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Efficient Time Allocation Strategies in Satellite Communication Networks

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Abstract – This paper introduces a novel time allocation algorithm designed for satellite communication networks, utilizing diverse communication links such as Radio Frequency (RF), Free Space Optical (FSO), and Long Range Wide Area Network (LoRaWAN). The proposed algorithm prioritizes gateway nodes based on key criteria, including priority levels and packet count, aiming to minimize delays and optimize overall throughput in satellite communication systems. LoRaWAN, known for its long-range communication capabilities, maximum device lifetime, multi-usage flexibility, bidirectional data transfer, low cost, and robust security, is particularly suited for such applications. Through a comprehensive study involving 200 gateway nodes, the algorithm's effectiveness in improving communication efficiency is demonstrated, offering a scalable solution for modern satellite networks.

Keywords – *Time allocation algorithm, satellite communication systems, communications efficiency.*

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I. INTRODUCTION

In an era marked by the relentless demand for seamless global connectivity, satellite communication has emerged as a cornerstone of modern telecommunications [1]. This technology enables coverage far beyond terrestrial networks, providing reliable communication across vast distances and making it indispensable for diverse applications, from global internet access to disaster recovery and remote sensing [2]. As the number of connected devices increases and data demands surge, optimizing satellite communication systems becomes critical to ensuring efficiency, reliability, and scalability.

Satellite communication systems have traditionally employed various multiplexing techniques to manage multiple users and optimize bandwidth usage. Among these, Time Division Multiple Access (TDMA) is a widely used method for improving system performance, allowing multiple earth stations to share satellite resources by dividing transmission time into distinct slots [3]. Early research demonstrated TDMA's potential to enhance channel efficiency, supporting various services over satellite links [4]. With the advent of emerging applications such as the Internet of Things (IoT) and 5G, there is mounting pressure to optimize TDMA-based satellite systems to handle higher traffic loads, reduce latency, and improve reliability.

Numerous studies have addressed these challenges by proposing solutions to enhance throughput, minimize latency, and improve resource management in satellite communication. For instance, recent work has reviewed state-of-the-art technologies, network architectures, and protocols designed to support direct-to-satellite (DtS) IoT applications, highlighting Long Range Wide Area Network (LoRaWAN) as a key enabler for satellite-based IoT in remote regions [3], [4]. Simulations have demonstrated the promise of combining Long Range (LoRa) technology with Low Earth Orbit (LEO) satellites for massive communications applications, showcasing the feasibility and reliability of packet reception in real-world trials [5], [6], [7].

Further advancements in satellite communication systems have focused on enhancing resource management techniques. One such method, dynamic TDMA (D-TDMA), adjusts time slots based on user demand and satellite capacity, optimizing bandwidth usage and reducing idle time [8]. Adaptive TDMA techniques have also been explored to balance resource allocation between multiple users while maintaining low-latency performance, particularly in satellite-ground communication systems [9]. These innovations are pivotal as the demand for satellite communication continues to grow with modern data-intensive applications.

Advances in coding and modulation techniques, such as Turbo Codes and Low-Density Parity-Check (LDPC) codes, have further improved satellite communication systems by increasing spectral efficiency and reducing bit error rates [10]. Additionally, the integration of satellite communication with emerging technologies like Software-Defined Networking (SDN) and Network Function Virtualization (NFV) has opened new pathways for dynamic resource allocation and network flexibility, particularly in multi-beam satellite systems [11], [12].

Building on this foundation, our paper delves into the intricacies of satellite communication systems, presenting a comprehensive overview of the communication process from initialization to reception. Our focus is on optimizing this process through the development and implementation of a prioritization algorithm for gateway nodes. This algorithm ranks gateway nodes based on priority levels and packet count, minimizing transmission delays and maximizing overall throughput in a satellite communication network.

To validate the effectiveness of the proposed algorithm, we conducted a detailed study involving 200 gateway nodes. Our methodology includes sorting nodes by priority and packet count, linking this prioritization process to fundamental steps in satellite communication. The results of our study highlight the efficiency gains achieved by the algorithm, revealing valuable patterns and insights for network management and resource optimization.

The paper is structured as follows: In Section II, we present the system model, providing details on the models for satellite communication networks. In Section III, we elaborate on the time allocation algorithm aimed at minimizing latency. Section IV presents numerical results along with a performance discussion. The paper concludes with Section V.

II. SYSTEM MODEL

Satellite communication is a cornerstone of modern connectivity, enabling seamless data exchange across vast distances, as illustrated in Fig. 1. This section provides a detailed overview of the processes governing communication between ground gateways and satellites, covering each step from initialization to data reception. Additionally, we introduce a prioritization algorithm aimed at optimizing communication by intelligently sorting gateway nodes based on priority levels and packet counts, thereby reducing latency and improving overall system throughput.

The foundation of satellite communication lies in a precise initialization process. To achieve efficient frequency utilization, both Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) techniques are employed [13]. FDMA divides the available frequency spectrum into channels, while TDMA allocates time slots within each channel to facilitate organized communication.

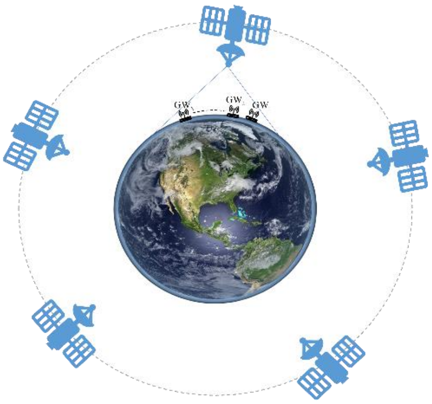

Fig. 1 Satellite Communication Network Under Consideration.

A. Key Components of the System Model:

- Gateway-Satellite Synchronization: Synchronization between ground gateways and satellites is critical for successful communication. This is typically achieved using Global Positioning System (GPS)-based synchronization methods, which ensure precise timing and coordination for data transfer between gateways and satellites.
- Satellite Wake-Up Signal (Beacon Transmission): As a satellite enters the range of a ground gateway, a wake-up signal (or beacon) is transmitted to notify the satellite of an upcoming data transmission. This signal acts as an alert for the satellite to prepare for communication.
- Satellite Wake-Up Confirmation: After receiving the wake-up signal, the satellite confirms its readiness to communicate by sending a Request to Send (RTS) signal, initiating the communication process between the satellite and the ground gateway.
- FDMA Channel Allocation: Efficient data transmission requires the allocation of suitable frequency channels. FDMA channels are assigned based on factors such as bandwidth availability, signal quality, and the communication system's operational requirements.
- TDMA Slot Allocation: To further optimize communication, specific time slots within the allocated FDMA channel are assigned for data transmission. This ensures an organized flow of data between the ground gateway and the satellite, minimizing the chances of interference and collisions.
- Data Encoding and Modulation: The data is then prepared for transmission by encoding and modulating it into a suitable format. Various modulation schemes, such as Binary Phase-Shift Keying (BPSK) or Quadrature Phase-Shift Keying (QPSK), are employed, along with error correction codes, to enhance data reliability during transmission.
- Signal Transmission: Once the data is encoded and modulated, it is transmitted via the assigned FDMA channel and TDMA time slot. Key considerations during this step include maintaining optimal power levels, ensuring adequate signal strength, and performing link budget calculations to achieve reliable communication.
- Reception at the Satellite: Upon reaching the satellite, the transmitted signals are received and demodulated using advanced techniques. The data is then decoded, and error correction mechanisms are applied if necessary, ensuring accurate data interpretation.
- Acknowledgment and Feedback: To confirm the successful reception of data, the satellite sends an acknowledgment signal back to the ground gateway. If errors are detected during reception, provisions for retransmission requests are in place to ensure data integrity.
- End of Transmission and Return to Idle State: Once the data transmission process is complete, both the ground gateway and the satellite return to an idle state, awaiting the next wake-up signal to initiate the next cycle of communication.
- Cyclic Nature of the Communication Process: This cyclical process of communication initialization,

transmission, reception, and acknowledgment continues in a loop. The prioritization algorithm introduced in this work adds an additional layer of optimization to this cycle by intelligently managing gateway node communication, thus enhancing the overall efficiency and throughput of the satellite network.

B. *Time Allocation Algorithm:*

Algorithm 1 describes a method for allocating time slots for communication from multiple gateways to a satellite, taking into account factors such as data transmission requirements and gateway priorities. The goal is to ensure an efficient allocation of time slots while meeting transmission needs. First, the gateways are sorted based on their data transmission requirements, and priority is given to those with higher transmission needs. Time slots are then allocated iteratively to gateways, starting with those with higher priority, and any remaining slots are distributed among lower-priority gateways. The result is a time slot allocation schedule for each service channel and slot, optimizing communication efficiency.

Algorithm 1: Time Slot Allocation for Communications from *N* Gateways to the Satellite

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Inputs: Number of gateways, total time slots, service slots, gateway priorities, and data transmission
1. Initialize Time Slot Allocation;
2. Set the total number of time slots per satellite coverage slot;
3. Determine the number of service slots and time slots per service slot;
4. Initialize an empty time slot allocation schedule for each service channel and service slot;
5. Sort Gateways based on Data Transmission Requirements:
    a. Sort gateways in descending order based on payload data transmission needs;
6. Allocate Time Slots to Gateways:
    a. For each service channel and service slot do:
        i. Initialize available time slots to the total number per service slot;
        ii. Separate gateways with higher priorities and calculate required time slots;
        iii. Allocate initial time slots to higher-priority gateways;
        iv. Sort remaining gateways in ascending order;
        v. For each gateway do:
            1. Calculate required time slots based on data transmission needs;
            2. If required time slots are within available slots:
                a. Allocate time slots to the gateway;
                b. Subtract allocated time slots from available slots;
            3. If available slots become zero, break the loop and proceed to the next service slot;
        vi. If there are remaining unallocated gateways, distribute remaining available slots evenly among them;
7. Update the time slot allocation schedule for the current service channel and service slot;
8. Output Time Slot Allocation Schedule:
    a. Output the final time slot allocation schedule for each service channel and service slot.
Output: Time slot allocation schedule for each service channel and service slot, optimized based on the gateways' data transmission requirements and priorities.
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III. NUMERICAL RESULTS

We consider 200 gateway nodes each with different priority levels and allocate different numbers of packets to each gateway. Fig.2 illustrates the time slot allocation schedule produced by the proposed algorithm. The algorithm's goal is to optimize time slot distribution across service channels and service slots based on each gateway's data transmission requirements and priority. The process begins by ranking gateways according to their payload transmission needs and assigning initial time slots to high-priority gateways. Remaining gateways are then sorted in ascending order of priority, and time slots are allocated accordingly, ensuring that higher-priority gateways receive sufficient resources to meet their transmission demands.

In this context, the figure visually represents three variables: gateway numbers (GW), the number of packets transmitted by each gateway, and their respective priority levels. Gateways with higher priority (depicted by the green dashed line) are allocated time slots first, ensuring their packets are transmitted promptly, as shown by the gradual stepwise increase in priority levels.

The result illustrates that higher-priority gateways, especially those with lower number of packets, receive earlier and more frequent time slot allocations. Gateways with lower priority have fewer time slots allocated, as indicated by the smaller number of packets and the overall decline in allocation toward the lower-priority gateways. This ensures that critical data transmission occurs with minimal delay, while also maximizing overall throughput and balancing the satellite network's resources.

The figure highlights the effectiveness of the algorithm in prioritizing gateways based on their packet count and priority levels, ensuring optimal use of available satellite time slots. By implementing this approach, the network improves both efficiency and scalability, essential for handling the growing demand for satellite communication in modern applications.

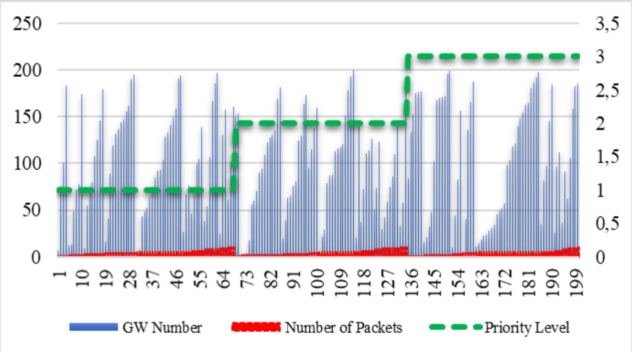

Fig. 2. Time Slot Allocation Schedule for Gateway Nodes

IV. CONCLUSION

In conclusion, this paper has presented a comprehensive approach to optimizing time slot allocation in satellite communication networks through the development of a prioritization algorithm. By systematically analyzing gateway data transmission requirements and prioritizing them based on defined criteria, the algorithm effectively enhances resource allocation and minimizes latency. The results demonstrate that prioritization not only improves throughput but also ensures that critical data is transmitted promptly, addressing the growing demand for efficient satellite communication. Future work may explore further refinements to the algorithm and its application in diverse network environments to adapt to emerging technologies and increasing connectivity needs.

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