Rock solid mobility innovations from 5G to 5G-Advanced

Solutions, performance and recommendations

White paper

Contents

Introduction

Well performing mobility solutions are at the heart of each mobile communications systems, with the first patent on handover for cellular dating back to 1972 by A.E. Joel from Bell Labs. Seamless handover between cells is essential for users to experience good quality of service while on the move. As an example, good handover performance is a prerequisite for users to move and engage freely with their physical environments without worrying about losing connectivity as they transit from indoors to outdoors and between neighborhoods or on the road. This requires highly agile and robust handover solutions with virtually zero interruptions. Today's 5G deployments largely rely on 3GPP Release 15 (the first 5G release) mobility mechanisms with traditional network (NW) controlled and user equipment (UE) assisted handovers, showing good mobility performance in the field. Mobility innovations continue to be introduced in the different 3GPP releases, including migration from the traditional NW controlled and UE assisted RRC-based handovers to more agile mobility solutions with higher degree of UE involvement and towards truly zero interruption time. Moreover, the innovations expand to new use cases such as e.g., high speed train (HST) scenarios, industrial IoT (IIoT) applications, and lately also to eXtended Reality (XR) as one of the prominent uses cases for 5G-Advanced that are in focus for 3GPP Release 18.

Mobility is one of the essential components of 5G-Advanced. 3GPP has already defined a set of functionalities and features that will be a part of the 5G-Advanced Release 18 package as illustrated in Fig. 1. These functionalities can be grouped into four areas: providing new levels of experience, network extension into new areas, mobile network expansion beyond connectivity, and providing operational support excellence. Mobility enhancements in Release 18 will be an important part of the 'Experience enhancements" block of features, with the goal of reducing interruption time and improving mobility robustness.

Figure 1. Overview of 5G-Advanced functionalities and features.

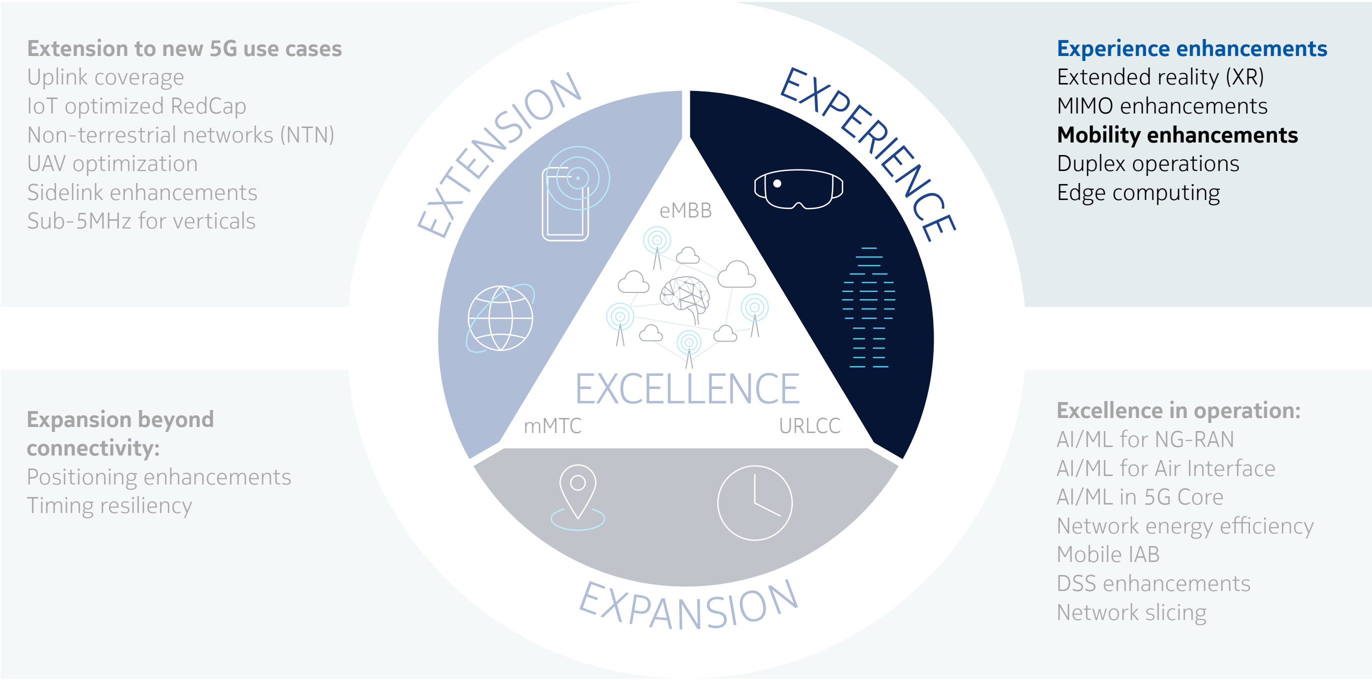
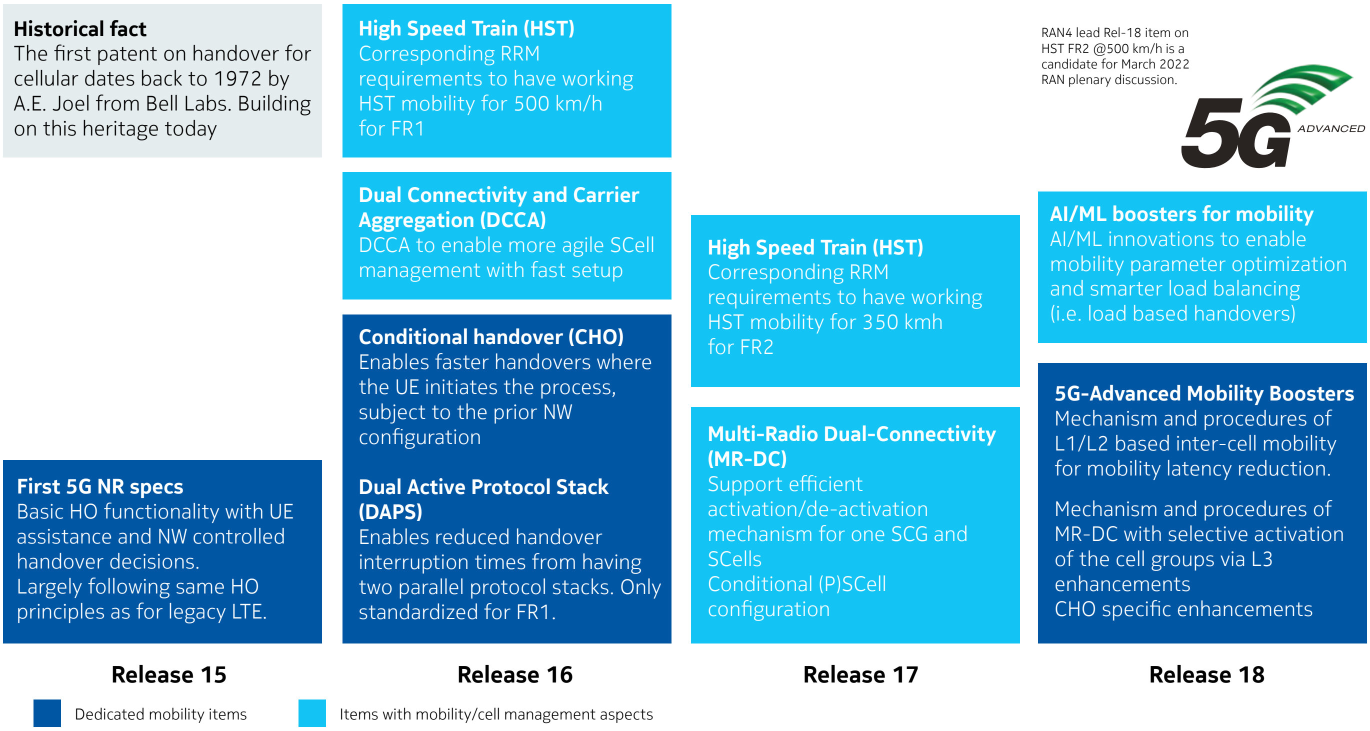


Fig. 2 shows a high-level schematic of mobility and dual connectivity (DC)/Carrier Aggregation (CA) related mechanisms that are introduced in the different 5G legacy releases towards 5G-Advanced in Release 18. Innovations such as Conditional Handover (CHO) and dual active protocol stack (DAPS) are introduced in Release 16. More efficient operation of carrier aggregation (CA), dual connectivity (DC), and the combination of those denoted as DCCA, as well as Multi-Radio Access Technology DC (MR-DC) are introduced through Releases 16 and 17. The enhancements for DCCA and MR-DC essentially enable more agile and efficient usage of such multi-carrier aggregation techniques to unleash their full potential by ensuring fast and timely configuration and activation of carriers in line with the traffic demands. MR-DC also provides a solution for non-standalone (NSA) deployment cases where a UE is connected to both Long Term Evolution (LTE) and 5G New Radio (NR) networks.

As pictured in Fig. 2, the first 5G-Advanced release (Release 18) is set to include additional mobility performance boosters making the handovers truly transparent for the end-user application with zero interruption time. It is desirable to achieve this with only a single transceiver in the devices including enhancements for inter-cell beam management. For enhancing mobility in millimeter wave frequency bands, the target is also to study improvements for the secondary cell setup latencies in carrier aggregation and dual connectivity to faster take advantage of the higher data rates from access to more bandwidth when needed. Essentially the enhancements will contribute to improved user experience as outlined in the 5G-Advanced white paper [1]. Finally, 5G-Advanced is also set to inject more artificial intelligence (AI) and machine learning (ML) technologies in the radio access network (RAN) and core network (CN). Among others, 5G-Advanced is expected to include innovations to facilitate smarter mobility parameter optimizations and decisions for triggering handovers.

In the rest of this white paper, we will present the main mobility aspects and provide an overview of the primary mobility enhancements introduced in 5G towards 5G-Advanced, as well as corresponding recommendations and best-practices. We address aspects related to both Frequency Range 1 (FR1) that covers up to 7.125 GHz and Frequency Range 2 (FR2) that covers mmWave frequencies up to 52.6 GHz. In addition, we describe the main enhancements that are introduced for DCCA where aggregation of FR1 and FR2 carriers is used and provide an overview about high-speed train scenarios.

Figure 2. Overview of mobility and DCCA related mechanisms in the different 5G and 5G-Advanced 3GPP releases.



Historical fact
The first patent on handover for cellular dates back to 1972 by A.E. Joel from Bell Labs. Building on this heritage today

First 5G NR specs
Basic HO functionality with UE assistance and NW controlled handover decisions.
Largely following same HO principles as for legacy LTE.

Release 15

High Speed Train (HST)
Corresponding RRM requirements to have working HST mobility for 500 km/h for FR1

Dual Connectivity and Carrier Aggregation (DCCA)
DCCA to enable more agile SCell management with fast setup

Conditional handover (CHO)
Enables faster handovers where the UE initiates the process, subject to the prior NW configuration

Dual Active Protocol Stack (DAPS)
Enables reduced handover interruption times from having two parallel protocol stacks. Only standardized for FR1.

Release 16

High Speed Train (HST)
Corresponding RRM requirements to have working HST mobility for 350 kmh for FR2

Multi-Radio Dual-Connectivity (MR-DC)
Support efficient activation/de-activation mechanism for one SCG and SCells
Conditional (P)SCell configuration

Release 17

RAN4 lead Rel-18 item on HST FR2 @500 km/h is a candidate for March 2022 RAN plenary discussion.

AI/ML boosters for mobility
AI/ML innovations to enable mobility parameter optimization and smarter load balancing (i.e. load based handovers)

5G-Advanced Mobility Boosters
Mechanism and procedures of L1/L2 based inter-cell mobility for mobility latency reduction.

Mechanism and procedures of MR-DC with selective activation of the cell groups via L3 enhancements
CHO specific enhancements

Release 18

■ Dedicated mobility items
□ Items with mobility/cell management aspects

Mobility framework in 5G

In NR, there are three Radio Resource Control (RRC) modes for the UE [2]:

- RRC Idle,
- RRC Inactive and
- RRC connected.

RRC Inactive is a new state that has been introduced for NR to reduce the latency in resuming the RRC connection after some inactivity. To this end, both control and user plane connections between 5G core (5GC) and RAN are maintained and the UE context is stored in the RAN and UE to enable fast resumption [2]. The basic mobility principles for RRC Idle and Inactive, defined in NR Rel. 15, follow the principles of UE controlled and network assisted procedures as also used for LTE, but are enhanced for considering the multi-beam operations and cell measurements [3]. Herein, RRC Idle/Inactive mobility is controlled by the UE where it decides on cell (re-)selection based on predefined conditions that are evaluated based on radio measurements and network configuration parameters. In contrast to RRC Idle UEs that are paged only by 5G core network for mobile terminated data, RRC Inactive UEs can be also paged by RAN in so-called RAN-based notification area (RNA).

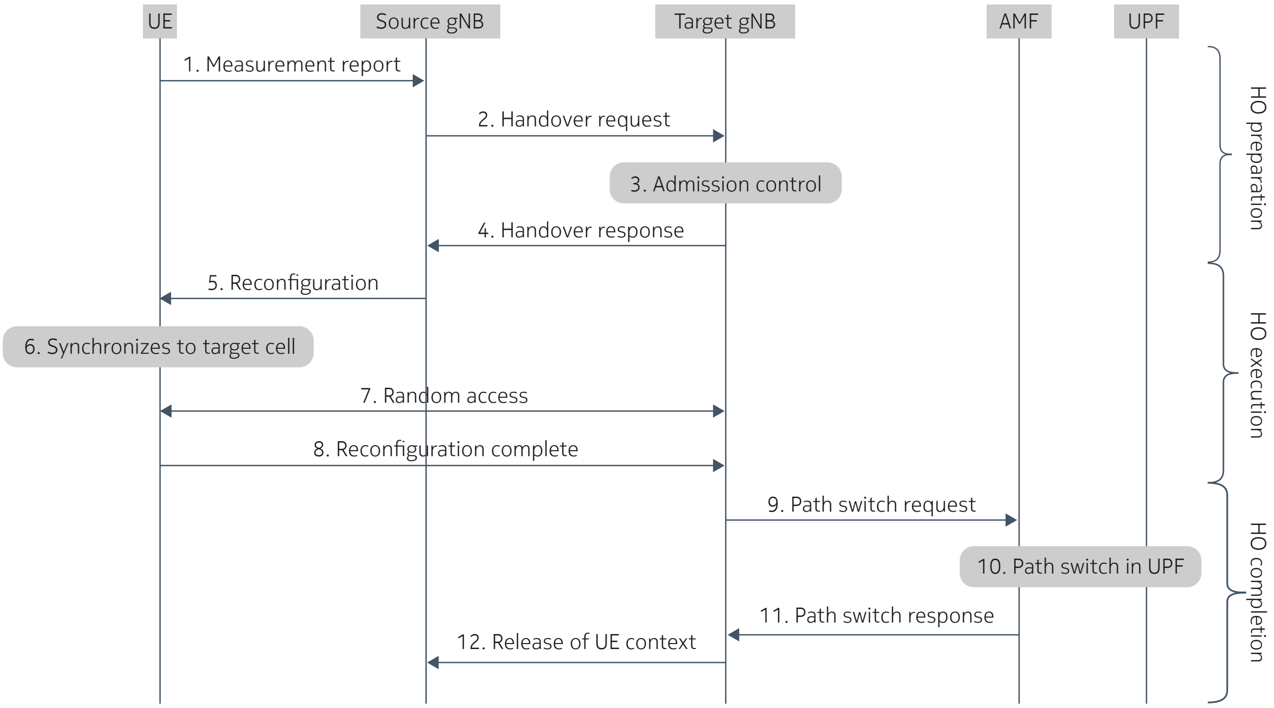
The main mobility enhancements that have been introduced in NR are rather for RRC Connected mode UEs. With the introduction of transmit beamforming in NR, 3GPP has distinguished from the beginning of Rel. 15 between inter-cell mobility of RRC Connected mode UEs, also known as handovers in case of Primary Cell (PCell) change [4], and Medium Access Control (MAC) based intra-cell beam management [5]. The beam management procedures have been defined to maintain a serving beam between the UE and the network. For beam management, the UE reports Layer 1 (L1) beam measurements of the serving cell and the network decides, based on the received measurements, on the beam(s) for the communication. The decision for beam switching, i.e., changing serving beam, is network-controlled by MAC protocol without involvement of upper Radio Resource Control (RRC) layer.

For the PCell change, which is one of the focus topics in this sequel, the UE switches the serving cell and monitors non-UE dedicated channels, e.g., broadcast and paging channels, from another cell. The decision for initiating the preparation of the PCell change is network-controlled and is given by RRC layer based on cell quality measurements that are reported by the UE. Depending on the network configuration, UE may apply additional L3 filtering to the L1 measurements in order to reduce the fluctuations in the measurements (caused by fast fading and measurement errors) and increase in turn the reliability of the cell change decisions. The decision for cell change can be either taken by the network or by the UE depending on the configured mobility solution.

UE mobility is supported in NR for high variety of scenarios including single connectivity and Multi-RAT Dual-Connectivity (MR-DC) [6], intra-/inter-frequency and intra-/inter-RAT cell changes. Moreover, mobility is supported for different types of architectures including standalone with monolithic gNBs and split architecture with Centralized Unit (CU)-Distributed Unit (DU) where the gNB consists of two separate entities, gNB-CU and gNB-DU, that are connected to each other by standardized F1 interface [7]. gNB-CU consists of two separate entities, gNB-CU-CP and gNB-CU-UP that are connected to each other by standardized E1 interface [8].

On high level, the baseline handover (HO) framework in NR Rel. 15 for PCell change consists of three main phases as shown in Fig. 3 [2].

Figure 3. Baseline handover framework in NR Rel. 15.



- Handover preparation: Based on measurements that are reported by the UE, the source gNB controlling the source cell can decide to trigger the preparation of a target cell in a target gNB. Upon receiving the handover request from a source gNB, the target gNB performs admission control, reserves radio resources that are needed to serve the UE, and generates a handover configuration to be applied by the UE at the time of handover execution.
- Handover execution: The UE applies the handover configuration of a candidate target cell by reconfiguring its protocol layers and synchronizes to the target cell by performing random access. Upon successful random access, the UE confirms to the network the completion of the reconfiguration.
- Handover completion: In the last phase of the handover, the target gNB triggers Access and Mobility Management Function (AMF) to switch the downlink user plane path of the User Plane Function (UPF) from the source gNB to the target gNB which will be serving the UE. The UE context is finally released from the source node.

The mobility enhancements that are specified for NR, up to Rel. 18, impact mainly the handover preparation and execution phases. The handover completion phase has been kept so far intact as data forwarding of the user plane data from source to target node during handover execution enables service continuity.

Main mobility metrics

In this section, we provide an overview about the main mobility metrics that have been considered by 3GPP as main targets for enhancements starting from Rel. 16 up to Rel. 18.

Mobility robustness

Robustness of the mobility procedures against failures is one of the key performance indicators. The baseline handover mechanism of NR Rel. 15 is robust and reliable solution achieving a low probability of mobility failures that is enough for many services and UEs. Nevertheless, as any other radio related procedure, the handover signaling is prone to failures which can have detrimental impact for some UE services requiring high reliability. There are two types of mobility failures depending on whether the failure happens before or during the handover execution. The failure during the handover execution phase where the UE fails to synchronize and perform random access to the target cell is called handover failure. On the other hand, the failure that occurs before the handover execution phase while the UE is still connected to the source cell is mainly referred to as Radio Link Failure (RLF).

To recover from the failures, UE performs RRC Re-establishment procedure to reconnect to a new target cell. The re-establishment procedure is costly as the UE needs to perform cell selection and read the system information of the target cell before performing a contention-based random access. Moreover, the target cell receiving the re-establishment request needs to fetch the UE context from the previous serving gNB and reconfigure the UE before it can start serving the UE. Most importantly, UE will experience interruption time during and after the mobility failure occurs until the UE completes the RRC Re-establishment procedure successfully. Thus, it is critical for the network to minimize and avoid such failures.

For UEs in DC mode, the primary cell of the secondary cell group (PSCell) may also fail. The failure of PSCell is less critical in terms of overall connectivity as the UE may still have a functioning connection with PCell of Master Cell Group (MCG). However, the failure of PSCell can be still harmful for services that are provided by SCG offering in some cases higher system bandwidth and user throughput than MCG. From this perspective, it is desirable also to minimize PSCell failures as much as the PCell failures.

Mobility interruption

Any mechanism for cell change may introduce a certain interruption in the on-going service, which is called mobility interruption. The duration between the point in time when the UE stops transmission/reception to/from the source gNB and the time when target gNB resumes the transmission/reception to/from the UE is called the mobility interruption time. For instance, in the baseline handover mechanism that is presented in Fig. 2, the interruption starts from the reception of the RRC Reconfiguration (step 5) until the transmission of the RRC Reconfiguration Complete to the target gNB (step 8). The mobility interruption time includes the processing of the RRC message, L2/3 reconfigurations, the random access procedure and the transmission of the RRC message confirming the reconfiguration to the target gNB. The mobility interruption time varies depending on the scenario, e.g., intra-frequency or inter-frequency handover, and can reach up to 80 ms [9].

Mobility interruption time is critical for services requiring high reliability or small outage. For example, AR/XR services may be hindered by the interruption time introduced by the handovers [10][11]. The same applies for URLLC or vehicular communication services such as “Automated Intersection Crossing” or “Cooperative Maneuvers”. Due to its high relevance, 3GPP has started to address mobility interruption time early in 5G with Rel. 16 and will continue to work on this in 5G-Advanced.

Mobility signaling overhead

Another mobility aspect is the signaling overhead that is associated with the change of cell, Secondary Cell (SCell) or cell group, i.e., Secondary Cell Group (SCG) or Master Cell Group (MCG) in NR-Dual Connectivity (NR-DC) deployments, and the high delay in triggering the cell change.

Up to Rel. 17, the UE releases all stored configurations for candidate target PCells or Primary Cells of Secondary Cell Group (PSCells) upon performing a successful handover or PSCell change, respectively. Triggering a subsequent handover or PSCell change requires the network to re-initiate the cell change preparation procedure from scratch even though the UE has stored configuration for the same candidate target cell before the switch to new cell group. This does not only increase the signaling overhead over the radio and network interfaces, but it also delays the execution of the handover or PSCell change which can lead to some outage or even failures. These aspects are especially relevant in high carrier frequencies where there is high number of cell group switches and UE received signal is more vulnerable to rapid degradation caused by blockage from user body, hand or other obstacles.

Mobility configuration and decisions

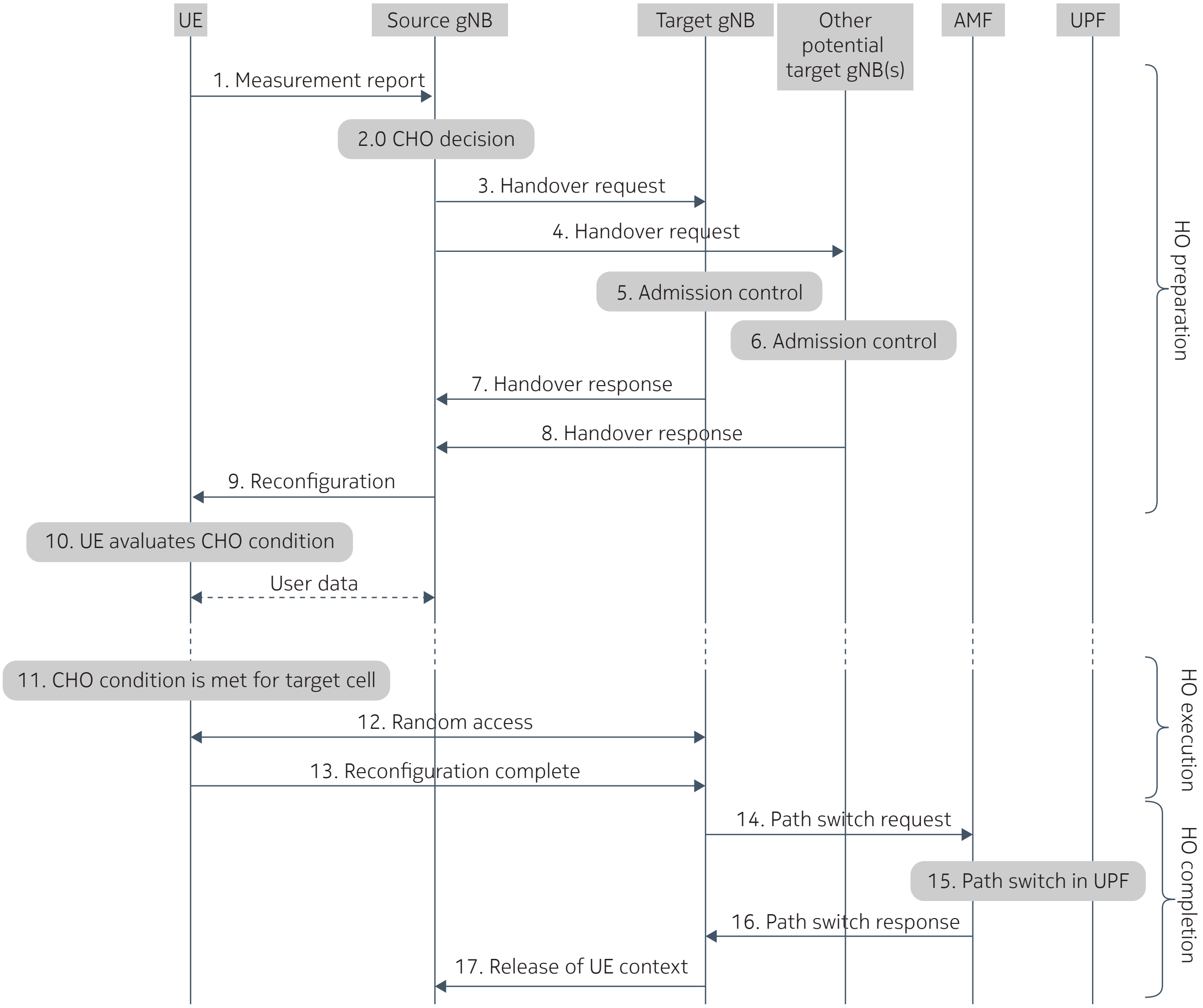
The performance of the mobility procedures highly depends on the proper configuration of the parameters controlling the handover and the decisions made by the source and target nodes. For instance, the handover parameters controlling the triggering of the measurement report in step 1 of Fig. 3 needs to be properly configured such that the UE can still receive the RRC Reconfiguration message from the source node in step 5 and at the same time be able to perform a successful random access to the target node in step 7. In addition, the source node should make in step 2 the right decision on the target cell to be prepared in the target node. To ease the handover parameter configuration for the network operators, Nokia has been developing Self Organizing Network (SON) solutions that automatically optimize the mobility parameters based on performance metrics that are collected periodically from the network. In 5G-Advanced, the optimization of the mobility parameters and decisions will benefit further from the cutting-edge AI/ML techniques that can leverage the dependencies among different handover parameters, cell borders and network nodes.

Mobility enhancements

Conditional handover for improved robustness

Most mobility failures are caused by the failure of receiving the handover command (step 5 of Fig. 3) on time from the source cell. To address this issue, CHO has been introduced in NR Rel.16 where the handover preparation is de-coupled from the execution phase as shown in Fig. 4. Herein, the source node triggers the preparation of one or more target cells early when the UE still has a very good radio link to the source node. The source node provides the configurations of the prepared target cells to the UE in step 9 along with a CHO execution condition that is associated with each prepared target cell.

Figure 4. Conditional Handover framework in NR Rel. 16.



After receiving the configurations of the target cells, the UE evaluates the CHO execution conditions to trigger the handover execution when the condition is met as shown in step 11. The remaining steps related to handover execution and completion are similar to baseline handover of NR Rel. 15 shown in Fig. 3, with some modifications to support early and late data forwarding from source node to the target node of the handover procedure [2].

Due to its improved mobility robustness performance, CHO has been adopted by many 5G verticals such as Non-Terrestrial Networks (NTN), Integrated Access and Backhaul (IAB) networks and NR-Unlicensed (NR-U) [12].

To improve the robustness of PSCell change in MR-DC scenarios, Conditional PSCell Change (CPC) has been introduced for intra-SN (PSCells from same node) and inter-SN (PSCells from different nodes) scenarios in Rel. 16 and 17, respectively. CPC follows the same conditional reconfiguration paradigm of CHO where the UE is prepared early with one or multiple candidate target PSCells and execute the change to a prepared target PSCell when its corresponding condition is met. This would improve the reliability of the PSCell change and reduce the interruption time for the services that are provided by SN.

Further enhancements for CHO in MR-DC scenarios will be studied in 5G-Advanced Rel. 18 [13]. Herein, the radio link quality of the target PSCell will be considered by the UE for initiating the random access to target SN when CHO execution condition is met for the corresponding target PCell. This inter-working between CHO and conditional PSCell addition/change will improve the robustness of both PCell and PSCell change in inter-MN handover scenarios.

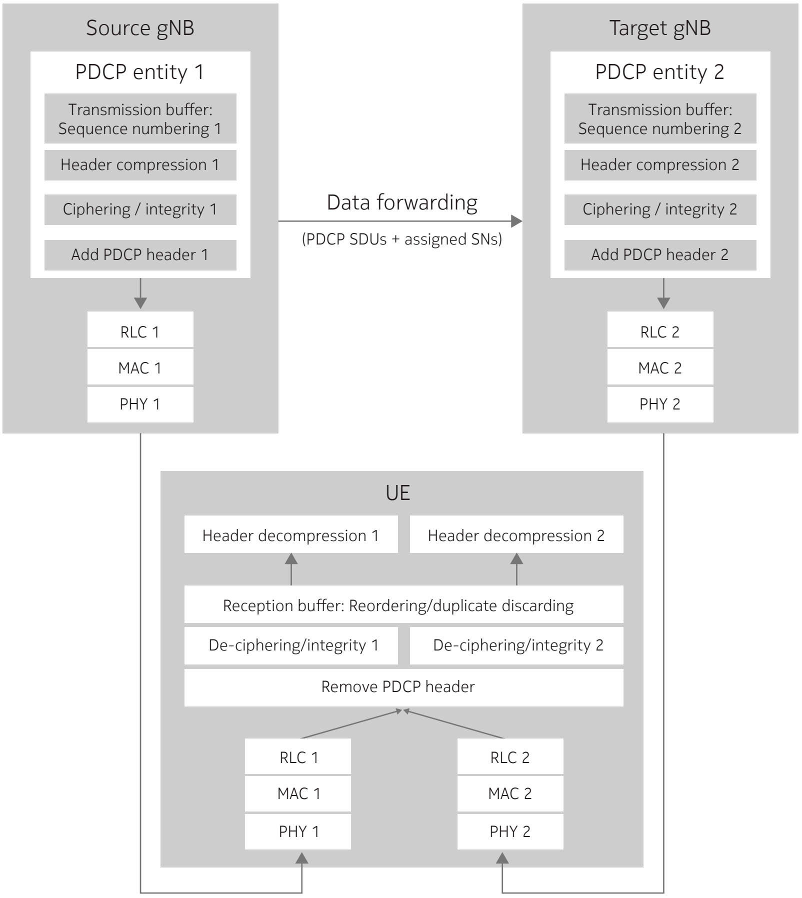
Mobility solutions for reduced handover interruption time

Dual Active Protocol Stack (DAPS) handover has been introduced by 3GPP in Rel. 16 as the first NR solution to reduce interruption time during the handover. The main difference between DAPS and baseline handover of Rel.15 is the handover execution phase which has been enhanced to minimize interruption time. Mainly, after receiving the handover command the UE maintains the connection with the source gNB and continues to receive user plane packets while performing access to the target gNB. This avoids that the UE experiences user plane outage while waiting for the target cell radio link to be ready. After completing the random access, the UE starts to receive user plane packets simultaneously from both the source and the target cells until the source cell is released by the target cell. The UE switches the uplink user plane transmissions to target cell when random access is completed. Path switch is then triggered during the handover completion phase by the target node in the same way as in baseline handover.

Fig. 5 illustrates the dual protocol stack maintained at the UE during DAPS handover to receive downlink packets simultaneously from both source and target cells. As can be noticed, the UE has dedicated physical (PHY), MAC and Radio Link Control (RLC) layers for source and target cells. Moreover, the Packet Data Convergence Protocol (PDCP) has been enhanced to support separate (de)-ciphering and header (de)-compression layers with common functionality to re-order and discard duplicate packets received from source and target cells [14].

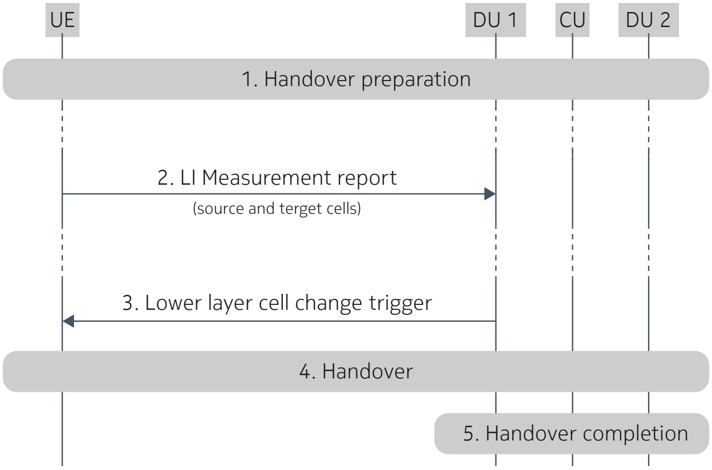
DAPS handover can reduce the handover interruption down to 2 ms [15]. As for the UL, there is an additional end-to-end delay, i.e., in addition to 2 ms, as the target gNB can send the received packets to UPF only after the target gNB contacts the source node and receives information about the first UL packet that needs to be forwarded.

Figure 5. Downlink operation of dual active protocol stack (DAPS) handover.



One limitation of DAPS handover is that it does not support the scenario where source and target cells operate in higher frequencies, thus leaving a gap for FR2 connectivity. The main reason for this is that 3GPP could not conclude in Rel. 16 that multi-panel UEs would be able to communicate simultaneously with two gNBs operating in FR2. Additionally, the implementation of two simultaneous active protocol stacks might be for the time being challenging for some UE vendors. For these reasons, 5G-Advanced will study L1/2 inter-cell mobility in Rel. 18 as an alternative solution to reduce the interruption time during handover for both FR1 and FR2. L1/2 inter-cell mobility is expected to work for UEs with single active protocol stack and to operate in CU-DU split architecture where the CU hosts the RRC and PDCP layer and the DU controls the lower PHY, MAC and RLC layers. Moreover, only intra-CU handovers will be considered at the first stage for L1/2 inter-cell mobility to reduce the interactions with other CUs/gNBs. Fig. 6 shows the high-level signaling for L1/2 centric mobility solution in 5G-Advanced.

Figure 6. High-level Signaling for L1/2 centric mobility.



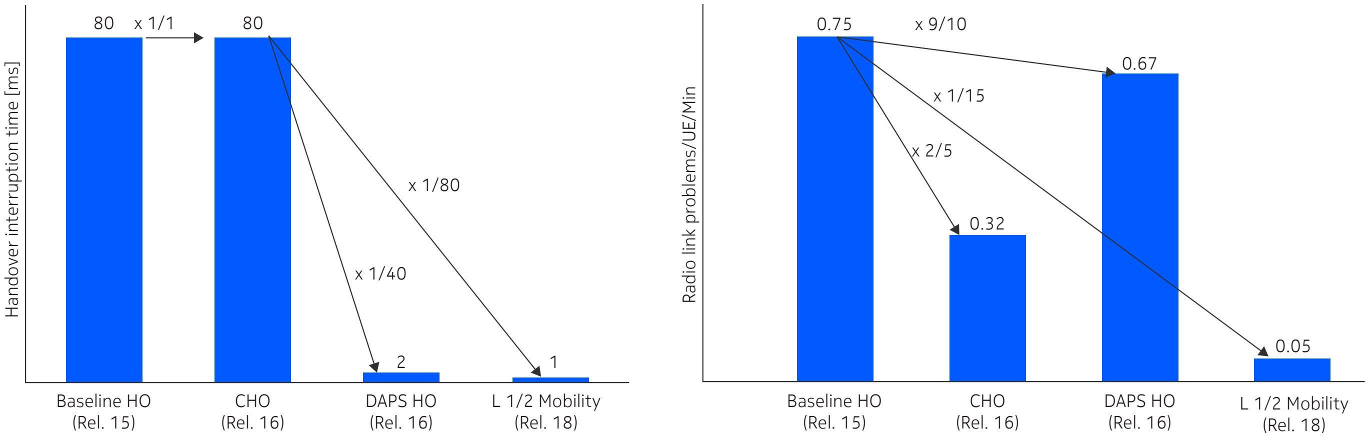
The CU may initiate in step 1 the preparation of multiple target cells in serving DU 1 or another DU 2 and provide their corresponding configurations to the UE. Based on L1 beam measurements for source and target cells that are reported to the network in step 2, the serving DU 1 may trigger the handover to another cell using lower layer signaling as shown in step 3. When executing the handover in step 4, the UE does not need to spend much time on reconfiguring the higher PDCP and RRC layers and may skip the random-access procedure in case of synchronized cells which reduce substantially the handover interruption time.

The performance of the main mobility enhancement procedures in 5G and 5G-advanced is illustrated in Fig. 7 with respect to handover interruption time expressed in ms and the normalized number of radio link problems (RLPs), i.e., the number of times the radio link quality of the serving cell falls below the acceptable level for reliable radio communication. The results for the RLPs are shown for 3GPP compliant Urban Macro (UMa) [16] with 7 sites, each with 3-sector applying analog beamforming, i.e., one serving beam at a time. The results are generated for a UE speed of 60 km/h.

According to the figure, the handover interruption time of CHO (Rel. 16) is similar to that of baseline handover of Rel. 15 which can be up to 80 ms as stated in [9]. DAPS HO of Rel. 16 reduces the handover interruption by a factor of x 1/40 compared to baseline HO/CHO. The upcoming L1/2 inter-cell mobility solution is expected to reduce the interruption even more by a factor of 1/80. As such, it should be possible to reduce the handover interruption time down to 1 ms in L1/2 centric mobility [9] which would be useful for services requiring ultra-high reliability.

In addition, CHO reduces the number of radio link problems by a factor of x 2/5 compared to BHO. This is because the UE receives the configurations of the candidate target cells early which allows the UE to autonomously trigger the cell change before the radio link of the serving cell fails. The number of RLPs did not improve much for DAPS HO which was aiming at reducing the handover interruption time and not improving mobility robustness. As for L1 centric inter-cell mobility, the number of radio link problems are reduced substantially by a factor of x 1/15 compared to baseline handover of NR Rel. 15. This is because the cell change is decided based on L1 beam measurements that do not suffer from the delay caused by L3 filtering and Time-To-Trigger (TTT) applied for cell quality measurements. This allows the network to react fast to the degradation in the radio link quality of the serving cell and trigger the handover fast with minimal interruption when needed. Fast triggering of the handover may lead to increase in ping-pongs (consecutive forth and back handovers). However, these ping-pongs are not that critical for L1/2 centric mobility given that the signaling between the source and target cells are handled in the same DU entity (in case of intra-DU cell change) and the interruption time during L1 cell change is small and not costly as in baseline handover or CHO.

Figure 7: Performance comparison of baseline handover, conditional handover (CHO), DAPS HO and L1/2 centric mobility.



Fast failure recovery mechanisms

Despite mobility failures are rare events in the network, fast recovery mechanisms are specified in 5G to mitigate the service interruption time caused by failures and the additional signaling overhead and delay of the re-establishment procedure.

In order to reduce the UE outage time before failure detection, 5G has adopted T312 timer which allows the UE to initiate the re-establishment procedure earlier, and consequently, recover the radio link faster [4]. The UE starts a timer T310 when the physical layer detects that the radio link of the serving cell is degrading. In case the UE sends a measurement report to the serving cell, i.e., identifying a target cell for handover, the UE can start another T312 timer if timer T310 was already running. If the UE does not receive from the serving cell a command to trigger the handover before T312 timer expires, UE declares RLF and initiates the re-establishment procedure. As the value of T312 is configured to be much less than that of T310, the UE can perform a faster failure recovery as it does not need to wait anymore for T310 timer to expire for initiating the re-establishment. Note that shortening the value of T310 timer is not an option as the UE may start to declare unnecessary failures that are caused by temporary signal degradations and which can be recovered without re-establishment procedure that is costly in terms of additional signaling and service interruption time.

CHO recovery is another feature that has been introduced by 3GPP in Rel. 16 to reduce the interruption time caused by failures for UE that is configured with conditional reconfigurations for multiple target cells. Despite CHO minimizes the probability of mobility failures, it is still possible that UE detects a failure due to misconfiguration of the mobility parameters or handover execution to wrong cell etc. Instead of performing re-establishment, a UE supporting CHO recovery feature can make use of the stored conditional reconfiguration for prepared target cells to recover from the failure. After the failure is declared, UE initiates the cell selection and if selected cell is one of the prepared target cells, UE executes the handover towards that cell using the configuration that was provided previously by the network. Otherwise, the UE initiates the re-establishment procedure to the selected cell if it does not have a corresponding conditional configuration. Hence, using CHO recovery, the UE can leverage the stored conditional configurations for target cells to initiate a CHO execution instead of costly re-establishment procedure, reducing thereby the interruption time after the failure.

Figure 8. Performance of CHO recovery [12].

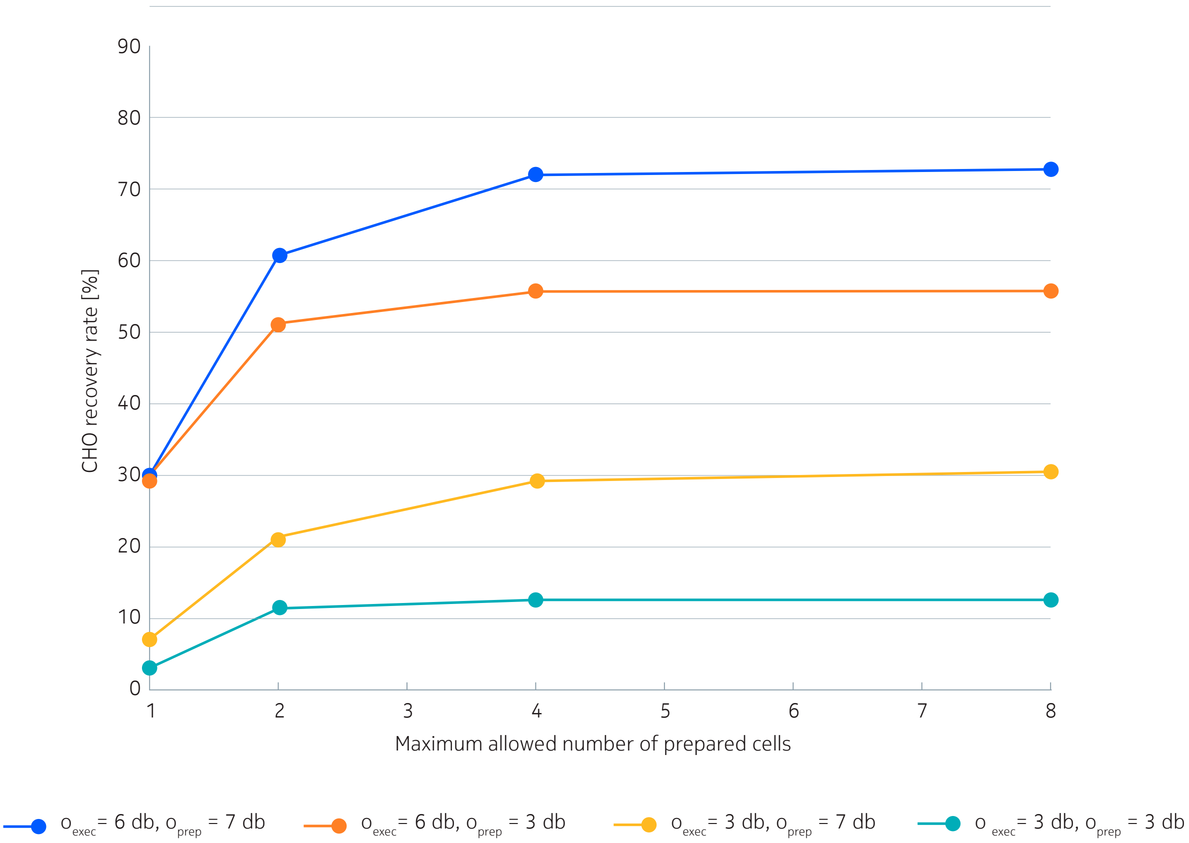


Figure 8 shows the mobility performance of CHO recovery mechanism. The CHO recovery rate, defining the percentage a CHO is executed after a failure instead of re-establishment procedure, is shown as a function of maximum allowed number of prepared cells for different CHO preparation offset o_{prep} and execution offset o_{exec} [12]. A target cell is prepared if it is not weaker than the source cell by more than o_{prep} dB and the CHO is executed if the target cell becomes o_{exec} dB stronger than the source cell. CHO recovery rate shows the percentage of the failures that are resolved by executing CHO instead of performing the costly re-establishment procedures. In those simulations, UMi-street canyon propagation channel model is used, where path-loss, shadow fading, fast-fading, and soft LOS are considered [16]. Each cell is configured with 12 transmit/receive beams and can schedule/activate 4 beams simultaneously for increased spatial multiplexing. The network layout is 7-site hexagon where each site has 120° sectoring (3 cells on one site) and there is 200 m inter-site distance (ISD) between the neighboring sites. In the simulated scenario, the mobility performance of the UEs is investigated for a user speed of 60 km/h.

The initial observation from Figure 8 shows that increasing the maximum number of prepared cells increases the chance that the CHO recovery could resolve the failure problems, i.e., CHO recovery rate increases by ~5% (shown in cyan) up to 45% (shown in dark blue). This is because when more cells are prepared, it is more likely that the cell selection procedure results in selecting one of the prepared cells to which the UE can perform CHO recovery. Apart from that, in either case, i.e., execution offset of o_{exec}=3 dB or o_{exec}=6 dB, CHO recovery rate increases by 20% when the preparation offset o_prep is increased by 4 dB since larger preparation offset enables earlier preparation of the target cells which can be a selected cell during cell selection after failure and CHO recovery. Last but not least, the benefit of the CHO recovery is pronounced more when the CHO execution offset o_{exec} is high, i.e., 6 dB where the higher CHO execution offset postpones the CHO execution and leads to failure. In those cases, UE can use the CHO recovery procedure where CHO recovery rate increases by 45% when o_{exec} is increased by 3 dB. Hence, delay caused by re-establishment procedure is mitigated by using CHO recovery mechanism.

As mentioned before, DAPS handover can reduce the handover interruption time close to zero ms. However, the execution of DAPS handover may not always be successful depending on the radio conditions of the source and target cells. It may happen that the DAPS handover is triggered early by the network leading to random access failure at the target cell. Unlike baseline handover procedure of NR Rel. 15, UE does not experience service interruption during target cell access failure since UE still maintains the connection with source cell. Thus, if the random access fails to the target cell and the radio link of the source cell is not in failure, the UE fallbacks back to the source cell configuration by releasing the protocol stack of the target cell. In this way, the UE remains connected to the network without the need to initiate the re-establishment procedure after a random access failure.

Slim mobility for fast cell switching

In order to reduce the signaling overhead associated with the cell change and reduce the delay in the execution, fast cell switching among candidate serving cells is considered in NR Rel. 18 under L1/2 inter-cell mobility. Herein, dynamic switching is foreseen among candidate serving cells and SCells using lower layer signaling, where the cells are controlled by the same Centralized Unit (CU). This is particularly relevant for FR2 scenarios where dynamic shadowing caused by user and moving obstruction is dominant resulting in high number of handovers.

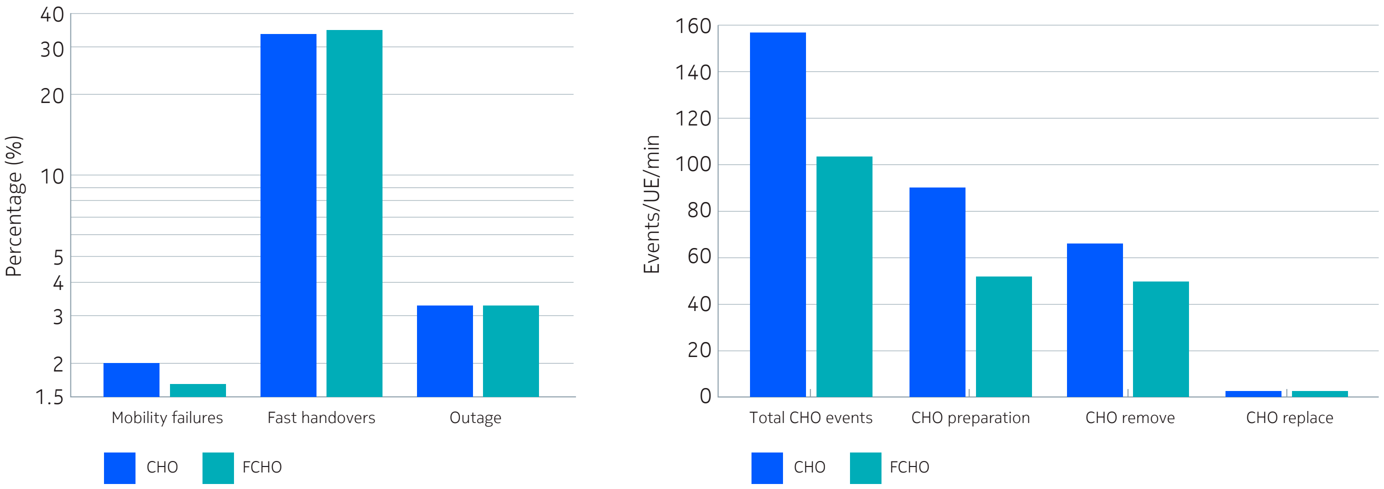
The concept is also candidate to be extended in NR Rel. 18 for L3 mobility where subsequent change of CG (at least for SCG) can be initiated without L3 reconfiguration in NR-DC deployment. Despite the differences in the approach of triggering the cell change and applicable scenarios, a common Radio Resource Control (RRC) signaling would be desired for both enhancements to leverage the synergies.

The solutions for fast cell switching require that the UE is prepared beforehand with multiple candidate serving cells, SCells or CGs in a similar way to CHO/CPAC. The set of cells/CGs to be prepared can be decided by the gNB using measurement reports that are configured to the UE. In contrast to CHO/CPAC, the UE and the network shall maintain at least some of the configured preparations after the cell/CG change is successfully executed. In this way, a subsequent change of the cell/cell group can be triggered without re-initiating the preparation and performing reconfiguration. For this to work, it is necessary that the stored configurations at the UE side remain valid for execution after the cell/CG change, i.e., does not lead to RRC reconfiguration failure when applied, and the UE is always configured with the preparation of the right candidate cells/CGs. For the latter case, the network may need to configure the UE with new cells/CGs and/or release some stored configurations that are no longer relevant for the mobility of the UE.

Applying fast switching for MCG can save the first five steps of Fig. 3 if the UE keeps the configurations of relevant prepared candidate cell groups after the CG change. This can result in saving at least 2 RRC messages on radio interface and 2 other messages on the Xn interface which in turn reduces the delay in triggering the CG change by at least 40-50 ms. For CU-DU split architecture, the benefits are even more pronounced as the signaling between CU and DU over F1 interface and between CU-CP and CU-UP over E1 interface are also saved.

The performance of fast selective switching of MCG based on CHO framework, denoted by FCHO, is compared against CHO in Fig. 9 [17]. The simulation scenario is the same as that used for Fig. 8. In FCHO, the CHO configurations of the candidate target PCells are kept after the handover whereas in CHO they are released by the UE after CHO execution/handover. The comparison is performed with respect to percentage of mobility failures, fast handover (consecutive handovers within short time comprising of ping-pongs and short stays), outage and total number of CHO events. The latter consists of the sum of CHO preparation events (number of times a target cell is prepared), CHO remove events (number of times a prepared target cell is released) and CHO replace events (number of times a prepared cell is replaced by another cell having better radio link quality). As shown in Fig. 9, the total number of CHO events is reduced by approximately 38 % compared to CHO. This is because the UE keeps the CHO configurations of candidate target cells after the handover, and consequently, the network does not have to re-trigger the preparation of the cells which reduces substantially the signaling overhead on the radio and network interfaces. In addition, the percentage of mobility failures decreases since the UE can trigger the handover faster given that it keeps the configurations of the candidate target cells.

Figure 9. Simulation results showing the benefits of fast selective switching of cell group [17]



Machine learning for mobility

It is challenging to find optimal settings for handover decisions with conventional mobility solutions and MRO methods which highly rely on the stationarity of the performance metrics collected from the network. In contrast, Artificial Intelligence (AI)/Machine Learning (ML) algorithms can learn the local context, e.g. radio environment, UE measurements, UE mobility pattern/trajectory, network traffic pattern, service-specific requirements, etc. , and provides the opportunity for a “tailor-made” handover triggering decisions. As such, a much better mobility performance is achieved considering dynamicity of the environment.

AI/ML solutions for mobility would aim at reducing the probability of mobility failures and ping-pongs by triggering the handover on time and selecting the right target cell of handover. Moreover, saving on network and radio resources can be achieved through, e.g., predictions of measurements or the time window in which the UE is expected to perform handover allowing a prepared target cell to make overbooking of the reserved resources.

3GPP Rel. 18 will specify for 5G-Advanced solutions for enabling AI/ML functionality in RAN and Core and the needed inputs and outputs for AI/ML. One of the considered main use cases is mobility optimization which is going to consider the following aspects [18]:

- The location of AI/ML model training and AI/ML model inference.
- AI/ML related signaling aspects between RAN nodes and UE.
- Input data from various network entities and UE for AI/ML model training and inference.
- Output of the model and performance feedback of AI/ML model.

Further information on AI/ML 3GPP study for RAN can be found in [19].

DCCA enhancements

Another mobility related aspect is efficient cell management for cases with Carrier Aggregation (CA) and/or Dual Connectivity (DC). For harvesting the full benefits of CA/DC techniques, it is important to have an agile framework where secondary cell(s) are timely identified and configured to the UE when needed. This is of importance for non-standalone (NSA) deployments where a carrier on NR should be quickly configured and activated to take advantage of 5G. Similarly, it is of importance for standalone (SA) cases where e.g. a UE with its Primary Cell (PCell) on NR Frequency Range 1 (FR1) wants to take additional carriers, either on FR1 and/or FR2 bands, into use. Thus, there is a need to support cases where the aggregated carriers are either from the same or difference sites. The management of such additional carriers for a UE shall be highly agile in line with the user traffic and QoS demands; quickly enabling usage of additional carriers when needed and again quickly released when no longer demanded to avoid unnecessary processing at the UE and to reduce its energy consumption. This is of particular importance for users with time-varying traffic demands (aka burst traffic conditions).

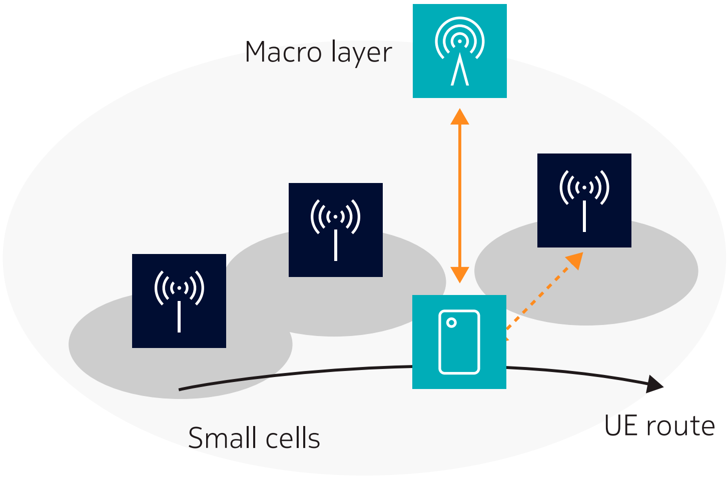
In the following, we describe how such carrier management is gradually improved by introducing enhancements for cell identification, RRM measurements and reduced reporting delays from UEs. As well as innovations related to Conditional PSCell Addition and Change (CPAC) and deactivation of secondary cell groups are outlined.

Early measurement reporting

Offloading traffic to small cells is one of the key enablers in achieving high peak data rates in a heterogeneous cellular network deployment. However, to maintain the benefit of robust mobility offered by the macro cell layer, ideally the connection to the macro cell is still maintained even when bulk of the user data is offloaded and served in a higher capacity small cell. Hence, enabling fast access to the offloading layer has the opportunity to increase the user data perceived throughput by a factor of 5x-10x.

In 3GPP based systems (LTE and 5G NR), multi-link setup getting the best of both worlds can be achieved by CA or DC – which one of these is used depends on the deployment and the back-haul latency between the macro and small cells. An example of heterogeneous network deployment with inter-site small cells (e.g. inter-site CA or DC) is illustrated in the schematic of Fig. 10.

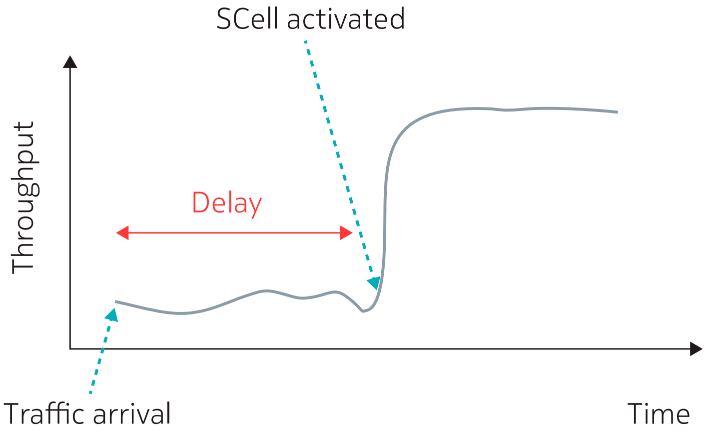
Figure 10. Heterogeneous network deployment with inter-site small cells.



A large part of the delay in accessing the (P)SCell comes from the inter-frequency or inter-RAT measurements (which can be 500+ ms, depending on number of measured frequency layers). This reduces the benefit of CA/DC as the larger bandwidth can be only configured later on, which may degrade connection throughput and latency that the user experiences. The challenge in this case is the delay in getting the best small cell configured for the UE fast enough to maximally benefit out of it, either as a Secondary Cell (SCell) in CA or as a cell in Secondary gNB (SgNB) in DC.

Delay in accessing the small cells represents the main challenge: In LTE, it can take over 500 ms (per measured carrier) to discover, measure (reliably), report, configure and activate a small cell as a SCell in CA. In NR, similar problem is experienced, and the magnitude of the delay in FR1 is similar to LTE. In practice, this means that the potentially very high data rate of the small cell (up to 10-100x data rate compared to the macro cell, depending on e.g. the bandwidth and cell load) is not truly perceived by the user due to the delay in setting up the SCell, as illustrated in Fig. 11.

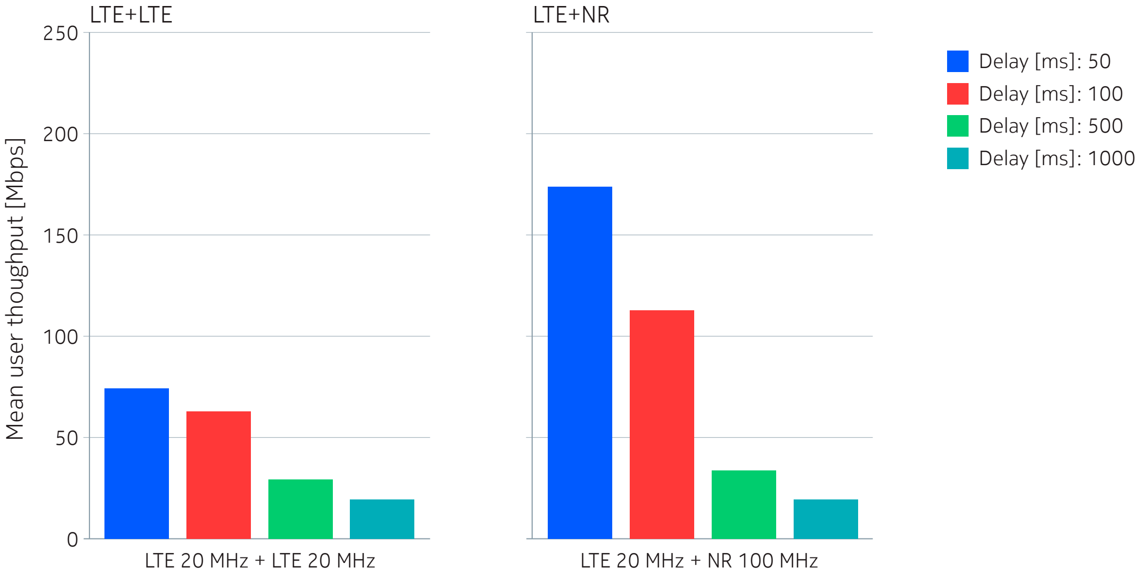
Figure 11. Illustration of the observed performance bottleneck resulting from the delay in setting up the CA/DC and getting inter-frequency small cell activated on time.



Nokia pioneered the solutions of the fast access in case of CA/DC, initiating and leading the work in Rel-15 LTE and continuing as co-leader in bringing the LTE approach to Rel-16 NR.

Reducing the measurement delay (i.e. biggest contributor to the (P)SCell setup delay) improves latency of (P)SCell set-up times for all scenarios including the transition from RRC Idle/Inactive to Connected for first time CA/DC setup and (P)Scell addition in RRC CONNECTED. This results in improved UE throughput and paradoxically, even achieves lower UE power consumption because UE easily ends up having shorter active time in CONNECTED. Standardized solution for both Rel-15 LTE and Rel-16 NR has in its fundamental the following structure: UE will perform Idle/Inactive mode cell measurements (or early measurements reporting (EMR)) to enable faster (P)SCell setup immediately after data arrival. This will lead to multiplying the user perceived throughput by a factor of >5x. Example benefits are given in Fig. 12 which shows the mean user throughput [ms] as a function of the measurement delay for both LTE + LTE and LTE + NR scenarios, and also illustrates how NR can provide more benefits due to larger amount of available bandwidth.

Figure 12. Performance analysis of fast CA/DC setup (Rel-15 LTE, Rel-16 NR)



The major benefits of CA/DC setup delay reduction are seen in both UE and NW side:

- Reduced CA/DC configuration and activation delays.
- Improved (P)SCell usage leading to more efficient (P)SCell utilisation.
- Faster data offloading from PCell.
- Enhanced resource utilization in the CA/DC network.
- Improved user throughput.
- Enhanced capacity, especially when PCell capacity is limiting and wide BW available for (P)SCell.

As a next step, 3GPP will study in Rel. 18 the impact of FR2 mobility measurement and reporting on the SCell/SCG setup/resume delay for a UE connecting from RRC Idle/Inactive mode. The outcome of the study may result in defining new UE measurement procedures or reporting and related RRM core requirements [13]. As a result, the CA/DC setup delay of SCell/SCG in FR2 will be reduced due to enhanced UE measurements.

Secondary cell activation time improvements

In this section, an overview of two main enhancements for SCell activation time is provided.

Direct SCell activation

With legacy CA, all SCells are in deactivated state upon configuration and after handover, requiring an additional MAC-based activation afterwards. As part of fast CA/DC set-up and configuration, an additional mechanism called Direct SCell Activation was introduced to improve the overall latency of setting up an activated SCell. As with EMR framework, Direct SCell Activation was first introduced in Rel-15 LTE and then later also introduced in Rel-16 NR. The Direct SCell Activation allows to have the SCell configured in activated state immediately, which reduces latency of SCell activation by removing the need for separate SCell activation message. This ensures more efficient CA since the network can retain previously activated SCells as active even during mobility or change of SCell. This was further enhanced in Rel-17 by adding better control of the beam management (i.e. TCI state) for the SCell, allowing more control for the network to select the beam serving the UE in the SCell.

TRS-based SCell Activation

When a deactivated SCell is activated, the UE needs to first receive Synchronization Signal Block (SSB) of the SCell for fine time tracking purposes. The periodicity of SSB transmission may vary and can be up to 160 ms, which introduces a fixed minimum delay to the overall SCell activation delay. Rel-17 NR introduced an additional method to aid the faster CA/DC setup, called temporary RS (TRS) - based SCell activation. The method enables the network to transmit a burst of UE-specific RS to aid the UE in time/frequency acquisition in the SCell, and UE will use additional RS signals for time tracking without having to wait for the cell-specific signals (SSB). As these additional reference signals are provided immediately after the MAC-CE command for SCell activation, they are available for the UE immediately and the UE can measure these without delay, which enables faster SCell activation by eliminating the fixed SSB acquisition delay.

Conditional SN addition and change for fast access

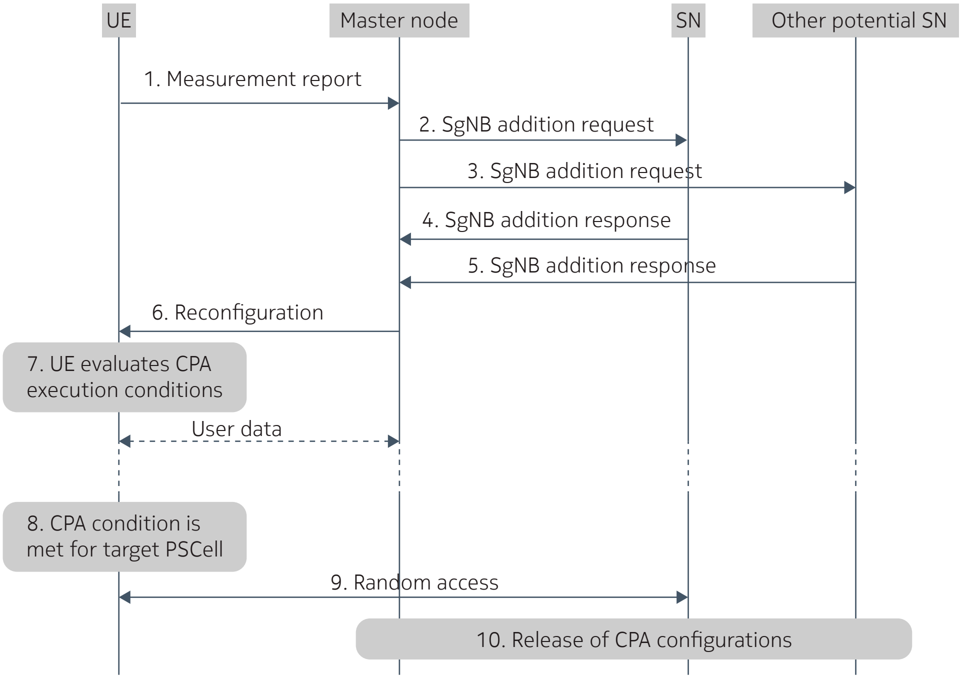
It takes time if the network wants to establish DC for the UE in RRC Connected and use additional radio link towards another node (Secondary Node). Several messages need to be exchanged – between the UE and the Master Node (MN) and also between the MN and the future Secondary Node (SN). Upon receiving an acknowledgement from the SN, MN reconfigures the UE which may then attempt to access the SN by performing random access procedure. As can be noticed, those multiple steps introduce a delay which elapses from the point in time when the radio measurements for candidate SN are to be reported to the MN until the UE is reconfigured. Enhancements have been introduced in 5G to reduce the latency in accessing the SN which in turn allow the UE to be benefit as early as possible from the high throughputs of small cells.

Conditional PSCell Addition Change (CPAC) has been defined as a part of 3GPP Release 17. The scope was twofold: to enable conditional setup of SN denoted by Conditional PSCell Addition (CPA) and to allow changing the PSCell in conditional manner denoted by Conditional PSCell Change (CPC). Both solutions (i.e. CPA and CPC) are aimed at reducing the delay to access the SN as the UE can perform random access to PSCell directly after the condition is met, without reporting the measurements to the network and awaiting the corresponding cell change configuration. As stated before, CPC brings additionally another benefit of improving the robustness of PSCell as the UE is prepared in advance with configuration of the candidate target PSCell.

Fig. 13 shows the high-level signaling diagram for CPA [6]. Upon receiving measurement report from UE identifying potential target PSCells, MN triggers the preparation of one or multiple PSCells that are controlled by same or different SNs as shown in steps 2-5. MN provides the configuration of the target

PSCells in step 6 along with CPA execution condition that is associated with each prepared target PSCell. After receiving the configuration, the UE evaluates the CPA execution conditions while continuing the user plane communication with MN. Once the CPAC execution condition is met for a prepared target PSCell, the UE executes the corresponding stored configuration and performs access to the target PSCell for quickly establishing DC in step 9, i.e., no further communication with the network (causing delay) before performing access. Finally, MN releases the CPA configurations and associated reserved resources from other prepared SNs.

Figure 13. High-level signaling for conditional PSCell addition (CPA) in MR-DC.



For CPC, there may be two slightly different approaches: MN-initiated CPC and SN-initiated CPC [6]. The former is triggered by the MN without any message exchange with the source SN. The latter is initiated by the source SN and the preparation on the NW's side is performed through the MN. The signaling diagram for both approaches is very similar to CPA of Fig. 13 except that the UE is configured to conditionally change a PSCell rather than adding it for first time. Moreover, there is no specification support for the direct interface between the source SN and candidate target SNs.

Activation of secondary cell group

The NR radio may not be actively used due to e.g., a temporarily unavailable radio connection because of interference or power saving reasons. In these cases, it is desirable to optimize the dual connectivity between LTE and NR such that the NR radio is directed to a power efficient state allowing UE to perform less measurements, thus saving the UE power consumption. This requires having possibility to quickly disable and re-enable the use of LTE-NR dual connectivity. Hence, MR-DC operation might need to be stopped for a while even during RRC Connected (e.g. due to UE power saving), but it would be beneficial to be able to reactivate it fast whenever needed.

In an MR-DC type of deployment, one valid question is what will happen to the second radio leg (i.e. the DC-leg) when the active data transmission (offloading) ends and the need for a second leg would be less. The obvious solution would be to revert back to single connection, where UE will keep the primary leg active which is needed for mobility anchoring (for example) or lower-intensity traffic activity, e.g., keep alive messages. However, this behaviour may not be desirable in case data traffic is bursty and data activity is quite unpredictable. In order to achieve a fast offloading and high peak data rate, the second radio leg needs to be set up fast and activated. On the other hand, when the data traffic is low, then there are clear UE power saving opportunities where UE would benefit of lower measurement effort.

To enable a fast offloading and high peak data rate, there is a trade-off that needs to be achieved between 1) fast offloading in case of secondary radio link activation and 2) UE power saving in case of low activity. Furthermore, compared to release and reconfiguration of the SCG, activating a suspended SCG reduces the latency and signaling overhead. For this, a new mechanism was introduced in MR-DC Rel. 17 work item [20] where gNB can indicate to UE to de-activate at least the NR part of the LTE-NR DC so that UE retains the configuration but does not use it. While SCG is de-activated, UE can be still configured by the network to perform radio link monitoring for primary cell of SCG (PSCell), i.e., to be able to declare SCG RLF (S-RLF), as well as RRC measurements, i.e., to be able to trigger RRM measurement reports. Additionally, UE can be configured to perform beam failure detection to ensure network is aware of beam failure occurrence.

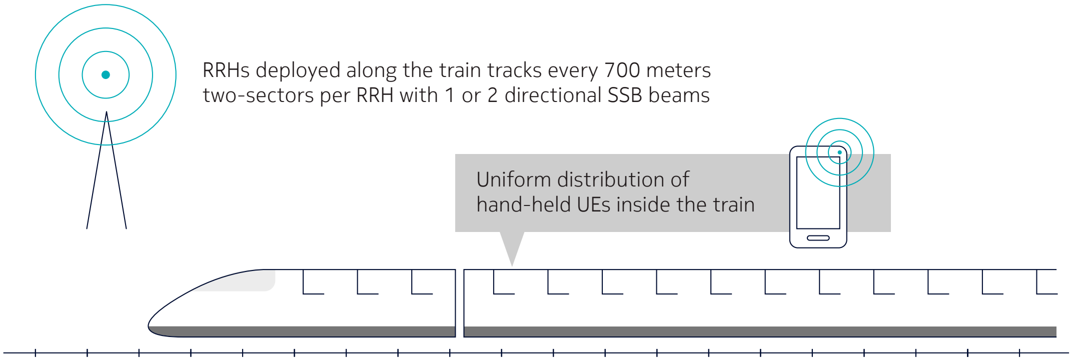
The difference with Rel.16 is the behaviour on PSCell, which in earlier releases was always active, while in Rel. 17 a new mechanism was defined for the case of being deactivated, i.e., to enable SCG de-activation. In practice this means that UE will not monitor the control channel (PDCCH), nor it will have CSI or Power Head Room (PHR) reporting for the deactivated PSCell or SCells of the deactivated SCG. In the event of reception of an SCG activation command from the network, the UE shall access the SCG again. This requires RACH towards the SCG only if PSCell has changed since the last time SCG was active, Timing Advance (TA) timer for the PSCell has expired or UE has detected an RLF or beam failure for the PSCell.

With this mechanism, the UE is able to de-activate the SCG and activate it fast if needed for a fast offloading opportunity, yet at the same time, saving battery if SCG is not in use. Hence, this achieves a positive trade-off between UE power saving and fast setup of DC.

High-speed train scenarios

High-speed train (HST) scenarios are obviously challenging from a mobility point of view due to the high velocity and therefore the needs for frequent handovers of UEs (or cell reselections for IDLE mode UEs). The UE requirements to ensure satisfactory HST mobility performance for FR1 was part of the Release 16 scope with special focus on ensuring sufficiently fast and reliable cell identification requirements, beam management requirements, and cell reselection requirements to support such use cases. Use cases with train velocities of up to 500 km/h with the hand-held UEs inside the train at 3.5 GHz carrier frequency were considered. As for the earlier LTE HST studies, the NR HST FR1 deployments with both so-called open space inter-RRH (Remote Radio Head) distances of 700 meters and Tunnel cases with inter-RRH distances of 300 meters were studied. Considering cases with one or two SSB beams per sector of the RRHs as pictured in Fig. 14, link-level studies confirmed that the higher Doppler shift (at 500 km/h) effects on the RRM measurement accuracy of SSB and CSI-RS did not impact the corresponding accuracy requirements. From advanced dynamic system-level simulations, it is concluded that with proper network configuration, the mobility performance is very good with low probabilities of radio link failures and ping-pong events. In this regard, we recommend that configurations with DRX cycles longer than 160 ms shall not be used for such HST scenarios. Using DRX cycles longer than 160 ms are challenging with the risk of experiencing more failures due to e.g. too late handovers. We also recommend that the SSB based Measurement Timing Configuration (SMTC) period should not be longer than 40ms for FR1 HST scenarios at 500 km/h. Furthermore, applying also short L1 filter length while in DRX is valuable to achieve low radio link failure and time-of-outage rates.

Figure 14: Simple illustration of HST FR1 scenario.



NR HST performance, and the related RF and RRM requirements, for FR2 is currently work in progress as part of Release 17 (to be concluded in 2022). The deployment scenario assumes a carrier frequency of 28 GHz for trains moving at 350 km/h with roof mounted customer-premises equipment (CPE). The CPE can have multiple directional antenna panels, while assuming only one directional antenna panel active at a time. The RRH deployed along the train tracks with 700 meters separation have 1-4 beams. Current simulation results show that good mobility performance is achievable also for such HST FR2 scenarios with hardly any beam failures or handover failures, when using proper network configurations (e.g. of A3 RRM events [4]) and modest use of DRX with recommended DRX cycle length below 80ms. If using longer DRX cycles, the HST FR2 mobility performance is impacted as also observed for HST FR1 cases. The good mobility performance is a result of the use of roof mounted CPE's at the train with directional antenna panel(s) and beamforming at the RRHs which results in good SINR conditions despite the operation at FR2.

The Release 17 HST FR2 item is set to be concluded during 2022, considering cases also with Dynamic Point Selection (DPS). The work on HST support in FR2 will also continue in the 3GPP Release 18 [21].

Summary of features

The main mobility and DCCA features in NR are summarized in Table 1 and Table 2, respectively, along with their corresponding 3GPP release and main benefits.

Table 1. Mobility features in NR.

Feature	3GPP Release	Benefits
Baseline handover [2]	Rel. 15	Allow service continuity during handover between cells
Conditional handover [2]	Rel. 16	Improved mobility robustness by reducing the number of radio link and handover failures
Dual-active Protocol Stack (DAPS) handover [2]	Rel. 16	Reduced interruption time during handover down to 2 ms in downlink
Timer T312 [4]	Rel. 16	Early detection of radio link failure and fast recovery of the connection
UE requirements for high-speed train deployment in FR1 [15]	Rel. 16	Defining UE requirements for satisfactory performance in FR1 high-speed train deployment
Conditional handover with SCG configuration [6]	Rel. 17	Enable conditional handover to dual-connectivity connection with target MCG and SCG configurations
UE requirements for high-speed train deployment in FR2 [15, 22]	Rel. 17	Defining UE requirements for satisfactory performance in FR2 high-speed train deployment
L1/2 Centric Mobility [13]	Rel. 18	Reduced interruption time during handover and improved mobility robustness for intra-CU scenarios
Selective Switching of Cell group [13]	Rel. 18	Allow subsequent cell group change without reconfiguration and re-initiation of the preparation
Conditional Handover with Candidate SCGs for CPC/CPA [13]	Rel. 18	Improved access of target SCG during conditional inter-MN handover
Machine learning for Mobility [19]	Rel. 18	Enabling AI/ML functionality in RAN for improved mobility performance

Table 2. DCCA features in NR.

Feature	3GPP Release	Benefits
SCG Addition and Change [6]	Rel. 15	Enable the addition and change of SCG in MR-DC
Intra-SN Conditional PSCell Change [6]	Rel. 16	Improved mobility robustness of primary cell of SCG and fast access to SCG within same SN
Early Measurement Reporting [4]	Rel. 16	Speed up the setup of dual connectivity after establishing or resuming the connection
Direct SCell activation [4]	Rel.16	Configure SCell as activated in handover, SCell change and SCell addition
TRS-based SCell activation [20]	Rel-17	Faster SCell access by eliminating the delay in SSB acquisition
Inter-SN Conditional PSCell Change and Conditional PSCell Addition [6]	Rel. 17	Improved mobility robustness of primary cell of SCG and fast access to SCG between different SNs
(De-)Activation of Secondary Cell Group [20]	Rel. 17	Reduced UE power consumption and fast resumption of the SCG
Enhancements for FR2 SCell/SCG measurement reporting [13]	Rel. 18	Fast and reliable setup of FR2 SCell/SCG

Conclusion and outlook

In this white paper, we have outlined the current 5G mobility solutions as well as the related innovations that are coming with 5G-Advanced. Today, 5G offers a powerful toolbox with numerous options for achieving excellent mobility performance under various conditions. That is, achieving efficient cell identification, low probabilities of mobility failures, as well as fast recovery in the rare events of failures. The basic mobility mechanisms rely on solid solutions for network controlled and UE assisted handovers. This is followed by introduction of CHO with higher level of UE autonomous behaviors and DAPS for reduced interruption times. Agile solutions for also quickly taking additional carriers (using CA and/or DC) into use are also introduced, offering attractive benefits for both NSA and SA cases, including cases with usage of FR1 and FR2 bands. Good mobility performance for challenging high-speed train scenarios is also confirmed. In the 5G-Advanced era that starts with Release 18, we foresee even tighter integration of intra-cell beam management and inter-cell mobility functionalities. That will likely include enhanced mechanisms and procedures of Layer-1 and Layer-2 based inter-cell mobility, aiming at zero interruption time handovers also for single-transceiver devices without having to rely on DAPS. Finally, new AI/ML functionalities will be introduced in RAN which will help to improve further the performance of mobility and DCCA and pave the way for more advanced and intelligent mechanisms.

In later stages of 5G-advanced (Rel. 19+), it is expected to introduce new mobility solutions that do not optimize a specific mobility metric but rather multiple ones such as low interruption time, high mobility robustness and throughput. This is particularly relevant for services requiring at the same time high reliability and throughput. For example, make-before-break (such as DAPS) and/or RACH-less features may be introduced for conditional handover or enhancements for DAPS to inter-work with CA/DC may be specified. Another potential area is to improve further the mobility robustness in FR2 considering different multi-panel UE architectures. In particular, the network and/or the UE can be enabled to consider Maximum Permissible Emission (MPE) events (causing UL degradation for UEs transmitting at full power) in mobility related decisions such as handover triggering or admission control. Furthermore, given that the performance of mobility solutions highly depends on the proper configuration of the mobility parameters, it is foreseen to introduce the capability of configuring and changing in a slim way the handover related parameters per group of beams. This would provide the network operator with much more degrees of freedom for controlling the mobility performance in different areas of the cell.

Future releases of 5G-advanced might aim beyond DC and introduce Multi-Connectivity (MC) where the UE may be configured with more than one active secondary node. This would enable the UE to achieve extremely high user throughputs and to perform secondary node change without having to suffer from interruption time. This would be particularly relevant for services like XR/AR, cloud gaming or 4K streaming which may be only provided by secondary node due to high available bandwidth in FR2. In addition, multi-connectivity would enable the network operator to leverage the spectrum available in multiple frequencies to provide extreme mobile broadband connection and high-end user experience.

Abbreviations

AMF	Access and Mobility Management Function
CA	Carrier aggregation
CG	Cell Group
CHO	Conditional handover
CPE	Customer-premises equipment
DC	Dual connectivity
DCCA	Dual connectivity carrier aggregation
DPS	Dynamic point selection
DRX	Discontinuous reception
FR	Frequency range
HST	High speed train
L1	Layer 1
MAC	Medium Access Control
MCG	Master Cell Group
MR	Multi-RAT
PCell	Primary Cell of Master Cell Group
PHR	Power Headroom
PSCell	Primary Cell of Secondary Cell Group
RAN	Radio access network
RAT	Radio access technology
Rel.	Release
RLF	Radio link failure
RRC	Radio resource control
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio resource management
SCell	Secondary Cell
SCG	Secondary Cell Group
SINR	Signal to interference noise ratio
SMTC	SSB-based Measurement Timing Configuration
UPF	User Plane Function

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