-first-served basis to minimize collisions. However, SALSA's performance diminishes in high-density scenarios. The proposed techniques enhance uplink efficiency by utilizing multiple frequency channels and adjusting transmission scheduling within visibility windows, resulting in up to an 80% increase in system uplink efficiency with smaller packet sizes and more available channels. By combining the two approaches, system performance improves further, ensuring over 50% uplink efficiency across four, six, and eight channels.*

Key Words: *Direct-to-satellite IoT (DtS-IoT), Low-Earth Orbit (LEO) satellites, Multiple access scheduling, Uplink efficiency, LoRa to LEO satellite scheduling algorithm (SALSA).*

1. INTRODUCTION

Future massive Machine Type Communication (MTC) solutions are anticipated to further digitalize and interconnect society. The MTC market is expected to reach a value of $12.6 trillion by 2030, driven by emerging Internet of Things (IoT) applications. However, realizing this potential market comes with inherent challenges in MTC systems. To address these, sixth-generation (6G) networks aim to overcome the limitations of 5G, such as device longevity, implementation costs, communication reliability, and hardware complexity. Despite these advancements, 6G's massive traffic could introduce new challenges, including medium access, mobility management, traffic offloading, and interference in densely populated areas.

Ensuring global MTC connectivity requires non-terrestrial networks, though these solutions are typically expensive. However, the reduced cost of launching miniaturized Low-Earth Orbit (LEO) satellites has made Direct-to-Satellite (DtS)-IoT systems more affordable and appealing. These low-altitude (160-1000 km) satellites offer low latency (~7 ms) and favorable orbital periods (~90 minutes), increasing satellite revisit rates. Both sparse and dense constellations of these satellites can deliver IoT connectivity globally at a relatively low cost, covering large underserved areas. DtS-IoT systems are critical for various sectors, such as agriculture, disaster response, and environmental monitoring, and can reduce costs in fields like public health, fisheries, tourism, and water management through remote monitoring.

As we move towards 6G, enhancing non-terrestrial networks to provide both global connectivity and high-quality service (QoS) is crucial. Medium Access Control (MAC) protocols are a key research area in DtS-IoT systems. To improve non-terrestrial IoT network efficiency, MAC protocols must consider the complexity of implementation and satellite orbits. Among MAC-related topics, transmission scheduling is particularly important and is the focus of this research. In previous studies, IoT devices used LoRa technology to transmit data in assigned time slots to a satellite-based gateway. Scheduling these time slots was handled by the LoRa to LEO satellite scheduling algorithm (SALSA), using a first-come-first-served (FCFS) policy in low-density scenarios, where each device transmits as soon as the satellite is visible.

However, in high-density situations, FCFS scheduling leads to congestion, preventing many devices from transmitting during the visibility window. To address this limitation, we introduce two novel low-complexity scheduling strategies for DtS-IoT networks. First, we propose the LoRa-to-LEO scheduling with permutation (L2L-P), which allows reordering device transmissions within the visibility window to optimize unused time slots left by SALSA. We also present the LoRa-to-LEO with Alternating Channels (L2L-A) strategy, which redistributes device transmissions across multiple channels for better efficiency. Numerical simulations demonstrate that combining both strategies into L2L-AP significantly enhances uplink performance, achieving approximately 95% uplink efficiency for IoT deployments over France. This is a substantial improvement compared to FCFS, which achieves around 15% in dense environments with 1,000 IoT devices.

The paper proceeds as follows: Section II reviews related literature and highlights the novelty of this work, Section III outlines the system model, Section IV formulates the proposed scheduling methods, Section V covers the simulation approach and parameters, Section VI discusses the simulation results, and Section VII concludes the study.

1.1 Background of the Work

In recent years, significant advancements have been made in low-power wide area networks (LPWANs), with LoRa technology achieving notable success by redefining long-range connectivity and low energy consumption for IoT systems. However, in specific scenarios, such as dense deployments or long transmission distances typical of Direct-to-Satellite IoT (DtS-IoT), the LoRaWAN protocol faces certain limitations. These challenges led to the development of a recent variant aimed at improving throughput in dense environments, though it still struggles with collision avoidance and energy efficiency.

A recent study highlights the challenges in DtS-IoT, particularly in relation to channel constraints, orbital dynamics, and limited IoT device capabilities. The authors argue that existing IoT Medium Access Control (MAC) protocols need to be reassessed, especially for enabling effective communication among thousands of devices in a short timeframe. In dense IoT clusters where devices use ALOHA-based protocols like LoRaWAN, the likelihood of collisions increases, leading to issues with scalability and energy inefficiency. Additionally, clustering algorithms for resource allocation, particularly in dense DtS-IoT scenarios, have become more relevant with the advent of 5G and beyond.

One recent proposal introduces a traffic allocation strategy for ALOHA networks, which maintains throughput even under high traffic load but remains energy inefficient. To address these limitations, the LMAC protocol was introduced as a more efficient carrier-sense multiple access (CSMA) solution for LoRa networks, promising a 2.2× improvement in performance and a 2.4× reduction in energy consumption compared to ALOHA. This approach, with its channel load balancing and global IoT node and gateway distribution, has gained attention in DtS-IoT applications

1.2 Motivation and Scope of the Proposed Work

This paper addresses the problem of scheduling IoT device transmissions in a DtS-IoT system using LoRa technology, adopting the setup from prior work but incorporating multiple frequency channels to handle simultaneous transmissions from devices with similar visibility windows. We propose an efficient method for rearranging time slots, creating new transmission opportunities for devices that might otherwise be unable to transmit. Unlike previous policies, our method delivers a collision-free, low-complexity channel access strategy, making it feasible for onboard satellite implementation. Compared to earlier approaches, our method is specifically designed for LoRa-based DtS-IoT networks, offering both low computational complexity and high effectiveness in dynamic environments.

While carrier-sensing protocols like CSMA hold promise for LoRa networks, their current implementation is not fully suited for DtS-IoT, as the high probability of hidden nodes during satellite passes remains a significant challenge. Ensuring fairness between different methods is difficult, so this work focuses on improving uplink efficiency within the SALSA framework rather than CSMA or ALOHA protocols.

2. METHODOLOGY

We now outline the proposed scheduling methods for dts-iot systems. These approaches build upon the salsa-fcfs policy, which follows a first-come-first-served strategy. In the salsa-fcfs method, the device that first enters the satellite's coverage area is given priority to transmit, followed by others in the order of their respective rise times. Initially, as presented in the prior work, we assume the use of a single frequency channel. The functioning of the salsa-fcfs scheduling policy is demonstrated below.

2.1 Permutation Of Scheduled Times: L2L-P

In the SALSA-FCFS approach, a device with a short visibility period may have limited chances to transmit unless it is among the first to appear in the satellite’s footprint. This issue becomes more pronounced as network density increases, with many devices sharing overlapping visibility periods. Moreover, the duration of visibility windows may vary significantly between devices. To address these challenges, we propose adjusting the

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scheduled transmission times from the initial SALSA-FCFS schedule by reordering them to enable uplinks that would otherwise be omitted by the FCFS method.

Algorithm 1 provides a detailed outline of the proposed LoRa-to-LEO with Permutation (L2L-P) method during the m-th satellite pass. The algorithm's inputs consist of the rise and set times of devices, which depend on their relative positions in relation to the satellite's orbit, as well as the start and end times scheduled by the SALSA-FCFS method. We define $V_m = \{V_m,1, \ldots, V_m,N\}$ as the set representing the visibility time intervals for each device during this pass. The algorithm checks which devices are allocated transmission windows according to the SALSA-FCFS strategy and forms the set $T_m = \{T_m,1, \ldots, T_m,N\}$ to store the assigned time windows for each device. The algorithm then identifies any unused time intervals and lists them in the free time set, F_m. Additionally, the devices are divided into two groups: J_m, consisting of scheduled devices, and D_m, which contains unscheduled devices for this pass.

2.2 Data Acquisition

For devices in J_m, the L2L-P algorithm calculates the unused time, $= \max(S_m,n) - \max(E_m,n)$, after the last scheduled uplink ($\max(E_m,n)$) and the visibility period of at least one device ($\max(S_m,n)$). The number of devices that could potentially be rescheduled within this unused time is p, calculated as $\lfloor 2/(+ \tau) \rfloor$. If $p \geq 1$, devices in J_m with $S_m,n > \max(E_m,n)$ are added to set P_m and ordered by decreasing S_m,n. The first device in P_m is rescheduled to the end of the visibility window, with its new E'_m,n equal to S_m,n. Its previously allocated time slot is moved from T_m to F_m. The process continues, decrementing p, and rescheduling subsequent devices if feasible, adjusting their transmission times to fill gaps left by previously reallocated devices.

For each device in D_m, the algorithm checks if its visibility window, V_m,n, overlaps by at least $(2 + \tau)$ with any interval in F_m. If a match is found, the device's transmission is scheduled during the available free time, positioning its start (B_m,n) at the left edge or its end (E_m,n) at the right edge of the free interval. The scheduled time slot T_m,n is then removed from F_m and added to T_m. By the end of this process, up to p devices from D_m may be moved to J_m, thereby increasing the overall uplink efficiency.

2.4 Flow Chart

The network performance in DtS-IoT is vulnerable to potential wireless interference, including mutual interference between users. Additionally, uplink transmission may be impacted by other sources. However, Semtech studies have announced the feasibility of LPWANs co-existing harmoniously with other high-power systems that generate frequency-selective interference. In our focus, the efforts are directed toward enhancing uplink efficiency. Finally, another potential issue of concern for practical deployments is that DtS-IoT communications are susceptible to the Doppler effect due to satellite movement. However, recent experiments based on LoRa technology revealed a minimum performance impact from the Doppler effect considering LEO satellites. Therefore, in line with the related literature, we do not consider this effect in this work as its practical implication should be minimal.

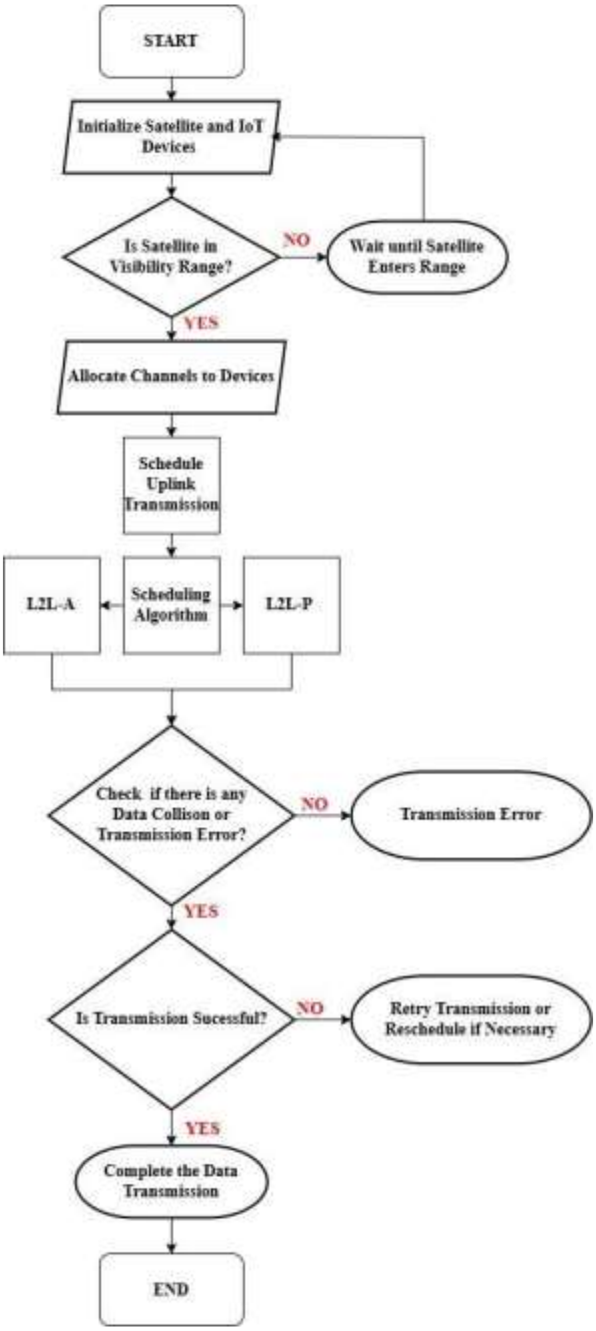

Fig -1- Flowchart

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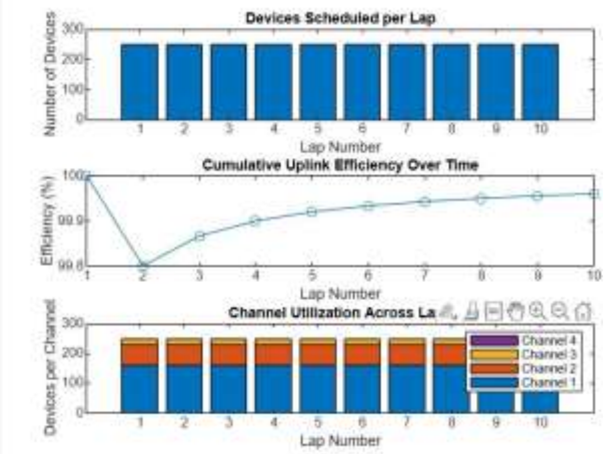
3. CONCLUSIONS

We presented two novel scheduling approaches to be used in a DtS-IoT network. The L2L-A algorithm is particularly tailored to exploit multiple frequency channels efficiently.Meanwhile, the L2L-AP algorithm incorporates the possibility of swapping the time slots of already allocated devices, making room for new transmission opportunities.The numerical results demonstrate that the proposed method scan considerably improve the uplink efficiency of DtS-IoT networks, even in dense scenarios. In future work, we intend to consider segmentation of the payload to take advantage of short unused times within a lap and the parallel transmission of a message. In addition, we aspire to explore the pros and cons of the proposed methods using SALSA versus multi channel LoRa-to-LEO scheduling for a real testbed.

Result And Simulation Output :



A computer simulation is deployed to evaluate the proposed scheduling methods in a realistic DtS-IoT scenario . Deployment of 250 IoT devices (blue circles) in France, covered by LacunaSat-3. the approach in SALSA , where the location of the N devices is randomly generated within a region. Then, we extract the location of each device on the ground, in terms of latitude and longitude, using geocoders from the Python GeoPy library. Satellite visibility times of IoT devices are estimated using the Python Skyfield astronomy library. This library uses public data information in the two-line element (TLE) set format, available from the CelesTrack platform, for determining the locations of the satellite according to the orbit and pointing time. Thus, the IoT devices are deployed in the target area, their visibility times are determined in each satellite lap, and the different scheduling strategies are evaluated. Such evaluation, analysis, and visualization of the results are carried out in MatLab.

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