Adaptive Multi-Connectivity Activation for Throughput Enhancement in 5G and Beyond Non-Terrestrial Networks

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***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 of such techniques. In MC, a User Equipment (UE), for example, a smartphone, can be connected to multiple Next Generation Node Bs (gNBs). In this paper, we present an adaptive MC activation scheme for throughput enhancement in 5G and beyond Non-Terrestrial Networks (NTNs).**

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

I. Introduction

According to the Ericsson's mobility report from 2021 [1], mobile networks carry 300 times more data than in 2011 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 may play a key role to meet these requirements since they can offer resources to remote areas where building TNs can be practically impossible. Satellites can also provide load balancing to highly loaded TNs, e.g., 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, 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 5G communications aim to offer, the use of bandwidth-efficient transmission techniques, is required. MC [4] is such a technique. It can be used to improve reliability, latency, and throughput in the transmissions. In MC, a UE (e.g., a smartphone) can be connected to multiple gNBs simultaneously. One of the gNBs acts as a Master Node (MN) and others as Secondary Nodes (SNs).

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, e.g., by improving coverage for handheld terminals and addressing mobility and service continuity between NTNs and TNs [5]. 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) [6] 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).

Regarding related work, the 5G ALLSTAR [7] project's goal was to facilitate the integration of satellite component to 5G. They provide mathematical formulations of multiple load balancing algorithms in [8]. The authors in [9] provide a comprehensive survey of NTN specification activities. [10] reviews Handover (HO) mechanisms in NTNs. The mechanisms include, e.g., evaluation of the users' locations relative to satellites and signal strengths. Same mechanisms may be used when evaluating SN addition. The following references consider SN addition in the TN case since the problem is not well researched in the NTN environment. A scenario where a UE can be connected to a macro and a small cell is considered in [11]. SN addition is based on Reference Signal Received Power (RSRP) measurements. In [12], 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 [13], SN addition is triggered based on Sounding Reference Signal (SRS) measurements.

The main contribution of this paper is to introduce a load-aware, per-need activated SN addition algorithm for throughput enhancement in 5G NTNs which is evaluated by simulations in a scenario consisting of two LEO satellites.

The rest of the paper is organized as follows. In section

II, system aspects related to MC in NTNs are elaborated. In section III, the SN addition algorithm is presented. Simulations evaluating the algorithm are detailed in section IV. Conclusions and future work are considered in section V.

II. 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 (e.g., SN addition) signaling, and data forwarding (e.g., 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 [14]. 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 [4], but in the figure, only the MN hosts an SDAP. The altitudes of LEO satellites can be 250-2000 km [15]. 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, e.g., 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.

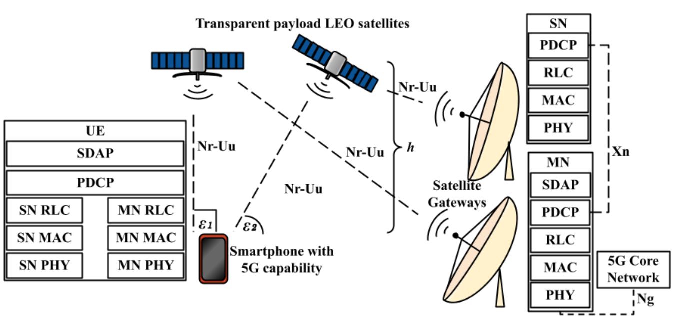

Fig. 1. MC illustration in NTN environment.

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 [16]. The gNBs transmit these signals and the UEs perform Layer 1 (L1) measurements. L1 measurements are useful to perform actions that require small delays, e.g., beam management procedures. Layer 3 (L3), i.e., RRC layer measurements are formed from the L1 measurements by filtering the measured values using L3 filtering. L3 measurements can be used, e.g., 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). The L3 measurements are mapped to reported values as defined in [17]:

$$r = \lfloor \min(\max(\lfloor R + 157 \rfloor, 0), 127) \rfloor, \tag{1}$$

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

III. 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 [12] elaborate, that using only an RSRP threshold to activate SN addition is a standard policy. In our MC activation scheme, we take into account multiple factors that can be used to enhance the per UE and per system throughputs. 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, i.e., 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 t_{add} parameter 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 is defined as the used data Resource Blocks (RBs) in a transmission slot divided by the available data RBs in the transmission slot.

Algorithm 1 presents the SN addition algorithm. The gNB i's transmission buffer occupancy (O^{ij}_{Tx}) towards the UE j is filtered every t_{update} using Exponential Weighted Moving Average (EWMA) and the value (o^{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^{ij}_{Tx} is the last time when o^{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 $\mathfrak{S}$ updated accordingly. Finding the best candidate SN k means finding the candidate SN with the highest RSRP for the UE where 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 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 ACK, and the UE can have the candidate as an SN. t and t^k_{last} refer to the current time and time when the last secondary connection was added to the candidate node k.

Algorithm 1: Secondary Node Addition Algorithm

for *every* O_{Tx}^{ij} *change* **do**
  if *the UE j is in single-connectivity state* **then**
    if $t - t_{\text{Tx}}^{ij} < t_{\text{update}}$ **then**
      continue ;
    Update o_{Tx}^{ij} ;
    if $o_{\text{Tx}}^{ij} < O_{\text{th}}$ **then**
      continue ;
    Remove the outdated RSRP measurements and update the set $\mathfrak{S}$ accordingly ;
    Find the best available SN k from the set $\mathfrak{S}$ 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 *found* **then**
      Send SN addition request to k ;
      /* At the candidate node k: */
      if $l^k \leq L_{th}$ *and* $t - t_{\text{last}}^k > t_{\text{add}}$ **then**
        Acknowledge the SN addition
      else
        Reject the SN addition
      /* At the candidate node k ^^ */
      Perform the needed configurations ;
end

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

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

where m_{filt}^t is the filtered value at time t, m_{filt}^{t-1} is the last filtered value, m_{meas}^t is the measured value and α^t is the weight. In our implementation, $\alpha^t \in [0.5, 1.0]$. The higher its value, the more closely the filtered values follow the original values. We define α^t as:

$$\alpha^t = 1 - 0.5^{\frac{t_i - t_{i-1}}{\beta}},$$

where β is a constant value that determines the degree of adaptation to varying values. α^t is affected by the time of the consecutive value updates to consider lost measurements.

IV. Simulations

Network Simulator 3 (ns-3) [18] is a packet-level simulator used, e.g., in the research of Internet systems. Users may add modules to the simulator. 5G LENA [19] is one of such modules that is used to simulate 5G capabilities. In this work, the simulations are run with a 5G NTN System Level Simulator (SLS) [20]. It is a realistic SLS that is used in specification and R&D activities. It is an extension with NTN capabilities to the 5G LENA module. For example, the SLS includes Radio Resource Management (RRM) enhancements, modeling of movement of satellites, a dynamic propagation model, as well as an NTN channel model defined in 3GPP Technical Report (TR) 38.811 [21]. MC modeling to the simulator is implemented following the specifications for MC found in [4].

A. Scenario and Assumptions

The simulation scenario consists of two satellites each with 7 beams. The satellites use different frequency bands, i.e., 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 of the 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. 2 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 satellite. The second satellite is outside the figure. The dashed lines are the connections between the UEs and beams.

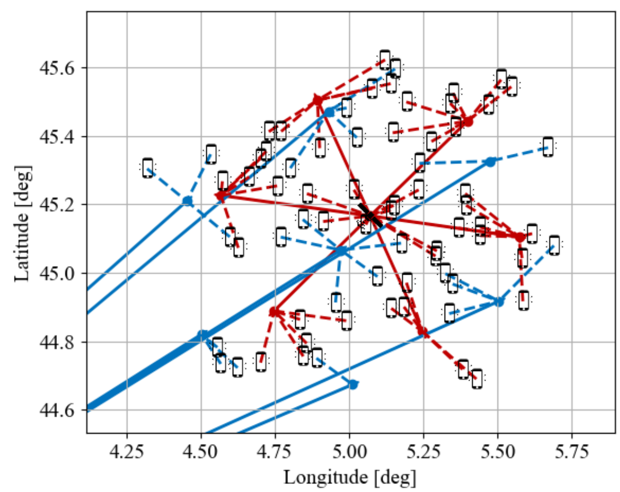

Fig. 2. The simulation scenario in one of the simulation runs after cell selection has been completed.

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 where satellites might not be visible to the UEs, e.g., due to buildings or trees. Simulations with the adaptive and simple (which refers to the SN addition algorithm that uses simply an RSRP threshold for SN addition) SN addition algorithms are each run with four different RSRP thresholds for SN addition. Namely, -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 10%, 35%, 66%, and 100% of the UEs in the considered simulation scenario (the values were obtained by running simulations). As stated in (1), 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, we consider the gNB too loaded for secondary connections with 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^{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.

For the data split between the MN and the SN, an even split is performed, i.e., for every UE that has an SN, the MN sends half of the data for the corresponding SN to send to the UE. Each simulation is run with five different Random Number Generator (RNG) seeds to introduce random variation, e.g., 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.

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, Table 6.1.1.1-1 [14]
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	-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^{ij}_{Tx} & l^k update interval	10 ms
RSRP measurement report interval	120 ms
RSRP validity time	120 ms
RNG Runs	5

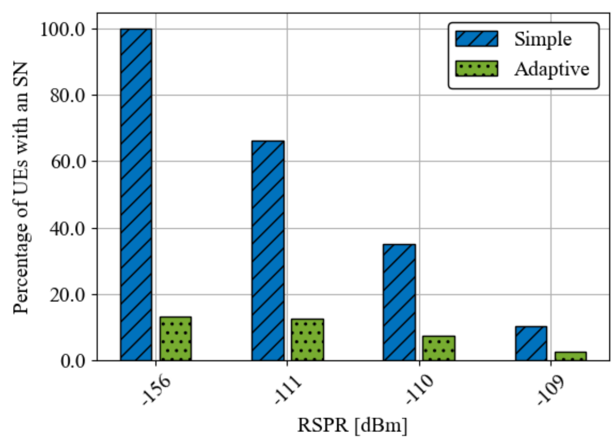

Fig. 3. Percentage of UEs with an SN for the different RSRP thresholds for SN addition.

B. Results

Fig. 3 shows the percentage of UEs with an SN for the simple and adaptive SN addition algorithms. It can be observed that when the RSRP threshold for SN addition is lowered, the simple 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 effect of the RSRP thresholds on the average per-user throughputs is captured in Fig. 4. Activating MC with either of the algorithms enhances the throughputs compared to when MC is turned off. The adaptive algorithm performs better in all the considered cases than the simple algorithm. The largest throughput enhancement for both algorithms compared to when MC is turned off is experienced when the RSRP threshold is -111 dBm. The simple algorithm offers on average 1597 kbps per user throughput, whereas the adaptive algorithm offers 1671 kbps. The offered throughput is 1538 kbps when MC is turned off. The adaptive algorithm performs 8.6% and 4.6% better compared to MC turned off and SN addition based on the simple algorithm in terms of offered average throughput per user, respectively. When the RSRP threshold is lowered to the extreme (-156 dBm), the throughputs suffer in the case of both SN addition algorithms. This is since the SN additions are performed to UEs with poor signal strengths to their SNs.

C. Summary

The developed SN addition algorithm performed better in terms of average throughput offered to the users in all the cases considered than the simple threshold-based SN addition logic and when MC was turned off. From the simulations, it was observed that even though the adaptive SN addition algorithm limits the SN addition count in all the RSRP thresholds considered, a too low RSRP threshold affects the throughputs

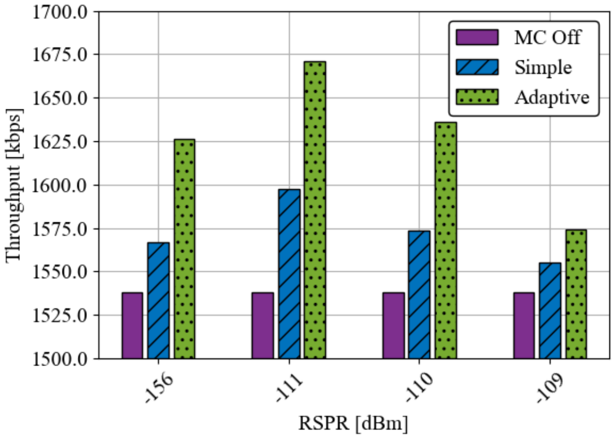

Fig. 4. Effect of the RSRP thresholds for SN addition on the average per-user throughputs.

negatively. In practice, this means that SN additions are performed between UEs and SNs with signal strength lower than the system noise. In reality, the system noise is known and the RSRP threshold should be at a minimum this value. Also, a connection between the UEs and nodes with the highest signal strength could be preferred which would lead to enhancement in the total system throughput.

Another way to enhance the system performance would be to use a more advanced traffic steering algorithm than the simple split one. Even if using smarter traffic splitting mechanisms, the use of only the RSRP threshold in the SN addition might lead to the addition of weak secondary connections leading to signaling overhead and other exhaustion of resources, both at the UE and gNB side.

V. Conclusions and Future Work

In this paper, we have discussed MC in NTNs. 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 co-operate 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, e.g., 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. We have presented an adaptive load-aware, per-need basis SN addition algorithm for MC in NTNs. The significance of the algorithm is its simplicity and efficiency which offers a simple solution to a complex problem. In the simulated scenario, it performed 4.6% better in terms of offered average per-user throughput than an SN addition algorithm that only considers the signal's strength.

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. More larger and more dynamic scenarios should also be addressed. These could include, e.g., different traffic requirements, movement of the satellites and UEs, and SN release.

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