INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2024, VOL. 70, NO. 4, PP. 923-933
Manuscript received June 17, 2024; revised October 2024. doi: 10.24425/ijet.2024.152079

Further mobility enhancements for 5G-advanced and beyond

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***Abstract*—The study on mobility is an inherent part of any generation of cellular technology. It is aimed at ensuring robust, reliable, and interruption-free handover of the mobile user connection. Such continuous improvement is necessary as the service requirements become more stringent which urge the mobility to meet the highest performance expectations. In this paper, it is described how such requirements are to be achieved by the 3GPP Release 18 components. It begins with the introduction to the world of mobility, covering the solutions that have been designed since the first generation of New Radio (NR). Then improvements pursued in consecutive 3GPP releases are outlined. Selected areas for Release 18 mobility enhancements have been evaluated using 5G-compliant system-level simulations and results thereof are presented below. These include wrong Primary Secondary Cell (PSCell) preparation in Conditional Handover (CHO) and the impacts of secondary cell setup delay in Dual Connectivity (DC). It is shown that preparing multiple PSCells in CHO ensures the user accesses the right cell in up to 96% of cases.**

***Keywords*—handover; mobility; 3GPP; 5G**

I. Introduction

ANOTHER generation of cellular standard has been frozen in June 2022 – 3GPP Release 17. This has been a symbolic milestone, indicating the beginning of next 5G era, namely the work towards 5G-Advanced, which shall continue the evolution of New Radio (NR). Immediately after finalizing one group of functionalities, 3GPP begins the work on the solutions to become a part of subsequent Release 18 with the aim to address even more challenging use cases. Specifications are frozen every 18 to 24 months, bringing to the market next set of crucial technology enablers in cellular domain.

One of such essential areas in wireless communications is to ensure that the connectivity between user equipment (UEs) and the network is sustained. Without supporting mobility, the gains of wireless communications are dramatically reduced as the UE is not able to experience a seamless transfer of the ongoing data connection while being in motion.

As noted in [1], the first patent concerning the handover (HO) in cellular networks [2] is already more than 50 years old and dates back to 1970. The author of [2] has pertinently defined that the main goal of mobility is to "maintain continuity of communication paths to mobile stations", which has become rather obvious to the contemporary cellular network users, operators, and designers: whenever the UE is at the cell border, it has to be handed over to the new cell without impacting the UE's connectivity. Otherwise, if the handover is not executed on time, the link with the network may be lost and the user's data connection will be interrupted.

The research and publication work on mobility has gained momentum in 1990s with the advent of personal communications services (PCS) and the standardization efforts on Global System for Mobile Communications (GSM). In [3] key questions were raised concerning the entity that shall initiate the handover and the trigger determining the need for handover. The same authors have analyzed in [4] the importance of overlay area between the cell's coverage and investigated the benefits of soft handoff. The introduction of packet-switched communications and smartphones has changed the type of service that needs to be handed over – data has become more important than voice. It has also brought new cellular deployments to be studied, such as mobility performance in heterogeneous networks (HetNet) [5].

Coordinating mobility in cellular network is not a trivial task, considering the number and different speed of UEs, their continuous movement, high service requirements and the need to maintain those services irrespective of the cell serving the UE. Thus, a proper mobility management for both Connected and Idle mode UEs is essential in each generation of mobile network technology. Similar observations, specifically for 5G, have been made in [6], wherein a comprehensive list of mobility challenges and potential solutions are provided.

There are two main approaches to mobility management in cellular networks, namely network-controlled and UE-autonomous. The former represents a more widespread model, where the UE is instructed by the base station (BS) to perform mobility actions, such as cell change. This is usually preceded by the UE measuring the neighbor cells' received signal power and reporting those measurements to the BS. On this basis, the network prepares a HO when such step is desirable and then initiates the UE's HO to the target cell. Another possibility is to transfer the HO decision, along with the configurations of the target cell that are needed during HO, to the UE. This eventually enables UE-autonomous mobility. In such case, there is no reporting and awaiting the network's response (e.g., in the form of a HO command). Instead, the user can trigger certain mobility actions directly after performing and analyzing the aforementioned measurements. Conditional Handover (CHO)

This work was supported by Grant no. POIR.01.01.01-00-1282/19-01. by The National Centre for Research and Development (NCBR).

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described and evaluated, e.g., in [7][8], relies on a similar principle – UE executes the handover when a condition, configured by the serving BS, is met. Additional step towards larger reduction of network's engagement is to leave even more autonomy to the UE by switching the well-established downlink (DL)-based mobility paradigm to uplink (UL)-dependent mobility. As described in [9], the mobility management at least in Ultra-Dense Networks (UDNs) can be ensured by user's UL transmission of narrowband beacons. The network is expected to track those signals, assigned individually to numerous UEs in the defined region, e.g., in a cell coverage or wider area. A key aspect in this concept is how to track each UE if it traverses over long distance and how to propagate this information efficiently within the network. Thus, these significant challenges would have to be resolved before UL-dependent mobility can become adopted by cellular standards and widely used in real deployments.

Handovers may be also classified according to the degree of connectivity. Soft handover or make-before-break is a type of mobility wherein the radio link towards the target cell is established prior to the release of source cell connectivity. On the contrary, hard handover or break-before-make implies the release of source link before obtaining a connectivity with the target cell. Another criterion which could be considered is whether the handover involves changing the frequency at which UE operates (i.e. inter-frequency or intra-frequency handover). Source and target cells may also originate from the same or different BSs. In this case the terms intra-BS and inter-BS are used, respectively.

Mobility performance is mainly assessed by monitoring the radio link failures and measuring interruption time the UE encounters. Resilience to link failures, also known as robustness, and interruption time need to be optimized to ensure HOs are seamless and do not impact user's Quality of Service (QoS). [10] indicates link failures are especially problematic in North America's downtown areas where even every fifth HO may be unsuccessful. [11] proves that the number handover failures is increased for vehicular users in HetNets. The failure may occur either when the UE is still connected to the source BS (i.e., before HO execution), or when the UE is unable to complete the access to target BS (e.g., failure during Random Access attempt). As upon link failure the UE is required to perform a re-establishment procedure to connect to a selected suitable cell, avoiding mobility failures is of utmost importance in mobile networks. Otherwise, the re-establishment requires non-negligible time and negatively impacts the achievable user data rates.

Mobility performance and failure avoidance can be achieved using various approaches, e.g. taking real-time actions or post-processing the collected statistics. For the latter, one solution, widely implemented in mobile networks, is to rely on Self-Organizing Network (SON) algorithms. [12] studied how to adapt key mobility parameters in an automated manner in reaction to changing network performance. [13] identifies that key mobility parameters to continuously optimize using SON are time to trigger (TTT) and hysteresis. The authors of [14] go beyond basic mobility parameter optimization and propose to involve UE's movement patterns and location in the process of minimizing the cost of handover.

Mobility interruption is the time during which the user data transmission/reception is not possible because of the ongoing cell change procedure. [15] provides a detailed analysis of the handover interruption components. The study was conducted for LTE, but most of the values and findings are applicable to NR as well. [16] expected the mobility interruption values for NR HO will not exceed 5 – 10 ms. The authors of [17] describe how this interruption can be reduced to zero when make-before-break type of handover is applied jointly with selective data forwarding. Nevertheless, for baseline NR handover, specified in 3GPP Release 15 and explained in section II, the mobility interruption typically reaches tens of milliseconds. In case of a mobility failure, the UE experiences also an interruption which is even higher - in the order of hundreds of milliseconds. The lower is the duration of such interruptions, the better is the overall user's QoS experience. There are services with critical requirements regarding the tolerable interruption time, e.g., Augmented Reality (AR) or Ultra-Reliable Low-Latency Communications (URLLC), the latter being essential to implement functionalities such as automated driving. [18] provides a broad analysis of the complexities and tradeoffs of URLLC design, including user mobility. Overall, it can be concluded that minimizing the interruption while maintaining high reliability is a desirable performance goal each mobility solution shall attempt to ensure.

As can be seen from the aforementioned mobility principles and history, this is a broad and appealing topic, for both industry and research communities. It shall come as no surprise, considering how vital role the mobility plays in cellular networks. With the plethora of various mobility solutions and enhancements, each 3GPP NR release had a study, followed by corresponding work towards closing the identified gaps in mobility management scheme. Proper understanding of the existing mobility principles and solutions is essential to determine the areas for performance study and potential enhancements. Such comprehensive overview of NR mobility, including the most recent advances towards Release 18, has been missing in the available literature. Thus, this paper provides insights into state-of-the-art mobility enhancements with a particular focus on those defined in 5G and 5G-Advanced standard. The performance of selected 3GPP Release 18 mobility solutions is assessed to verify if the standards-related work was pertinent and justified. The aim is also to show where mobility issues may still remain.

The rest of this paper is organized as follows. In section II NR mobility is described in detail, considering all specification releases finalized until now. Section III focuses on mobility enhancements that were recently addressed in 3GPP Release 18 (5G-Advanced). In section IV performance evaluation of the Release 18 mobility solutions is revealed by simulation results. Lastly, in section V the main findings are echoed and paper's summary is provided.

II. NR MOBILITY

In this section, the mobility enhancements introduced in the previous 3GPP releases (i.e. Release 15 to Release 17) are explained to show the full evolution of NR mobility procedures. The timeline of 3GPP NR releases is shown in Fig.1.

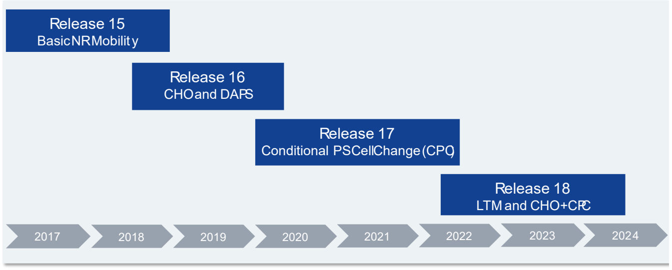

Fig.1. 3GPP New Radio Release Timeline and Mobility Features.

As can be seen, the NR standardization work was initiated by Release 15 in 2017 and was recently continued via Release 18. The projected freeze of Release 18 (5G-Advanced) is by the middle of 2024, with a similar time span as the previous releases had. However, it is expected that the evolution of NR will continue long after Release 18 [1]. Mobility aspects studied and enhanced in each of the releases mentioned in Fig.1 are described in the following subsections of this paper.

A. *3GPP Release 15*

First NR release has introduced a baseline handover (BHO), mostly similar to what has been used in LTE system. It relies on the network-controlled and UE-assisted principle, highlighted in the Introduction, where the Source BS receives measurement reports (MRs) from the mobile terminal and – if necessary - decides on initiating the HO of the UE. This is illustrated in Fig.2. Once the reporting condition is met, e.g., a neighbor cell becomes an offset dB stronger than the serving cell for time-to-trigger (TTT) seconds, the UE sends MR (step 1).

Source BS checks if the measurement results indicate that the HO towards the target cell is necessary and contacts the potential target cell (step 2). If the preparation is successful (i.e., Target BS can admit a new UE), Source BS sends a HO command to the UE (step 3). UE initiates HO execution immediately after receiving and processing the aforementioned command. The link with the Source BS is discarded already at step 4 when the UE attempts to access the Target BS. This implies NR Rel-15 HO is a "break-before-make" procedure, wherein the connection with the source cell is released before establishing the connection to the target cell.

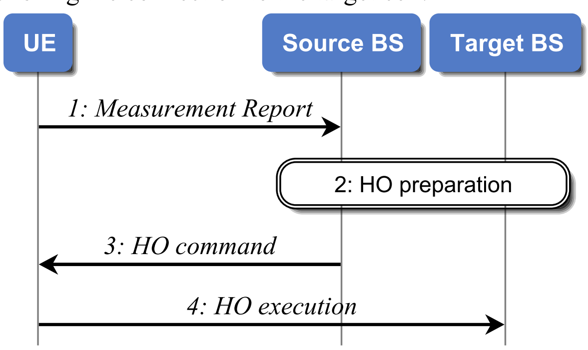

Fig. 2. Simplified diagram for NR Rel-15 handover.

One significant difference between LTE and NR mobility frameworks is that the latter is designed to serve in beam-based system. The UE performs signal measurement on the individual downlink (DL) beams of the serving and neighbor cells. Those measurement results are filtered and consolidated by the UE to derive the cell-level quality result which is then used to decide if the MR shall be triggered and provided to the network (step 1 in Fig.2). The UE can report those individual beam-level results in the same MR. The NR measurement model is explained with all details in [19].

It is problematic in Rel-15 HO to trigger the cell change exactly when it is needed. All relies on the measurement event triggering the MR, as shown in step 1 of Fig.1. The UE may be configured to send such report early or late. The former may lead to a too early HO execution and Handover Failure (HOF) when accessing the target cell. The latter can result in the Radio Link Failure (RLF) as the UE is not instructed to perform HO before the quality of the radio link with the source cell deteriorates. Thus, sending the HO command and timely execution of HO are critical in mobile networks. In the following subsection it is outlined how these issues can be mitigated.

B. *3GPP Release 16*

As the BHO defined in Release 15 was neither interruption-free, nor extremely reliable, the NR mobility framework was enhanced in Release 16 by the introduction of CHO and Dual Active Protocol Stack (DAPS) handover. The purpose of CHO was to increase the handover's reliability by decoupling the HO preparation and execution phases (cf. the too early or too late HO dilemma described in II.A). Thanks to this, the UE can be prepared with HO early, when the source cell link is good enough, while the actual HO execution happens later, when the candidate target cell has already become better (e.g., by an offset) than a source cell.

The basic CHO scheme is depicted in Fig.3. The major difference in comparison to BHO (Fig. 2) concerns what occurs after step 3, i.e., when the UE receives a HO or CHO command. In CHO, there is no immediate target cell access attempt, but instead the UE starts CHO execution condition evaluation (defined as a measurement event – similar to the one triggering a MR). The actual handover is executed when the condition associated with candidate target cell is fulfilled. The aim of such approach is twofold: to reduce the number of RLFs experienced due to unsuccessful HO command delivery (step 3 in Fig.2) and to reduce the number of HOFs experienced due to too early HO execution. In addition, postponed CHO execution can diminish the number of too-early (TE) handovers and so-called "ping-pongs" (the return to the source cell within 1 s from the last cell change). More details about CHO and its performance can be found in [7][19][20].

Finally, it has to be emphasized that CHO improves the mobility robustness but does not reduce the interruption time as the UE cannot exchange the data with the network while executing the HO. Thus, additional mobility enhancements are needed to minimize the interruption.

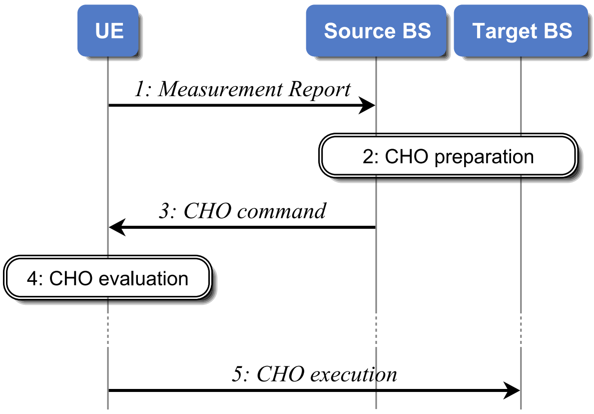

Fig. 3. Simplified diagram for NR Rel-16 Conditional Handover.

Dual Active Protocol Stack (DAPS) handover is a solution aimed at reducing the interruption time experienced during handover. This gain is achieved as the UE does not discard the source BS connection upon reception of HO command. The source BS link is maintained, and user plane packets are exchanged between the UE and the network while the UE attempts to access the target BS. After successful random access at the target BS, the UE can temporarily receive user data via both source and target links. However, this comes at certain expense - the UE needs to create a dedicated protocol stack for the target BS, while maintaining the same set of protocols for the source. As estimated in [22] DAPS can reduce the handover interruption time to as little as 2 ms. This is a substantial improvement when compared to BHO and CHO, where the latency of up to 80 ms is encountered.

C. 3GPP Release 17

The conditional reconfiguration principle, defined in Release 16, has been extended to Dual Connectivity (DC) in subsequent 3GPP release. In DC the UE has two radio links with the network – one towards the Primary Cell (PCell), provided by the Master Node (MN), another with the Secondary Node (SN). MN is the main BS, usually responsible for controlling the connection, while SN is added for user throughput gain or coverage extension purposes. Release 17 enabled the possibility to provide the UE with a Conditional PSCell Addition (CPA) or Conditional PSCell Change (CPC) configurations. The former is aimed at faster establishment of DC, achieved via addition of a Primary Secondary Cell (PSCell). The latter is the DC equivalent of CHO, enabling conditional change of PSCell, aimed at making the SN change more robust. The UE attempts to access the new PSCell immediately upon the condition is met, i.e., without the necessity to report measurements to the network and await the corresponding PSCell change command.

To accelerate the DC establishment, i.e., establishing UE's radio connection with both PCell and PSCell, joint DC and CHO configuration has been also supported as a part of Release 17. In this case the UE is provided simultaneously with CHO and the configuration for PSCell change at the time of CHO preparation. When the condition for handover is met, the UE accesses the target PCell and also tries to establish a link with the target PSCell. However, as entering the PSCell was not associated with any PSCell-related condition, it may lead to a failed access attempt. The signal quality of PSCell candidate provided at the time of joint preparation may become too weak when the UE performs CHO and is supposed to access also the PSCell in this single step. The problem may not be marginal, as one typical DC deployment assumes the MN (comprising PCell) at lower frequency band where the cell coverage is usually larger, while the SN (comprising PSCell) can use the spectrum from higher frequency ranges, so with the smaller expected cell coverage. In this scenario, it is likely the PSCell's signal quality will not necessarily be sufficiently good when CHO execution condition is met and the UE attempts to access both cells. These assumptions have been investigated by us and the results are shown in section IV.B. Our primary aim was to confirm the problem and then study how it can be resolved as a part of 3GPP Release 18 work.

III. Further Enhancements in 5G-Advanced

Previous section described how the basic NR mobility has been defined and what enhancements have been added in consecutive releases. Even though the solutions such as CHO, DAPS or CPC provide mobility robustness, reduce interruption, or allow to optimize the DC mobility, there is still area for improvement. For example – processing the handover in lower protocol layers for faster cell access or enabling a series of handovers based on a single configuration. In this section the main objectives of further enhancements to 5G mobility are outlined. These are on the verge of becoming a part of Release 18 3GPP standard and will aim to address the aforementioned mobility deficiencies.

A. Lower Layer Mobility

In this subsection technical aspects of L1/L2 Triggered Mobility (LTM) are provided. This functionality is one of the main areas addressed as a part of Release 18 mobility work. Its purpose is to reduce the latency associated with the handling of mobility procedures.

The mobility described in the previous section relied on higher layers of the UE's protocol stack (details in [19]). Whenever a cell change occurred, the UE had to process the higher layer message, sent at Layer 3 (L3), using Radio Resource Control (RRC) protocol.

Applying the entire RRC configuration and the need to involve all layers in the protocol stack makes the HO a slow procedure and with a lot of necessary signaling between the network and the UE.

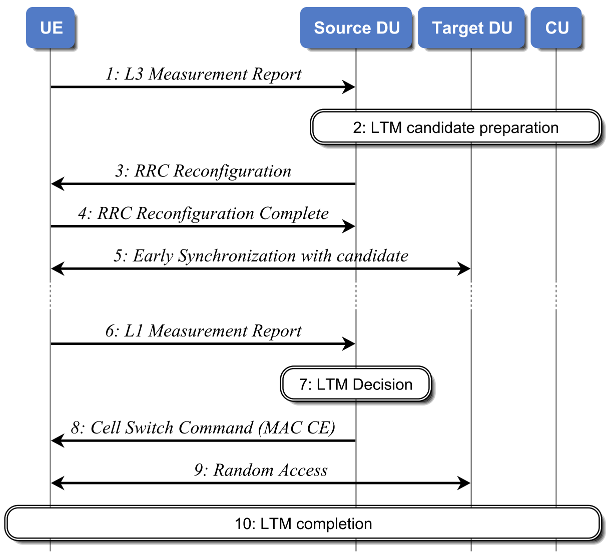

Fig. 4. Simplified diagram for 3GPP Release 18 LTM.

LTM proposes to implement the mobility in the form of a beam change, involving just lower layer reconfiguration. LTM is triggered via network indication using Medium Access Control Channel Element, MAC CE, instructing the UE to change the beam and cell as a result. Such approach is feasible especially in the distributed architecture, where the functional split exists and involves Central Unit (CU) and Distributed Units (DUs). The former is responsible for higher layer protocols: RRC and Packet Data Convergence Protocol (PDCP), while the latter terminates the lower layers such as Radio Link Control (RLC), MAC or physical layer. In such case, intra-DU and inter-DU intra-CU mobility can be executed without re-establishing higher layer protocols as this happens without changing the CU. As a result, L3 command to trigger the handover (also known as RRC Reconfiguration) is avoided and the entire procedure is accelerated.

The basic steps of LTM, as designed in Release 18, are shown in Fig.4. In step 1 the UE sends the L3 measurement report to the source DU. This is forwarded to CU which is responsible for RRC protocol. Source DU, jointly with the CU and Target DU prepare the handover, based on measurements reported in step 1. If the network decides to configure the LTM handover, the corresponding reconfigurations are forwarded via Source DU to the UE (step 3). The UE acknowledges such reconfiguration (step 4) and from then onwards it is prepared to execute LTM. The UE may perform early synchronization with a subset of candidate LTM cells (step 5) if instructed to do so by the network. The UE reports Layer 1 (L1) measurements, conducted on individual beams (step 6). These are processed fast in the network without sending them to higher layers (step 7) and if the results are relevant for commanding a serving cell change, this occurs in step 8. MAC CE is sent for that purpose. In response to such command, the UE attempts to access a new DU (in case of a cell change in the inter-DU scenario) via a random-access procedure, if early synchronization to that cell was not executed in step 5. Ultimately, the network completes the handover by releasing the UE's context in the source DU and switching the paths from core network (step 10).

Thanks to applying the aforementioned scheme it is possible to reduce the latency associated with mobility. On the other hand, LTM is expected to bring gains only in specific deployment scenarios (i.e., using DUs and for intra-CU handover). The extension of LTM scheme to inter-CU scenarios is expected in 3GPP Release 19 (expected completion date – end of 2025).

B. Selective Activation of Cells

In this subsection we focus on selective activation of cells. This is another part of the mobility enhancements towards 5G-Advanced. In this scheme the UE can be prepared in a single step for a series of serving cell changes. After a single change is executed, the UE does not have to be prepared from scratch but may continue evaluating the execution conditions for subsequent cell changes. This can lead to signaling overhead reduction as well as the timely execution of cell change as there is no need for additional reconfiguration from the new accessed cell. Such solution can be especially beneficial in Frequency Range 2 (FR2, above 24 GHz), where large macro cell may be deployed jointly with a number of small cells operating in FR2 (i.e., in the scenario referred also in section II.C). Each of these small cells may become a potential primary cell of secondary cell group (PSCell) for the UE and the access can be seamless, with no further reconfiguration from the network.

The whole solution relies on the principles of CHO and CPC, described in the preceding section, so a cell change will be triggered when a corresponding condition is met. The Release 18 work is initially focused on addressing the PSCell changes via CPC, whereas a series of PCell modifications using CHO framework could be addressed in the future 3GPP releases.

C. Conditional Handover with CPC

Using the radio links towards multiple cells is essential for boosting the UE's achievable data rates. Thus, it is important to establish DC as promptly as possible, also when PCell is changed (as argued in section II.C). That is why CHO should coexist with CPC – something that was not supported until Release 18. The UE should be configured with separate conditions – one for changing the PCell, another related to PSCell. Due to such combination of conditions, each of those cells is changed when relevant and corresponding signal quality is checked individually. Such approach can be one of the ways to mitigate the issue mentioned in section II.C and evaluated in section IV.B, where it is shown how frequently the preparation of wrong PSCell in CHO might occur.

D. FR2 Measurement Enhancement for Dual Connectivity/ Carrier Aggregation (CA)

DC and CA are among NR-supported technologies that provide significant enhancements for diverse set of UE/network QoS requirements by exploiting available radio resources of SN. One of the key elements to make the most benefits of having an additional communication path is to reduce the secondary link establishment delay, especially for a UE connecting from idle/inactive mode and when the secondary band is in Millimeter-Wave (mm-Wave) frequency range, e.g., 3GPP FR2. Faster DC/CA setup increases the user-experienced throughput and reduces packet transmission latency. It also enables the network to balance the load between different carrier bands and cells. Eventually, it can also lead to lower UE power consumption by reducing the transmission/reception time and allowing the UE to switch to idle/inactive modes.

To extend the coverage and compensate for high path loss of mm-Wave communications, the NR BS transmits signals through highly directional narrow beams. mm-Wave devices are also expected to be designed with multiple antenna panels, each with directional coverage. Those panels will be located at different sides of the device to offer spherical coverage [21]. The current 3GPP assumptions for mm-Wave devices imply that the UE can receive/transmit from one panel at a time. Hence, to detect and measure a cell properly, the UE needs to sweep through its panels and search for the BS-broadcasted reference signals (RSs). This imposes substantial additional measurement time needed in FR2, compared to that required for FR1.

Analysis of DC/CA activation delay reveals that cell detection and measurement procedures are the dominant components contributing to radio link establishment delay [22],[23]. Connected mode CA/DC inter-carrier FR2 measurement delay may take seconds and that is several times higher than at FR1 [24]. Early Measurement Report (EMR) has been proposed in NR Release 16 to enable faster DC/CA setup by configuring the UE to perform idle-mode measurements on potential DC/CA frequencies/cells while a specific timer is running. The UE prepares a report and sends it to the network once entering the

RRC-connected state. Even though EMR can speed up DC/CA establishment for FR1, FR2 idle-mode measurement delay is in the order of minutes [22][24]. Considering that the cell sizes in FR2 deployment are relatively small while radio channel variation is quite fast, such a high measurement delay may lead to incomplete, inaccurate, and outdated measurements that result in sub-optimal carrier/cell selection, especially for mobile UEs.

Based on the above discussion, among the objectives of Release 18 Further NR mobility enhancements work item [25] was to investigate the impact of measurement acquisition delay on CA/DC establishment by focusing on UEs that connect from the idle/inactive modes. The study included evaluating the impacts of measurement delay on different user/network performance factors using both analytical methods and 3GPP compliant system-level simulations. The aim was also to exploit the feasible enhancements and assess corresponding costs/benefits for the network and UEs [25].

It has been envisioned to achieve the goal by optimizing and performing improved measurements, defining new procedures, and exploiting additional network assistance of providing the UE with supplementary information to perform the measurement effectively [25]. Some potential enhancements include employing advanced UE panel measurement techniques to reduce the sweeping time. Machine learning and artificial intelligence algorithms are promising approaches in this regard. Another solution is to shrink the measurement duration by reducing the number of samples and the gap between measurement instances. However, this may result in the inaccuracy of the measurement and hence sub-optimal cell/carrier selection. Yet another area for investigation is to provide the UE with configurations to perform new or continue EMR-related measurements during connection step or resume procedure. Moreover, it is advantageous to optimize EMR timer length and idle-mode search threshold values considering FR2 operation limits [24]. It is expected that the findings of this study may lead to further reduction of the DC/CA setup delay in FR2 and hence increase the achievable UE throughput.

In Section IV.C simulation results based on our study on SCell setup delays [24] are presented, aimed at justifying the work on the enhancements described in this section, either in Release 18 or beyond.

IV. Evaluation Results

In the previous sections mobility problems and solutions addressed in each of the 3GPP NR releases have been presented. In this section performance results associated with the selected functionalities and problems described in section III are provided. Section IV.A contains the system model description and common parameters used for the simulations in both sections IV.B and IV.C. Specifically, the problem of measurements of the PSCells at the time of CHO preparation and execution, introduced in section III.C, is analyzed in Section IV.B, while the impact of SCell setup delay on throughput and load, described in section III.D, is further investigated in IV.C.

A. System Model Description

A fully fledged, dynamic system-level simulator was adapted accordingly and used for performance evaluation. The simulator is fully compliant with 3GPP simulation and modeling specifications. It has been used in numerous research papers that have been published and awarded in prestigious conferences and journals, e.g. [21][23][26]. The simulator operates in OFDM symbol resolution in time domain and subcarrier resolution in frequency domain. Dynamic packet scheduling, link adaptation and Hybrid Automatic Repeat Request (HARQ) are modeled in detail. Received power and Signal to Interference and Noise Ratio (SINR) are based on detailed channel modeling for serving and interfering links including antenna gain, pathloss, shadowing, line-of-sight and fast fading effects according to Urban Macro model in [22] as well as Linear Minimum Mean Square Error - Interference Rejection and Combining receiver (LMMSE-IRC). Effective SINR is calculated using Exponential Effective SNR mapping and to determine data reception success the effective SINR is compared against error probability tables, which are obtained from link-level simulations for each Modulation and Coding Scheme (MCS). Simulator also has a detailed model of UE mobility, RRC and beam management [23].

TABLE I
COMMON SIMULATION PARAMETERS.

Parameter	Value
Network layout	NR Dense Urban with two frequency layers 21 Macro layer (FR1): hexagonal layout with seven 3-sector sites Micro layer (FR2): semi-random antenna panel orientation with 3 cells per macro area
Carrier frequency	Macro layer (FR1): 2.1 GHz Micro layer (FR2): 28 GHz
Subcarrier bandwidth	60 kHz
Frequency reuse factor	1 (Macro layer)
Channel Model	Macro layer: UMa [19] Micro layer: UMi [19]
Noise Figure	Macro Cells: 5 dB Micro Cells: 8 dB UE: 9 dB
BS beams	Macro cells: 8 beams, 4 azimuth 2 elevation Micro cells: 16 beams, 8 azimuth, 2 elevation

Table I shows common simulation parameters used for all simulation studies presented in this article. Figure. 5 and Fig. 6 represent the coverage maps without the impact of slow and fast fading for macro and micro cells, respectively. These figures are included merely to present how the coverage differs for macro and micro cells. Slow fading shows its impact predominantly over long distances and therefore is evident in cells with larger coverage whereas in micro cells fast fading will have a highly visible impact. The scenario consists of macro cell layer deployed in hexagonal grid with 200 meters inter-site distance and micro cell layer with 3 cells deployed per macro hexagonal area. Macro cells are using 2.1 GHz carrier frequency whereas micro cells are using 28 GHz carrier frequency. To reflect operator's real-world deployment and to be aligned with 3GPP simulation scenarios, frequency reuse factor of 1 is used in our simulation.

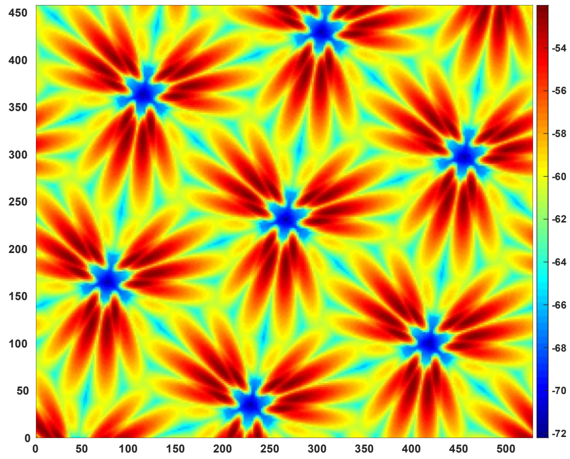

Fig. 5. Coverage map of macro cells without fading (distance in meters in horizontal and vertical axis, DL received signal strength in dBm in the vertical bar).

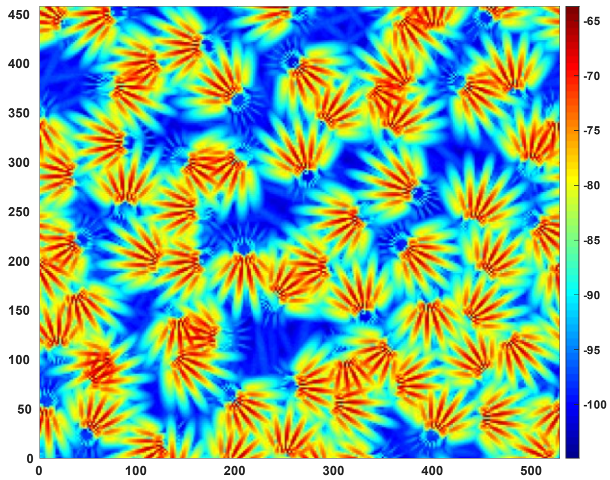

Fig.6. Coverage map of micro cells without fading (distance in meters in horizontal and vertical axis, DL received signal strength in dBm in the vertical bar).

B. *False/Wrong PSCell Preparation*

System level simulations are performed in order to analyze the problem of wrong PSCell preparation as described in section II.C. Therefore, the prepared strongest PSCell measurement at the time of CHO preparation is compared with the PSCell measurement at the time of CHO execution. Moreover, the impact of preparing multiple PSCells at the time of CHO preparation on wrong PSCell preparation is evaluated. The details of the parameter settings for the simulation can be found in Tables I and II. Table II outlines the configuration of the mobility simulations including the user movement and handover procedure details. In following, it is investigated if preparing only the strongest PSCell at the time of CHO preparation can lead to wrong PSCell preparation. Wrong PSCell preparation is recorded in case another PSCell is found to be stronger than the prepared PSCell(s) at the time of CHO execution.

PSCell preparation analysis is shown in Fig.7 for different preparation thresholds and for the case when target MN prepares at most one target PSCell. The number of PSCell preparation events is shown in blue, while the number of events, where another PSCell was stronger than prepared PSCells at the time of CHO execution, is shown in red.

TABLE II
PARAMETERS FOR WRONG PSCELL PREPARATION.

Parameter	Value
Carrier bandwidth	Macro layer (FR1): 20 MHz Micro layer (FR2): 20 MHz
Traffic	Full Buffer Traffic UL disabled
UE deployment	Macro - Uniform random drop of UEs which move with constant speed in random directions UE speed 120 km/h 420 Users
BS antenna configuration (Number of horizontal elements, number of vertical elements, polarization)	Macro cells: (4, 8, 2) Micro cells: (8, 16, 2)
UE antenna configuration	2 RX, 1 TX antennas with isotropic radiation pattern
Handover Procedure (PCell change)	Metric: L3-RSRP (Reference Signal Received Power) A3 event for preparation or execution: -3 dB/3dB Time-to-trigger (TTT): 160 ms Preparation delay: 40ms HO interruption time: 80ms

The statistics are normalized per UE and per time (minute). At the time of CHO preparation, the network compares the PSCell measurements that are reported by the UE and prepares only the strongest PSCell if its L3-RSRP value is higher than the preparation threshold which is shown in the x-axis.

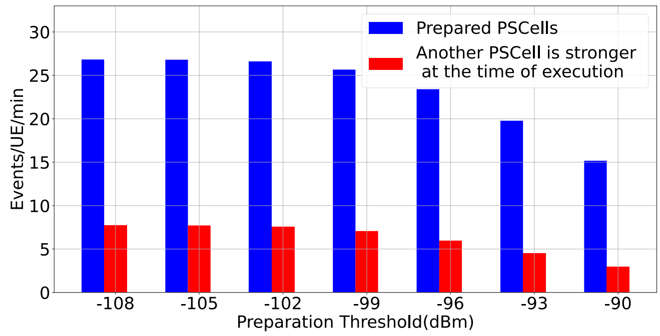

Fig.7. The number of PSCell preparations (in blue) and wrong PSCell preparations (in red) as a function of the preparation threshold in dBm for the case when up to a single target PSCell can be prepared.

The results in Fig.7 show that in ~28% of cases the prepared PSCell is not the strongest at the time of CHO execution for preparation threshold of -108 dBm. It is also observed that increasing the preparation threshold to -90 dBm can reduce the wrong PSCell preparation ratio to ~19%. However, this also reduces the number of PSCell preparations at the time of CHO preparation (blue bar in Fig.7) and creates additional delay for UE to obtain configuration of PSCell after CHO execution. In addition, it is worth underlining the results for lower PSCell preparation thresholds, such as -117 dBm, do not differ from these for -108 dBm threshold. Thus, they were not included in Fig. 7. This means that there was always at least one PSCell whose signal quality was 10 dB better than the noise level of -118 dBm at the time of CHO preparation. The main reason behind this observation is the use of dense micro cell deployment, i.e. 3 micro cells per macro site, in the simulations where at each macro cell border, there were candidate micro cells, as shown in Fig.6. Thus, the performance results depicted in Fig.7, may be differ for various network layouts. L3-RSRP measurements of the prepared PSCells are observed both at the time of CHO preparation, and at the time of CHO execution. Then, the L3 measurements at the time of preparation are subtracted from those of execution to obtain the power difference between the two L3-RSRP measurements, ΔRSRP, to analyze the divergence of the measured power of a prepared PSCell until the CHO is executed. Fig.8 shows CDF of the ΔRSRP value for two different preparation thresholds of -90 dBm, illustrated in green, and -108 dBm marked with red line.

In Fig. 8 it can be seen for both preparation thresholds that ~60% of the time, the signal strength, i.e. L3-RSRP of the prepared PSCell, gets worse (ΔRSRP is lower than zero).

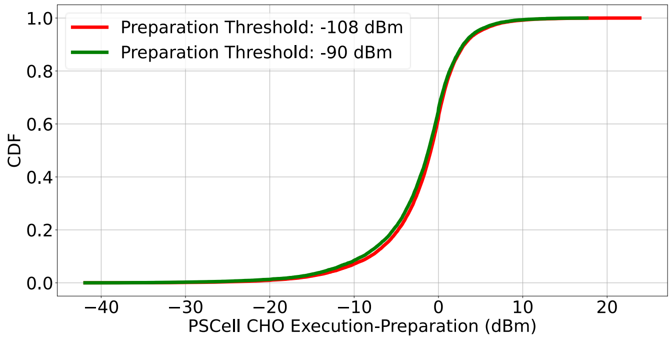

Fig.8. CDF of the difference between the measurements of the prepared PSCell at the time of CHO execution and preparation.

It can be noticed that both thresholds result in similar CDF curve, but higher preparation threshold of -90 dBm is slightly closer to the lower ΔRSRP values than the lower threshold (-108 dBm). Fig.8 indicates that even if higher preparation threshold of -90 dBm is used the prepared PSCell signal strength at the time of CHO execution is worse 60% of the time. Both Fig. 7 and Fig. 8 indicate that single PSCell preparation at the time of CHO preparation can lead to mobility problems such as another PSCell's signal gets better at the time of CHO execution or prepared PSCell signal might even drop below the noise level. Therefore, the interruption time to setup PSCell connection after CHO procedure will be increased. One reason behind this problem may be related to the high fluctuations of the signal in FR2 micro cells due to user movement and shadowing. Another reason can be related to the improper configuration of the parameters for handover procedures, e.g. CHO preparation and execution offsets in the network layout.

To tackle the abovementioned issues, it is proposed to provide more than one candidate PSCell at the time of CHO preparation if their signal strength is higher than the preparation threshold. This was not supported by the 3GPP mobility framework prior to Release 18 completion. In this proposal, at the time of CHO preparation, the target handover node prepares the PSCells whose measurements exceed the preparation threshold set by the network. To enable this, the source node forwards to the target node, during CHO preparation, the measurement report that was sent by the UE.

The PSCell measurement analysis, as explained for Fig.7, is performed again and illustrated in Fig.9 and Fig.10 when the network prepares at the time of CHO preparation up to two and four strongest PSCell candidates, respectively.

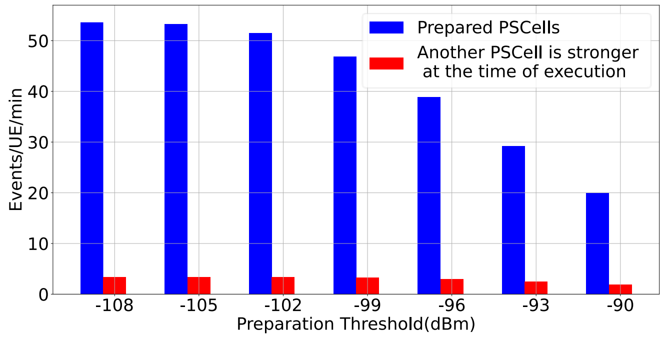

Fig.9. The number of PSCell preparations (in blue) and wrong PSCell preparations (in red) as a function of the preparation threshold in dBm for the case when up to two target PSCells can be prepared.

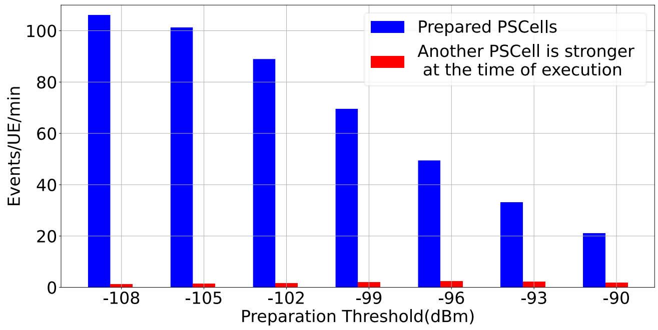

Fig.10. The number of PSCell preparations (in blue) and wrong PSCell preparations (in red) as a function of the preparation threshold in dBm for the case when up to four target PSCells can be prepared.

It can be seen that with -108 dBm preparation threshold, the ratio of having another PSCell which is stronger than any of the prepared PSCells (red bar in Fig.9 and Fig.10) is reduced to ~12% and ~4% for two and four prepared PSCells, respectively. As the network prepares two or four strongest PSCells at the time CHO preparation, the likelihood of having another PSCell which is not prepared is significantly reduced. Furthermore, the wrong PSCell preparation cases, denoted by the red bars, specifically for preparation threshold of -108 dBm at the time of CHO execution, for 1, 2 and 4 prepared PSCells have been analyzed. The strongest prepared PSCell's L3-RSRP is subtracted from the strongest PSCell L3-RSRP value at the time of CHO execution to obtain $\Delta RSRP_{wrong}$ of wrong PSCell preparation. Then, the CDF of the obtained $\Delta RSRP_{wrong}$ is drawn and shown in Fig.11.

It is illustrated that the measurement difference between the strongest PSCell and strongest PSCell at the time of CHO execution is reduced if multiple PSCells are prepared. This indicates that if the network prepared multiple PSCells, it is more likely that it will prepare the PSCell whose measurements are the strongest also at the time of CHO execution. However, it should be noted that preparing multiple PSCells at the time of CHO preparation might not be favorable as the cost of PSCell resource reservation is high for the network. Additional PSCell preparations can lead to inefficient usage of network resources e.g. random-access preambles and may excessively increase network signaling - necessary to prepare multiple PSCells and subsequently release the unused resources. It is an inherent trade-off between resource efficiency and the likelihood the UE will have a proper cell to access at the time of CHO execution. The decision is network-specific and can depend on how latency-critical or throughput-critical the service offered to the UE is.

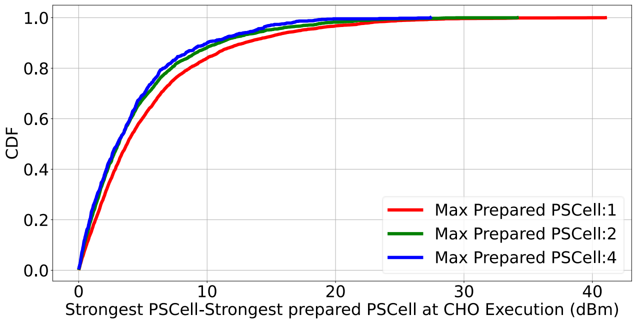

Fig.11. CDF of strongest and prepared PSCell measurement difference at the time of CHO execution.

C. *SCell Setup Delay and Its Throughput Impact*

System level simulations to study the impact of various levels of SCell setup delay and offered load to UE and system performance have been performed. SCell setup delays have been selected according to analysis and estimations provided in [23] [24]. For reference the results with ideal 0 ms setup delay are also shown. 100 ms is selected to give a more realistic estimate of best-case scenario when all potential enhancements are applied including up to date EMR related idle-mode measurements from micro cell layer. 760 ms is the setup delay in the connected mode for FR1 and 4160 ms for FR2, according to current 3GPP specification [22], elaborated also in [24]. The evaluated scenario was NR Dense Urban scenario with both macro and micro cell layers. Macro cells were deployed at FR1 and micro cells at FR2. FTP model 1 [30] traffic type was used with mixed file size and 60-120 Mbps offered load target per macro area. More detailed description of parameters is in Table I and Table III.

Fig.12 shows average user throughput for all UEs deployed in the simulated scenario for different offered load per macro cell and SCell setup delay. It is observed that SCell setup delay impacts the average user throughput. Shorter SCell setup delays enable higher user throughput, and the same observation holds for all simulated offered loads. For highest offered load, i.e., 120 Mbps per macro cell shown in turquois, the gain in average user throughput from reducing the delay from 4160 to 760 ms is 25%. Reducing the delay further to 100 ms would give 109% gain compared to 4160 ms delay while ideal 0 ms case gives 257% gain.

Fig.13 shows average load share in micro cells which are in this scenario only used for SCell purpose, so they fully reflect the impact from SCell setup delay. Load share is calculated as per (1). $\text{received}_{B_{micro}}$ is the total amount of successfully received bytes in micro cells during simulation and $\text{received}_{B_{total}}$ equals the total amount of successfully received bytes in the whole simulated network.

$$Load_{micro} = \frac{received_{B_{micro}}}{received_{B_{total}}} \times 100\ [\%] \qquad (1)$$

One can observe that with the highest setup delay of 4160 ms the micro cells load share is under 1% even with high offered load and even though there are three micro cells deployed per macro cell area. With shorter delay of 760 ms the load share increases to 9-16 % depending on the offered load. Load share with SCell setup delay 100 ms is 36-39% and with ideal 0 ms delay 44-46%.

TABLE III
PARAMETERS FOR SCELL SETUP DELAY EVALUATION.

Parameter	Value
Carrier bandwidth	Macro layer (FR1): 50 MHz Micro layer (FR2): 200 MHz
Traffic model	Downlink traffic FTP model 1 [30] with 2 MB and 20 MB file sizes 50% of UEs receive each file size
Network load	Offered load per macro cell: 60, 80, 100, 120 Mbps
UE deployment	80% of UEs indoor 20% of UEs outdoor
UE speed	3 km/h
BS antenna configuration (Number of horizontal elements, number of vertical elements, polarization)	Macro cells: (8, 8, 2) Micro cells: (8, 16, 2)
UE antenna configuration (Number of horizontal elements, number of vertical elements, polarization)	FR1: Omni reception FR2: 4 directional antenna arrays (2,2,2) with 90-degree separation between the direction of the panels
SCell setup delay	0, 100, 760, 4160 ms

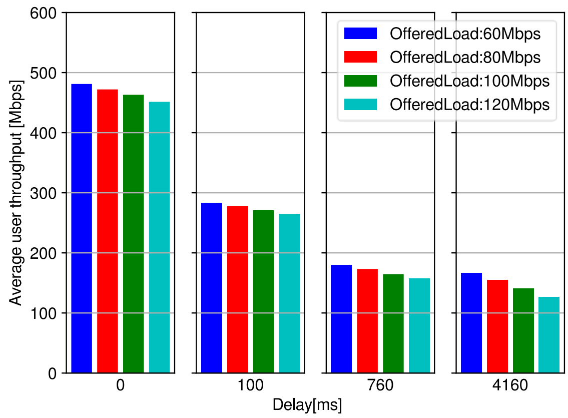

Fig.12. Average user throughput for all UEs deployed in the simulated scenario for different offered load and delay values.

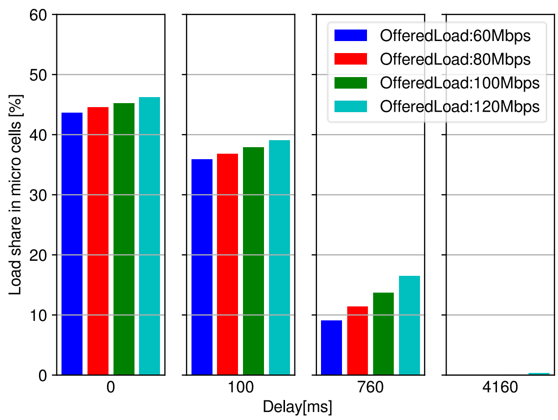

Fig.13.Load share in micro cells compared to the total load in network.

These results show that improvements in SCell setup delay significantly increase the efficiency of SCell micro cell use in this scenario.

Fig.14 shows user throughput CDF for all UEs in the simulated network for offered load of 120 Mbps. Very significant throughput gains for coverage (5-percentile) and median (50-percentile) throughputs when reducing the delay from 4160 ms to 760 ms can be observed. When reducing the delay further to 100 ms there is also gain in peak throughput (95-percentile) in addition to the coverage and median throughputs. Due to two different file sizes (2 and 20 MB) used in traffic model along with two frequency layers and some users not situated in the micro cell coverage area, the CDFs have significant number of samples close to 200 Mbps. In this scenario there are about 37% of users outside micro cell coverage area.

In Fig.15 user throughput CDFs for only the UEs that are in micro cell coverage area are shown. One can notice that the gain in throughput from shorter SCell setup delay becomes more significant even for coverage (5-percentile) throughput, because only the users that can connect to micro cells are considered. Those users that are outside micro cell coverage area are impacted by the SCell setup delay only indirectly through higher load in macro cell layer when SCell setup delay is longer.

Fig.16 shows CDF of delays for the FTP model 1 file receptions. There is also a sub-figure that is zoomed in to lower x-axis values to see the impact on UEs in the best signal conditions. The delay values are inversely proportional to user throughput and shorter file reception delay with the shorter SCell setup delays can be observed. The absolute difference in file reception delays is very clear in 95-percentile of the CDFs indicating significant improvements from shorter SCell setup delays also for UEs in the least favorable signal conditions that are prone to longer file transmission time. The effect of the longest 4160 ms SCell setup delay is pronounced in the file transmission delays, where 95-percentile is at 3000 ms and already with SCell setup delay of 760 ms the file reception delay decreases by 50%.

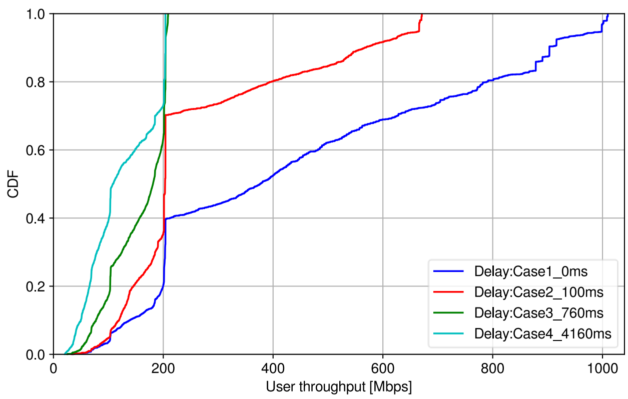

Fig.14.User throughput CDF for all UEs (in and outside micro cell coverage area) with offered load 120 Mbps.

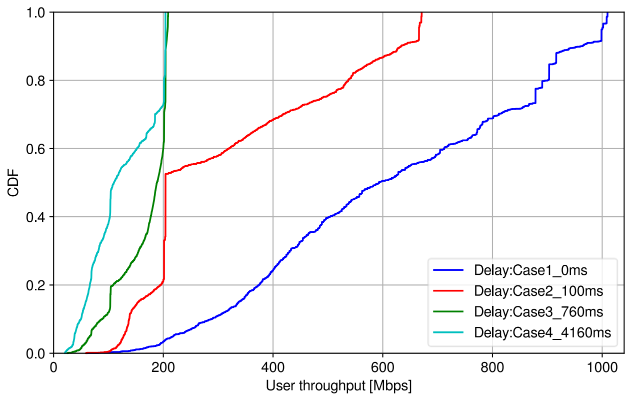

Fig.15.User throughput CDF for UE in micro cell coverage area with offered load 120 Mbps.

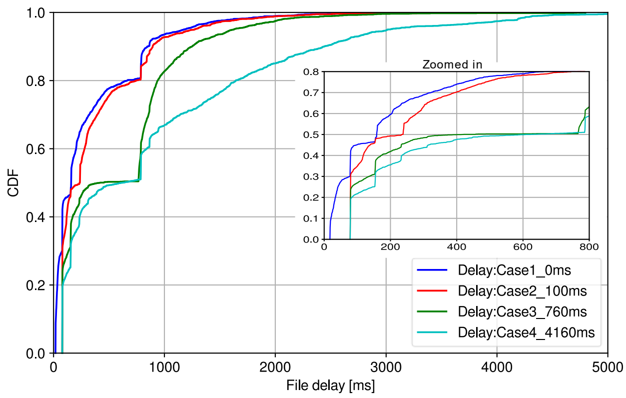

Fig.16. File reception delay CDF for all UEs (in and outside macro cell coverage area) with offered load 120 Mbps (sub-Fig. is zoomed in to lower x-axis values).

V. Conclusion

This article has exhaustively described NR mobility mechanisms, starting from baseline handover defined in 3GPP Release 15, through mobility enhancements pursued in consecutive releases. It has been explained what the main approaches to mobility management are and which performance indicators are of paramount importance. It is worth reiterating NR already offers the solutions to reduce the interruption time during HO (DAPS) and to improve the reliability – for both the PCell change (CHO) and PSCell modification (CPC). Next set of seamless mobility enablers are on the verge of finalization as a part of 3GPP Release 18 (5G-Advanced), with the expected completion in 2024. Among those solutions one can find LTM, selective activation of cells and means for reduced SCell setup delays. These are addressing various mobility requirements.

Our paper also provided the evaluation results for selected areas in the scope of 3GPP Release 18 work. It has been analyzed how likely the wrong PSCell preparation might be when this happens at the time of CHO configuration. It has been illustrated how increasing the number of prepared PSCells per configured CHO allows to reduce the number of wrong preparations. Preparing four candidate cells ensures in 96% there is a relevant PSCell at the time of CHO execution. Next part of our analysis involving simulation has focused on secondary cell setup delays. It has been shown how the user throughput increases with the reduced time for SCell setup in FR2. The throughput gains observed started at 25% for smallest reduction of SCell setup delay but exceeded 250% when ideal 0 ms setup delay was considered. This has clearly justified the enhancements to FR2 SCell setup time, pursued as a part of 3GPP Release 18.

As Release 18 is not the end, but just the beginning of the whole new chapter called 5G-Advanced, we also share our brief opinion on the subsequent enhancements. In our view, one of the most important goals would be to ensure all key mobility performance indicators (i.e. reliability, interruption, and throughput) can be kept at high level with just a single handover solution applied. Another interesting research area would be related to multi-panel, multi-antenna UEs where challenges related to hand blockage or random access at higher frequency bands need to be addressed.

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