Author(s): Majamaa, Mikko; Martikainen, Henrik; Sormunen, Lauri; Puttonen, Jani

Title: Multi-Connectivity for User Throughput Enhancement in 5G Non-Terrestrial Networks

Year: 2022

Version: Accepted version (Final draft)

Multi-Connectivity for User Throughput Enhancement in 5G Non-Terrestrial Networks

Mikko Majamaa*†, Henrik Martikainen*, Lauri Sormunen* and Jani Puttonen*
*Magister Solutions Ltd, Jyväskylä, Finland
†University of Jyväskylä, Jyväskylä, Finland
{firstname.lastname}@magister.fi

***Abstract*—To meet the increasing throughput and reliability demands, satellites may be used to complement the Fifth Generation (5G) Terrestrial Networks (TNs). To increase the efficiency of the satellite communications involved, research on bandwidth-efficient techniques is needed. Multi-Connectivity (MC), where a user can be connected to multiple Next Generation Node Bs (gNBs) simultaneously, is one of such techniques. In this paper, the focus is on MC in Non-Terrestrial Networks (NTNs) to improve users' experienced throughputs. First, a study of relevant specifications and algorithms is conducted. Then, the designed load-aware Secondary Node (SN) addition and traffic steering algorithms are presented and evaluated in a realistic two-satellite Low Earth Orbit (LEO) network scenario. The simulation results indicate that usage of MC can be beneficial in 5G NTNs.**

***Keywords*—Multi-Connectivity, Non-Terrestrial Networks, 5G, Satellite, Communications, Network Simulator 3, ns-3, SATCOM**

I. Introduction

5G wireless systems aim to tackle such use-cases as Ultra-Reliable Low Latency Communications (URLLC), massive Machine-Type Communications (mMTC), and enhanced Mobile Broadband (eMBB). Some concrete examples from these use-cases include, but are not limited to, telesurgery, the Internet of Things (IoT), and Virtual Reality (VR). To meet the increasing throughput and reliability demands, satellites may be used to complement the 5G TNs, for example, in rural areas, in case of emergencies, or areas with peak demands. Especially Non-Geostationary Orbit (NGSO) satellite systems have been under intense research activities in recent years because of the low latency associated with them, advancements in technology, and relatively cheap price. These systems are being deployed by such companies as Amazon, Telesat, and SpaceX, among many others.

European Commission has ambitious goals for future communications requirements [1]. A satellite component may play a key role to meet these requirements. To increase the efficiency of the satellite communications involved, the "Dynamic spectrum sharing and bandwidth-efficient techniques for high-throughput MIMO Satellite systems" (DYNASAT) [2] project researches techniques aimed to improve reliability, as well as throughput, in mobile communications. MC in NTNs where a user can be connected to multiple gNBs simultaneously is a bandwidth-efficient technique under the study in this paper.

MC is a generalization of Dual Connectivity (DC), where a User Equipment (UE) can be connected to two radio base stations simultaneously, that is, to a Master Node (MN) and a SN. In MC, there could be multiple SNs. The data that is to be sent to the UE first arrives to the MN. The MN can then decide to send the data to the UE or to forward it to the SN who will then send the data to the UE. MC can be used to enhance throughput and/or reliability, for example, when a UE is at a cell edge where throughput requirements are not met or a UE has a demand for URLLC. URLLC consists of, for example, telesurgery and automated traffic. In this paper, the focus is to research MC in NTNs, specifically to improve users' experienced throughputs, with means of system simulations. For this purpose, we present dynamic secondary node addition and traffic steering algorithms we have designed.

The rest of the paper is organized as follows. In section II, relevant architectures related to MC in specifications are presented. In section III, algorithms related to MC are reviewed. The description of the implementation of the MC feature to a 5G NTN System Level Simulator (SLS) is given in section IV, as well as the designed algorithms. In section V, the simulation scenario, assumptions, and results are presented. Finally, the work is concluded in section VI.

II. Multi-Connectivity and Related Architectures

3rd Generation Partnership Project (3GPP) is a standardization organization that provides specifications for mobile communications. The recently finalized 3GPP Release 17 includes basic functionalities for NTNs to support New Radio (NR), the air interface of 5G. Release 18 will enhance the NR operations in NTNs, for example, by addressing mobility and service continuity between NTNs and TNs [3]. MC in NTNs is one of the candidate features of Release 19. MC is specified for TNs in Technical Specification (TS) 37.340 (Release 15) [4] but is not yet specified for NTNs. Thus, in the following sections, specifications and research related to TNs are used as a reference.

Multi Radio-Dual Connectivity (MR-DC), as specified in TS 37.340 [4], is a generalization of Evolved Universal Terrestrial Access (E-UTRA) intra DC, as described in TS 36.300 [5]. In MR-DC, a UE can be connected to a MN and a SN, where one node provides NR access and the other either NR or E-UTRA access. From the UE perspective, there are three different bearers in MR-DC: Master Cell Group (MCG), Secondary Cell Group (SCG), and split bearers. In the MCG and SCG bearers, only the MN or SN radio resources are involved, respectively. In a split bearer, radio resources of both nodes are involved. In MR-DC, the MN is connected to the Core Network (CN) entity. The MN and SN are connected through an interface for control signaling and coordination. The data that is to be sent to the UE first arrives at the MN's Packet Data Convergence Protocol (PDCP) layer. The MN can then decide to send the data to the UE or to forward it through the X2/Xn interface to the SN who will then send the data to the UE.

Technical Report (TR) 38.821 (Release 16) [6] discusses solutions for NR features, including MC, to be supported in NTNs. The report describes satellites with different types of payloads. In the case of transparent payload satellites, the satellite repeats the signal, corresponding to an analog Radio Frequency (RF) repeater, whereas with regenerative payloads, (part of) the base station (for example, gNB) capabilities are on-board of a satellite, for example, demodulation, decoding, re-modulation, and re-coding functionalities. The report also provides architectural aspects in which in MC there might be included satellites with different kinds of payloads and a terrestrial base station. In this work, the interest is in the transparent payload LEO satellites. MC with two transparent payload satellites involved is depicted in Fig. 1.

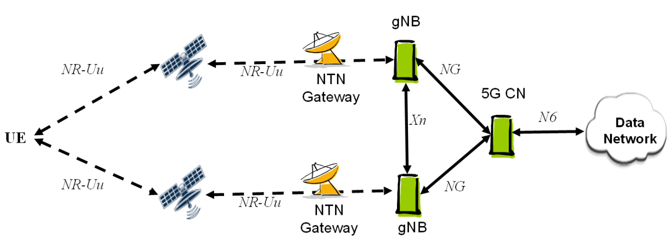

Fig. 1. MC with two transparent payload satellites involved [6].

As in the figure above, the NR-Uu interface connects the UE to the gNBs. As the satellites are transparent payload satellites, the satellites repeat the signal from the UE to the gNB and vice versa. The Xn interface is the connection between the two gNBs. The NG interface connects the gNBs to the 5G CN, whereas the N6 interface is the connection between the CN and data network.

III. Review of Algorithms Related to Multi-Connectivity

Algorithmic considerations for MC include 1) cell association, that is, whether to enable MC for a UE, also known as SN addition and 2) traffic steering, that is, how to split the data traffic between the MN and SNs. Mostly, papers related to TNs are used as a reference due to the lack of relevant work related to NTNs.

A. Secondary Node Addition Algorithms

The authors in [7] consider DC in Heterogeneous Networks (HetNet) with 5G, where a UE can be connected to a macro and a small cell. Enabling of DC for a UE, that has a small cell as a MN, is done by Reference Signal Received Power (RSRP) measurements. This sort of configuration corresponds to what is also done in [8]. The same authors as in [8], present a more novel algorithm for the configuration of DC in [9]. It is a modified opportunistic cell association algorithm. In [10], the authors consider dynamic MC activation for URLLC. As a base, it uses an RSRP threshold to enable MC. In addition, the algorithm stores latency budgets for the users to keep track of the urgency to activate MC. MC for URLLC is considered, but the algorithm could be modifiable for throughput enhancement as well. In the algorithm proposed in [11], each user maintains a list of candidate secondary cells in a preferable order by distance and tries to subscribe to a cell in that order. The cell then either accepts the subscription if it is not overloaded or if the subscription would lead to a better estimated throughput than with the worst current subscription to the cell, discarding the worst subscription.

The authors in [12] consider DC between Fourth Generation (4G) and 5G communications. This is useful since high frequencies of 5G can cause the links to be susceptible to failures, for example, when confronting obstacles. Moreover, this kind of DC may be considered in the deployment phase of 5G when the base stations providing 5G are still sparsely available. In the paper, a simulation framework [13], extended to support the DC feature, for Network Simulator 3 (ns-3), is detailed. In the implementation, each UE is primarily connected to a 4G base station, that is, an Evolved Node B (eNB). Then, by Sounding Reference Signal (SRS) measurements in the uplink direction, the best available gNB is chosen as a SN. The data traffic is first served to the MN by the Serving Gateway (SGW). Then at the PDCP layer, if there exists a SN, the data is sent to it for it to direct it to the UE. The implementation of DC maintains two links toward the UE, but the traffic is directed only through one of them. Maintaining the two links towards a UE allows switching a link faster to another, for example, in the case of a link failure, avoiding the use of hard handover where the connection might be lost completely for a while.

B. Traffic Steering Algorithms

The data split between a MN and SN is studied in [8]. The data is forwarded from the MN to the SN per-request basis, where the SN requests data from the MN that is to be sent to the UE. The amount of the data to be requested is based on pending data requests, scheduled throughput for the UE in the SN, and the buffer status of the SN. The traffic control algorithm the authors designed is also used in [14] where MC is evaluated in cloud and distributed HetNet architectures. Multiple load balancing algorithms and their mathematical formulations were considered in the 5G-ALLSTAR project [15], where the interworking of a TN-NTN system was researched. The algorithms include using techniques such as reinforcement learning, Wardrop Equilibrium, Friend or Foe Q-Learning, Game Theory, Linear Programming, and Analytic Hierarchy Process (AHP). Finally, in [16], the Wardrop Equilibrium control-based algorithm, which is chosen in the 5G-ALLSTAR for final Proof-of-Concept (PoC) [17], is further elaborated.

The wireless network simulator, that is used to evaluate the algorithm, is provided in [18]. For this work, the simulator is too simplified since it models mostly downlink and uplink allocations, but not the actual data transmission or protocols in a detailed enough manner.

The authors in [19] formulate the data split problem into an optimization problem with binary variables, in the case of a 5G NR TN network. The problem is then modified to be computationally feasible by first maximizing the number of served users and only after that the resources are divided between them. In [20], the problem is also formulated into an optimization problem with binary variables, in the case of millimeter-wave networks. The problem is attacked by partitioning the problem into a master problem and a pricing problem. In the partition problem, the number of possible connection configurations is reduced, and then the master problem is solved. Loads of the SNs and RSRPs are considered in the traffic steering problem solution in [21]. The SNs inform the MN about their load statuses as well as their RSRPs after the SN addition has been completed. Then out of these values, by scoring each connection, the MN computes the partition that it directs to each of the SNs.

IV. Implementation

In the following subsections, the SLS used in the research is described, as well as the MC extension to it. Then, the developed SN addition and traffic steering algorithms are described.

A. 5G Non-Terrestrial Network System Level Simulator

The 5G NTN SLS [22] is a 5G NTN extension to ns-3 [23] that can be used for system-level simulations of standardization processes (for example, in testing the current 3GPP Release 17 solutions, as well as in standardization in later releases), in testing of Radio Resource Management (RRM) algorithms, different parameterizations, and scenarios. In the DYNASAT project, the 5G NTN SLS is used to simulate the spectrum sharing and bandwidth-efficient transmission techniques under the research, for example, Dynamic Spectrum Allocation (DSA) and MC.

ns-3 is an open-source discrete-event network simulator for Internet systems. It is mostly used for educational and research purposes. Some common use-cases include studying new network topologies, different parameterizations of networks, and new protocols. The simulator can be used to simulate network technologies such as Wi-Fi, WiMax, LTE, and 5G, just to mention a few. Users may add new modules to the simulator. The 5G LENA [24] is one of such modules, which is an evolvement of the work done before in the LTE/EPC Network Simulator LENA [25]. The 5G LENA simulator was chosen as the starting point of the 5G NTN SLS development, because of its availability, maintenance, community support, and previous experience and competence. The NTN extension includes key features to model NTNs. Some of these include modeling of the antennas, channels (as defined in TR 38.811 [26]), and movement of the satellites. Different user environments (for example, urban and suburban), propagation delay model, and RRM enhancements are also implemented, to list a few. In the 5G NTN SLS, a gNB is modeled as a satellite's beam. A transparent payload satellite can then be modeled with a propagation delay that considers the user and feeder links. For elaborate description of the simulator, the reader is referred to [22]. Fig. 2 lays out the high-level components that form the 5G NTN SLS.

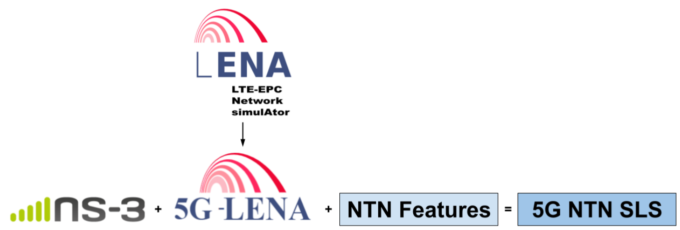

Fig. 2. The high-level components of the 5G NTN SLS.

B. Multi-Connectivity Extension

In the SLS, MC is implemented at the Radio Resource Control (RRC) and PDCP layers, for the control plane and user plane, also known as the data plane, respectively. Both the MN and SN(s) have their own RRC states for each UE that is connected to them, whereas the UE only has a single RRC state (based on the MN's RRC state), as described in TS 37.340 [4].

The SN addition process, defined in TS 37.340 [4], is initiated by the MN. It sends a SN addition request message to the desired SN, which replies with an acknowledgment. The MN then sends an RRC reconfiguration message to the UE, which does the needed configurations to be able to start receiving data from the SN. The UE responds after the reconfiguration is completed to the MN which then indicates that to the SN.

Code-wise, most of the SN addition procedure takes place in the RRC parts of the LTE module. Fig. 3 presents the updated architecture of the 5G LENA with MC. Changes to the original End-to-End (E2E) architecture include a SN that is connected to a MN through an Xn interface and to a UE through a wireless channel. Currently, DC is considered for simplicity, but the modification to the SLS to add multiple SNs is straightforward. The most fundamental change to the net device architecture is that now the UE must be able to manage different protocol stacks that are each related to receiving data from different gNBs. In the figure, these stacks refer to the MCG and SCG bearers, as described in TS 37.340 [4].

C. Secondary Node Addition Algorithm

The designed SN addition algorithm is based on three steps: identification 1) whether a UE needs a secondary node, 2) whether there is an available candidate to be a SN for a UE based on RSRP measurements, and 3) whether the desired gNB can be added as a SN based on its current loading conditions. The first step is based on the occupancy of the

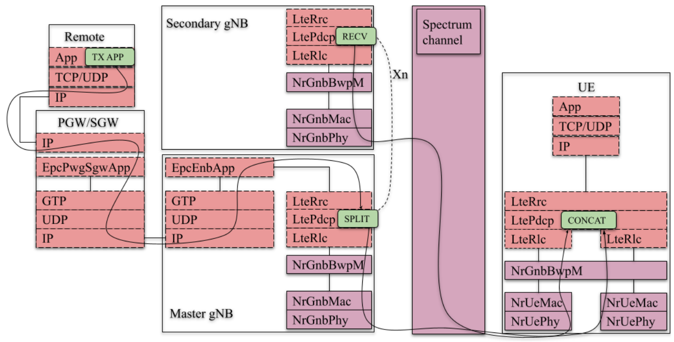

Fig. 3. The 5G LENA architecture with MC. The dashed red blocks are the ns-3 and LENA components, whereas the solid purple boxes are the 5G NR features. The arrow shows the data traversal in the downlink direction. Adapted from [24].

transmission (Tx) buffer of the data to be sent to the UE by the MN. If a parameterizable threshold value is hit, for example, 80% of the buffer size is occupied, the UE is considered to require a SN. The second step is based on a parameterizable RSRP threshold, that is, the SN addition request can be triggered when an RSRP value greater than a threshold is measured from a non-serving cell. In addition, SN addition requests can be sent to a target node from a source node at a maximum every $t_{\text{req\_interval}}$ to reduce the number of rejections and the Xn traffic. At this point, a SN addition request is sent to the target gNB through the Xn interface. The third point is evaluated by the desired SN when the request is received. If the SN's load is less than or equal to a parameterizable threshold value and no UE has been added in $t_{\text{add\_period}}$, then the request is accepted, and the UE can have the desired node as a SN. Otherwise, a message rejecting the SN addition request is sent. $t_{\text{add\_period}}$ is used so that the recently added secondary connections have posed their effect on the node's load, avoiding acknowledging new secondary connections to whom the node couldn't offer resources. The load of the gNB i is computed by

$$L^i = \frac{\text{RB}_{\text{used}}}{\text{RB}_{\text{tot}}}, \tag{1}$$

where RB_{used} is the total number of data Resource Blocks (RBs) used in the transmission slot and RB_{tot} is the total available data RBs in the transmission slot.

The transmission buffer occupancy for each UE (that is used to evaluate the UEs' need for the SN addition), as well as the cells' loads, are filtered using weighted average filtering. The values stored are updated every 10 ms (when available) giving more weight to more recent values which mitigates the problems of possibly high variances in the values. At each transmission buffer occupancy update, the need for SN addition is evaluated.

D. Traffic Steering Algorithm

After the SN addition for a UE has been done, the decision of the traffic split must be performed by the MN since it will receive the UE's data traffic. That is, the MN must decide whether it sends the data to the UE or steers it through the Xn interface at the PDCP layer to the SN who will then send the data to the UE. A key aspect of the traffic steering algorithm designed is the data requests, inspired by [8]. After the SN has been added to the UE, the SN starts to send periodic data requests to the MN through the Xn interface. Note that if a SN is added to a UE that already has been added to a UE with the same MN, the data requests are not initiated, that is, the data requests are sent per gNB basis. This is convenient to reduce the Xn traffic. The procedure for sending the data requests is illustrated in Fig. 4. The period of sending the data requests is Δt. From the figure, it can be observed that between the third and fourth request, the period is $3\Delta t$. This is due to the fact the SN only sends the data requests if it is not overloaded. This is determined similarly as in the SN addition algorithm's step 3.

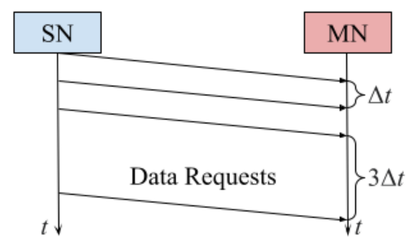

Fig. 4. The SN sends periodic data forward requests to the MN (if capacity is available).

The amount of data to be requested is computed with the help of Shannon's formula [27] which gives the theoretical maximum bitrate of a communication channel:

$$R = B \cdot \log_2(1 + \text{SINR}), \tag{2}$$

where B is the available bandwidth and SINR is the Signal-to-Interference-plus-Noise Ratio. In the computation of the data amount to be requested, the highest control channel SINR (related to the SN) for the UEs that have the gNB as a SN is used. The UEs report the control channel SINRs for all the gNBs they are connected to (including the SNs). These values are stored by the gNBs. In practice, the control channel SINR corresponds to the worst-case SINR, that is, if all the interfering data channels were fully occupied while transmitting data to a UE. The control SINR in the simulator is measured from the control symbols when all the gNBs send the Master Information Block (MIB) and System Information Block (SIB), thus, it is representing the full load SINR. One could get this kind of (estimated) SINR in reality from reference signals, that is, RSRP-SINR. The best control channel SINR is used in the computation of the data amount to be requested as a compromise since, after all, it is the best worst-case SINR. As opposed to using, for example, the average SINR would cause the data requests to be too pessimistic. Overloading the SN is preferable to it being idle when maximizing throughput. This leads to the amount of data (in bits) to request to be:

$$D = \alpha \cdot (1 - L_{\text{pr}}^{i} - L_{\text{off}}) \cdot B_{\text{tot}} \cdot \log_2(1+\text{SINR}) \cdot (\Delta t + t_{\text{off}}), \quad (3)$$

where α is a parameter used to compensate for the fact that the actual application data is less than the transmitted bits, because of the processing of the data in the different layers of the protocol stack. For example, TR 38.803 [28] defines this value to be 0.6 for downlink. L_{pr}^{i} is the load to the cell i posed by the primary connection UEs, thus, the available bandwidth B in the computation of the data amount to request is the bandwidth available left from the primary connection UEs. L_{off} is an offset value that can be used to, by parametrization of the simulations, artificially manipulate the load considered in the computation of the amount of data to request. t_{off} is used to compute the data to be requested (if desired) ahead of time, for example, as a precaution to prevent the SN from being idle.

Table I gives a summary of the Xn data request message that is sent to the MN. The MN then stores the latest request it has received (per gNB basis). Note that the data request message is our design and cannot be found in the specifications.

TABLE I
STRUCTURE OF THE XN DATA REQUEST MESSAGE.

Field	**Details**
Data amount requested	Computed as defined in (3).
Request valid until	The time until the request is valid. Defined as $t_{\text{current}} + \Delta t$.
Source cell ID	SN's cell ID.
Target cell ID	MN's cell ID.

At this point, the SN has been added to the UE(s), and the SN has started (if capacity is available) sending the data requests. Now, the MN first determines whether the traffic is needed to be steered to the SN. This is determined similarly as in the SN addition algorithm's step 1 but also a threshold value that can be used to favor steering the traffic to the SN (or to send by the MN) is defined. That is, the traffic is preferred to be steered to the SN if $O_{\text{Tx}}^{ij} + O_{\text{Tx\_off}} > O_{\text{th}}$, where O_{Tx}^{ij} is the occupancy of the UE j's (the UE for whose traffic the steering decision is made) Tx buffer at the MN (cell i), $O_{\text{Tx\_off}}$ is the occupancy offset, and O_{th} is the threshold value. If this condition is met, the MN checks whether there are valid data requests by the UE's SN. If there are not, the MN sends the data itself. Otherwise, the data is forwarded to the SN and the amount of data that can be forwarded is updated accordingly. Furthermore, we utilize a scheduling scheme where the UEs are scheduled otherwise in a Round Robin fashion but the primary connection UEs are always prioritized over the secondary connection UEs.

V. SIMULATIONS

A. Simulation Scenario and Assumptions

The simulation scenario consists of two satellites each with 7 beams. The satellites belong to different constellations and use different frequency bands, that is, they do not interfere with each other. The beams of the different satellites are partially overlapping. The first satellite's elevation angle is 90 degrees, whereas the second satellite's elevation angle is 60 degrees. In consequence, the beam patterns of the different satellites differ to some degree. There are 10 UEs placed randomly in the area of each beam of the first satellite. At the beginning of the simulations, the UEs use cell selection to connect to the strongest cell of any one of the two satellites. One tier of Wraparound (WA) beams surrounding each of the satellites is included. The WA beams consist of UEs that overload the corresponding WA beam. These beams are used to introduce interference for the actual system of interest and are not included in the statistics collection. In the simulations, only downlink is considered. Fig. 5 shows the output of the simulator in one of the simulation runs after the scenario has been created and the UEs have performed cell selection to the strongest cell, leaving out the WA beams and UEs. The red and blue circles correspond to the beam centers of the first and second satellite, respectively. The dashed lines depict the connection of the UEs to the beams. The second satellite is outside of the area depicted in the figure.

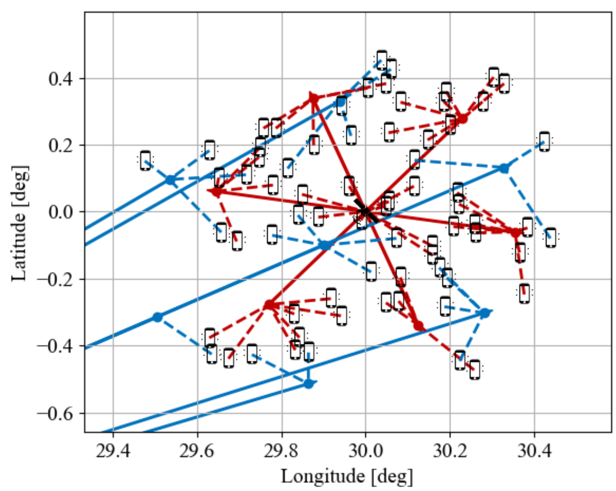

Fig. 5. Output of the simulator in one of the simulation runs after the scenario has been created and the UEs have performed cell selection to the strongest cell.

The satellites and UEs are considered stationary because the simulation time is so short that the movement is considered insignificant. Dynamic Non-Line of Sight (NLOS) channel condition is considered where satellites might not be visible to a UE, for example, because of obstacles. For lower elevation angles, the NLOS probability is higher.

The RSRP threshold for the SN addition is chosen to be such that it covers about 60% of UEs' measured RSRP values in all of the simulations. By simulations, it was observed that in the scenario what limits the SN addition is the load of the candidate SNs. By lowering the RSRP threshold, no more SN additions were made, because the SNs were already occupied which led to rejections of the SN addition requests. This is the expected behavior in scenarios where the SNs become highly loaded. Some important simulation parameters can be found in Table II. Realistic satellite and antenna parameters are used that are found in TR 38.821 [6] which provides calibration cases for SLSs.

TABLE II
IMPORTANT PARAMETERS OF THE SIMULATIONS RELATED TO MC.

Parameter	Value
Simulation Time	2.0 s
Satellite Mobility	Stationary
UE Mobility	Stationary
Channel Condition	Dynamic NLOS
Bandwidth per Satellite	15 MHz
Carrier Frequency	2 GHz (S band)
Frequency Reuse Factor	3
Satellite Orbit	600 km
Satellite Parameter Set	Set 1, Table 6.1.1.1-1 [6]
UE Antenna Type	Handheld
Traffic	CBR with UDP
UDP Packet Size	400 B
UDP Packet Interval per UE	1 ms
Atmospheric Absorption	Enabled
HARQ	Enabled
Scintillation	Enabled
Fast Fading	Disabled
Shadowing	Enabled
SN Addition RSRP Threshold	-125 dBm
SN Addition Load Threshold	0.9
Load Offset (L_{off})	0.0
SN Addition Tx Buffer Size Threshold	0.8
Tx Buffer Size Offset ($O_{\text{Tx\_off}}$)	1.0 (always forward the data according to the active data requests)
Data Request Period (Δt)	100 ms
Data Request Period Offset (t_{off})	25 ms
$t_{\text{req\_interval}}$	25 ms
$t_{\text{add\_period}}$	25 ms
Scheduler	Round Robin (primary connection users prioritized)
RNG Runs	5

B. Simulation Results

Three distinct simulations are examined. These include running the simulations with MC turned off (corresponding to the 3GPP Release 17 NR NTN functionality) and MC turned on. Furthermore, a single satellite scenario is also included where there is only a single satellite with an elevation angle of 90 degrees without MC functionality, that is, the scenario described in the previous section without the second satellite. All the distinct simulations are run five times each with different Random Number Generator (RNG) seeds to introduce random variation to the simulations. Results from all the RNG runs are then combined.

Fig. 6 shows the empirical Cumulative Distribution Function (eCDF) of the UEs' application throughput. It can be observed that the throughputs are the worst in the single satellite scenario since half of the cells are providing services to the UEs compared to the other cases. In the single satellite scenario, the average throughput for the UEs is 699.8 kbps. In the two-satellite, MC off scenario, the average throughput is 1393.7 kbps. As anticipated, using MC enhances the throughputs. The average throughput when MC is turned on is 1597 kbps.

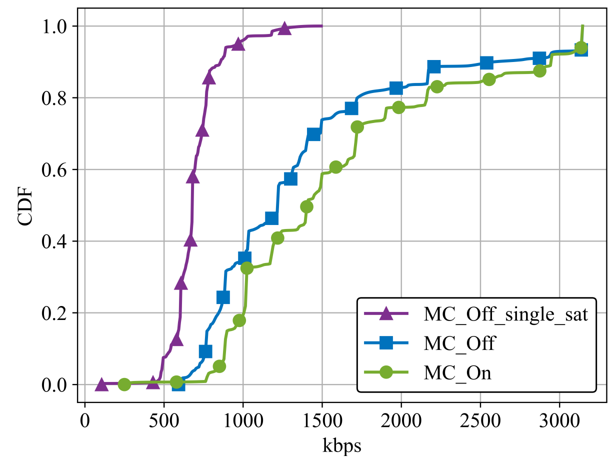

Fig. 6. eCDF of the UEs' application throughputs in the simulations related to MC.

The Spectral Utilization Efficiency (SUE) over the cell area is captured in Fig. 7. SUE is defined as the data rate provided over the bandwidth. Introducing the second layer of cells from the second satellite without MC reduces the SUE by approximately 0.05 b/s/Hz compared to the single satellite case where SUE is about 0.6 b/s/Hz. This is mostly explained by the fact that some of the cells of the second satellite are partly or completely unutilized as not enough users select those cells. One reason for that is the higher NLOS probability due to the lower elevation angle of 60 degrees. However, enabling MC will increase the SUE slightly above the single satellite case because the secondary connections can be more flexibly enabled, and thus all the cells of the second satellite are better utilized.

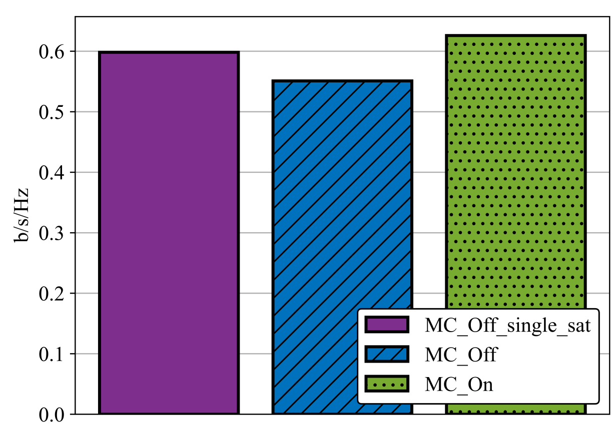

Fig. 7. SUE per cell area.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, a review of architectures and algorithms related to MC was conducted. After that, an MC feature was implemented to a 5G NTN packet-level SLS. Furthermore, the designed dynamic SN addition and traffic steering algorithms were presented. The implementation was tested in a realistic scenario consisting of two LEO satellites, each with seven beams. The simulation results show that benefits to user throughput enhancement, as well as to SUE, can be obtained using MC in NTNs with the designed algorithms. The feature developed to the 5G NTN SLS can be used in future research activities in algorithm development and testing, as well as in standardization work.

The ability to test different SN addition and traffic steering algorithms opens possibilities to conduct more interesting research. Even though the simulations were already relatively realistic, even more dynamicity in the simulations should be considered. The movement of the satellites and UEs could be one of the options. More options include SN release, leaving/arriving users, TN/NTN scenarios, and the addition of multiple SNs.

Acknowledgment

This work has been funded by the European Union Horizon-2020 Project DYNASAT (Dynamic Spectrum Sharing and Bandwidth-Efficient Techniques for High-Throughput MIMO Satellite Systems) under Grant Agreement 101004145. The views expressed are those of the authors and do not necessarily represent the project. The Commission is not liable for any use that may be made of any of the information contained therein.

References

[1] "Connectivity for a Competitive Digital Single Market - Towards a European Gigabit Society," European Commission, Directorate-General for Communications Networks, Content and Technology, 2021.

[2] "About DYNASAT," accessed on: June 13, 2021. [Online]. Available: https://www.dynasat.eu/about-dynasat/.

[3] X. Lin, "An Overview of 5G Advanced Evolution in 3GPP Release 18," 2022, arXiv:2201.01358.

[4] "TS 37.340: NR; Multi-connectivity; Overall description; Stage-2," V16.7.0, Sept. 2021.

[5] "TS 36.300: Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2," V16.6.0, June 2021.

[6] "TR 38.821: Solutions for NR to support Non-Terrestrial Networks (NTN)," V16.0.0, Jan. 2020.

[7] N. H. Mahmood, M. Lopez, D. Laselva, K. Pedersen, and G. Berardinelli, "Reliability Oriented Dual Connectivity for URLLC services in 5G New Radio," *2018 15th International Symposium on Wireless Communication Systems (ISWCS)*, pp. 1–6, 2018.

[8] H. Wang, C. Rosa, and K. I. Pedersen, "Inter-eNB Flow Control for Heterogeneous Networks with Dual Connectivity," *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*, pp. 1–5, 2015.

[9] H. Wang, G. Pocovi, C. Rosa, and K. I. Pedersen, "Configuration of Dual Connectivity with Flow Control in a Realistic Urban Scenario," *2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*, pp. 1–5, 2015.

[10] N. H. Mahmood and H. Alves, "Dynamic Multi-Connectivity Activation for Ultra-Reliable and Low-Latency Communication," *2019 16th International Symposium on Wireless Communication Systems (ISWCS)*, pp. 112–116, 2019.

[11] G. Simsek, H. Alemdar, and E. Onur, "Multi-Connectivity Enabled User Association," *2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pp. 1–6, 2019.

[12] M. Polese, M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, "Improved Handover Through Dual Connectivity in 5G mmWave Mobile Networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 2069–2084, 2017.

[13] M. Mezzavilla, M. Zhang, M. Polese, R. Ford, S. Dutta, S. Rangan, and M. Zorzi, "End-to-End Simulation of 5G mmWave Networks," *IEEE Communications Surveys Tutorials*, vol. 20, no. 3, pp. 2237–2263, 2018.

[14] D. S. Michalopoulos, A. Maeder, and N. Kolehmainen, "5G Multi-Connectivity with Non-Ideal Backhaul: Distributed vs Cloud-Based Architecture," *2018 IEEE Globecom Workshops (GC Wkshps)*, pp. 1–6, 2018.

[15] "5G ALLSTAR," accessed on: June 13, 2022. [Online]. Available: https://5g-allstar.eu/.

[16] F. Delli Priscoli, E. De Santis, A. Giuseppi, and A. Pietrabissa, "Capacity-constrained Wardrop equilibria and application to multi-connectivity in 5G networks," *Journal of the Franklin Institute*, vol. 358, no. 17, pp. 9364–9384, 2021.

[17] "Deliverable D4.3 – Implementation of the multi-RAT load balancing algorithms and technical specifications of the relevant interfaces." 5G ALLSTAR, 2021.

[18] E. De Santis et al., "5G-ALLSTAR Wireless Network Simulator." accessed on: Dec 28, 2021. [Online]. Available: https://github.com/trunk96/wireless-network-simulator.

[19] J. Elias, F. Martignon, and S. Paris, "Optimal Split Bearer Control and Resource Allocation for Multi-Connectivity in 5G New Radio," *2021 Joint European Conference on Networks and Communications 6G Summit (EuCNC/6G Summit)*, pp. 187–192, 2021.

[20] C. Tatino, I. Malanchini, N. Pappas, and D. Yuan, "Maximum Throughput Scheduling for Multi-connectivity in Millimeter-Wave Networks," *2018 16th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, pp. 1–6, 2018.

[21] J. Burgueño, I. de la Bandera Cascales, D. Palacios Campos, and R. Barco, "Traffic Steering for eMBB in Multi-Connectivity Scenarios," *Electronics*, vol. 9, p. 2063, Dec 2020.

[22] J. Puttonen, L. Sormunen, H. Martikainen, S. Rantanen, and J. Kurjenniemi, "A System Simulator for 5G Non-Terrestrial Network Evaluations," *2021 IEEE 22nd International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, pp. 292–297, 2021.

[23] G. F. Riley and T. R. Henderson, "The ns-3 Network Simulator," in *Modeling and Tools for Network Simulation*, K. Wehrle, M. Güneş, and J. Gross, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 15–34.

[24] N. Patriciello, S. Lagén, B. Bojović, and L. Giupponi, "An E2E simulator for 5G NR networks," *Simulation Modelling Practice and Theory*, vol. 96, 2019.

[25] N. Baldo, M. Miozzo, M. Requena-Esteso, and J. Nin-Guerrero, "An Open Source Product-Oriented LTE Network Simulator Based on Ns-3," in *Proceedings of the 14th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*. New York, NY, USA: Association for Computing Machinery, 2011, p. 293–298.

[26] "TR 38.811: Study on New Radio (NR) to support non-terrestrial networks," V15.4.0, Sept. 2020.

[27] C. E. Shannon, "A Mathematical Theory of Communication," *The Bell System Technical Journal*, vol. 27, no. 3, pp. 379–423, 1948.

[28] "TR 38.803: Study on new radio access technology: Radio Frequency (RF) and co-existence aspects," V14.2.0, Sept. 2017.