Performance Analysis of Carrier Aggregation Scheduling Schemes in Satellite Communication Systems

Hayder Al-Hraishawi, Eva Lagunas, Sumit Kumar, and Symeon Chatzinotas
Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg.

***Abstract*—Satellites have an integral role in the evolving 6G wireless networks to provide ubiquitous broadband connectivity, extending their reach to remote and underserved regions where terrestrial infrastructure is limited. This is crucial in meeting the escalating demand for higher data rates, as satellite communication systems become increasingly instrumental in addressing connectivity challenges and bridging digital divides. Consequently, the need for innovative techniques arises to efficiently utilize radio resources and address the soaring data requirements. One such promising solution is carrier aggregation, which involves combining multiple carriers across the available spectrum. This approach has the potential to significantly improve peak data rates and enhance the overall user experience. However, to effectively aggregate multiple heterogeneous satellite links, an efficient data packet scheduler at the gateway is essential to prevent out-of-order packet delivery and the subsequent queuing delays at the receiver end. This paper delves into the performance evaluation of three schedulers, Round Robin, load balancing, and adaptive algorithm, through comprehensive end-to-end system simulations. The analysis reveals design trade-offs and highlights the advantages and drawbacks of each scheduler, offering insights for the practical design of satellite communication systems.**

***Index Terms*—Carrier aggregation, load balancing, satellite communications, scheduling algorithm, TCP.**

I. Introduction

Satellite communication systems have an essential role in ensuring ubiquitous data traffic coverage by providing seamless connectivity to diverse users across various platforms [1]. Whether users are stationary or mobile on land, sea, or air (such as trains, ships, or airplanes), satellite systems offer wide coverage and reliable connectivity to satisfy their data communication needs [2]. Moreover, the recent developments in satellite communications industry are mainly directing towards deploying reconfigurable satellite payloads in order to establish generic and software-based solutions [3]. Thus, these advances have opened up the satellite potentials to convey and perform several innovative use cases and new services from space [4]. Therefore, satellite traffic demand is steadily increasing for provisioning low-cost and accessible wireless connectivity especially to the underserved and unserved areas [5]. However, satellite radio resources are scarce, and it becomes critical to devise new techniques to improve radio resource utilization and to satisfy the high data rate requirements [6], [7].

In this context, carrier aggregation is one of the most successful features in long term evolution-advanced (LTE-A) networks as it allows to several component carriers to be simultaneously aggregated for a user terminal, which effectively increases the peak achievable data rate [8]. Carrier aggregation has been also adopted to 5G New Radio (NR) owing to its capability of boosting the network performance through maximizing the spectrum utilization and satisfying the extremely high throughput requirements in certain circumstances [9], [10]. Additionally, carrier aggregation enables network operators to maintain user's quality of service through its effective interference management and avoidance capabilities [11]. Consequently, satellite communications community has paid more attention recently to utilize and implement carrier aggregation within satellite system architectures in order for provisioning a high-quality user experience and to harness the multiplexing gain through flexibly distributing traffic demands over multiple carriers [12].

Satellite data demand is largely diversified and randomly distributed over the coverage areas from various users with different quality-of-service (QoS) requirements [13]. Thus, employing carrier aggregation in such systems can support accommodating the asymmetry and heterogeneity of the traffic demands. In this direction, several research works have studied the development of carrier aggregation in satellite communications systems. For instance, a multi-band carrier aggregation scheme is proposed in [14] for channel capacity enhancement in satellite mobile networks. More importantly, the research activity in [15] was funded by the European Space Agency (ESA) to investigate the integration of carrier aggregation into satellite systems, where several implementation scenarios have been analyzed through a software-based demonstrator [16]. Further, the works in [17] and [18] have investigated the deployment scenarios of multi-beam multi-carrier geostationary earth orbit (GEO) satellites such as intra-satellite carrier aggregation. Specifically, both inter-transponder and intra-transponder carrier aggregation have been considered at the satellite payload level of the communication stack to address the difficulty of carrier-user assignment in an environment of multiple users that can be multiplexed in each carrier.

Corresponding author: *Hayder Al-Hraishawi (hayder.al-hraishawi@uni.lu)*.
This work has received funding from the Luxembourg National Research Fund (FNR) under the project FlexSAT (C19/IS/13696663) and from the European Space Agency (ESA) funded activity CADSAT: Carrier Aggregation in Satellite Communication Networks. The views of the authors of this paper do not necessarily reflect the views of ESA.

Furthermore, an uplink carrier aggregation algorithm is developed in [2] to optimize throughput and latency in multi-orbital satellite networks. Reference [19] proposes a carrier aggregation scheme aiming at guaranteeing a fair user-demand satisfaction across the system, where two use-cases are considered, i.e. intra-beam and inter-beam carrier aggregation. Moreover, an architecture with a detailed design for embedding carrier aggregation in satellite systems from a link layer standpoint has been proposed in [20], [21]. Particularity, the required blocks to enable carrier aggregation are demonstrated, which are a data packet scheduler at the gateway and a traffic merging unit at the user terminal. One of the most critical part of carrier aggregation mechanism is the packet scheduling module that is responsible for distributing user data packets among the aggregated carriers. Specifically, the assignment of each incoming data packet to a certain carrier has to be tailored with the carrier radio resources and channel conditions.

Channel characteristics of the aggregated links have to be taken into account during the scheduling decision because otherwise packet-ordering issues will occur more frequently due to link heterogeneity [22]. For instance, when a data packet with the lower sequence number arrives at the receiver side after the arrival of the packets with the higher sequence numbers, then the receiver has to buffer that packet with the higher sequence number and waits until receiving all the packets whose sequence number is lower than the higher sequence number. Out-of-order problems can cause queuing delays and reduces system throughput. Thus, data packet scheduler block is a crucial for using carrier aggregation, which has to be carefully designed in order to ensure efficient resource allocation and satisfactory system performance [23]. Specifically, opportunistic resource scheduling algorithms such as load balancing and adaptive transmission can improve the overall performance of the networks by taking advantage of the time varying channels and the multi-user diversity [24].

Moreover, satellite link characteristics have a substantial impact on the transport protocols due to bandwidth asymmetry, latency, and losses resulting from error links and congestion [25]. To tackle these satellite channel impairments, the TCP protocol of Performance Enhancement Proxy (PEP) solution has been developed and is currently the most widely adopted architecture in satellite communications [26]. Thus, it is crucial to investigate the performance of carrier aggregation scheduling algorithms in terms of their suitability for TCP protocols. However, TCP performance for the scheduling algorithms in satellite systems with carrier aggregation has not been studied in the open literature. Therefore, this observation has motivated this work to evaluate the performance of the carrier aggregation scheduling schemes using TCP PEP protocols.

Furthermore, carrier aggregation in satellite communication systems can introduce several challenges for TCP performance, primarily related to the handling of multiple carriers. These challenges include:

- Out-of-order packet delivery: One of the fundamental challenges is managing out-of-order packet delivery. In carrier aggregation, data packets may traverse different carriers with varying latency and congestion levels. As a result, packets may arrive at the receiver out of order. When packets arrive out of order, it can lead to increased latency as the TCP protocol must re-order and reassemble them in the correct order. This can have a significant impact on the overall system performance.
- TCP queuing delays: The use of multiple carriers can lead to variations in network conditions on each carrier, including differences in latency and available bandwidth. TCP's congestion control algorithms may interpret these variations as congestion, leading to increased queuing delays. Excessive queuing delays can degrade system throughput and communication reliability.
- Complexity: Carrier aggregation involves the intricate task of scheduling data packets across multiple carriers. The complexity of the scheduling algorithms arises from the need to efficiently allocate available resources, while taking into account the channel conditions. This complexity in scheduling can significantly influence the performance of TCP within such systems.

Accordingly, studying these challenges is essential for maximizing the benefits of carrier aggregation in satellite communication systems.

Contributions: The main objective of this paper is examining how TCP performs in satellite communication systems employing carrier aggregation technique. Understanding TCP behavior in this context is crucial for optimizing data transmission efficiency and communication reliability in such systems. Then, the key contributions can be outlined as follows:

- Conduct comprehensive experiments utilizing a software-based experimental platform to scrutinize the performance of scheduling algorithms, namely Round Robin, load balancing, and adaptive transmission, with the aim of facilitating the deployment of carrier aggregation within satellite communication systems.
- Investigate the performance of link layer scheduling algorithms in the context of TCP interaction, focusing on their ability to manage re-ordering issues and TCP queuing delays.
- Analyze the advantages and limitations of each carrier aggregation scheduling algorithm while identifying their most suitable use cases and applications.
- Provide design guidelines for creating novel scheduling schemes that effectively address the identified limitations and challenges.

The rest of the paper is structured as follows. The considered system model is presented in Section II. Section III outlines the existing scheduling algorithms for carrier aggregation. Section IV provides overview about TCP protocols. We evaluate the scheduling algorithms in Section V. Finally, conclusions are drawn in Section VI.

II. System Model

The forward link of a multi-beam GEO satellite system is considered that employs multi-carrier transponders. In this system, carrier aggregation can be applied to either scenario of intra-beam or inter-beam. Specifically, a user may aggregate carriers across or within the satellite beams that might originate from the same or different gateways as depicted in Fig.

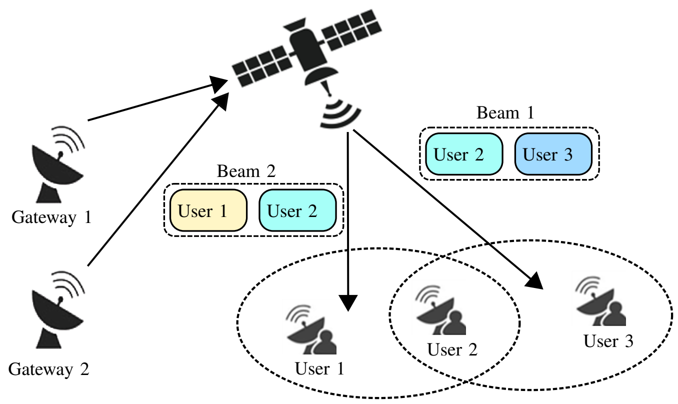

Fig. 1: Schematic diagram of inter-beam carrier aggregation in a multi-beam satellite system.

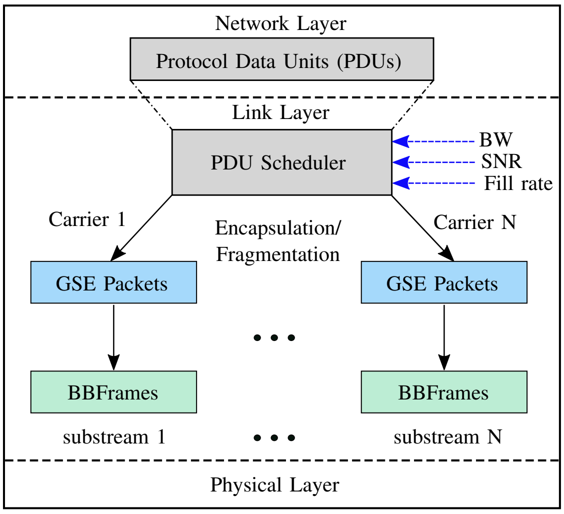

Fig. 2: The protocol stack of carrier aggregation.

1. Different beams can be aggregated to leverage the under-utilized spectrum and offer extended bandwidth to the users with high traffic demands. Moreover, this carrier aggregation scenario is beneficial to the poor coverage spots at the beam edges. In this system, the transponders are covering the same region, which can be done either through Frequency Division Multiplexing (FDM) or using two polarization (e.g., horizontal and vertical polarization) within same bandwidth. Additionally, a four-color reuse frequency scheme is considered, which allows frequency reuse with minimal interference between neighboring beams [17].

The fluctuation in satellite channel conditions has been considered in this study through employing the Digital Video Broadcasting-Satellite (DVB-S2X) standards, which are widely used among most of the satellite operators worldwide. these standards are characterized by practical features such as a flexible input stream adapter that is suitable for operation with single and multiple input streams of diverse formats. Within the DVB-S2X specifications, a powerful FEC (Forward Error Correction) system is incorporated based on LDPC (Low-Density Parity Check) codes concatenated with BCH (Bose–Chaudhuri–Hocquenghem) codes, allowing efficient adaptive operations. Additionally, a wide range of code rates and constellations that are optimized for operation over non-linear transponders are also adopted in the standards alongside with a set of multiple spectrum shapes for different roll-off factors [27]. Moreover, adaptive coding and modulation (ACM) technique is employed here for flexible changing the modulation and coding (MODCOD) according to the channel condition between the satellite and the user terminal, i.e. ACM technique provides a dynamic link adaptation to propagation conditions [28].

As explained earlier, integrating carrier aggregation into satellite system architectures requires a packet scheduler embedded at the link layer to allocate the protocol data units (PDUs) among the aggregated carriers. Since link layer protocols maintain the proper coordination of frame transmissions, the scheduler is responsible for distributing the incoming PDUs in an efficient manner in order to achieve high data rate while ensuring that the transmitted PDUs are going to be delivered in the correct order. In this direction, some data packets scheduling algorithms have been developed to adopt carrier aggregation to satellite link layer protocols. These algorithms are designed to take user's PDUs as input together with the carrier parameters such as bandwidth (BW) and Signal-to-Noise Ratio (SNR), and then, constituting multiple separated substreams, one for each of the carrier as depicted in Fig. 2. The SNR here accounts for additive noise, as well as the radiated signal strength and attenuation. Furthermore, fill rate factor, denoted as f_r, is introduced as another input parameter to the scheduling algorithms, which accounts for the percentage of the base-band frame (BBFrame) that can be utilized by the intended user for carrier aggregation, see Fig. 3 for an illustration. In this, the presence of other users served by the same carrier is also taken into consideration.

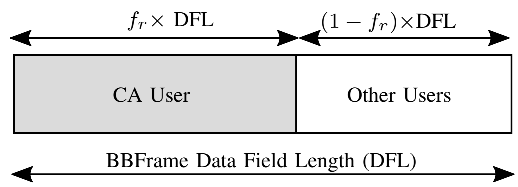

Fig. 3: Fill rate illustration in the BBFrame structure.

III. Scheduling Schemes

In this section, three different carrier aggregation scheduling algorithms are presented.

A. Round Robin Algorithm

Round Robin [29] is the simplest scheduling strategy with a straightforward implementation, which distributes the incoming PDUs across the aggregated carriers in a cyclic way without considering the instantaneous channel conditions. It gives each aggregated carrier an equal opportunity for serving the user with its current available resources. Round Robin scheduling offers greater fairness in the sense that the same amount of data packets are scheduled over each carrier. It is mostly used for time sharing systems for scenarios other than the high speed point to point communications. However, Round Robin is not efficient in terms of achieving higher peak data rate, and it usually leads to a poor system performance and more frequent out-of-order packet deliveries at the receiver.

B. Load Balancing Schemes

Load balancing algorithm [20] distributes the PDUs across the aggregated carriers based on the available carrier capacities. Unlike Round Robin, this algorithm is designed to efficiently utilize the aggregated carriers by taking into account the offered capacity and fill rate of each carrier during the scheduling decision. The scheduling process is decided based on a load balancing factor (α), which is calculated based on the offered capacity of each aggregated carrier. Specifically, the carrier with the highest capacity among other carriers will be the reference point to calculate the first load balancing factor (α_1) with respect to the other slower carriers, and the carrier with the higher capacity after the first carrier will the next reference point to calculate the next load balancing factor (α_2) with the rest of the slower carriers, and so forth. Thus, the number of load balancing factors equals to the number of aggregated carriers (N) minus one, namely, the load balancing factor (α) for the case of aggregating two carriers can be calculated as follows:

$$\alpha = \frac{C_2 f_{r,2}}{C_1 f_{r,1}}, \quad \text{where} \quad C_1 f_{r,1} \geq C_2 f_{r,2} \tag{1}$$

where C_i and $f_{r,i}$ account for the capacity and fill rate of the i-th carrier, respectively, and $i \in \{1, 2\}$. In (1), C_i is the rate at which information can be transmitted through the channel, which can be obtained by multiplying bandwidth (BW) times spectral efficiency (SE), where SE can be obtained from the DVB-S2 specifications as follows:

$$SE = \frac{(K_{bch} - 80)}{\eta_{ldpc}} \frac{S}{(S+1)} \log_2(M) \tag{2}$$

Where η_{ldpc} is the number of bits of LDPC coded block, K_{bch} is the number of bits of BCH uncoded block, S is the number of slots per XFECFrame, and M is the cardinality of the constellation. Thereby, the offered useful capacity (C_i) in a carrier that can used for aggregation and sending PDUs can be computed as

$$C_i = SE_i \times BW_i \tag{3}$$

Similarly, aggregating three carriers requires two load balancing factors, which are computed by using the following formula:

$$\alpha_1 = \frac{C_2 f_{r,2} + C_3 f_{r,3}}{C_1 f_{r,1}}, \quad \text{and} \quad \alpha_2 = \frac{C_3 f_{r,3}}{C_2 f_{r,2}}, \tag{4}$$

where $C_1 f_{r,1} \geq C_2 f_{r,2} \geq C_3 f_{r,3}$. For each load balancing factor (α) there is a carrier allocation sequence that determines the scheduling order of the incoming PDUs among the aggregated carriers. **Algorithm 1** presents the pseudocode for obtaining the allocation sequence ($\mathbf{S}$) based on α factor for aggregating two carriers [20].

Algorithm 1: Load balancing algorithm

Input: $\alpha = 0.01$
$\mu =$ Number of PDUs

Generate $\mathbf{v_2} = 1 : 1 : \mu$
while $\alpha \leq 1$ **do**
  Generate $\mathbf{v_1} = \alpha : \alpha : \alpha\mu$
  $\mathbf{w} = [\mathbf{v_1}\mathbf{v_2}]$ Merge the two vectors
  Sort $[\mathbf{w}]$ Ascendingly
  Find j, index of the first duplicate values in $[\mathbf{w}]$
  $\mathbf{A} = \mathbf{w}(1 : j+1)$
  $\mathbf{S} = \mathbf{A}(\mathrm{mod}(0 : \mu - 1, \mathrm{length}(\mathbf{A})) + 1)$
end

C. Adaptive Transmission

This scheme is more complicated than the former two algorithms because it considers the load balancing between carriers and tracks each PDU allocation process with the objective of mitigating the reordering routine at the receiver side. In this method, the following key variables are obtained and compared; (i) PDU length, (ii) the occupied DFL in the current BBFrame in each carrier, and (iii) the number of transmitted BBFrames in the aggregated carriers. Then, the trade-off between channel capacity and the instantaneous available resources is analyzed in order to ensure link adaptation while scheduling. Accordingly, BBFrame transmission is conducted in a dynamic manner, where it has to constantly check the BBFrame creation process of the aggregated carriers in a parallel manner to verify if any further adjustment to the allocation sequence is required. The adaptive scheduling should outperform other schedulers owing to its adaptive tracking operation. A step-by-step procedure describing the allocation process using the adaptive transmission scheduler is detailed in [21].

IV. Background of TCP Mechanism

TCP is a bidirectional connection-oriented protocol providing reliable communication link to different applications. It achieves the reliability by using a sliding flow control window and loss detection algorithms, which are based on timers adjusted by the transmitter. Besides, the receiver responds to a successful packet reception by returning an acknowledgment to the transmitter. These acknowledgments are used by the transmitter to determine if retransmissions are required for the packets. However, TCP in a satellite network environment faces various challenges such as large latency, variance of the round-trip time (RTT) estimate, and more importantly, asymmetric bandwidth of satellite channels; and hence, all these factors exacerbate TCP performance [30]. Accordingly, several studies have investigated the factors that are limiting TCP performance over a satellite link and proposed different solutions to address these issues.

One of these solutions is Performance-Enhancing Proxy (PEP)-based TCP splitting which is proven to enhance the performance of TCP over satellite links [31], [32]. In PEP, the native TCP connection is splitted into three segments:

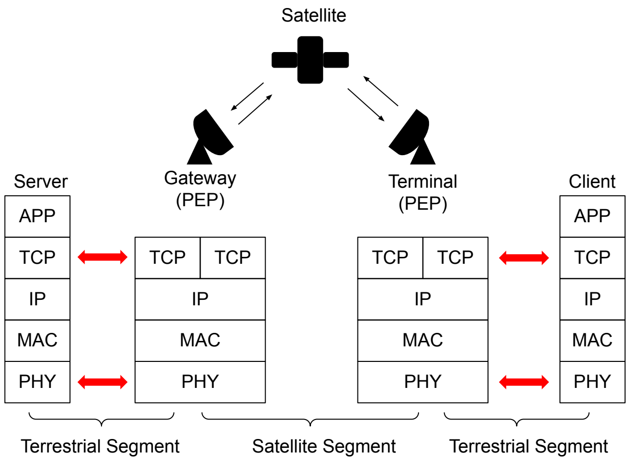

Fig. 4: PEP based TCP splitting for satellite links

two terrestrial and one satellite by isolating the satellite link between two PEP agents. The TCP flow coming from the application is terminated at the gateway to the satellite and a new TCP session is setup at the other side of the satellite link. An illustration of PEP scheme is shown in 4. The terrestrial segments in the shown scheme has small RTT and error free, hence, can apply standard TCP versions; the satellite segment has longer RTT and prone to error, hence, this link can be optimized independent of the terrestrial segment with the most obvious parameters being optimized are TCP window size and congestion control algorithms.

V. Performance Evaluation

In this section, we evaluate the performance of the three scheduling algorithms by using the developed carrier aggregation simulation model shown in Fig. 5. We consider common performance metrics relevant to TCP functionality that give clear indicators about the behavioral differences of the scheduling algorithms. In particular, the schedulers will be evaluated in terms of in-order PDU delivery success rate (that is the ratio of the received PDUs in the correct order to the total number of transmitted PDUs), number of retransmissions, and the delays caused by buffer queues while calling TCP functions.

A. Experimental Platform

The simulator we have developed is a MATLAB-based experimental platform, which is illustrated in Fig. 5, designed in accordance with the DVB-S2 standards and GSE (Generic Stream Encapsulation) protocols as detailed in [33]. Within this simulation tool, a critical component is the scheduler block, which operates at the link layer. This scheduler plays a pivotal role in the distribution of incoming PDUs across the aggregated carriers, optimizing the use of available resources.

At the transmitter side, we have implemented a GSE function responsible for the fragmentation and encapsulation of PDUs. This process results in the creation of GSE packets. Subsequently, a GSE packet scheduler function is employed to organize these completed GSE packets based on the available space within the BBFrame data field of each carrier.

On the receiver side, the simulator includes a GSE decapsulation function. This function is tasked with processing the received BBFrames and extracting the GSE packets. These extracted GSE packets are then passed through another function, which is responsible for PDU reconstruction. PDU reconstruction involves the defragmentation of the segmented PDUs that were originally prepared on the transmitter side. To ensure data integrity, the link layer performs a CRC (Cyclic Redundancy Check) code verification on the reconstructed PDUs.

TABLE I: The ranges of carriers parameters.

Parameter	Minimum	Maximum
Bandwidth (MHz)	15	90
SNR (dB)	-2	10
Fill rate (%)	20	90
Load-balancing factor	0.2	1

B. Experiment Setup

In this framework, we consider a GEO satellite with altitude 35,786 km and longitude 13°E. Number of carriers per beam is 2, transmit power per beam is set to 10 Watt, downlink carrier frequency is 19.5 GHz with dual polarization, and the roll-off factor is 20%. To investigate the performance of the scheduling algorithms under different channel conditions and diverse spectral resources for the aggregated carriers, we have run a set of 300 different experiments, where each experiment applies different combination of parameters for two carriers that are going to be aggregated to serve a user.

The considered ranges of carriers' parameters are summarized in Table I. In particular, carriers' bandwidths can be any value between 15 MHz and 90 MHz, while each carrier has an SNR value that is randomly selected between -2 dB and 10 dB. Similarly, the fill rate parameter of each carrier is randomly selected from the range of $[20 : 90]\%$.

The load balancing factor for the relevant schedulers is calculated for each experiment and it varies between 0.2 and 1, namely, the consider parameters' combinations are changing the aggregated carriers from being unbalanced when α is a small value to gradually balanced carriers when α grows to higher ratios, until they are perfectly balanced when $\alpha = 1$. Further, a stream of 200 PDUs of length 1400 bytes is randomly generated for each experiment to be transmitted using carrier aggregation mode. Further, in order to present all the obtained results from this large number of experiments, we have averaged the results of each metric with respect to each unique α value in order to smooth out the presented curves.

In our performance evaluation, as outlined in Section IV, we employed the PEP-based TCP approach, which is a well-established and commonly used in satellite links. By using PEP-based TCP, we can assess its effectiveness in mitigating issues related to out-of-order packet delivery and TCP queuing delays, which are crucial for providing reliable satellite communications. This approach provides insights into the practi-

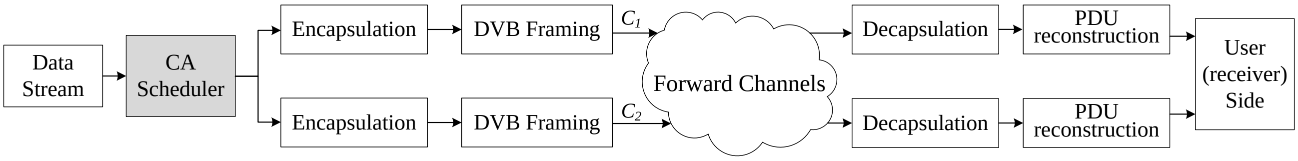

Fig. 5: Carrier aggregation simulator based on the DVB-S2 specifications and GSE protocols

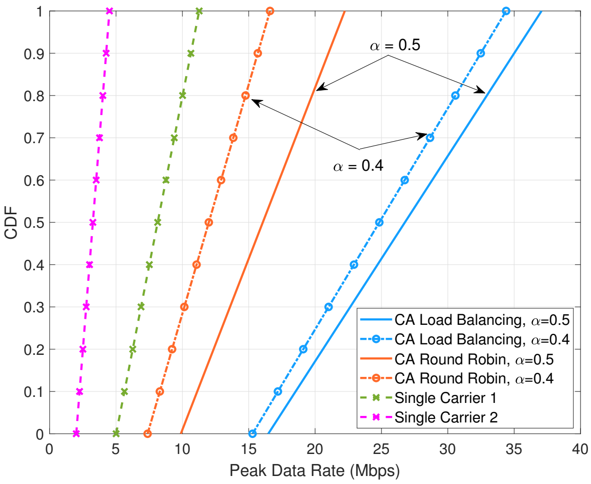

Fig. 6: CDF of the peak data rate with carrier aggregation using Round Robin and load balancing schedulers. Both carriers have similar bandwidth and SNR, BW = 10 MHz and SNR = 5 dB, while $f_{r,1} = 0.4 : 0.05 : 0.9$, and $f_{r,2} = \alpha f_{r,1}$.

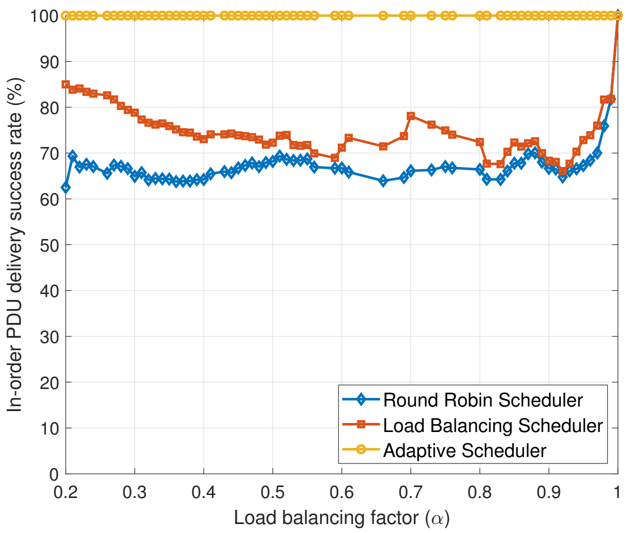

Fig. 7: In-order PDU delivery success rate versus load balancing factor (α).

cality and efficiency of the scheduling algorithms, emphasizing the performance trade-offs under various scenarios.

C. Simulation Results

To show the benefits of employing carrier aggregation in satellite systems, we have analyzed the achievable peak data rates of a user utilizing two different carriers for a single carrier transmission, and then compared to the achievable peak data rate of aggregating both carriers using (i) Round Robin scheduling method and (ii) the load balancing scheduler. Specifically, Fig. 6 shows CDF curves of the variations in user peak data rate under these transmission modes. Clearly, enabling carrier aggregation achieves higher peak data rate comparing to a single carrier transmission. Moreover, the load balancing scheduler outperforms the Round Robin method in terms of the achievable peak data rate owing to the load balancing ability in efficiently utilizing the available resources by sending more traffic through the fastest carrier. The load balancing has showed data rate increments of approximately 67% and 94% with respect to Round Robin when α values are 0.5 and 0.4, respectively. When α value approaches one, that means the aggregated carriers are balanced and Round Robin can perform better in this case because it distributes data packets equally between both carriers. The performance of the adaptive scheduler is similar to the load balancing one in this metric.

Next, performance of the scheduling algorithms in terms of in-order PDU delivery success rate versus α is evaluated and shown in Fig. 7. We observe the following:

- The Round Robin scheduler cannot guarantee the order of the received PDUs unless both carriers are perfectly balanced ($\alpha = 1$), i.e., both carriers offer identical resources to serve the user.
- Although the load balancing scheduler distributes PDUs resourcefully between the aggregated carriers but that is still not enough to accomplish in-order delivery because it does not take into consideration the available DFL in each BBFrame of the aggregated carriers.
- Adaptive scheduler achieves the highest delivery accuracy with zero out-of-order PDU owing to its design that cautiously considers channel properties along with the instantaneous available resources.

Clearly, the adaptive scheduler outperforms other schedulers in terms of in-order PDU delivery because of its capability of finding the best link adaptation when allocating a PDU to a carrier. On the other hand, load balancing method is better than Round Robin in terms of spectral utilization and it has less computational complexity than the adaptive scheduler.

The number of retransmissions is plotted against α in Fig. 8, and here are the key findings. The adaptive scheduler does

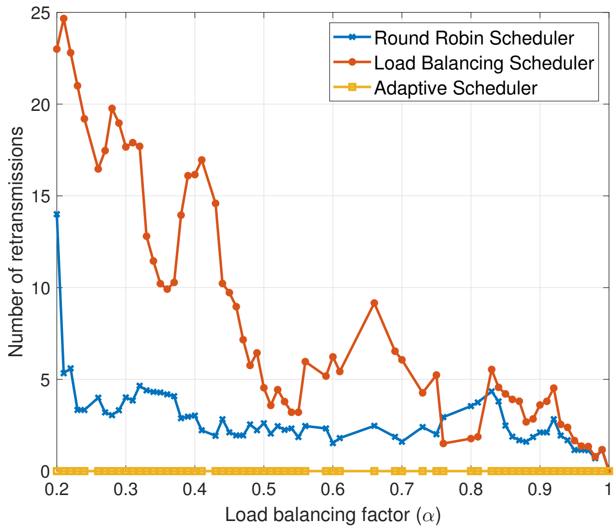

Fig. 8: Number of retransmissions versus load balancing factor (α).

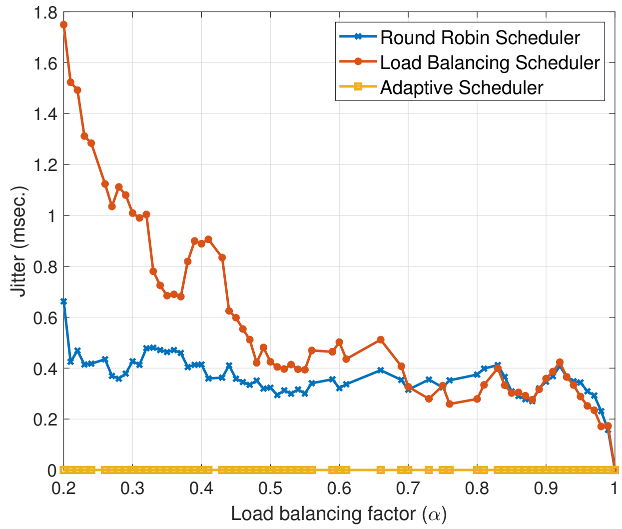

Fig. 10: Performance of Round Robin, load balancing, and adaptive schedulers in terms of jitter versus load balancing factor α.

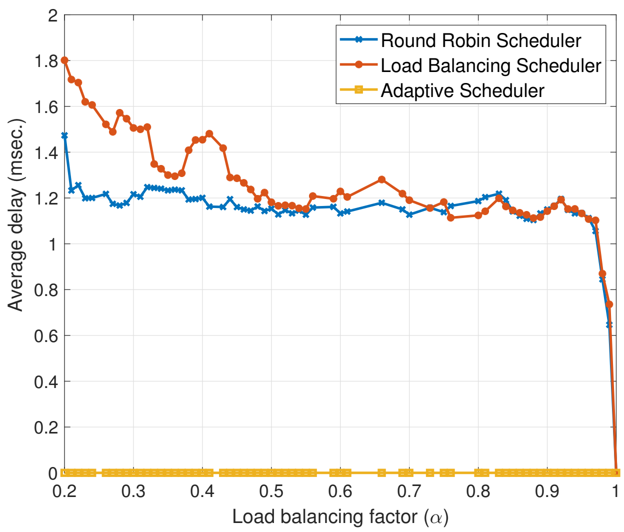

Fig. 9: Performance of Round Robin, load balancing, and adaptive schedulers in terms of average delay versus load balancing factor α.

not need to retransmit as there was no ordering problems at the receiver. Round Robin surprisingly outperforms load balancing especially when the aggregated carriers are unbalanced, where the latter has a higher number of retransmissions due to link asymmetry. This problem happens because the load balancing scheduler essentially prioritizes sending more PDUs over the faster carrier, so when a PDU sent through the slower carrier faces an out-of-order delivery or the acknowledgment was delayed, then multiple retransmissions will be triggered till this problem resolves. In contrast, ordering problems in Round Robin case stay in short ranges because it allocates PDUs in a cyclic way and does not favor a specific carrier.

Delay due to calling TCP function to fix the ordering problems is evaluated for all of the considered scheduling algorithms by comparing their performances under the aforementioned carrier parameters' combinations. Specifically, average delay and jitter variation (jitter is also known as standard deviation delay) are plotted versus α as shown in Fig. 9 and Fig. 10, respectively. Since load balancing scheduler sends more retransmissions than Round Robin when aggregating unbalanced carriers ($\alpha < 0.7$), then the average delay of the former is slightly higher as shown in Fig. 9. Moreover, average delay decreases when the aggregated carriers are going to be balanced ($\alpha \rightarrow 1$). Since there is no TCP call needed for adaptive scheduler, then the average delay is zero.

Fig. 10 depicts the jitter introduced by TCP functionality versus α. The load balancing scheduler introduces more jitter because of the non-uniformity of out-of-order occurrence due to considering different allocation patterns based on the offered capacities for carrier aggregation, which bounces the delay from one TCP call to another. Whereas, Round Robin scheduler causes less jitter because the carrier allocation sequence is fixed and the ordering problems occur in a repetitive pattern. The adaptive scheduler does not bring jitter in the conducted experiments as there was no TCP calls. Thus, Round Robin and load balancing schedulers can be applied when the transport layer protocol considers user datagram protocol (UDP) with high tolerance to out-of order delivery, but still the load balancing is superior in terms of peak date rate and spectral resource utilization.

Finally, Table II summarizes the performance of the studied schedulers for carrier aggregation in satellite communication systems. In particular, both Round Robin and load balancing methods can be used for applications that have high tolerance to out-of-order PDUs with taking into consideration that the load balancing scheduler outperforms the Round Robin in

TABLE II: Performance summary of the scheduling algorithms.

Metric / Scheduler	Round Robin [29]	Load balancing [20]	Adaptive [21]
Peak data rate	low	high	high
Resource utilization	inefficient	efficient	efficient
In-order delivery	bad	good	Superior
Complexity	very low	low	high
Retransmissions	medium	medium	very low
Average delay	medium	medium	very low
Jitter	low	medium	very low

terms of the radio resource utilization and the achievable peak data rate. Whereas, the adaptive scheduler is more suitable to the highly reliable communications owing to its capability of avoiding the delays originating from calling TCP functionality. The adaptive is able to suppress the introduced jitters resulting from reassembling the received packets in the correct order.

VI. Conclusions

This paper has investigated the practical significance of various scheduling algorithms designed for the adoption of carrier aggregation in satellite communication systems. Carrier aggregation has emerged as a promising approach in satellite systems, enabling wider bandwidths and significant increases in link-level peak data rates. Through the evaluation of TCP performance, this paper has examined three carrier aggregation schedulers in terms of achievable data rates, in-order PDU delivery success rates, retransmissions, and queuing delays. The Round Robin and load balancing schedulers are suitable for applications with high tolerance for out-of-order delivery. Among them, the load balancing algorithm demonstrates higher throughput and improved spectral utilization compared to the Round Robin approach, while maintaining a lower computational complexity compared to the adaptive scheduler. On the other hand, the adaptive allocation method offers an efficient solution for highly reliable communications, albeit at a higher computational complexity. Furthermore, aggregating carriers with balanced resources contributes to reduced delays and retransmissions.

In future work, our focus will extend to developing multi-orbit carrier aggregation scenarios within GEO, MEO, and LEO satellite systems, aiming to explore their potential benefits and challenges in further enhancing the performance of satellite communication networks.

References

[1] H. Chen, M. Xiao, and Z. Pang, "Satellite-based computing networks with federated learning," *IEEE Wireless Commun.*, vol. 29, no. 1, pp. 78–84, 2022.

[2] M. N. Dazhi, H. Al-Hraishawi, M. R. B. Shankar, and S. Chatzinotas, "Uplink capacity optimization for high throughput satellites using SDN and multi-orbital dual connectivity," in *IEEE Int. Conf on Commun. Workshops (ICC Workshops)*, 2022, pp. 1–6.

[3] S. Xu, X.-W. Wang, and M. Huang, "Software-defined next-generation satellite networks: Architecture, challenges, and solutions," *IEEE Access*, vol. 6, pp. 4027–4041, 2018.

[4] M. N. Dazhi, H. Al-Hraishawi, M. R. B. Shankar, S. Chatzinotas, and B. Ottersten, "Energy-efficient service-aware multi-connectivity scheduler for uplink multi-layer non-terrestrial networks," *IEEE Trans. Green Commun. Netw.*, vol. 7, no. 3, pp. 1326–1341, 2023.

[5] J. Li, K. Xue, D. S. L. Wei, J. Liu, and Y. Zhang, "Energy efficiency and traffic offloading optimization in integrated satellite/terrestrial radio access networks," *IEEE Transactions on Wireless Communications*, vol. 19, no. 4, pp. 2367–2381, 2020.

[6] Y. Kawamoto, T. Kamei, M. Takahashi, N. Kato, A. Miura, and M. Toyoshima, "Flexible resource allocation with inter-beam interference in satellite communication systems with a digital channelizer," *IEEE Transactions on Wireless Communications*, vol. 19, no. 5, pp. 2934–2945, 2020.

[7] E. Lagunas, M. G. Kibria, H. Al-Hraishawi, N. Maturo, and S. Chatzinotas, "Precoded cluster hopping for multibeam GEO satellite communication systems," *Frontiers in Signal Processing*, vol. 1, p. 721682, Oct. 2021.

[8] ETSI TS 136 300, "Evolved universal terrestrial radio access (E–UTRA) and evolved universal terrestrial radio access network (E–UTRAN); Overall description; Stage 2," 3rd Generation Partnership Project (3GPP), Standard, Jun. 2012.

[9] 3rd Generation Partnership Project (3GPP), "NR inter-band Carrier Aggregation (CA) Rel-16 for 4 bands Down Link (DL) / 1 bands Up Link (UL)," Standard, 2019.

[10] R. Joda, M. Elsayed, H. Abou-Zeid, R. Atawia, A. B. Sediq, G. Boudreau, and M. Erol-Kantarci, "Carrier aggregation with optimized UE power consumption in 5G," *IEEE Netw. Lett.*, vol. 3, no. 2, pp. 61–65, 2021.

[11] H. Lee, S. Vahid, and K. Moessner, "A survey of radio resource management for spectrum aggregation in LTE-advanced," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 745–760, 2014.

[12] H. Al-Hraishawi, H. Chougrani, S. Kisseleff, E. Lagunas, and S. Chatzinotas, "A survey on non-geostationary satellite systems: The communication perspective," *IEEE Commun. Surveys Tuts.*, 2022.

[13] H. Al-Hraishawi, E. Lagunas, and S. Chatzinotas, "Traffic simulator for multibeam satellite communication systems," in *10th Advanced Satellite Multimedia Systems Conference and the 16th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, 2020, pp. 1–8.

[14] Y. Z. Gao, X. Yang, X. Geng, J. B. Li, and J. J. Wu, "A multi-band carrier aggregation scheme for mobile satellite communications," in *Achievements in Engineering Sciences*, ser. Applied Mechanics and Materials, vol. 548. Trans Tech Publications Ltd, 6 2014, pp. 1282–1285.

[15] European Space Agency (ESA), "CADSAT - Carrier aggregation in satellite communication networks," https://artes.esa.int/projects/cadsat.

[16] S. Chatzinotas *et al.*, "Carrier aggregation demonstrator for satellite communication systems," https://wwwen.uni.lu/snt/research/sigcom/sw-simulators/cadsat.

[17] M. G. Kibria, E. Lagunas, N. Maturo, H. Al-Hraishawi, and S. Chatzinotas, "Carrier aggregation in satellite communications: Impact and performance study," *IEEE Open Journal of the Communications Society*, pp. 1390–1402, 2020.

[18] M. Kibria, E. Lagunas, N. Maturo, D. Spano, H. Al-Hraishawi, and S. Chatzinotas, "Carrier aggregation in multi-beam high throughput satellite systems," in *IEEE Global Commun. Conf.*, Dec. 2019.

[19] E. Lagunas, M. Kibria, H. Al-Hraishawi, , N. Maturo, and S. Chatzinotas, "Dealing with non-uniform demands in flexible GEO satellites: The carrier aggregation perspective," in *10th Advanced Satellite Multimedia Syst. Conf. 16th Signal Process. Space Commun. Workshop*, Oct. 2020.

[20] H. Al-Hraishawi, N. Maturo, E. Lagunas, and S. Chatzinotas, "Perceptive packet scheduling for carrier aggregation in satellite communication systems," in *IEEE Int. Conf on Commun. (ICC)*, Jun. 2020, pp. 1–6.

[21] H. Al-Hraishawi, N. Maturo, E. Lagunas, and S. Chatzinotas, "Scheduling design and performance analysis of carrier aggregation in satellite communication systems," *IEEE Trans. Veh. Technol.*, vol. 70, no. 8, pp. 7845–7857, 2021.

[22] Y. Liu, C. Li, X. Xia, X. Quan, D. Liu, Q. Xu, W. Pan, Y. Tang, and K. Kang, "Multiband user equipment prototype hardware design for 5g communications in sub-6-ghz band," *IEEE Trans. Microw. Theory and Techn.*, vol. 67, no. 7, pp. 2916–2927, 2019.

[23] L. Diez, A. Garcia-Saavedra, V. Valls, X. Li, X. Costa-Perez, and R. Agüero, "LaSR: A supple multi-connectivity scheduler for multi-RAT OFDMA systems," *IEEE Trans. Mobile Comput.*, vol. 19, no. 3, pp. 624–639, 2020.

[24] A. Alorainy and M. J. Hossain, "Cross-layer performance analysis of downlink multi-flow carrier aggregation in heterogeneous networks," *IEEE Access*, vol. 7, pp. 23 303–23 318, 2019.

[25] S. L. Kota, K. Pahlavan, and P. A. Leppanen, "Satellite tcp/ip: Technical challenges," in *Broadband Satellite Communications for Internet Access*. USA: Kluwer Academic Publishers, 2004, ch. 7, pp. 165–227.

[26] J. Kim, J. Oh, S. Lee, and J. Kim, "PEP with scheduled resource allocation on disruptive satellite communication," in *Int. Conf. on Info. and Commun. Technol. Converg. (ICTC)*, 2016, pp. 781–783.

[27] ETSI TR 102 376-2, "Digital Video Broadcasting (DVB): Implementation guidelines for the second generation system for broadcasting, interactive services, news gathering and other broadband satellite applications;part 2: S2 extensions (DVB-S2X)." European Telecommunications Standards Institute, Standard, 2015, (http://www.etsi.org).

[28] M. A. Vazquez Castro and G. S. Granados, "Cross-layer packet scheduler design of a multibeam broadband satellite system with adaptive coding and modulation," *IEEE Trans. Wireless Commun.*, vol. 6, no. 1, pp. 248–258, 2007.

[29] X. Yuan and Z. Duan, "Fair round-robin: A low complexity packet schduler with proportional and worst-case fairness," *IEEE Trans. Comput.*, vol. 58, no. 3, pp. 365–379, March 2009.

[30] R. Liang, H. Tan, J. Han, and S. Lim, "Performance analysis of TCP/IP/Q-persistence ARQ over satellite links," in *IEEE Aerosp. Conf.*, 2007, pp. 1–5.

[31] A. Pirovano and F. Garcia, "A new survey on improving TCP performances over geostationary satellite link," *Netw. Commun. Technol.*, vol. 2, pp. 1–18, 2013.

[32] I. Ahmad, J. Suomalainen, P. Porambage, A. Gurtov, J. Huusko, and M. Höyhtyä, "Security of satellite-terrestrial communications: Challenges and potential solutions," *IEEE Access*, vol. 10, pp. 96 038–96 052, 2022.

[33] ETSI TS 102 606-1 V1.2.1, "Digital Video Broadcasting (DVB): Generic stream encapsulation (GSE); part 1: Protocol technical specifications," European Telecommunications Standards Institute, Standard, 2014, (http://www.etsi.org).