Performance Evaluation of Forward Link Packet Scheduling in Satellite Communication Systems with Carrier Aggregation

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***Abstract*—The rapidly growing demand for increased data rates and spectrum scarcity in satellite communication systems require new paradigms to effectively utilize radio resources. Of many candidate techniques, carrier aggregation (CA) is a promising solution that combines multiple carriers across the available spectrum to achieve a substantial increase in peak data rate and improve user experience. The concept of CA was introduced in 3GPP standards for the terrestrial communication systems and has been successfully deployed and commercialized worldwide. Recently, satellite communication community has investigated the requirements for adopting CA technique to satellite infrastructures. In this setting, aggregating multiple heterogeneous satellite links to boost a single-user peak throughput requires an efficient data packet scheduler at the gateway in order to avoid the out-of-order packet issues and the subsequent queuing delays at the receiver side. Thereby, several research efforts have been devoted to circumvent this challenge through developing packet schedulers that are aiming at delivering data packets without perturbing their original transmission order. In this paper, the performance of the developed schedulers is evaluated using end-to-end system simulations to investigate the impact of different network metrics. The obtained results demonstrate the design tradeoffs and summarize the pros and cons of the schedulers.**

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

I. Introduction

Carrier aggregation (CA) is one of the most successful features in Long Term Evolution (LTE) as it allows to several component carriers to be simultaneously aggregated for a user terminal, which effectively increases the peak achievable data rate [1]. CA 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 [2]. Additionally, CA enables network operators to maintain user's quality of service through its effective interference management and avoidance capabilities [3]. Consequently, satellite communications community has paid more attention recently to utilize and implement CA 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 [4].

Generally, satellite traffic is largely diversified and randomly distributed over the coverage areas from various users with different quality-of-service (QoS) requirements [5]. Thus, employing CA in such systems would help in accommodating the asymmetry and heterogeneity of the traffic demands. In the last few years, several research works have studied the development of CA in satellite communications systems. For instance, a multi-band CA scheme is proposed in [6] for channel capacity enhancement in satellite mobile networks. More importantly, the research activity in [7] was funded by the European Space Agency (ESA) to investigate the integration of CA into satellite systems, where several implementation scenarios have been analyzed through a software-based demonstrator [8]. In this context, the works in [9] and [10] investigate the scenarios of multi-beam multi-carrier geostationary earth orbit (GEO) satellites, i.e., intra-satellite scenario. Specifically, both inter-transponder and intra-transponder CA 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.

Furthermore, an uplink CA algorithm is developed in [11] to optimize throughput and latency in multi-orbital satellite networks. Reference [12] proposes a CA 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 [13], [14]. Particularity, the required blocks to enable CA 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 CA mechanism is the packet scheduling module that is responsible for appropriately allocating the transmitted data packets among the aggregated carriers. Specifically, the assignment of each incoming data packet to a certain carrier has to be tailored with the available resources of that carrier and its link layer functionalities, particularly Protocol Data Units (PDUs) fragmentation in order to be encapsulated in one or more Generic Stream Encapsulation (GSE) packets that eventually generates BBFrames (Baseband Frames).

Additionally, channel characteristics of the served users have also to be taken into account during the scheduling decision because otherwise packet-ordering issues will occur more frequently due to link heterogeneity. For instance, when a 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. Therefore, the packet scheduler is a crucial part while deploying CA and has to be carefully designed for satisfactory system performance and efficient resource allocation.

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 [15]. 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 [16]. Thus, it is crucial to investigate the performance of CA scheduling algorithms in terms of their suitability for TCP. However, scrutinizing TCP performance of the packet scheduling algorithms in satellite systems with CA has not been studied in the open literature. Therefore, this observation has motivated this work to fill this gap and evaluate the performance of the packet scheduling schemes introduced at the link layer for integrating CA into satellite communication systems by using TCP PEP protocols.

Contributions: Our main distinct contributions in this work can be summarized as follows:

1) Carrying out a thorough comparison between the different packet scheduling algorithms for enabling CA in satellite commutations.
2) Investigating TCP interaction with the studied link layer scheduling algorithms through evaluating their performance in terms of handling the re-ordering issues and the TCP queuing delays.
3) Studying the benefits and pitfalls of each scheduling algorithms with pointing out their most suitable uses cases and applications.

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 CA. 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, CA 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. 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 CA scenario is beneficial to the poor coverage spots at the beam edges. In this setup, a four-color reuse frequency scheme is considered, which allows frequency reuse with minimal interference between neighboring beams [9].

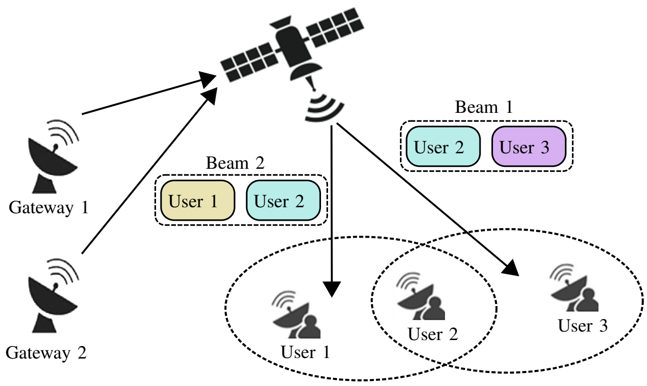

Fig. 1. Schematic diagram of inter-beam carrier aggregation in a multi-beam satellite system.

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. They are also characterized by important features such as a flexible input stream adapter that is suitable for operation with single and multiple input streams of diverse formats. These standards incorporate a powerful FEC (Forward Error Correction) system 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 both standards alongside with a set of multiple spectrum shapes for different roll-off factors [17]. Moreover, Adaptive Coding and Modulation (ACM) technique is employed here to assist changing modulation and coding (MODCOD) on the ongoing communication according to the channel condition between the satellite and the user terminal, i.e. ACM technique provides a dynamic link adaptation to propagation conditions.

Integrating CA into satellite system architectures requires a packet scheduler embedded at the link layer to allocate the PDUs among the aggregated carriers. Since link layer protocols maintain the proper coordination of frame transmissions, the packet 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 CA to satellite link layer protocols. These algorithms are designed

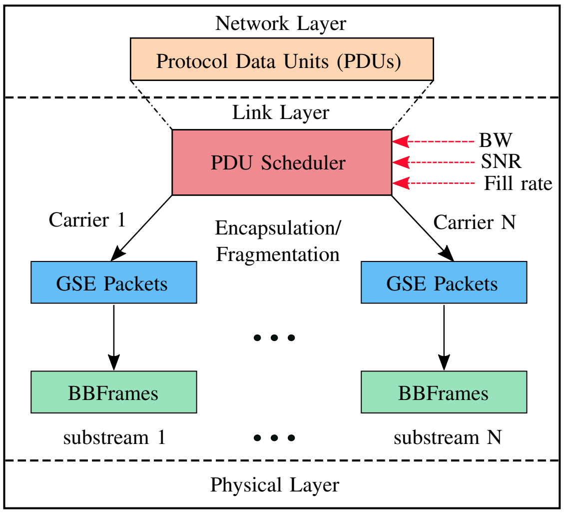

Fig. 2. The protocol stack of carrier aggregation.

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. Fill rate factor is also considered to be another input parameter to the scheduling algorithms, which accounts for the percentage of the BBFrame data that can be utilized by the user for CA in a certain carrier, as presented in Fig. 3. Thus, the presence of other users served by the same carrier is not neglected.

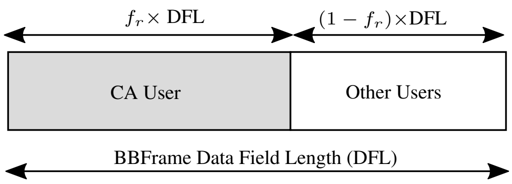

Fig. 3. Fill rate illustration in the BBFrame structure.

III. Carrier Aggregation Scheduling Algorithms

In this section, the CA scheduling algorithms in satellite systems are presented.

A. Round Robin Algorithm

Round Robin [18] is the simplest scheduling strategy that 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 scheduling 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 [13] distributes the incoming PDUs across the aggregated carriers based on channel conditions and the available carrier resources. 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), that is the ratio between capacities and fill rates of the aggregated carriers. 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 [13].

Algorithm 1: Load balancing scheduling algorithm

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

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

C. Adaptive Scheduling Algorithm

This scheduling algorithm is more complicated than the former two algorithms because it considers the load balancing between carriers and tracks each packet allocation process with the objective of mitigating the packet reordering routine at the receiver side. In this scheduler, 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. This scheduler analyzes the tradeoff between channel capacity and the instantaneous available resources, and then, distributes the incoming PDUs while ensuring link adaptation. 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 this scheduler is presented in Algorithm III in [14].

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 [19]. Accordingly, several studies have investigated the factors that are limiting TCP performance over a satellite link and proposed different solutions to address these issues.

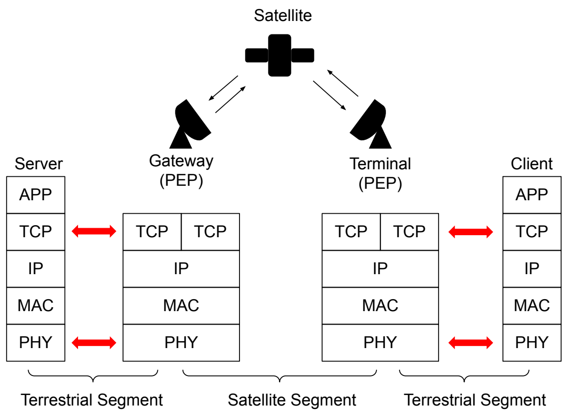

Fig. 4. PEP based TCP splitting for satellite links

One of these solutions is Performance-Enhancing Proxy(PEP)-based TCP splitting which is proven to enhance the performance of TCP over satellite links [20]. In PEP, the native TCP connection is splitted into three segments: 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 illustraion 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 a software-based experimental platform developed by University of Luxembourg [8]. 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 simulation results presented in this section are obtained using a software-based demonstrator that is described in [8]. This demonstrator is a *MATLAB* experimental platform built based on the DVB-S2 standards and

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

GSE protocol as detailed in [21]. In this tool, the scheduler block is embedded at the link layer, which is responsible for distributing the incoming PDUs across the aggregated carriers. Specifically, a GSE function is constructed at the transmitter to perform PDU fragmentation and encapsulation, and then, the GSE packets are created. Afterwards, a GSE packet scheduler function is implemented to put together the completed GSE packets based on the available space inside the BBFrame data field of each carrier.

Whereas, at the receiver side, a GSE decapsulation function is implemented to process the received BBFrames and extract the GSE packets. These extracted GSE packets are further passed to another function that is responsible for PDU reconstruction. PDU reconstruction includes defragmentation of the segmented PDUs at the transmitter side. The integrity of the reconstructed PDUs is also checked at the link layer using a CRC (Cyclic Redundancy Check) code. The developed structure in this system aims at focusing the implementation efforts on the gateway side, so that the user terminal remains as simple as possible with minimum changes required to support CA. To this end, a simple first-in first-out (FIFO) traffic-merging block is implemented to take the reconstructed PDUs streams of the aggregated carriers as inputs to produce a single stream of PDUs and pass them to the upper layers.

B. Experiment Setup

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 CA 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.

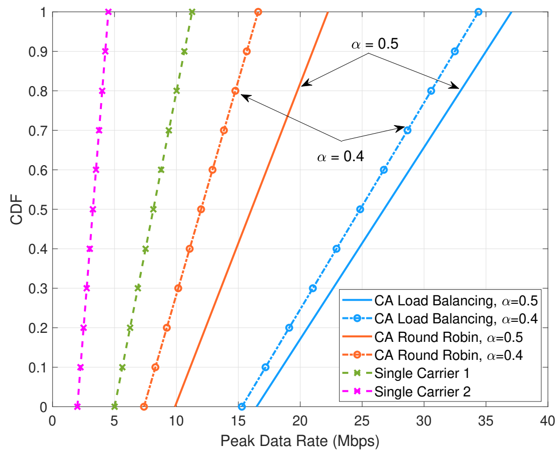

Fig. 5. CDF of the peak data rate with CA using Round Robin and load balancing schedulers. Both carriers have similar bandwidth and SNR, BW = 10 MHz and SNR = 5 dB, while $f_{r,1} = 0.4 : 0.05 : 0.9$, and $f_{r,2} = \alpha f_{r,1}$.

C. Simulation Results

To show the benefits of employing CA 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. 5 shows CDF curves of the variations in user peak data rate under these transmission modes. Clearly, enabling CA 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. 6. 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.

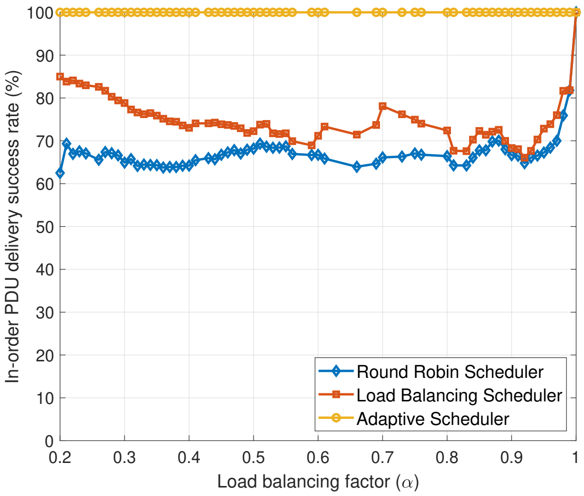

Fig. 6. In-order PDU delivery success rate versus load balancing factor (α).

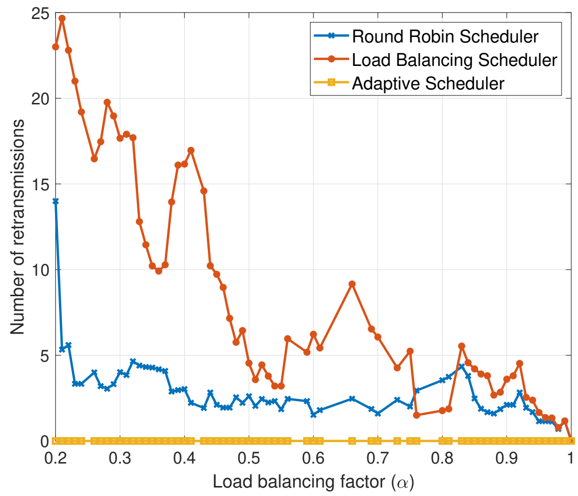

Fig. 7. Number of retransmissions versus load balancing factor (α).

- 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. 7, and here are the key findings. The adaptive scheduler does 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. 8 and Fig. 9, 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. 8. Moreover, average delay decreases when the aggregated carriers are going to be balanced ($\alpha \to 1$). Since there is no TCP call needed for adaptive scheduler, then the average delay is zero.

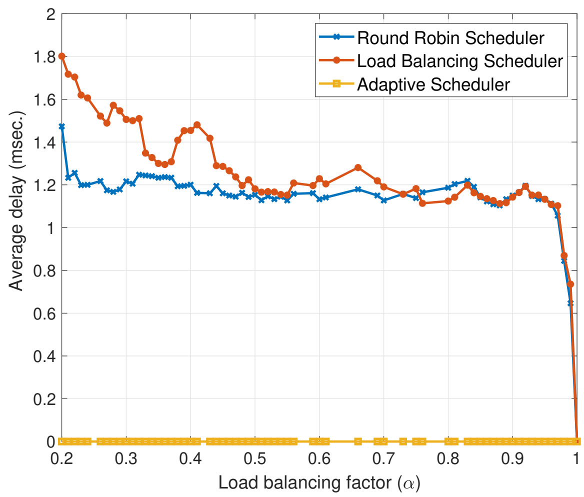

Fig. 8. Performance of Round Robin, load balancing, and adaptive schedulers in terms of average delay versus load balancing factor α.

Fig. 9 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

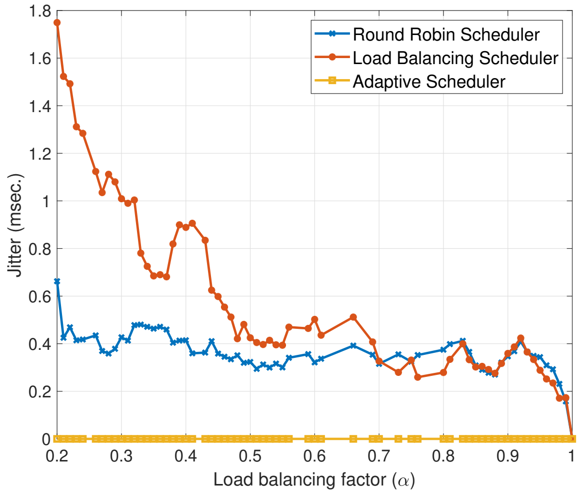

Fig. 9. Performance of Round Robin, load balancing, and adaptive schedulers in terms of jitter versus load balancing factor α.

TABLE II
PERFORMANCE SUMMARY OF THE SCHEDULING ALGORITHMS.

Metric / Scheduler	Round Robin [18]	Load balancing [13]	Adaptive [14]
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

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 CA 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 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 sheds light on the practical significance of different scheduling algorithms that are developed for adopting CA to satellite communication systems. CA has been introduced to satellite systems due to its distinctive feature of offering wider bandwidths to achieve a considerable increase in link-level peak data rate. This paper has evaluated the TCP performance of three CA schedulers in terms of the achievable date rate, in-order PDU delivery success rate, retransmissions, and queuing delays. On one hand, Round Robin and load balancing schedulers can be used for the applications that have high tolerance to out-of-order delivery. Load balancing algorithm achieves higher throughput and better spectral utilization than Round Robin approach under same circumstances with a lower computational complexity than adaptive scheduler. On the other hand, the adaptive allocation method can be seen as an efficient solution for highly reliable communications at the expense of a higher computational complexity. Moreover, aggregating balanced carriers, that are offering similar resources, decreases delays and retransmissions. In future work, we are developing multi-orbit CA scenarios within GEO, MEO, and LEO satellite systems.

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