Multi-Connectivity in 5G and Beyond Non-Terrestrial Networks

Mikko Majamaa, Henrik Martikainen, Lauri Sormunen, and Jani Puttonen

***Abstract*—The Fifth Generation (5G) communications systems aim to serve such service classes as Ultra-Reliable Low Latency Communications (URLLC), enhanced Mobile Broadband (eMBB), and massive Machine-Type Communications (mMTC). To meet the growing requirements posed to mobile networks, satellites can be used to complement the Terrestrial Networks (TNs). To increase the efficiency of the satellite communications involved, bandwidth-efficient techniques should be used. Multi-Connectivity (MC) is one such technique. In MC, a User Equipment (UE), for example, a smartphone, can be connected to multiple Next Generation Node Bs (gNBs) simultaneously. In this paper, an adaptive MC activation scheme for throughput enhancement in 5G and beyond Non-Terrestrial Networks (NTNs) is presented. The algorithm is evaluated by system simulations using different traffic split algorithms, namely, even split, data request per connection and per gNB algorithms. In the considered simulation scenario, the maximum throughput enhancement of 9.1%, compared to when MC is turned off, is experienced when using the adaptive Secondary Node (SN) addition algorithm with the combination of the data request algorithms.**

***Keywords*—3rd Generation Partnership Project (3GPP) standardization, 6G, Beyond 5G (B5G), Low Earth Orbit (LEO) satellite, satellite network simulator, throughput enhancement.**

I. Introduction

The amount of mobile network traffic has increased enormously in recent years. According to the Ericsson's mobility report from 2022 [1], mobile networks carry double the data than two years ago and in the growth, there is no end in sight. Moreover, European Commission ambitiously states that at least 100 Mbps Internet connections should be offered to every household in Europe by the year 2025, regardless of the location [2]. Satellites play a key role to meet these requirements since they can offer resources to remote areas where building Terrestrial Networks (TNs) can be practically impossible. Satellites can also provide load balancing to highly loaded TNs, for example, in areas with peak demands. Non-Geostationary Orbit (NGSO) satellites have been under intense research activities during the past years because of the relatively low propagation delays and cheap prices compared to Geostationary Orbit (GEO) satellites. Mega-constellations of Low Earth Orbit (LEO) satellites can provide coverage to the whole earth and are being deployed by companies such as Telesat, Amazon, OneWeb, and SpaceX. China and USA are also planning or already deploying their own LEO constellations [3]. For the EU to retain its digital sovereignty, efforts to launch an EU-based LEO constellation have been made.

Since the growing needs of data traffic requirements, as well as the service classes that the Fifth Generation (5G) communications aim to offer, the use of bandwidth-efficient transmission techniques, is required. Multi-Connectivity (MC) [4] is such a technique. It can be used to improve reliability, latency, and throughput in transmissions. In MC, a User Equipment (UE) (for example, a smartphone) can be connected to multiple Next Generation Node Bs (gNBs) simultaneously. One of the gNBs acts as a Master Node (MN) and others as Secondary Nodes (SNs). To form secondary connections to a UE, the serving node can send secondary node addition requests to other nodes. The nodes can then reject the requests or acknowledge them.

3rd Generation Partnership Project (3GPP) [5] is a standardization organization that provides specifications for mobile communications. It was founded initially in 1998 to provide specifications to 3G communications. Since then, numerous participating actors have been contributing to its specification activities. History was made in 3GPP Release 17 since it included specifications for mobile communications not only in TNs but also in Non-Terrestrial Networks (NTNs). This is a big step for the satellite communications industry since these specifications can help the actors in the field to build systems that can cooperate seamlessly and with less effort with TN operators. In the past, the NTNs and the TNs have been considered as more separate and competing components. The 3GPP Release 16 included Technical Report (TR) “Solutions for NR to support NTNs” [6], which discussed possible enhancements (if any) needed for NR specifications to apply to the NTN environment. MC was also touched slightly. When using MC in NTNs, the satellites involved may be transparent or regenerative payload satellites, that is, the satellite simply repeats the signal, or part of the base station functionalities is on board the satellite, respectively. MC between TN and NTN nodes was also considered.

Release 17 includes basic functionalities for NTNs to sup-

Manuscript received November 16, 2022; revised December 6. Date of publication December 30, 2022. Date of current version December 30, 2022.

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. This paper was presented in part at the International conference on Software, Telecommunications and Computer Networks (SoftCOM) 2022.

The authors are with the Magister Solutions Ltd., Jyväskylä, Finland (email: {firstname.lastname}@magister.fi).

M. Majamaa is with the University of Jyväskylä, Jyväskylä, Finland.

Digital Object Identifier (DOI): 10.24138/jcomss-2022-0155

port New Radio (NR), the air interface of 5G. Release 18 will enhance the NR operations, for example, by improving coverage for handheld terminals and addressing mobility and service continuity between NTNs and TNs [7]. MC in NTNs is yet to be specified and is one of the candidate features of Release 19. Since MC in NTNs is not profoundly investigated, research on MC in NTNs is needed. The "Dynamic spectrum sharing and bandwidth-efficient techniques for high-throughput MIMO Satellite systems" (DYNASAT) [8] project researches bandwidth-efficient techniques in NTNs. One of the techniques is MC. Research of MC in NTNs includes factors such as the logic to add secondary connections and to split the traffic between the MN and the SN(s). Moreover, scenarios, in which MC in NTNs may be utilized need to be identified.

The main contribution of this paper is to introduce a load-aware, per need activated SN addition algorithm for throughput enhancement in 5G NTNs. The algorithm is evaluated by simulations with a packet-level 5G NTN System-Level Simulator (SLS) in a scenario consisting of two LEO satellites. This article is an extension of the work presented in [9]. This article's contribution in relation to the previously published work is manyfold. First, the analysis is deepened by providing a more detailed literature review, as well as a description of the filtering used to account for the possibly quickly varying loads and buffer sizes (the filtered values are used in the algorithms' decisions). Furthermore, on top of using an even split for the traffic splitting logic between an MN and SN, a more sophisticated method is also included. The method is introduced in [10]. The further development of this method is introduced in this article.

The rest of the paper is organized as follows. First, a review of related work in Section II is provided. In Section III, system aspects related to MC in NTNs are elaborated. In Section IV and V, the SN addition and traffic split algorithms are presented, respectively. Simulations evaluating the algorithms are detailed in Section VI. Conclusions and future work are considered in Section VII.

II. Related Work

The authors in [11] provide an extensive survey of the 3GPP specification activities in 5G and Beyond networks. Whereas the previous survey gives a broader view of the specification activities, [12] delves more into the technical details of the same topic. In [13], the current system architecture and assumptions for NR in NTNs are discussed. Furthermore, the methodology for link budget analysis for such systems is provided.

Mobility management shares some features that can be useful in MC as well, for example, Handover (HO) triggering mechanisms could be used for SN addition. The conventional 5G NR HO algorithm's performance in 5G NTNs is researched in [14]. By system-level simulations, the authors show that radio link failures and outages increase in the NTN use case. Mobility management in 5G NTNs is also discussed in [15], in which a HO algorithm based on antenna gain is introduced. System-level simulations are provided to back up the discussion. In [16], different HO mechanisms in NTNs are compared. Namely, the mechanisms are based on location, signal strength, and timer.

Research related to MC in TNs has been conducted extensively. In [17], benefits and challenges related to MC in mobile networks are laid out. The architectures and protocol layer design for MC are discussed. The authors in [18] discuss MC as an enabler for Ultra-Reliable Low Latency Communications (URLLC). An overview of standardization in the 3GPP and IEEE standards related to MC is given. Also, possible further research directions regarding characteristics of the carrier separation and aggregation, paths used for MC, and scheduling issues are provided. A recent article [19], provides a comprehensive survey of MC. The authors start by reviewing the existing standards and enabling technologies for MC. A taxonomy that enables the classification of the different elements characterizing MC (for example, the objective/strategy/Radio Access Technologys (RATs) for MC) is then defined. The taxonomy definition is followed by a review of existing solutions utilizing MC in terms of Quality of Service (QoS) improvement, energy efficiency, fairness, mobility, and spectrum and interference management. Furthermore, open challenges and future directions are discussed. Some suggested directions include multi-operator MC, multi-criteria-based cell association, and MC in combination with Device-to-Device (D2D) communications.

A scenario in which a UE can be connected to a macro and a small cell is considered in [20]. SN addition is based on Reference Signal Received Power (RSRP) measurements. In [21], dynamic MC activation for URLLC is considered. The algorithm introduced uses an RSRP threshold to trigger SN addition as a base but also latency budgets of users are stored to keep track of the urgency to activate SN addition. In [22], SN addition is triggered based on Sounding Reference Signal (SRS) measurements in the uplink direction. The users try to subscribe to candidate SNs based on distances. The candidates can accept the requests if it would lead to better estimated throughput than with the current worst subscription, dropping the worst subscription. The traffic split between an MN and SN is researched in [23]. The SN requests data from the MN. The amount of data is computed based on pending data requests, historical data of the throughputs provided, and the buffer status of the SN. The same traffic split algorithm is also used in [24] in which MC is studied in cloud and distributed Heterogeneous Networks (HetNet) architectures.

Work related to MC in NTNs has not been extensively performed, yet. The 5G-ALLSTAR project's [25] goal was to ease the integration of a satellite component into 5G mobile networks. One of the studied items was MC. In [26], a solution for MC-assisted load-balancing in HetNet is provided, in which the RAN nodes provide both, terrestrial and satellite connectivity.

In the authors' previous work, MC in a transparent payload LEO satellite environment was researched. In [10], the simulator design to study MC in NTNs is introduced. Furthermore, simulation results with the designed MC activation and traffic split algorithms are provided. The designed adaptive MC activation algorithm is further elaborated in [9], in which it is compared against a baseline algorithm.

III. System Aspects

MC in NTNs is illustrated in Fig. 1. It consists of a UE (a smartphone in this case) that receives transmissions from two separate transparent payload LEO satellites. In the DYNASAT project, the satellites under focus are transparent payload LEO satellites. The MN is connected to the Core Network (CN) through an Ng interface. The gNBs are connected through an Xn interface for control (for example, SN addition) signaling, and data forwarding (for example, when sending data from an MN for an SN to send to a UE). Both, the service, and the feeder links utilize Nr-Uu interface in the case of transparent payload satellites [6]. In the figure, the 5G user plane protocol stacks for the gNBs and the UE are shown. The data that is to be sent to the UE first arrives at the MN's Packet Data Convergence Protocol (PDCP) layer which can then forward the data for the SN to send to the UE. The UE must be able to receive separate transmissions from the gNBs. The data is then combined at the PDCP layer. Both, the MN, and the SN could host Service Data Adaption Protocol (SDAP) layers for each Protocol Data Unit (PDU) session towards the UE, but in the figure, only the MN hosts an SDAP. This indicates that, in this case, the MN may do decisions on how to realize QoS flows as different types of bearers [4]. The altitudes of LEO satellites can be 300-1500 km [13]. In the figure, h refers to the altitudes of the satellites, whereas ϵ_1 and ϵ_2 to the elevation angles. Non-Line of Sight (NLOS) probability is higher with lower elevation angles, for example, because of trees and buildings. The gateways serving the satellites can be the same, close to each other or they can even reside on different continents.

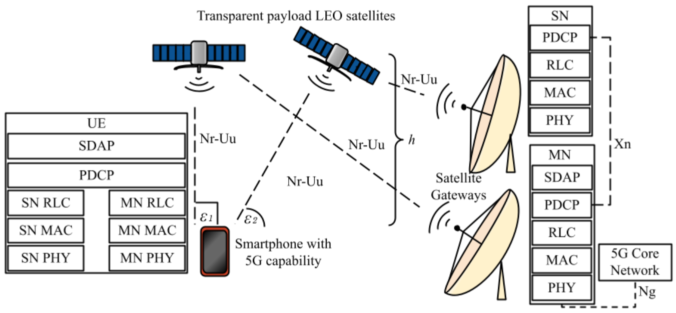

Fig. 1. MC illustration in NTN environment.

To determine possible HO or SN candidates, signal strength measurements are required. Reference signals can be used for that purpose. Secondary Synchronization RSRP (SS-RSRP) is one such signal. It is defined as the linear average over the power contributions (in watts) of the resource elements that carry secondary synchronization signals [27]

$$\mathrm{RSRP} = \frac{\sum_{k=1}^{K} \frac{\sum_{m=1}^{M}(P(k,m))}{M}}{K}, \tag{1}$$

in which $P(k, m)$ is the signal power of the Resource Element (RE) m within the Resource Block (RB) k, M is the number of REs carrying the reference signal in an RB and K is the number of RBs.

The gNBs transmit these signals and the UEs perform Layer 1 (L1) measurements. L1 measurements are useful to perform actions that require small delays, for example, beam management procedures. Layer 3 (L3), that is, RRC layer measurements are formed from the L1 measurements by filtering the measured values using L3 filtering. L3 measurements can be used, for example, in HO and SN addition decisions. L3 filtering allows a longer view of the signal's strength and thus possibly reduces ping-pong effects in HOs/SN additions (and releases). In practice, the values can be mapped to reported values [28] with the following formula, in the case of L3 SS-RSRP measurements

$$r = \lfloor \min(\max(\lfloor R + 157 \rfloor, 0), 127) \rfloor, \tag{2}$$

in which r is the reported RSRP value and R is the measured value. The L3 SS-RSRP measurements are used in the SN addition algorithm's decisions.

IV. The Secondary Node Addition Algorithm

Many of the SN addition schemes only consider an RSRP threshold value when deciding whether to enable MC for a UE. The authors in [21] elaborate, that using only an RSRP threshold to activate SN addition is a standard policy. In the MC activation scheme considered in this work, multiple factors that can be used to enhance the per UE and per system throughputs are taken into account. These factors include the need for SN addition based on occupancy of the data that is to be transmitted to UE j by gNB i, that is, the gNB i's transmission buffer occupancy towards the UE j, candidate SNs (set $\mathfrak{S}$) for the UE j based on RSRP measurements, the candidate SNs' loads, an interval (t_{req}) in which SN addition requests can be sent by a gNB to a candidate SN and t_{add} which defines the minimum time between requests in which a gNB accepts them. The parameter t_{add} is used to give the candidate SN time to adapt to recent secondary connection additions. The t_{req} parameter is used to reduce sending SN addition requests that would likely result in rejections. The load of a gNB i is defined as the used data RBs in a transmission slot divided by the available data RBs in the transmission slot

$$L_i = \frac{\mathrm{RB}_{\mathrm{used}}}{\mathrm{RB}_{\mathrm{tot}}}, \tag{3}$$

in which $\mathrm{RB}_{\mathrm{used}}$ and $\mathrm{RB}_{\mathrm{tot}}$ are respectively the total numbers of data RBs used in the transmission slot and the total available data RBs in the transmission slot.

Algorithm 1 presents the SN addition algorithm. The gNB i's transmission buffer occupancy ($O_{\mathrm{ij,Tx}}$) towards the UE j is filtered every t_{update} using Exponential Weighted Moving Average (EWMA) and the value ($o_{\mathrm{ij,Tx}}$) is stored for the algorithm's use. The UE is considered to need an SN if the value is greater than or equal to a parametrizable threshold O_{th}. The variable $t_{\mathrm{ij,Tx}}$ is the last time when $o_{\mathrm{ij,Tx}}$ was updated. The RSRP measurements are reported and are valid for parametrizable times. Thus, the outdated RSRP measurements are cleared and the set $\mathfrak{S}$ is updated accordingly. Finding the best candidate SN k means finding the candidate SN with the highest RSRP for the UE so that the threshold is met and to which the current serving gNB has not sent SN addition requests in less than t_{req}. If a candidate SN is found, an SN addition request is

Algorithm 1: Secondary Node Addition Algorithm

```
for every O_ij,Tx change do
    if the UE j is in single-connectivity state then
        if t − t_ij,Tx < t_update then
            continue ;
        Update o_ij,Tx ;
        if o_ij,Tx < O_th then
            continue ;
        Remove the outdated RSRP measurements and
          update the set S accordingly ;
        Find the best available SN k from the set S in
          terms of the highest RSRP for the UE j and
          to which an SN addition request has not been
          sent in less than t_req ;
        if k is found then
            Send SN addition request to k ;
            /* At the candidate node k do the following
              */
            if l_k ≤ L_th and t − t_k,last > t_add then
                Acknowledge the SN addition
            else
                Reject the SN addition
            /* At the candidate node k ^^ */
            Perform the needed configurations ;
end
```

sent. The gNBs' load values are also filtered using EWMA filtering and the values are used when accepting/rejecting SN addition requests. If the candidate SN's filtered load (l_k) is less or equal to a parametrizable threshold L_{th} and no secondary connections have been added in t_{add}, the candidate responds with an acknowledgment, and the UE can have the candidate as an SN. t and $t_{k,\text{last}}$ refer to the current time and time when the last secondary connection was added to the candidate node k.

EWMA filtering is used to mitigate reacting to possibly highly varying loads and buffer size changes. The filtering is defined as

$$m_{\text{filt}}(t) = \alpha(t) \cdot m_{\text{meas}}(t) + (1 - \alpha(t)) \cdot m_{\text{filt}}(t-1), \quad (4)$$

in which $m_{\text{filt}}(t)$ is the filtered value at time t, $m_{\text{filt}}(t-1)$ is the previous filtered value, $m_{\text{meas}}(t)$ is the measured value and $\alpha(t)$ is the weight. In this implementation, $\alpha(t) \in [0.5, 1.0]$. The higher its value, the more closely the filtered values follow the original values. In this work, $\alpha(t_i)$ is defined as

$$\alpha(t_i) = 1 - 0.5^{\frac{t_i - t_{i-1}}{\beta}}, \quad (5)$$

in which β is a constant value that determines the degree of adaptation to varying values. $\alpha(t)$ is affected by the time of the consecutive value updates to consider lost measurements. Fig. 2 depicts the filtering of a changing load as a function of time using different values for β. Here, samples are taken every 10 ms and the stored values are updated using the filtering.

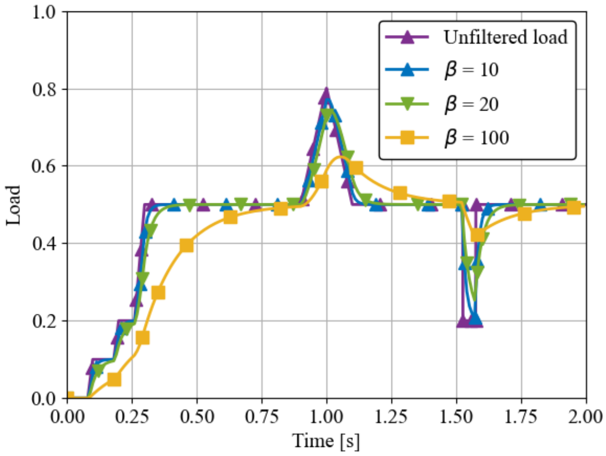

Fig. 2. EWMA filtering of a changing load as a function of time using different values for β.

V. The Traffic Split Algorithm

After the secondary node addition to a user, the decision on how to split the traffic between the MN and SN must be done. In the authors' previous work [10], a traffic split algorithm that is based on data requests was introduced. The SN sends data requests to the MN periodically. The amount of data requested is computed using the Shannon's formula [29]. According to the previous work, the requests are sent per gNB basis, that is, when multiple users have a certain gNB as an SN, the request combines the amount of data for all these users. The amount of data is computed using the available load of the SN and the highest Signal-to-Interference-plus-Noise Ratio (SINR) of the secondary connection users related to the SN. The data requests are illustrated in Fig. 3. It can be noticed that the requests are not sent (the increased time between the third and fourth requests) if there is no capacity to offer to the secondary connection UEs.

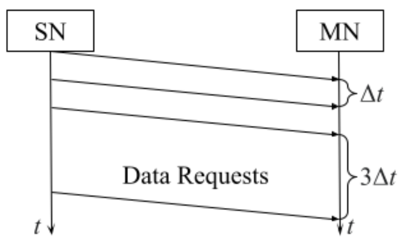

Fig. 3. The data requests illustrated. [10]

In this work, a more granular version of the algorithm is introduced. Instead of sending the requests per gNB basis, they are sent per user basis. The amount of data for a user j is then computed as follows

$$D = \gamma \cdot \frac{1 - L_{i,\text{pr}}}{n_s} \cdot B_{\text{tot}} \cdot \log_2(1 + \text{SINR}_{ij}) \cdot (\Delta t + t_{\text{off}}), \quad (6)$$

in which γ is an attenuation factor used to compensate for implementation losses, that is, the actual application data is less than the transmitted bits. This is, for example, due to the processing of the data in the different layers. TR 38.803 [30] defines 0.6 as the factor for downlink. $L_{i,\text{pr}}$ is the load caused to cell i by the primary connection UEs. n_s is the number of secondary connection UEs connected to the SN. B_{tot} is the total available bandwidth. Practically speaking, the bandwidth that is left from the primary connection UEs, is used in the computation of the data amount to request. SINR_{ij} is the SINR of the UE j related to the cell i. Δt is the data request period. t_{off} is an offset parameter that can be used to request data ahead of time. The previous request is overwritten on the MN side (for the specific connection) when a new one arrives.

VI. Simulations

The 5G (TN-)NTN SLS [31] used in this work has been used extensively in previous R&D efforts. For example, within the European Space Agency (ESA) ALIX project [32] targeting successful standardization of NTN at 3GPP, and now in the DYNASAT [8] project. The simulator is an extension of Network Simulator 3 (ns-3) [33] which is an open-source, discrete-event simulator mainly targeted for research and educational use providing a common C++ framework for developing packet-level simulators of various technologies. ns-3 can be categorized as a Non-Real Time (NRT) network-level system simulator which models the protocols from the Physical (PHY) layer up to the application layer with a quite high level of accuracy. The PHY/link layer performance is abstracted underneath a so-called Link-To-System (L2S) mapper and a set of Modulation & Coding (MODCOD) specific SINR-to-Block Error Rate (BLER) mapping curves. The simulator calculates SINR for each received packet including received power, noise, and co-channel interference, and uses the L2S to convert that into a BLER. To model 5G networks, ns-3 has been extended with 5G LENA [34] which models PHY and Media Access Control (MAC) layers of NR and implements terrestrial propagation and channel models of 3GPP TR 38.901 [35]. 5G LENA implements the channel and NR PHY and MAC protocol layers, algorithms, and procedures, but Radio Link Control (RLC) and PDCP layers are reused from the ns-3 LTE module [36]. 5G LENA focuses only on TN deployment scenarios. To support NTN-specific features, 5G LENA and ns-3 have been extended by adding support for 3GPP TR 38.811 [37] based channel and antenna/beam modeling along with the global coordinate system, and the system-level calibration scenarios presented in TR 38.821 [6]. The ns-3 platform shall also provide the higher protocol layers, that is, network, transport, and application layers. The high-level components of the NTN simulator are presented in Fig. 4.

The system-level calibration scenarios presented in TR 38.821 [7] function as a baseline for satellite scenario deployments and parameterizations. This contains for example different LEO satellite orbits (LEO-600, LEO-1200, GEO), frequency bands (S-, Ka-band), link budget parameterizations (Set-1, Set-2), terminal assumptions (Very Small Aperture Terminal (VSAT), handheld), and frequency reuse patterns (reuse 1, 3 and 2+2). These function as baseline scenarios, but all parameters can be also configured separately. In addition, the hybrid TN and NTN scenarios can be studied,

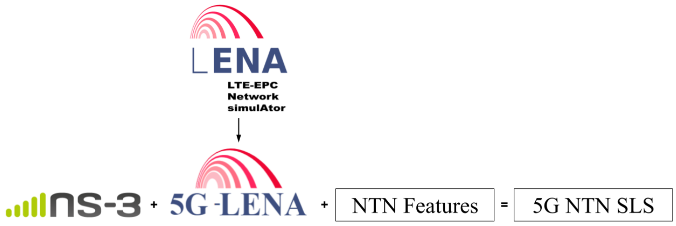

Fig. 4. The high-level components of the 5G NTN SLS. [10]

for example, deployed to the same, adjacent, or completely separated frequency bands. Satellites assume so-called Bessel equation-based beam patterns defined in TR 38.811 [37], in which the beam parameters, beam count, and beam spacing can be configured using different parameters.

The MC modeling to the simulator is implemented following the specifications for MC found in [4]. The process for SN addition is initiated by the MN. MN sends an SN addition request message to a candidate SN. The candidate then replies with an acknowledgment or rejects the request. Then the MN sends a Radio Resource Control (RRC) reconfiguration message to the UE. The UE then does the required configurations to receive data from the SN. After the reconfiguration has been completed, the UE indicates this to the MN which notifies the SN. The simulator architecture (which is adapted from [34]) with MC can be found in Fig. 5.

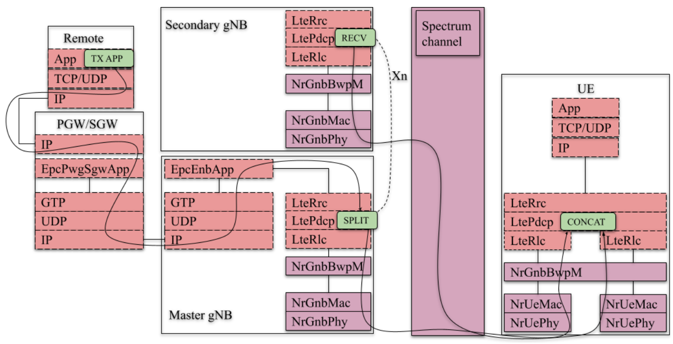

Fig. 5. The 5G NTN SLS architecture with MC. The dashed red blocks present the ns-3 and LENA features. The solid purple boxes are the 5G NR components. The data traversal in the downlink direction is depicted by the arrow. [10]

A. Scenario and Assumptions

The simulation scenario consists of two satellites each with 7 beams. The satellites use different frequency bands, that is, they do not interfere with each other. The two satellites have partially overlapping coverages. The center beam elevation angle for the first satellite is 90 degrees and 60 degrees for the second satellite. Because of the different elevation angles, the beam patterns on earth differ slightly. In the scenario, there are 10 randomly placed UEs in the area of each of the first satellite's beams. At the beginning of the simulations, the UEs perform cell selection to connect to the best cell. One tier of Wraparound (WA) beams (12 beams), each with one full buffer UE, is used for both satellites. The WA beams and UEs are used to introduce interference to the actual system of interest and are not included in the statistics collection. Fig. 6 shows the simulation scenario in one of the simulation runs after cell selection has been completed. The WA beams and UEs are left out of the figure. The red and blue circles depict the beam centers of the first and second satellites. The second satellite is outside the figure. The dashed lines are the connections between the UEs and beams.

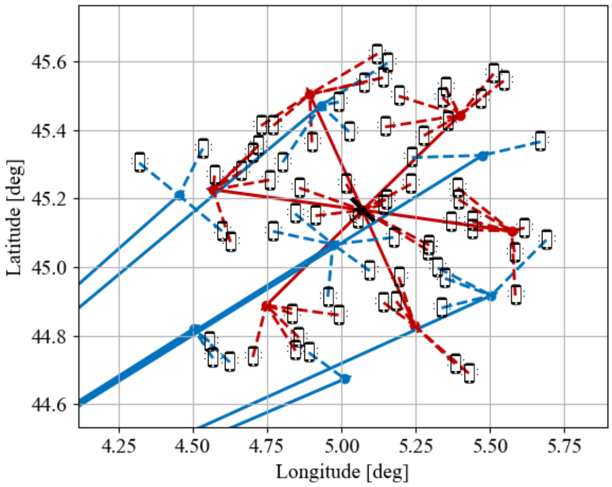

Fig. 6. The simulation scenario in one of the simulation runs after cell selection has been completed.

Due to the short simulation time (2.0 s), the satellites and UEs are considered stationary. In this work, SN release is not considered. Dynamic NLOS channel condition is utilized in which satellites might not be visible to the UEs, for example, due to buildings or trees. The simulations are run in a so-called quasi-static manner which in this case means that the simulations are run for a short time letting the system stabilize. Stabilizing the system in the MC case means, for example, letting all the secondary connections be formed. Because the users only connect to satellites that are LOS, fast fading is considered negligible, and thus it is disabled. This rationale for the choice of the simulation parameters makes the effect of MC, and the related algorithms, easier to analyze. Research regarding scenarios with more dynamicity is left for future work.

Simulations with the adaptive and standard (which refers to the SN addition algorithm that uses simply an RSRP threshold for SN addition) SN addition and traffic split algorithm combinations are each run with four different RSRP thresholds for SN addition. For the data split between the MN and the SN, three different cases are considered. Namely, these are even split, data request per gNB and data request per connection. In the case of an even split for every UE that has an SN, the MN sends half of the data for the corresponding SN to send to the UE. Half of the data, the MN sends to the UE itself. The data request-based solutions are described in section V.

The different RSRP thresholds considered are -156, -111, -110 and -109 dBm. If only the RSRP threshold for SN addition was considered these values would mean turning on MC for approximately 100%, 69%, 36%, and 9% of the UEs in the considered simulation scenario (the values were obtained by running simulations), respectively. As stated in (2), the RSRP values below -156 dBm are mapped to the same reported value. In consequence, -156 dBm is the lowest meaningful value that can be used as a threshold value. In the simulations, a gNB is considered too loaded for secondary connections with a load over 90% (that is, when $l_k > 0.9$). A UE is considered to need an SN if the transmission buffer of the current serving node towards the UE is at least 80% occupied.

The parameters t_{req} and t_{add} are chosen large enough (25 ms) so that the gNBs have some time to adapt to recently added secondary connections before adding new ones. The values ($o_{\text{ij,Tx}}$ and l_k) updated using the EWMA filtering are updated every 10 ms to reduce excess computations. The parameter β used in the filtering is chosen empirically. The RSRP measurement report interval (and the measurements' validity) is chosen small enough so that the SN addition decisions can be made fast enough when a need arises but also large enough so that no excess overhead is caused by the reporting activities.

Each simulation is run with five different Random Number Generator (RNG) seeds to introduce random variation, for example, to UEs' locations, and the results are then combined. In the simulations, downlink is considered, and the traffic is Constant Bit Rate (CBR) with User Datagram Protocol (UDP). For simplicity, the UEs can only have a single secondary connection. With more secondary connections, the bottom conclusions should hold. The most important simulation parameters are found in Table I.

B. Results

Fig. 7 shows the percentage of UEs with an SN for the standard and adaptive SN addition and different traffic split algorithm combinations. It can be observed that when the RSRP threshold for SN addition is lowered, the standard algorithm keeps adding secondary connections. For the adaptive algorithm, the addition count is limited due to the candidate SNs' load conditions and the UEs' need for SN addition. The difference caused to this statistic by the different traffic split algorithms is negligible. Though, minor differences can be observed when the adaptive SN addition is used. This is caused by the different load conditions caused by the different traffic split algorithms.

The effect of the RSRP thresholds on the average per user throughputs is captured in Fig. 8. Activating MC with any of the algorithm combinations enhances the throughputs compared to when MC is turned off. The adaptive SN addition algorithm performs better in all the considered cases than the standard SN addition algorithm when the even split is considered. The largest throughput enhancement for all of the algorithm combinations compared to when MC is turned off is experienced when the RSRP threshold is -111 dBm. For the standard SN addition algorithm, when the traffic is split evenly, data is requested per gNB, and data is requested per connection, the average per user throughput is respectively 1600 kbit/s, 1672 kbit/s, and 1675 kbit/s. For the adaptive SN addition algorithm, the corresponding values are 1655 kbit/s,

TABLE I
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 [6, Table 6.1.1.1-1]
UE Antenna Type	Handheld
Traffic	CBR
Communication Protocol	UDP
UDP Packet Size	400 bytes
UDP Packet Interval per UE	1 ms
Atmospheric Absorption	Enabled
HARQ	Enabled
Scintillation	Enabled
Fast Fading	Disabled
Shadowing	Enabled
SN Addition RSRP Threshold	-156, -111, -110, -109 dBm
L_{th}	0.9
O_{th}	0.8
t_{req}	25 ms
t_{add}	25 ms
Scheduler	Round Robin (primary connection users prioritized)
β	20
$o_{\text{ij,Tx}}$ update interval	10 ms
l_k update interval	10 ms
RSRP measurement report interval	120 ms
RSRP validity time	120 ms
Data Request Period (Δt)	25 ms
Data Request Period Offset (t_{off})	25 ms
RNG Runs	5

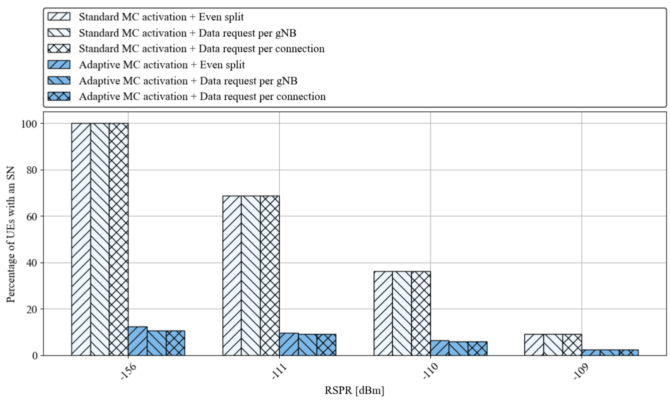

Fig. 7. Percentage of UEs with an SN with the different SN addition and traffic split algorithm combinations.

1681 kbit/s, and 1686 kbit/s. The offered average per user throughput is 1535 kbit/s when MC is turned off.

When the RSRP threshold is lowered to the extreme (-156 dBm), the throughputs suffer in the case of all the algorithm combinations. This is because the SN additions are performed to UEs with poor signal strengths to their SNs. At the lowest RSRP threshold, the throughputs are better when using the data request algorithm in combination with the standard SN addition algorithm when compared to using them with the adaptive algorithm. This may be explained due to the fact that with the standard SN addition, every UE gets a secondary connection. With the adaptive SN addition, the number of UEs with a secondary connection is limited. Furthermore, because the signal strength criterion is in practice ignored, the users with weak signal strengths (to candidate secondary nodes) may get a secondary connection. In the case of the adaptive SN addition, these users possibly block the users with better signal strengths from forming a secondary connection. When the RSRP threshold is the highest considered, the throughputs for the data request algorithms with the combination of the different SN addition algorithms are approximately the same. This is explained by the small number of users with secondary connections.

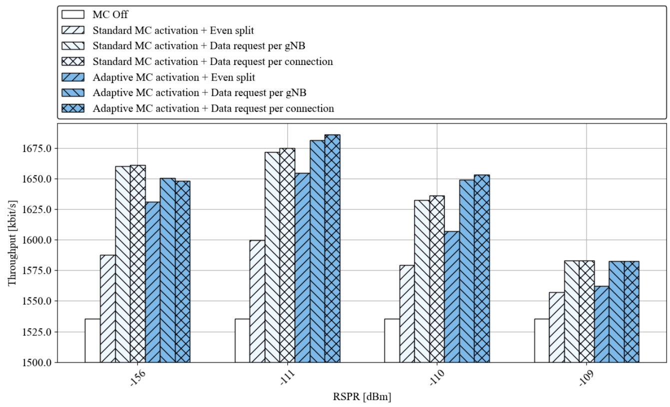

Fig. 8. Average per user throughputs for the different SN addition RSRP thresholds with the different SN addition and traffic split algorithm combinations.

Fig. 9. shows the effect of using different βs with the EWMA filtering for the load and Tx buffer size values (see Section IV) on the average per user throughputs when the RSRP threshold for SN addition is -111 dBm. It can be seen that in this setting, by choosing $\beta = 15$, instead of the initial $\beta = 20$, the throughputs can be even further improved when using the adaptive SN addition with the data request algorithms. The average user throughputs are 1689 kbit/s with the combination of the adaptive SN addition and per gNB and per UE data request algorithms.

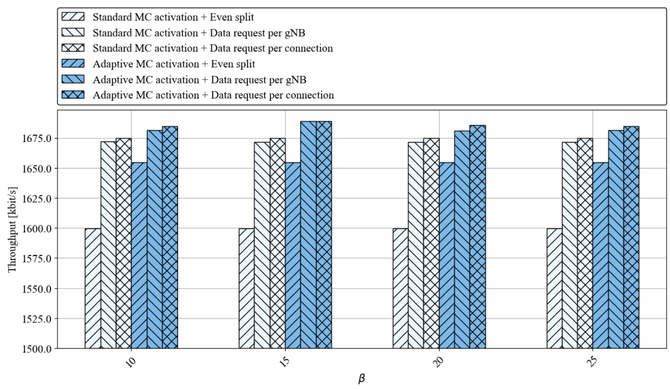

Fig. 9. Effect of using different βs with the EWMA filtering for the load and Tx buffer size values on the average per user throughputs when the RSRP threshold for SN addition is -111 dBm.

C. Summary

When using the adaptive SN addition algorithm with the combination of the even split traffic split algorithm, the average user throughputs were enhanced in all the cases when compared to using the standard SN addition logic or not activating MC at all. When using smarter traffic split, that is, the data request-based split, the differences between using the standard and adaptive SN addition algorithms were diminished (as was anticipated in [9]). Though, there was still a benefit of using the adaptive SN addition. With the lowest RSRP threshold considered, using the standard algorithm with the data request algorithms performed slightly better than using the data request algorithms with the adaptive SN addition. This may be explained by more diverse opportunities to split the traffic, that is, there are more UEs with secondary connections.

VII. Conclusions and Future Work

In this paper, MC in NTNs was discussed. NR, the air interface of 5G, has specifications to operate both, in the TN and NTN environment. This allows the actors in the satellite and TN industry to cooperate more seamlessly. A satellite component in 5G can be seen to complement the TNs, instead of competing with them. An NTN component can help provide resources to, for example, remote areas. MC has already been specified by 3GPP in the TN environment. Specification activities for NTNs to support MC are to be done in the future.

An adaptive load-aware, per need basis SN addition algorithm for MC in NTNs was presented. The significance of the algorithm is its simplicity and efficiency which offers a standard solution to a complex problem. Furthermore, the algorithm was used in combination with per gNB and per UE data request traffic split algorithms. In the simulated scenario, the maximum average per user throughput gain that was reached with the developed algorithms, compared to when MC was turned off, was from 1535 kbit/s to 1689 kbit/s, (9.1%). Comparing the developed algorithms to the standard algorithms (that is, the MC activation criterion is based on the signal strength and the data is split evenly), the maximum gain was from 1600 kbit/s to 1689 kbit/s (5.3%).

In the future, more research activity related to MC in NTNs is required. For example, MC in TN/NTN co-existence needs to be studied in terms of interference mitigation and dynamic spectrum allocation between the networks. Larger and more dynamic scenarios should also be addressed. These could include, for example, different traffic requirements, movement of the satellites and UEs, and SN release. The requirements for the UE need to be taken into consideration. These include, for example, the hardware requirements, especially for multiple SN additions per UE, and the effect of delay spread. Furthermore, Machine Learning (ML) is an appealing option to be applied to the MC setting in NTNs. It could be applied, for example, to the SN addition or traffic split problem. Also, reliability and latency enhancements with the aid of MC should be considered since URLLC is of vital importance in 5G.

References

[1] "Ericsson Mobility Report," Ericsson, June 2022.

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

[3] J.-P. Darnis, "Space as a Key Element of Europe's Digital Sovereignty," Notes de l'Ifri, Ifri, Dec. 2020.

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

[5] "3GPP," accessed on: June 3, 2022. [Online]. Available: https://www.3gpp.org/.

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

[7] X. Lin, "An Overview of 5G Advanced Evolution in 3GPP Release 18," *IEEE Communications Standards Magazine*, vol. 6, no. 3, pp. 77–83, 2022, doi:10.1109/MCOMSTD.0001.2200001.

[8] "About DYNASAT," accessed on: June 13, 2022. [Online]. Available: https://www.dynasat.eu/about-dynasat/.

[9] M. Majamaa, H. Martikainen, L. Sormunen, and J. Puttonen, "Adaptive Multi-Connectivity Activation for Throughput Enhancement in 5G and Beyond Non-Terrestrial Networks," *2022 International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, 2022.

[10] M. Majamaa, H. Martikainen, L. Sormunen, and J. Puttonen, "Multi-Connectivity for User Throughput Enhancement in 5G Non-Terrestrial Networks," *2022 18th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2022.

[11] F. Rinaldi, H.-L. Maattanen, J. Torsner, S. Pizzi, S. Andreev, A. Iera, Y. Koucheryavy, and G. Araniti, "Non-Terrestrial Networks in 5G & Beyond: A Survey," *IEEE Access*, vol. 8, pp. 165 178–165 200, 2020, doi: 10.1109/ACCESS.2020.3022981.

[12] X. Lin, S. Rommer, S. Euler, E. A. Yavuz, and R. S. Karlsson, "5G from Space: An Overview of 3GPP Non-Terrestrial Networks," *IEEE Communications Standards Magazine*, vol. 5, no. 4, pp. 147–153, 2021, doi: 10.1109/MCOMSTD.011.2100038.

[13] A. Guidotti, A. Vanelli-Coralli, A. Mengali, and S. Cioni, "Non-Terrestrial Networks: Link Budget Analysis," in *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, 2020, pp. 1–7, doi: 10.1109/ICC40277.2020.9149179.

[14] E. Juan, M. Lauridsen, J. Wigard, and P. E. Mogensen, "5G New Radio Mobility Performance in LEO-based Non-Terrestrial Networks," in *2020 IEEE Globecom Workshops (GC Wkshps*, 2020, pp. 1–6, doi: 10.1109/GCWkshps50303.2020.9367419.

[15] E. Juan, M. Lauridsen, J. Wigard, and P. Mogensen, "Handover Solutions for 5G Low-Earth Orbit Satellite Networks," *IEEE Access*, vol. 10, pp. 93 309–93 325, 2022, doi: 10.1109/ACCESS.2022.3203189.

[16] Y. I. Demir, M. S. J. Solaija, and H. Arslan, "On the Performance of Handover Mechanisms for Non-Terrestrial Networks," in *2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring)*, 2022, pp. 1–5, doi: 10.1109/VTC2022-Spring54318.2022.9860505.

[17] C. Pupiales, D. Laselva, Q. De Coninck, A. Jain, and I. Demirkol, "Multi-Connectivity in Mobile Networks: Challenges and Benefits," *IEEE Communications Magazine*, vol. 59, no. 11, pp. 116–122, 2021, doi: 10.1109/MCOM.111.2100049.

[18] M.-T. Suer, C. Thein, H. Tchouankem, and L. Wolf, "Multi-Connectivity as an Enabler for Reliable Low Latency Communications—An Overview," *IEEE Communications Surveys Tutorials*, vol. 22, no. 1, pp. 156–169, 2020, doi: 10.1109/COMST.2019.2949750.

[19] T. Sylla, L. Mendiboure, S. Maaloul, H. Aniss, M. A. Chalouf, and S. Delbruel, "Multi-Connectivity for 5G Networks and Beyond: A Survey," *Sensors*, vol. 22, no. 19, 2022, doi: 10.3390/s22197591.

[20] 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, doi: 10.1109/ISWCS.2018.8491093.

[21] 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, doi: 10.1109/ISWCS.2019.8877325.

[22] 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, doi: 10.1109/JSAC.2017.2720338.

[23] 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, doi: 10.1109/VTCSpring.2015.7145881.

[24] 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, doi: 10.1109/GLOCOMW.2018.8644234.

[25] "5G ALLSTAR," accessed on: June 13, 2022. [Online]. Available: https://5g-allstar.eu/.

[26] 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, doi: 10.1016/j.jfranklin.2021.09.025.

[27] "TS 38.215: 5G; NR; Physical layer measurements," V16.2.0, July 2020.

[28] "TR 38.133: 5G; NR; Requirements for support of radio resource management," V15.3.0, Oct. 2018.

[29] C. E. Shannon, "A mathematical theory of communication," *The Bell System Technical Journal*, vol. 27, no. 3, pp. 379–423, 1948, doi: 10.1002/j.1538-7305.1948.tb01338.x.

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

[31] 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, doi: 10.1109/WoWMoM51794.2021.00054.

[32] "ESA AO 8985," accessed on: Oct 18, 2022. [Online]. Available: https://artes.esa.int/projects/alix.

[33] 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, doi: 10.1007/978-3-642-12331-3_2.

[34] N. Patriciello, S. Lagén, B. Bojović, and L. Giupponi, "An E2E simulator for 5G NR networks," *Simulation Modelling Practice and Theory*, vol. 96, 2019, doi: 10.1016/j.simpat.2019.101933.

[35] "TR 38.901: Study on channel model for frequencies from 0.5 to 100 GHz," V17.0.1, March 2022.

[36] 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*, ser. MSWiM '11. New York, NY, USA: Association for Computing Machinery, 2011, p. 293–298, doi: 10.1145/2068897.2068948.

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

Mikko Majamaa received his B.Sc. and M.Sc. degrees from LUT University (Lappeenranta, Finland) in 2020 and 2022, respectively. In both, his B.Sc. and M.Sc. studies, his program was computational engineering with a major in applied mathematics. Majamaa has been working at Magister Solutions Ltd since the beginning of 2020 participating in R&D activities in satellite communication research projects. He is also a Ph.D. candidate at the University of Jyväskylä. His research areas include, but are not limited to, resource management, bandwidth-efficient techniques, and usage of ML in NTNs-based communications.

Henrik Martikainen is a Senior Researcher at Magister Solutions. He received his M.Sc. and Ph.D. degrees from the University of Jyväskylä in 2006 and 2012, respectively. From 2006 to 2010 he was a researcher at the University of Jyväskylä doing system-level WiMAX simulation research work in an industry-led research project. Martikainen joined Magister Solutions in 2010 as a senior researcher and since then he has been working on system-level simulation research projects. The topics he has worked on include LTE-A and 5G cell and beam mobility procedures, uplink power optimizations, and lately various resource utilization optimizations for 5G NTN. His expertise includes defining, implementing, and analyzing complicated system-level simulations using self-optimizing approaches.

Lauri Sormunen received his M.Sc. in mathematics and information technology from the University of Jyväskylä in 2016. Since joining Magister Solutions as a researcher in 2015, he has developed various LTE, 5G, and SatCom simulators and authored multiple satellite industry-oriented technology articles. His special expertise includes mathematical modeling, channel models, co-existence, and performance analysis of wireless networks and lately 5G NTN. He currently works as a Senior Researcher for Magister Solutions and is a Ph.D. student at the University of Jyväskylä.

Jani Puttonen received his M.Sc. and Ph.D. degrees from University of Jyväskylä in 2003 and 2006, respectively. Years 2006-2021, he worked at Magister Solutions as Senior Research Scientist and Principal Scientist with a focus on network-level simulations, performance analysis and development of radio resource management algorithms for both mobile and SatCom networks. In 2020, he took a position of Director of Simulation Services leading and managing the R&D and simulation projects of Magister as well as being commercially responsible for the Magister SimLab simulation service. Currently, from January 2022 onwards, he has been working as the acting CEO of Magister Solutions. He has published over 50 articles in international journals and conferences and has been the inventor of several patents in the area of wireless communications.