5G Multi-RAT integration evaluations using a common PDCP layer

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***Abstract*—5G is expected to operate in a wide frequency range to support new challenging use-cases. Multi-RATs (Radio Access Technologies): NR (New Radio) and evolved LTE (Long Term Evolution) will together constitute 5G. Utilizing NR at high frequencies will have a significant impact on radio propagation conditions with e.g. unfavorable higher path loss and increased outdoor-to-indoor penetration losses. In order to provide a reliable communication from the outset of 5G deployment and to minimize the standardization and implementation complexity, 5G UP (User Plane) instances of 5G AIs (Air Interface) related to evolved LTE and NR need to be aggregated on a certain layer of the protocol stack. This paper sheds light on how to integrate 5G AIs into a single 5G AI framework and explores which protocol stack layer could be used as aggregation layer. Inter-RAT hard handover is the state of the art technique to integrate multiple RATs in order to support mobility and reliability across different RATs. However, the hard handover incurs a transmission interruption which stands as an obstacle along the way of accomplishing 5G design. According to simulation results, a common PDCP (Packet Data Convergence Protocol) layer improves the hard handover functionality and stands out as a basis for tight interworking between evolved LTE and NR. By means of simulation, it is shown that the multi-RAT UP aggregation can achieve three times higher user throughput, when NR is using 28 GHz and LTE 2 GHz, compared to stand-alone NR.**

Keywords— NR; 5G; LTE; METIS; mmMagic; multi-RATs; interworking; tight integration; common PDCP; Dual Connectivity;

I. INTRODUCTION

Standardization of the 5G NR was recently kicked off by 3GPP (3rd Generation Partnership Project), paving the way for the introduction of emerging 5G features and services such as eMBB (enhanced Mobile Broad Band), URLLC (Ultra Reliable Low Latency Communication), and IoT (Internet of Things).

The 5G AIs is expected to be consisted of evolved LTE (Rel-13 and beyond) and NR. Based on OFDM (Orthogonal Frequency Division Multiplexing) the 5G AIs aims to operate at frequencies from below 1 GHz and up to 100 GHz [1]. In this paper, the AI of a RAN (Radio Access Network) is considered as a full protocol stack, including PHY (Physical), MAC (Medium Access Control) and PDCP/RLC (Packet Data Convergence Protocol/Radio Link Control) as well as all related functions.

UEs (User Equipment) demand ubiquitous mobile coverage, thus, from the first day of 5G deployment the system flexibility must be provided. Although the migration to 5G offers numerous benefits, it also introduces several paradigm shifts and challenges that call for new innovations and solutions to make it a true success. For example, operating at high frequencies implies a significant impact on the achievable coverage due to harsh radio propagation conditions e.g., higher path loss and outdoor-to-indoor penetration loss. Hence, the coverage might be even more spotty and sensitive to both time and space variations as NR will need to rely on massive antennas and beamforming to overcome the propagation losses. In addition, attenuation at higher frequencies is more severe resulting in poor coverage especially inside buildings and behind obstacles. As ITU (International Telecommunication Union) and 3GPP also considers deployments at 28 GHz and above, where providing coverage may be even more challenging.

The required 5G services and AI flexibility increases the complexity of standardization and implementation. The initial key RAN design questions are:

1. How to reduce the complexity of 5G?
2. How can NR operate over a wide frequency range, where carriers at high and low frequencies are aggregated to support different use-cases simultaneously, leading towards efficient service multiplexing?
3. How to integrate multi-RATs, evolved LTE and NR, into one 5G AI framework and determine on which protocol layer 5G AIs should be aggregated?

In [2], the first RAN design question is examined. The 5G UP instances related to different AIs can be harmonized at any layer such as PHY, MAC or PDCP/RLC. Harmonization was defined as follows: two protocol stacks of two AIs can be harmonized if each of them exhibits an identical protocol stack, where the individual functions and parameters might be different. Furthermore, two UP protocol stack instances of two AIs can be aggregated on a certain layer if they have one joint instance of each protocol stack layer on and above this layer. This subset of harmonization is referred to as UP aggregation, and it enables a UE to receive or transmit data flows via different links. These different links can either be from the same AI, as in LTE, or from different AIs. In addition, an aggregated layer appears as a common layer.

The second design question was addressed in [3], where PHY layer harmonization and aggregation aspects are examined. The OFDM waveform is an excellent choice for all link types in NR, due to its high time localization, low complex transceiver design, high spectral efficiency, and easy integration with MIMO technologies. Therefore, NR AI should implement the CP-OFDM (Cyclic Prefix OFDM) waveform supported by various numerologies.

In [4], the second design question is further elaborated regarding NR L2 (Layer2) design aspects. A number of new solutions are proposed on L2 to cope with the changes in PHY (e.g., application of massive antenna beamforming), i.e., the extended frequency range. The proposed solutions include a new concept of transport channels as being either direct or re-transmittable, new 5G scheduling features, and a new contention based access model for URLLC traffic.

This paper addresses the third design question. The prevailing solution to integrate multi-RATs is to use hard handovers in order to support mobility and reliability across different RATs. However, the hard handovers incur a transmission interruption, which presents an obstacle along the way of accomplishing 5G requirements [5]. Therefore, enhancing the hard handover function with dual connectivity functionality on a common PDCP layer appears as a promising UP aggregation option for the 5G AIs. The reasons are explained in the following sections of this paper.

The remainder of the paper is structured as follows: Section II elaborates on why the PDCP protocol layer is appropriate for multi-RAT aggregation, while Section III describes aggregation features of the PDCP layer. Section IV presents evaluation assumptions and simulation results. Finally, we draw some conclusions in Section V.

II. Integration of 5G AIs

When 5G NR reaches the market, it is expected that LTE is already widely deployed, so the interworking of evolved LTE and NR is important to consider. Also, the interworking has been endorsed by 3GPP [6] where it is stated that “the new 5G radio interface should support high performing inter-RAT mobility and aggregation of data flows via at least dual connectivity”.

Tight integration at the PHY layer is not even considered as an integration option between evolved LTE and NR since the two AIs are assumed to have e.g. various numerologies. Also, the PHY level tight interworking would require significant changes in the standards which will be prohibitively costly.

The LTE MAC layer functions perform mapping between the logical channels and transport channels and provide services to the RLC layer. In principle, integration on the MAC layer (i.e., the existence of a common MAC layer between evolved LTE and NR) might provide a good coordination between the RATs, and would enable features such as cross-carrier scheduling for both radios for dual-radio capable UEs. The challenge to realize MAC-based aggregation is to provide synchronization functions in time- and frequency-domain between evolved LTE and NR. However, to be able to design such a MAC layer integration, synchronicity will also be needed above the MAC layers of both evolved LTE and NR (i.e., in the RLC layers). Eventually, the MAC layer integration might work in case of co-located deployments, where time-frequency synchronization is inherent, whereas in non-collocated cases will be more challenging.

Integration at the RLC layer is also challenging due to the lack of synchronicity across PHY and MAC layers as well as between RLC layers of the different AIs. Particularly, to perform segmentation/reassembly of data units, the RLC layer should know the scheduling decisions in terms of resource blocks for the next TTI (transmission time interval), which in consequence is a function of PHY layer information. On the other hand, a joint instance of two AIs would not work without common synchronized scheduling functions which would result in additional processing delay. Due to these potential limitations, the RLC layer integration is undesirable.

The LTE PDCP functions for the CP (Control Plane) are ciphering/deciphering and integrity protection while for the UP, the main functions are ciphering/deciphering, header compression and decompression using ROHC (Robust Header Compression), in-sequence delivery, duplicate detections, and retransmissions (used in handovers). The existing PDCP functions are very much access/service-agnostic functions and 3GPP assumes that the same LTE DC (Dual Connectivity) functions can be used as a baseline in LTE-NR interworking [6].

Intra-RAT hard handover relies on LTE-PDCP functions to handle lossless mobility e.g., data forwarding, retransmission of PDCP SDUs (Service Data Units) as well as the possibility to have the PDCP instances preserved, which might reduce the interruptions. The LTE intra-RAT mobility also benefits from having a common CN (Core Network) connection that exists for both CP and UP via S1-C and S1-U interfaces.

A high performing solution for intra-RAT mobility within NR and inter-RAT mobility between the evolved LTE and NR should be designed. Especially in early deployments where full coverage of NR might not be available, the inter-RAT mobility between evolved LTE and NR will occur quite often. A single PDCP instance could be defined as a possible solution which would be re-located when a UE moves from NR to evolved LTE or vice versa. Such solution would also help to handle a few lower layer issues e.g. duplicate detection and PDU (Protocol Data Unit) reordering. Moreover, it would reduce the signaling compared to the current LTE inter-RAT hard handover as well. Additionly, a desired hard handover functionality should be implemented and it should target the following:

- High robustness against packet losses (lossless handover), handover failures and radio link failures;
- Low interruption delays (seamless mobility);
- Low signaling overhead:
    - Between the UE and both AIs;

- Between the CN and RAN nodes of evolved LTE and NR

By implementing a common PDCP layer, high performance inter-RAT mobility between evolved LTE and NR can be supported as required [5]. The solution would be transparent to the CN and that allows the UE to move between 5G AIs without notifying the CN. This would especially be an advantage in non-collocated deployments of evolved LTE and NR. Additionally, since the PDCP layer has no strict lower layer (i.e. PHY, MAC, and RLC) synchronization requirements, the common PDCP functions between the evolved LTE and NR would allow a clean slate design of the lower layers of NR. Thereby, the 5G AIs can be easily adapted to the new requirements without any significant changes to the LTE standard. Therefore, a common PDCP layer can be a suitable candidate as the integration layer, especially for the non-collocated deployments.

DC aims to increase the user throughput by utilizing radio resources from more than one eNB (evolved Node B) and it is standardized by 3GPP for LTE small cell enhancements. DC allows UEs to receive data simultaneously from different eNBs, via the X2* interface as illustrated in Fig. 1. Consequently, another advantage of having a common PDCP layer is that the DC features i.e., UP fast switching and flow aggregation can be enabled.

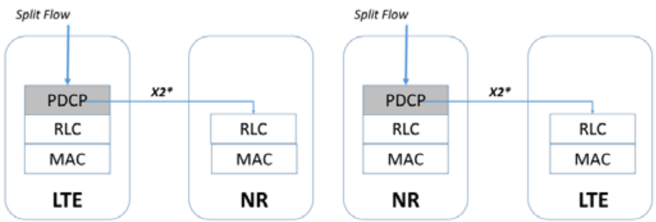

Fig. 1: A common PDCP layer aggregation for 5G AIs.

III. PDCP Layer Aggregation Features for LTE-NR Interworking

The state of the art hard handover intra-RAT mobility function can be enhanced by providing additional DC functions on the common PDCP layer. Therefore, in this section hard handover functionality (as the baseline) and DC features are briefly described.

A detailed illustration of the UP PDCP aggregation between evolved LTE and NR is shown in Fig. 2. The aggregated UPs are illustrated with green color and a single CP instance of both RANs (Radio Access Network) is depicted by pink color. The NR node is depicted as the master node, and it is worth mentioning that the LTE eNB also can be configured as the master.

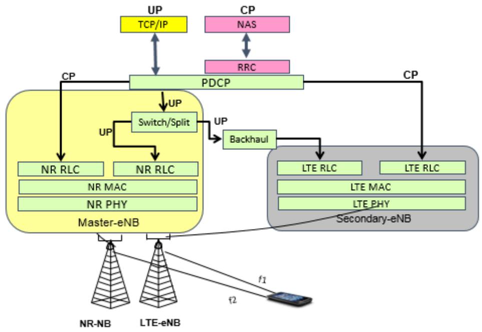

Fig. 2: Evolved LTE and NR protocol stack for fast switching.

a) UP fast switching (Flow routing)

The UP fast switching DC feature assumes that the UP packets are switched at PDCP layer to either NR or evolved LTE very quickly (it is very similar to the hard handover but much quicker, and considering no link set-up failure). The UE uses only a single RAN AI at a time for DL (Downlink) to receive the user data, while it uses both the NR CP and LTE CP to receive the control signals in DL. Compared to hard handover, the main advantage of this feature is a decreased link set up delay and packet loss, as well as decreased handover failure probability. Besides these benefits, the UP fast switching feature allows the UE to use a single transceiver at a time by swapping between the two transceivers (evolved LTE and NR). However, the switching might require some more control signaling between the UE and the network, although it will be much lower compared to the hard handover feature since it is transparent to the CN and relies on existing PDCP functions. Differences between UL (Uplink) and DL variants shall be studied in the future.

b) Flow aggregation (Flow splitting)

The flow aggregation DC feature allows a single flow to be aggregated over multiple AIs simultaneously. This means that different flows of the same UE may be mapped on different AIs. The benefits of this feature are increased user throughput, pooling of resources and support for seamless mobility. The flow aggregation variant may have limited benefits when multiple AIs provide different latency and user throughput. The solution has also limitations to work only for dual transceiver devices. As with the previous feature, differences between UL and DL variants shall also be studied in the future.

IV. Evaluations

In this section, numerical evaluation results on LTE-NR interworking, are presented. A professional Java based in-house developed network system simulator is used. The simulator is state of the art and capable of performing simulation scenarios over various wireless access network technologies, such as LTE and NR, and supports a tremendous amount of networking functions, like for instance DC.

In what follows, performance of hard handover is simulated as a baseline to be able to compare the described DC features, namely UP fast switching and flow aggregation, on a common PDCP layer between evolved LTE and NR.

a) *Simulation assumptions and deployment models*

The parameter settings are given below. Table 1 briefly summarizes the most important parameters used in the simulation experiments.

TABLE 1: SIMULATION PARAMETERS

Parameters	Evolved LTE	NR AI
Backhaul	Ideal	Ideal
Carrier Frequency	2 GHz	2.6 and 28 GHz
TTI	1 ms	0.2 ms
User speed	10 m/s	
Bandwidth	20 MHz	
Transmitter power	40 W	
Deployment	LTE and NR co-sited	
Traffic	FTP download of one 10 MB file.	
RAT selection	RSRP (Reference Signal Received Power)	
DC selection	RSRQ (Reference Signal Received Quality)	

The deployment model is the 3GPP case 1 with typical urban channel model [7], and is illustrated in Fig. 3. The evolved LTE and NR nodes are co-sited and a number of different potential 5G frequency bands are investigated, namely, are 2 GHz, 2.6 GHz, and 28 GHz. In order to be able to compare the performance simulation results, evolved LTE and NR bandwidths are set to 20 MHz equally. Note that all signaling is ideal, i.e., all control signaling is always received correctly. This means that there are no handover failures.

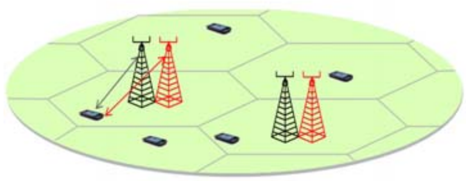

Fig. 3: 5G system topology: evolved LTE and NR co-sited deployment

b) *Simulation results*

The simulation results compare the state of the art hard handover and the two DC features:

- Hard handover is used as our baseline case, modeled as a 300 ms (bad case) service interruption delay, and UE cannot transmit and receive data during the interruption delay.
- Flow routing (flow switch) is modeled with UP switches between the radio links with zero delay, since there is no need to signal when one AI or the other is being used.
- Flow aggregation packets are simply transmitted simultaneously over both AIs.

Fig. 4 shows the DL user throughput performance vs. the load (throughput per cell). Evolved LTE operates at 2.0 GHz while the NR AI exploits 2.6 GHz in this simulation scenario. The gain for flow aggregation, as compared to hard handover is around 80% for the best users (90th percentile user throughput) at low load and around 90-100% gain for the worst users (10th percentile user throughput). Thus, since flow aggregation uses double amount of resources, the throughout can almost be doubled at low load compared to stand-alone deployments. The difference between flow routing and hard handover is negligible for 90th percentiles users and around 10-15% for 10th percentile users.

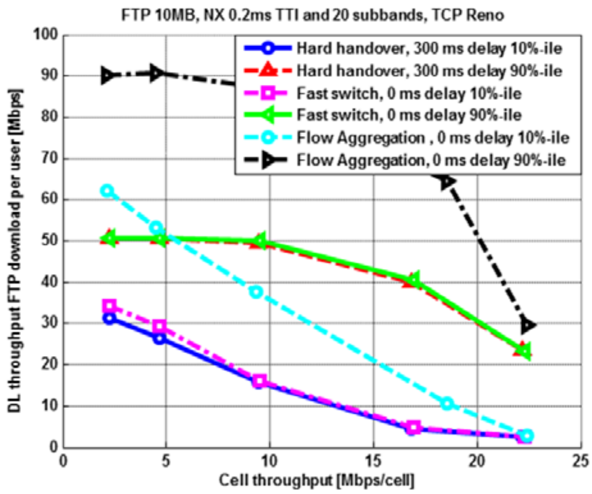

Fig. 4: User throughput vs. cell throughput (load) for NR (0.2 ms TTI) and evolved LTE (1 ms TTI).

Fig. 5 compares the user throughput performance vs. the cell throughput when reducing the TTI from 1 ms (as in LTE) to 0.2 ms (as proposed for NR) for the flow routing alternative. There is a small TCP (Transmission Control Protocol) gain by using a lower TTI for the 90th percentile user throughput. This occurs because TCP slow start increases the congestion window faster since the round-trip-time is reduced due to the lower TTI. Consequently, the fast switch feature has better potential to exploit the best link.

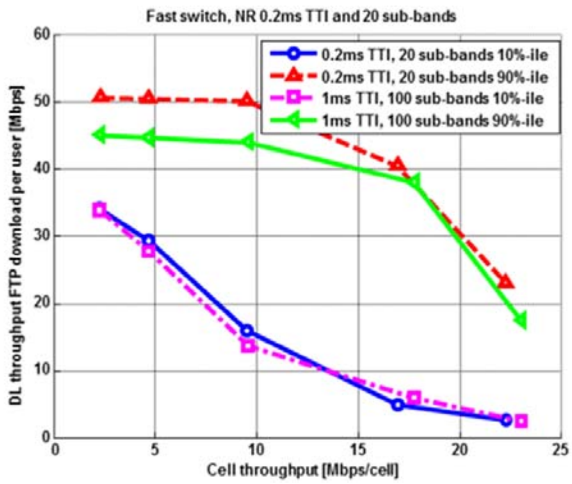

Fig. 5: User throughput vs. cell throughput (load) for NR (0.2 ms TTI, 2.6 GHz) and evolved LTE (1 ms TTI, 2 GHz).

Fig. 6. Focuses on a scenario where the NR operates at 28 GHz and the evolved LTE at 2 GHz. The 28 GHz frequency has in average 24 dB/km worse pathloss, as well as much faster varying fast fading compare to the 2 GHz case. Three cases are shown: flow aggregation, hard handover and stand-alone NR at 28 GHz and considering a 40 MHz bandwidth. The gain for flow aggregation compared to hard handover for the 10th percentile is in this case around 50% at low load, not 90-100% gain as in Fig. 4. The reason for this is that the NR link has a very bad user throughput for the 10th percentile, which is visible for the stand-alone case. The user throughput for flow aggregation is around three times higher than the NR stand-alone case for the 10th percentile users at low load. However, for the 90th percentile user throughput at low load, NR has the highest throughput, around 85 Mbps compared to 70 Mbps for flow aggregation. Additionally, the NR user throughput rapidly decreases when the load slightly increases and flow aggregation performs henceforth better in case of medium load. The major reason for this is that the reduced coverage and SINR (Signal-to-Interference-Noise-Ratio) of NR requires relatively more resources (resource blocks) than the flow aggregation case to transmit the data to the users at the cell edge. In fact, at very high load the 90th percentile increases for hard handover even increases a bit. The reason is that the system is overloaded and only the best users get any throughput.

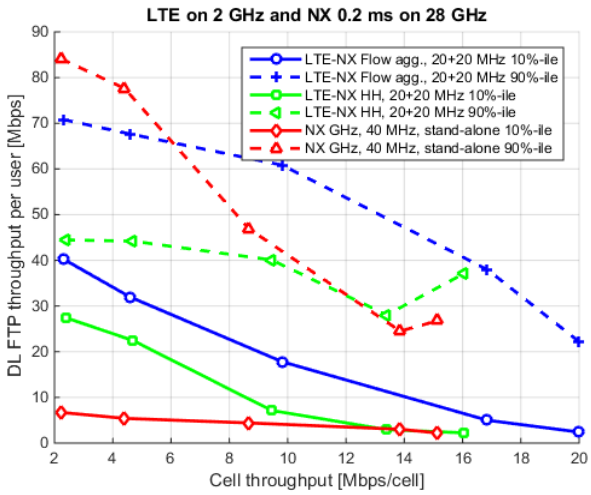

Fig. 6: User throughput vs. cell throughput (load) for NR (0,2 ms TTI, 28 GHz) and evolved LTE (1 ms TTI, 2 GHz) in fast user plane switch case.

V. CONCLUSIONS

5G NR standardization has already started in 3GPP. Evolved LTE and NR will constitute the 5G radio access solution supporting spectrum ranges from below 1 GHz up to 100 GHz. 5G is expected to utilize different numerologies at the PHY layer to support different use-cases and spectrum bands. However, the radio propagation conditions at higher frequencies might result in higher outdoor-to-indoor penetration losses and less diffraction, and need to rely on massive usage of beamforming. Furthermore, a high performing solution for intra-RAT mobility in NR and inter-RAT mobility between evolved LTE and NR should be designed. Besides that, in order to minimize the standardization and implementation complexity; the 5G UP instances related to evolved LTE and NR needs to be aggregated. Therefore, LTE-NR interworking needs to be supported to provide reliable communication as soon as 5G commercialized. According to simulation results, the user plane aggregation on a common PDCP layer, similar to the LTE DC feature can provide large user throughput gains. For the case when both NR and LTE are using similar carrier frequencies and same bandwidth, the user throughput is also almost doubled at low load compared to hard handover which is the state of the art solution. Such gains become even more emphatic when NR is using 28 GHz and LTE 2 GHz, and the 10^{th} percentile user throughput gain for the user plane aggregation solution is in the order of 300% compared to a stand-alone NR deployment.

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