RESEARCH ARTICLE

X2-Based Signalling Mechanisms for Downlink Uplink Decoupling in Next Generation Communication Systems

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ABSTRACT Cell selection in cellular networks is an important aspect that impacts the quality of service. The traditional cell selection mechanism is based on downlink received power. Despite the dense deployment of macrocells, mobile network operators are still confronting the daunting challenge of providing capacity and coverage. Deployment of a large number of small cells has emerged as a promising solution towards addressing this problem. However, this success expands the heterogeneous cellular networks where there is a significant disparity in the transmit power of the different base station types. Downlink and Uplink Decoupling (DUDe) can improve efficiency by associating the downlink cell based on the downlink received power and the uplink based on the pathloss. While the higher layer signalling has not been proposed in detail for the DUDe mechanism yet, we aim to propose a solution for the problem. This work addresses four different signalling mechanisms to realise decoupled up/downlinks connections in the radio access network for the next-generation communication systems with handling mobility. Our proposed signalling mechanisms cover uplink decoupling, downlink coupling, downlink decoupling, and uplink coupling scenarios. We analyse the proposed signalling mechanisms using ns3 simulation and present the impact of applying the DUDe mechanism, which mainly shows improvements for the uplink. For the selected mobility scenario, delay and lost packets are reduced by 30% and 26%, respectively. Delay and lost packets are reduced by 36% and 27% for the fix location scenario, respectively. The improvements imply that it reaches particular demand considering next-generation communication systems, with a massive number of smart devices demanding high quality of service requirements.

INDEX TERMS LTE-A, 5G, decoupling, uplink, downlink, macrocell, small cell, handover, ns3.

I. INTRODUCTION

The rapid growth of mobile connectivity demand and the wide range of smart devices in smart environments and smart cities are expected to fulfill services' requirements and be market drivers for small cells, especially indoors. Different use cases ranging from health and home security to interactive gaming have increased demand for high data rates, high reliability, and low latency, which demand further advancements to existing communication systems.

The communication systems have made advancements in this direction by applying a combination of several systemic concepts such as the use of millimetre-wave communications and small cells, the use of multiple Radio Access Technologies (RATs), increasing the density of evolved NodeBs (eNBs) and Next Generation NodeBs (gNBs), the use of device-to-device (D2D) communications, the use of mobile edge communication (MEC) using software defined networks
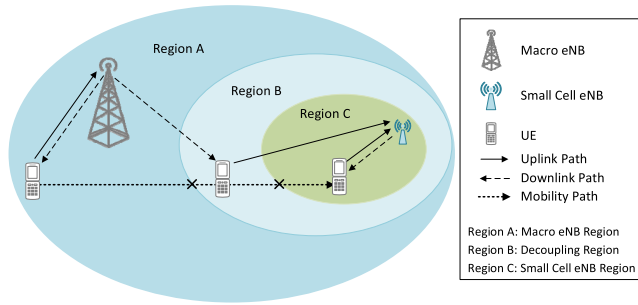
FIGURE 1. System model for the up/downlink decoupling.

FIGURE 2. Suggested DUDe architecture.

(SDN) and network function virtualisation (NFV), the use of fix mobile convergence (FMC), prioritised access to the spectrum, large intelligent surface and software defined materials, orbital angular momentum, and visible light communications [1] to be able to serve the growing number of wireless devices (predicted to be around 37 billion connected devices by the year 2025 [2]) with a continual increase in demand for communication systems data traffic. Achieving an agreed level of Quality of Service (QoS) will be very important in next-generation wireless communications for such defined performance criteria as well as energy efficiency [3], particularly for reduced capability devices such as smartwatches and other wearables.

Furthermore, efficient cell association can improve delivered QoS. Cell association in cellular networks has traditionally applied the downlink received signal strength, which is adequate for homogeneous networks. In a heterogeneous network (HetNet) that overlays high power and low power cells: macro and small cells (macrocells and small cells, respectively), due to the cell transmit power disparities, users may face a phenomenon called the uplink and downlink (up/downlinks) imbalance problem: the best serving cell, based on the received signal, is different for both up/downlinks, meaning up/downlinks power transmissions and interference levels differ significantly. In other words, the downlink coverage of the macrocell is much broader than the small cell due to the significant difference in the transmit powers of both. However, all the transmitters (battery-powered mobile devices) in the uplink have the same transmit power and thus the same range. Hence, a UE connected to a macrocell in the downlink, from which it receives the highest signal level, may want to connect to a small cell in the uplink where the pathloss is lower. Downlink uplink decoupling (DUDe) is suggested in 3GPP [14] where the downlink association is based on the downlink received signal power and the uplink is based on the pathloss (Fig. 1). The gains and motive of DUDe based on a real testing scenario grounded by Vodafone's LTE network cellular is also demonstrated in [5] with a focus on the physical layer considerations, which shows sum-rate gains in the order of 100-200% in dense HetNet.

To address user mobility, we can divide the network environment into three regions based on pathloss for uplink
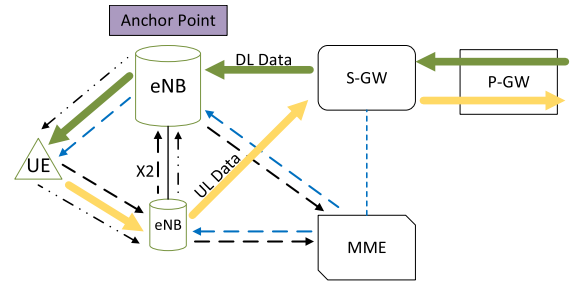
selection and received signal strength indicator (RSSI) for downlink eNB (macrocell) selection, as shown in Fig.1. In region A, where the macrocell pathloss and RSSI factors show better connection than the small cell, the up/downlinks are connected to the macrocell. In region B, where the pathloss of the small cell is better than the macrocell while the RSSI of the macrocell is better than the small cell, the up/downlinks are connected to the small cell and macrocell, respectively. In region C, where the small cell's pathloss and RSSI of the small cell are better than the macrocell, both uplink and downlink are connected to the small cell.

For the up/downlinks connections, a mechanism needs to be in place to handle the two connections' flows under the same session from a higher layer point of view, including updating the core network (CN), as shown in Fig. 2. In this architecture, the UE can transfer data and control messages to both the eNBs. Also, a complete separation of the up/downlinks traffics are considered, i.e., if the UE communicates in the only uplink to the small cell, no downlink is maintained in the small cell. Control messages can be transferred between eNBs within the X2 interface. Hence, this architecture requires the signalling information to be sent with minimal delay via the downlink of the macrocell. The challenge here is that the X2 needs to facilitate close-to-zero delay communications; the advantage is that radio capacity is completely freed in the small cell's uplink and the macrocell's downlink.

Considering the suggested DUDe architecture, we look at the current cellular technology. 3GPP defines two deployment scenarios for 5G: Standalone (SA) and Non-standalone (NSA). In the SA scenario, the 5G new radio (NR) and the 5G CN are operated alone. In the NSA scenario, the NR cells are combined with LTE radio cells using dual connectivity to provide radio access and evolved packet core (EPC), or 5G core (5GC) provide CN depending on the choice of operator [7]. The SA option is a simple solution for operators to deploy and manage as an independent network by typical inter-generation handover between 4G and 5G. The NSA scenario is chosen by the operators that wish to leverage existing 4G deployments, combining LTE-A [8] and NR radio resources with existing EPC and/or that demand new 5GC to deliver 5G mobile services. In the NSA scenario, due to the combination of LTE-A and 5G, more resources are used, and this is cost-efficient, but this solution requires tight interworking with the

LTE radio access network. Three types of NSA are defined in 3GPP as follows:

Option #3- using EPC and an LTE eNB acting as master and NR en-gNB acting as secondary;

Option #4- using 5GC and an NR gNB acting as master and LTE ng-eNB acting as secondary;

Option #7- using 5GC and an LTE eNB acting as master and an NR gNB acting as secondary.

Concerning the 5G development process, as the transition from EPC to 5GC is time-consuming, option #3 of the NSA scenario is selected first by the operators. This work also looks at signalling requirements considering the NSA scenario with option #3 to handle decoupled up/downlinks connections for a decoupled scenario. The UE can perform decoupling based on either signal strength/ pathloss measurement or as a result of mobility to a macro/small cell. The main contributions of this paper are four signalling mechanisms in considering mobility scenarios for handling DUDe: First, uplink decoupling where the UE moves from region A to region B (Fig. 1). Second, downlink coupling where the UE moves from the region B to region C. Third, downlink decoupling where the UE moves away from the region C towards region B. Fourth, uplink coupling where the UE moves from region B to region A. The handling of signalling mechanisms for the DUDe at the Network layer will provide a possibility of taking the most advantages from the DUDe and make it practical for the next generations of communication systems. Moreover, we analyse our proposed signalling mechanisms using simulation to compare network performance when up/downlinks connections are decoupled.

The rest of this paper is presented as follows: Section II provides an overview of the related research; section III discusses four possible proposed signalling scenarios for handling decoupled communication. Simulation results and analysis are presented in section IV. Finally, section V provides the conclusion and future research directions.

II. RELATED WORKS

The DUDe concept has been discussed in future cellular networks in [5], [7], and [8]. Boccardi *et al.* [9] discussed how to decouple up/downlinks in existing LTE-A networks from the architecture perspective. the authors discussed three approaches, namely centralised processing, shared cell-ID, and dual connectivity. For centralised processing and shared cell-ID approaches in a practical LTE-A rollout, the deployment is thus limited to remote radio units connected to a centralised baseband processing node. The dual connectivity approach is limited for inter-frequency deployments, and two cells operate separately, handling their scheduling and control signalling. The disadvantage is that radio capacity is busy in the downlink for the small cell and the uplink for the macrocell.

Uekumasu *et al.* [10] considered the case where the up/downlinks use different frequency bands and proposed two macrocell selection methods in DUDe using multiple frequency channels. Wan Lei *et al.* [13] investigated the 5G

NR and 4G LTE coexistence through the UL sharing known as up/downlinks decoupling. The 5G-NR provides a tool to extend its coverage with C-Band deployment. It makes it possible to deploy a C-Band 5G-NR network using existing LTE sites for seamless coverage, demonstrating the feasibility of DUDe for the described NSA 5G deployment scenario. Jia *et al.* [14] investigated dual connectivity for all possible up/downlinks decoupled access modes, derived association probabilities after simplifying the conditions for the association, and derived uplink coverage probabilities using tools from stochastic geometry to achieve uplink average coverage probability. However, in [9], [10], [12], and [13], authors did not discuss mobility handling and required handover mechanisms when a session is transmitted over decoupled up/downlinks connections.

Smiljkovikj *et al.* [11] outlined DUDe enabling architectures, based on 3GPP architecture, from the perspective of Access-Stratum (AS) and Non-Access Stratum (NAS) signalling where AS signalling refers to Layer 1, Layer 2, and RRC control messages exchanged between UE and small/macrocell. NAS signalling refers to control messages exchanged between UE and the CN. It includes, e.g., establishing and managing bearers, authentication and identification messages, mobility management, and tracking area update. Authors proposed three options for the possible architectures: NAS-Decoupling with radio access network (RAN) Anchor Point, NAS-Decoupling with CN Anchor Point, and AS-Decoupling with RAN Anchor Point. However, the authors have left signalling mechanisms designing and analysing to future researches.

Elshaer *et al.* [5] studied physical layer gains that the DUDe technique can achieve in terms of uplink capacity and throughput and studied the effects of the DUDe approach on interference using a realistic scenario of a cellular network with a dense HetNet deployment. It was shown that the DUDe technique could achieve between 100% and 200% improvement in the 5th percentile uplink throughput and even more than that in the 50th percentile throughput. Furthermore, authors have shown that the outage rate is decreased from 90% to below 10% on the macro layer in networks with high minimum throughput requirements. Yet, the authors have left alternative control signalling delivery mechanisms in the CN as future work.

Authors in [30] proposed a location-based scheme for coupled/decoupled cell association. They divide the user into two types. First uplink-downlink Coupled Association users and the second uplink-downlink decoupled access called the CoA users and DUDe association policy. Also, the authors proposed the practical realisation and, based on the proposed scheme, simple analytical closed-form expressions for decoupled users derived without ignoring noise to quantify decoupled access advantages. However, they studied the physical layer parameters and did not propose a required higher layer signalling.

Giluka *et al.* [25] proposed handover schemes for up/downlinks decoupling in HetNets from the physical layer

perspective. They presented various handover schemes with up/downlinks decoupled access. Mathematical analysis for up/downlinks decoupling shows the signal-to-noise-plus-interference ratio (SINR) received by the small cell in the decoupling region will be greater than that of the macrocell, even after including the interference due to other small cells. The authors simulated two scenarios, first a single small cell scenario and a multiple small cells scenario. In the first case, which is called the single cell non-interference scenario, they considered one macrocell and one small cell and analysed power consumption which resulted in decreased power consumption. In the second case which is called the multiple cells interference scenario, they considered one macrocell, multiple small cells and, multiple devices to create interference and analysed the cumulative distribution function of uplink SINR received by different small cells. Results show decoupling always outperforms the coupled connection.

In particular, the authors measured the consumed power by a UE based on a mathematical formula and illustrated the results for 1 to 90 UEs within a DUDe scenario. They reported UEs are consuming more power in the conventional scheme even if they are performing fewer number of handovers in comparison to using the DUDe scenario. Also, the authors reported the transmit power of a UE for the DUDe vs. conventional scheme. In the DUDe case, the transmit power is lower than the conventional scheme, due to existing the decoupling region in the DUDe mechanism [25]. However, they did not propose the detail of signalling for the network layer and they did not study the performance metrics of the network layer.

The general LTE-A architecture divides into RAN and a CN. In [26], the Third Generation Partnership Project (3GPP) presents the signalling mechanisms in the CN and RAN for X2 based handover. The presented CN signalling mechanisms contain all the message sequences between Mobility Management Entity (MME), Serving Gateway (S-GW), and Packet Delivery Network Gateway (PDN GW).

For the handover scenario, 3GPP represents two signalling message sequences; the first for X2 based handover without S-GW relocation and the second X2 based handover with S-GW relocation. In the first case, the MME sends a Modify Bearer Request to the S-GW, and S-GW forwards the message to the PDN GW, then PDN GW sends the Modify Bearer Response message to the S-GW, and S-GW forwards the message to the MME. In the second case, the MME sends the Create Session Request message to the target S-GW, and the target S-GW forwards the message to the PDN-GW, then PDN GW sends the Modify Bearer Response message to the target S-GW and the target S-GW forward the message to the MME. After the MME receives the Create Session Response message, the MME sends a Delete Session Request message to the source S-GW and the source S-GW replies by the Delete session Response message.

Also, the 3GPP mentions Dual Connectivity in RAN and CN. In Dual Connectivity concept, a cell and other network elements should support two different RATs and if the UE supports Dual Connectivity as well, it can take the advantage of both RATs one as a primary and the other as secondary. However, the required DUDe signalling mechanisms are not covered within the standard [26].

While [5] and [25] shows the physical layer gain, we are aiming to propose a solution for higher layers signalling to focus on intra PDN GW mobility. Based on [7], we concentrate on AS-decoupling with RAN anchor point as we consider NSA scenario option #3 (EPC is the core, LTE eNB acting as a master, and NR gNB acting as secondary radio resources).

III. PROPOSED DECOUPLING SIGNALLING

Dual Connectivity, an extension first introduced in 3GPP Rel-12, allows a terminal to be simultaneously connected to two cells to aggregate data flows or DUDe (Fig. 2). The two cells operate separately, handling their scheduling and control signalling and thereby significantly relaxing the backhaul requirements compared to the centralised baseband approach [5], [11]. Both cells have data connections to the S-GW and control connections to MME. Depending on which cell serves as an uplink or downlink cell to the UE, the uplink cell has a control and data connection to the UE in the only uplink direction, and the downlink cell has a control and data connection to the UE in the only downlink direction. Therefore, for the UE, the radio resources of the uplink cell in the downlink direction and the radio resources of the downlink cell in the uplink direction are free.

In a DUDe scenario, we have proposed details of messages sequence of four possible cases in terms of access level signalling architecture to work with the discussed core signalling in [26].

1. Up/downlinks are connected to the macrocell and uplink is transferred from the macrocell to the small cell (transferring from Region A to Region B in Fig. 1). Proposed signalling for this case is illustrated in Fig. 3.
2. Up/downlinks are connected to the small cell and the macrocell, respectively, and downlink is transferred from the macrocell to the small cell, i.e. reverts from the decoupled state to the coupled state (transferring from Region B to Region C in Fig. 1). Designed signalling for this case is illustrated in Fig. 4.
3. Up/downlinks are connected to the small cell and downlink is transfers from the small cell to the macrocell (transferring from Region C to Region B in Fig. 1). Proposed signalling for this case illustrates in Fig. 5.
4. Up/downlinks are connected to the small cell and the macrocell, respectively, and uplink transfers from the small cell to the macrocell, i.e., reverts from the decoupled state to the coupled state (transferring from Region B to Region A in Fig. 1). Advised signalling for this case illustrates in Fig. 6.

For the first case, where up/downlinks connected to macrocell (downlink eNB) and uplink is transferred from macrocell to small cell (uplink eNB), based on the UE's measurement reports on the RSSI of the current cell and the neighbouring

cells' pathloss, the macrocell can decide to decouple uplink and downlink cells. The first step in this process is to send an Uplink Decoupling Request message from the macrocell (where the uplink and downlink connect to that) to the small cell (where the uplink will transfer to it). As described in ETSI TS 136 423 [27], this message contains all relevant information about the subscriber and all relevant information about the connection to the UE. The small cell then checks if it still has the resources required to handle the additional subscriber.

Mainly, supposedly the connection of the subscriber requires a specific QoS. In this case, the small cell might not have enough capacity on the air interface left during a congestion situation and might thus reject the request. If the small cell grants access, it prepares itself by selecting a new Cell Radio Network Temporary Identifier (C-RNTI) for the UE and reserves resources on the uplink. So the UE performs a non-contention- based random-access procedure once it tries to access the small cell. This is crucial as the UE is not synchronised, which is unaware of the timing advance necessary to communicate with the small cell.

The small cell then confirms the request to the macrocell with an Uplink Decoupling Request Acknowledge message. The message contains all the information that the UE requires to access the small cell. As the decoupling needs to execute as fast as possible, the UE should not read the SI messages in the small cell. Hence, the Uplink Decoupling Request Acknowledge message contains all the system parameters that the UE requires to configure to communicate with the small cell. The information needed comprises the carrier bandwidth, the physical cell identity (PCI), physical hybrid automatic retransmission request indicator channel (PHICH) configuration, sounding reference signal (SRS) parameters, random access channel (RACH) parameters, reference signal configuration, etc. Once the macrocell receives the message, it immediately issues a decoupling command to the UE and ceases to transmit user data in the uplink direction to the S-GW. After issuing the decoupling command, data arriving from the UE forwards over the X2 interface to the small cell. The macrocell sends a sequence number (SN) status transfer message to the small cell. This message contains the sequence number of the last valid uplink data block, which is received from the UE by the macrocell and require for the seamless decoupling process. If the small cell detects an uplink data block is missing, it sends the data retransmission request to the UE via macrocell. While in LTE, there is no dedicated decoupling command, a radio resource control (RRC) Connection Reconfiguration message is used that contains all the parameters necessary to connect to the new cell. Upon receiving the RRC message, the UE communicates with the small cell and stops transferring data in the uplink direction to the macrocell. Also, the macrocell stops receiving data from UE. As the UE has already performed measurements, there is no need to search for the new cell. Hence, the UE can immediately transmit a random access preamble on the physical random access channel (PRACH). As dedicated
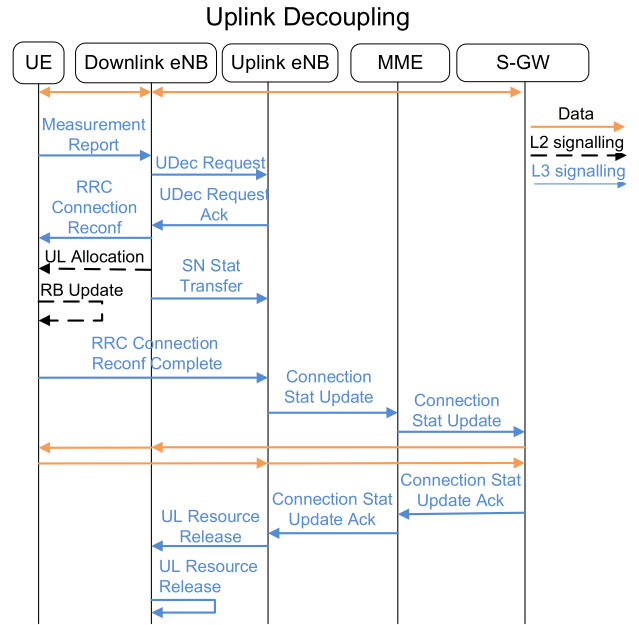

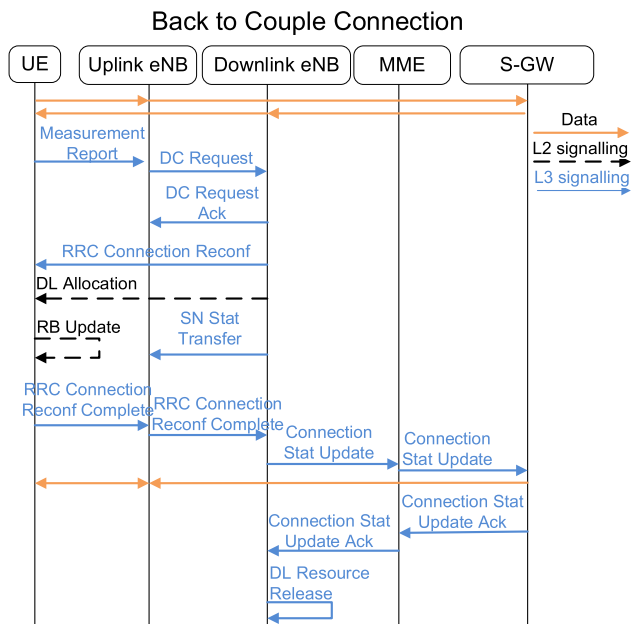**FIGURE 3.** Signalling mechanism for uplink decoupling.

FIGURE 4. Signalling mechanism for downlink coupling.

resources use for the RACH sequence, the UE does not have to identify itself, and merely the first two messages in the RACH sequence are sufficient.

The RRC Connection Reconfiguration Complete message from the UE, which forward to the small cell, ends the decoupling procedure from the UE point of view, and it can immediately resume transmitting data in the uplink direction with the small cell and downlink direction with the macrocell. However, in the radio and CNs, additional steps are required to reconfigure the S1 tunnel for working with both the macrocell and small cell.

The S1 user data tunnel redirection and an MME context update are invoked with a Path Switch Request message that the small cell sends to the MME. The MME then updates the subscriber's Decoupling record and checks if the small cell should continue to be served by the current S-GW or if this should be changed as well, for instance, for a better load balancing or to optimise the path between the CN and the radio access networks.

If the S-GW remains the same, a Modify Bearer Request message is required to be sent to the current S-GW to inform it of the new tunnel endpoint of the small cell. The S-GW makes the necessary changes and returns a Modify Bearer Response message to the MME. The MME, in turn, confirms the operation to the small cell with a Path Switch Request Acknowledge message. Finally, the small cell informs the macrocell that the decoupling has performed successfully and that the user data tunnel on the S1 interface has reconfigured with an Uplink Resource Release message, then the macrocell release all resource in the uplink direction.

In the first case, after the decoupling is complete, the small cell and macrocell only keep the uplink and downlink resources (data channels and control channels), respectively, for the UE. Data blocks transfer in the uplink direction to the small cell, and the macrocell transfer the downlink data blocks to the UE. When the small cell wants to send the control messages to the UE, first, the small cell forwards that to the macrocell by X2 interface, and the macrocell sends that to the UE. Also, the control messages needed to send from the UE to the macrocell forward to the small cell; then, the small cell transfers the control messages to the macrocell via the X2 interface. Hence, based on the suggested architecture (Fig. 2), the downlink resources for the small cell and the macrocell's uplink resources are entirely released when we use the proposed signalling.

The second case is back to the couple state from the decoupled state, where up/downlinks are connected to the small cell (Uplink eNB) and the macrocell (Downlink eNB), respectively and downlink transfers from the macrocell to the small cell. Essential signalling illustrates in Fig. 4. Based on the UE measurement reports on the RSSI, when the RSSI of the small cell is better than the macrocell, and the small cell has enough resources, the small cell triggers the back to the couple connection. This case can be occurred due to UE mobility (transferring from Region B to Region C in Fig. 1). Also, this case may occur due to loading and congestion control mechanisms received in the small cell by the X2 interface from the macrocell. The first step is sending a Downlink Coupling Request message from the small cell to the macrocell.

Similar to the Decoupling Request message, a Downlink Coupling Request message contains all relevant information about the subscriber and all relevant information about the connection to the UE. In addition, this message contains the reserved resources on the downlink. The macrocell then confirms the request to the small cell with a Downlink Coupling Request Acknowledge message. Also,

the macrocell immediately sends the RRC Connection Reconfiguration message to the UE and stops transmitting S-GW data in the downlink direction to the UE. The macrocell sends an SN status transfer message to the small cell as the first case. After issuing the decoupling command, data arriving from the S-GW forward over the X2 interface to the small cell. Upon receiving the reconfiguration message, the UE reconfigures itself to communicate with the small cell and stops receiving data from the macrocell's downlink direction. As the UE has already connected to the small cell in the uplink direction, there is no need to search for the new cell. Hence, the UE can immediately transmit a random access preamble on the PRACH. As dedicated resources are used for the RACH sequence, the UE does not have to identify itself, and merely the first two messages in the RACH sequence are sufficient.

The RRC Connection Reconfiguration Complete message from the UE to the small cell ends the decoupling procedure from the UE point of view, and it can immediately resume transmitting data in the up/downlinks directions with the small cell. The small cell forward RRC Connection Reconfiguration Complete message to the macrocell to inform the CN to reconfigure the S1 tunnel to work with only the small cell. The S1 user data tunnel redirection and an MME context update are invoked with a Path Switch Request message that the macrocell sends to the MME. The MME then updates the subscriber's coupling record. Then a Modify Bearer Request message must be sent to the current S-GW to inform it of the new tunnel endpoint of the small cell. The S-GW makes the necessary changes and returns a Modify Bearer Response message to the MME. The MME, in turn, confirms the operation to the macrocell with a Path Switch Request Acknowledge message. Finally, the macrocell releases all resources relevant to the UE.

After the second case signalling is complete, the up/downlinks are connected to the small cell. At the beginning of the signalling mechanism for downlink coupling, the small cell makes the coupling decision. As described above, the decision trigger by the receiving measurement reports or loading and congestion control mechanisms in the macrocell or small cell. The measurement reports periodically send to the small cell in the uplink direction. If the macrocell wants to decide about the back to couple connection, the measurement reports should forward to the macrocell via the X2 interface. It injects a traffic load to the X2 interface. While the loading and congestion mechanisms can occur in both macrocell and small cell, they should be transferred via X2 interface to the cell, which decides the coupling. Hence we consider the small cell as a node that decides about the coupling. Depending on which measurements report algorithms are used and congestion situations, selecting which cell decides the coupling needs further analysis. We left this analysis to future works.

In the third case, up/downlinks are connected to the small cell (in Fig. 5 noted as uplink eNB), and downlink is transferred from the small cell to the macrocell (in Fig. 5 noted

as downlink eNB). The small cell can decouple the downlink based on the UE measurement reports on the neighbouring cells RSSI. As shown in Fig. 5, the first step in this process is sending a Downlink Decoupling Request message from the small cell to the macrocell. Similar to the Uplink Deccouplink Request Message, the Downlink Decoupling Request message contains all relevant information about the subscriber and all relevant information about the connection to the UE. The macrocell then checks if it still has the resources required to handle the additional subscriber.

If the macrocell grants access, it prepares itself by selecting a C-RNTI for the UE and reserves resources on the downlink. The macrocell then confirms the request to the small cell with a Downlink Decoupling Request Acknowledge message. The message contains all the system parameters that the UE requires to configure to communicate with the macrocell. Once the small cell receives the message, it immediately issues a downlink decoupling command to the UE by an RRC Connection Reconfiguration message. Also, the small cell ceases to transmit data in the downlink direction. After the small cell sends the decoupling command, data arriving from the S-GW forwards over the X2 interface to the macrocell. Similar to the previous cases, the small cell sends an SN status transfer message to the macrocell. This message contains the sequence number of the last valid downlink data block, which is received from the S-GW by the small cell.

Upon receiving the RRC message, the UE communicates with the macrocell and stops receiving data in the downlink direction from the small cell. The UE sends the required control messages to the macrocell via the small cell. The small cell transfers these messages by X2 interface to the macrocell.

The RRC Connection Reconfiguration Complete message from the UE, which forward to the small cell, ends the decoupling procedure from the UE point of view, and it can immediately resume transmitting data in the uplink direction with the small cell and downlink direction with the macrocell. The S1 user data tunnel redirection and an MME context update are invoked with a Path Switch Request message that the macrocell sends to the MME. The MME then updates the subscriber's Decoupling record and checks if the macrocell should continue to be served by the current S-GW or if this should be changed. If the S-GW remains the same, a Modify Bearer Request message is required to be sent to the current S-GW to inform it of the new tunnel endpoint of the macrocell. The S-GW makes the necessary changes and returns a Modify Bearer Response message to the MME. The MME, in turn, confirms the operation to the macrocell with a Path Switch Request Acknowledge message. Finally, the macrocell informs the small cell that the decoupling has performed successfully and that the user data tunnel on the S1 interface has reconfigured with a Downlink Resource Release message, then the small cell release all resources in the downlink direction.

As we described for the first case in the third case, after the decoupling is complete, the small cell and macrocell only keep the uplink and downlink resources (data channels and control channels), respectively, for the UE. Data blocks transfer in the uplink direction to the small cell, and the macrocell transfer the downlink data blocks to the UE. When the small cell wants to send the control messages to the UE, first, the small cell forwards that to the macrocell by X2 interface, and the macrocell sends that to the UE. Also, the control messages needed to send from the UE to the macrocell forward to the small cell; then, the small cell transfers the control messages to the macrocell via the X2 interface.

The fourth case is back to the couple state from the decoupled state. In this case, up/downlinks are connected to the small cell (Uplink eNB) and the macrocell (Downlink eNB), respectively, and uplink transfers from the small cell to the macrocell. Essential signalling illustrates in Fig. 6. Based on the UE measurement reports on the path loss, when the path loss of the macrocell is better than the small cell, the small cell triggers the back to the couple connection. The first step is sending an Uplink Coupling Request message from the small cell to the macrocell.

Similar to the Decoupling Request message, an Uplink Coupling Request message contains all relevant information about the subscriber and all relevant information about the connection to the UE. The macrocell then checks if it still has the resources required in the uplink direction. If the macrocell grants access, it prepares itself by reserves resources on the uplink and confirms the request to the small cell with an Uplink Coupling Request Acknowledge message. This message contains all the information that the UE requires to access the macrocell in the uplink direction. Also, the macrocell immediately sends the RRC Connection Reconfiguration message to the UE. The small cell sends an SN status transfer message to the macrocell and stops transmitting UE data in the uplink direction to the S-GW. Data arriving from the UE forward over the X2 interface to the macrocell.

Upon receiving the reconfiguration message, the UE reconfigures itself to communicate with the macrocell and stops sending data to the small cell in the uplink direction. The RRC Connection Reconfiguration Complete message from the UE to the small cell ends the uplink coupling procedure from the UE point of view, and it can immediately resume transmitting data in the up/downlinks directions with the macrocell. The small cell forward RRC Connection Reconfiguration Complete message to the MME to inform the CN to reconfigure the S1 tunnel to work with only the macrocell. The MME then updates the subscriber's coupling record. Then a Modify Bearer Request message must be sent to the current S-GW to inform it of the new tunnel endpoint of the macrocell. The S-GW makes the necessary changes and returns a Modify Bearer Response message to the MME. The MME, in turn, confirms the operation to the small cell with a Path Switch Request Acknowledge message. Finally, the small cell releases all resources relevant to the UE.

After the fourth case signalling is complete, the up/downlinks are connected to the macrocell. Similar to the second case, the small cell makes the coupling decision

at the beginning of the signalling mechanism for uplink coupling. As described above, the decision trigger by the receiving measurement reports. The measurement reports periodically send to the small cell in the uplink direction. If the macrocell wants to decide about the back to couple connection, the measurement reports should forward to the macrocell via the X2 interface. It injects a traffic load to the X2 interface. Hence we consider the small cell as a node that decides about the coupling.

In the proposed signallings, no CN node changes. Under some conditions such as to optimise user data path between the radio network and CN, load balancing, processing, and user plane capacity reasons, when the new cell is in a timing advance that the current MME does not serve, and etc. the CN nodes have to be changed. In these cases, the decoupling/coupling signallings are extended with additional procedures to include the network elements becoming newly responsible for the connection in the overall process. From the UE point of view, this procedure just increases the time of decoupling/coupling signalling execution. The procedures are the same as the required procedures for traditional handover. The CN procedures are explained in [28] and not in our scope of work.

The UE downlink uplink decoupling in a two-tier cellular network can be described by the three states state diagram capsuled in Fig. 7. States A and C represent where the up/downlinks are connected to the macrocell and small cell, respectively. State B describes where the uplink is connected to the small cell, and the downlink is connected to the macrocell. The UE starts the measurements from state A and, based on the macrocell decision, enters state B if the decoupling condition occurs using the first case signalling. During the first case signalling, if the small cell does not grant access, the UE remains in state A. In state B, the UE will fall into state C if the RSSI of the small cell is better than the macrocell, and the small cell grants access by using the second case of proposed signalling. If the macrocell path loss is better than the small cell and has enough resources, the UE will fall to state A by the fourth case of proposed signalling. Otherwise, it remains in state B. In state C, based on UE measurement reports, if the RSSI of the macrocell is better than the small cell and the macrocell has enough resources to serves in the downlink direction, the UE will fall into the state B using the proposed third case signalling. Otherwise, it remains in state C.

In state B, three other situations may occur depending on the measurement reports: The uplink transfers to a new small cell, the downlink transfers to a new macrocell and, up/downlinks transfer to a new small cell and a new macrocell, respectively. The possible situation transforms state B to a composite state that is shown in Fig. 8.

For the first situation, where the uplink is transferred from the current small cell to a new small cell, the current small cell runs the back to couple connection signalling (fourth case of proposed signalling). Then the macrocell immediately runs the uplink decoupling (first case of proposed signalling).

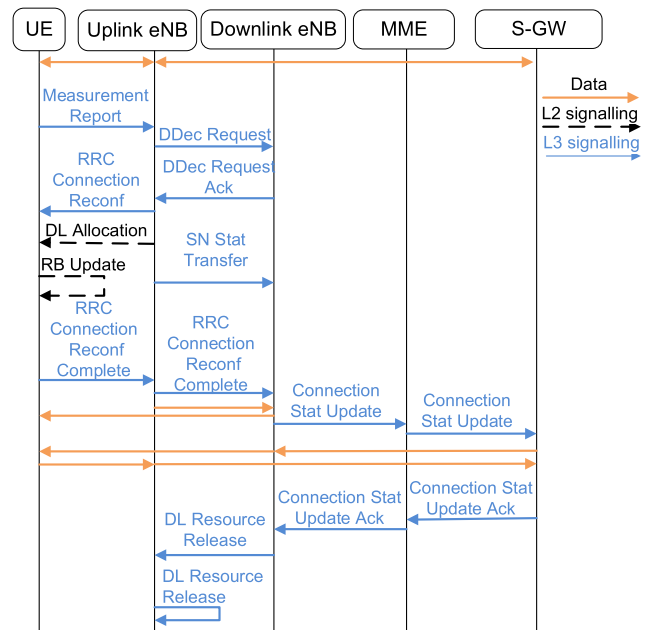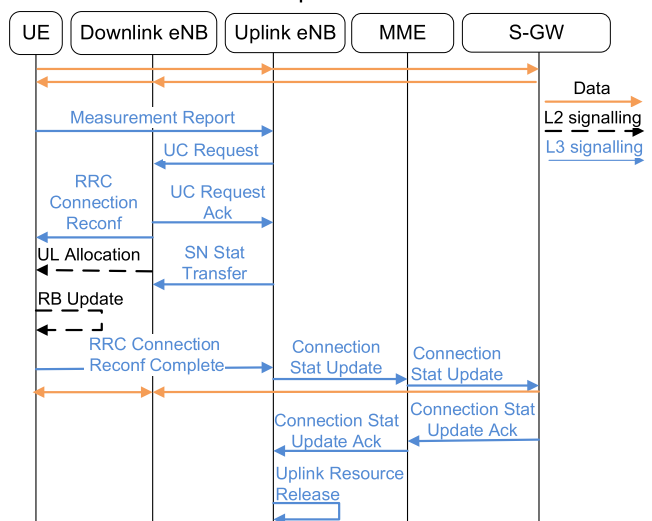**FIGURE 5.** Signalling mechanism for downlink decoupling.

FIGURE 6. Signalling mechanism for uplink coupling.

For the second situation, where the downlink is transferred from the current macrocell to a new macrocell, the current small cell runs downlink coupling signalling (second case of proposed signalling). The small cell immediately runs the downlink decoupling signalling (third case of proposed signalling).

For the third situation, where the up/downlinks transfer to a new small cell and a new macrocell, respectively, the combination of required first and second situations signallings can consider. The order of execution may affect the decoupling delay. We left the analysis to the future works.

In state A, we cannot consider the situation where the uplink or downlink transfers to the new macrocell because the
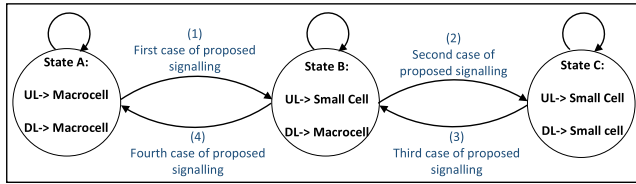
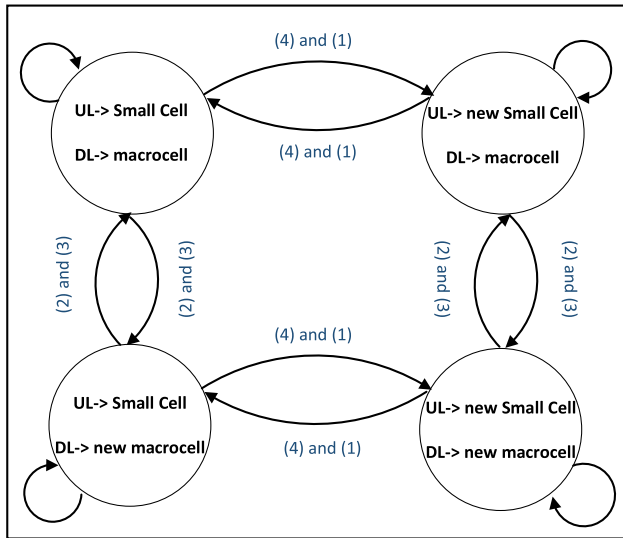**FIGURE 7.** The UE downlink uplink decoupling state diagram.

FIGURE 8. The Substates of state B (1, 2,3, and 4 are transition numbers as illustrated in Fig. 7).

FIGURE 9. IP level solution for DUDe.

FIGURE 10. Simulation scenario for decoupled up/downlinks.

decoupling occurs in heterogeneous networks. Only the traditional handover occurs for cell changes. Similar to state A, state B also cannot divide.

The conditions that occur the transition between states in Fig. 7 and Fig. 8 are based on UE measurement reports on the path loss for the uplink and RSSI for downlink. Also, the transition between states can occur due to loading and congestion control mechanisms. In this work, we do not concentrate on the cases that happened by the loading and congestion control mechanisms and left that to future works.

Another solution for DUDe higher layers connection handling is focusing on the intra PDN gateway mobility DUDe mechanism, which can be implemented without any changes in LTE signalling. This solution affects the TCP and network layer using storing two data flows for a single connection between a source wireless device and a destination. A network address translation (NAT) table can map the interface/IP address for a mobile node with the corresponding small/macrocell. As shown in Fig. 9, when a UE (source node) **F** discovers and selects two different small/macrocells for its uplink and downlink communications, it sets up an uplink path via small cell **D** and a downlink path via macrocell **E**. We propose to include a NAT table that should contain the uplink information to alter F's address interface to be reachable from **E** on the downlink. This method works for the intra-gateway mobility. Our discussion does not cover
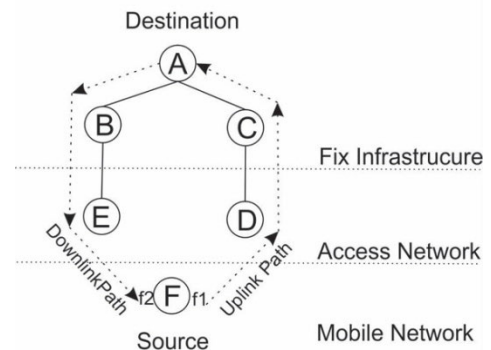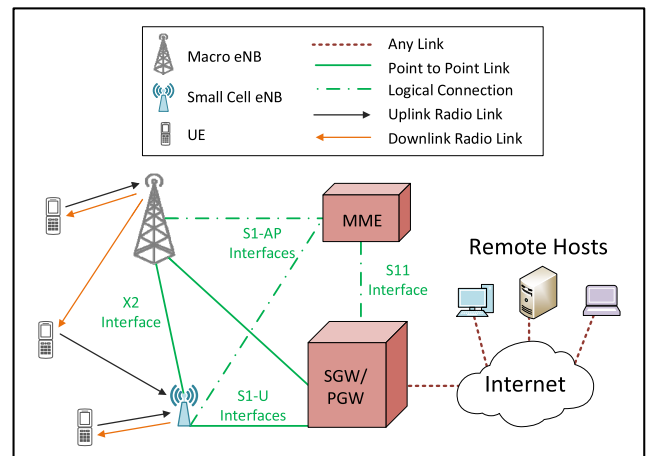
the inter-gateway mobility scenario where the PDN should be involved. Analysis of connection handling using NAT mechanism is left for future works.

IV. SIMULATION ANALYSIS

To simulate our proposed signalling mechanism, we use the publicly available codes[1] for ns3 simulation tools [15] and implement the proposed signalling represented in section III (the general simulation scenario is shown in Fig. 10.) We have applied two simulation scenarios for our analysis:

Scenario 1: UEs are mobile and move based on a selected mobility model. Applications in this category are smart city: management of vehicular traffic in large cities, self-driven cars [16], Patient Monitoring (It is being admitted to hospital), etc.

Scenario 2: UEs are fixed and do not move during the simulation time. This scenario simulates use cases such as smart factories (fix sensors/actuators in the factories), smart homes (fix sensors/actuators in home send/receive data periodically), smart hospital (where the hospital is in the vicinity of one macrocell), smart grids, smart farming [17], water supply, shopping malls, airports, stadiums, etc.

[1]LENA

We refer to the first and second scenarios as with/without mobility in the rest of the paper.

We analysed the without mobility case to study the gain of up/downlinks decoupling for a fix UE in the decoupling region (region B in Fig.1). For a non-invasive change in the existing cell selection mechanism, we consider up/downlinks of a UE with the fixed location first connect to a macro-cell (traditional cell selection mechanism) then based on the received measurement reports and the pathloss calculation, the eNB decides to decouple the uplink (as shown in Fig. 3.). Also, when the resource of a small cell at the vicinity of UE is released/congested or a new small cell deployed, UE needs to couple/decouple connection.

For both scenarios, we have considered the case of using DUDe or using conventional set-up based on represented signalling mechanism in [26] (using handover for with mobility case and using the traditional cell selection for without mobility case), which is called with/without DUDe. Therefore, in the with DUDe case, we use the proposed signalling mechanisms to implement DUDe, and in the without DUDe case, we use the conventional set-up as mentioned above. Also, authors in [25] showed that the multiple UEs, which create interference for other cells if assigned the same resources, did not affect the comparison of the SINR level in the decoupling region. Hence in both scenarios, we consider one UE. We select a smart city application for with mobility scenario where a vehicle is considered our UE. We adopt our previous simulation mobility model [18] to simulate the realistic mobility pattern in smart cities in part of Pittsburgh, PA, with width and height of 1.6 and 1.8 km. We use SUMO [19] to generate random mobility in the urban area based on the Pittsburgh, PA map. The maximum UE speed is 15 m/s, and the mobility is the SUMO randomtrip [20] which generates a set of random trips with uniform distribution. The macrocells deployment is based on real positions on the Pittsburgh, PA map. We did not have access to the actual deployment of small cells on the map of Pittsburgh, PA. For optimal cell deployment, a simulation is first performed by the operator. Then the simulation output is optimised. Finally, by placing the cells in the obtained locations and adjusting their parameters, the optimal coverage is achieved in the actual environment, which is highly overpriced and not within our scope of work. In an attempt to consider suitable coverage for small cells, we have followed the results in [21].

Authors in [21] have studied the increase in network capacity relative to the increase in the number of small cells per macrocell. They have shown in most cases, deploying more than three small cells per macrocells is not worthwhile. We consider two small cells per macrocell because some of the macrocells are on the selected area's border on the Pittsburgh, PA map.

We use the pathloss model defined in 3GPP TR 37.885 [22], [23] for the urban scenario. In the simulations for the UE, we assume that we know the value of pathloss anywhere. This is implemented in simulation through a public entity. In real life, the pathloss can be predicted by the prediction
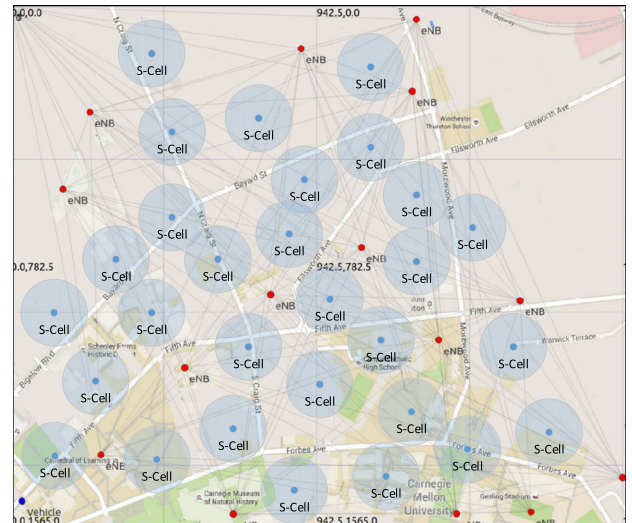

FIGURE 11. Simulation scenario for with mobility case.

methods represented in [29] or by the actual measurement maps in the target environment, which can be prepared and given to the network as input. In another way, if the small/macrocell knows the other cells send power, it can easily calculate pathloss from the received power in the UE because the small/macrocell in the proposed signalling decides about the decoupling. Also, Fig. 11 illustrates our simulation scenario map with eNBs as macrocells and small cells for with mobility scenario. Lines connected to eNBs represent the X2 interface that provides communication between eNBs. The red circles represent the macrocells (eNBs), the light blue circle indicates the small cells, and the blue circle represents the UE.

In without mobility case, we consider one UE with a fixed location using DUDe (uplink is connected to small cell and downlink is connected to macrocell) which is called without mobility with DUDe, and one UE with a fixed location with a conventional connection which is called without mobility without DUDe (uplink and downlink are connected to macrocell). Fig. 12 illustrates the simulation scenario map for without mobility case. In our simulations, parameters of packet delay, the number of lost packets, and signalling overhead are measured.

In these simulations, we consider a CBR traffic in the uplink direction that is sent from the UE to the remote host and a CBR traffic in the direction of the downlink that is sent from the remote host to the UE, and by increasing the traffic rate, we examine the behaviour of the DUDe mechanism. It should be noted that the packet length is 1250 Bytes. We have decreased the packet generation intervals to increase traffic rates. Simulation results are collected based on a 90% confidence level. Table 1 represents our simulation parameters.

The data rate is increased based on the suggested peak rated in 3GPP rel. 11 [12], i.e., uplink up to 1.5 Gbps and downlink up to 3 Gbps.
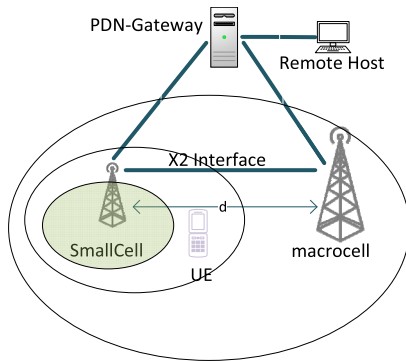
FIGURE 12. Simulation scenario for without mobility case.

TABLE 1. Considered simulation parameters.

Simulation Parameters		
	With mobility	Without mobility
Topology Size	1.6×1.8Km2	1 cell (1 km radius)
UE	1	1
Macro eNB	15	1
small cells	30	1
Macro eNB Tx	46 dB	46 dB
Small cell Tx	23 dB	23 dB
MAC Protocol	LTE	LTE
Propagation Model	3GPP TR.37.885	Nakagami and Three Log Distance
Confidence Level	90%	90%
Distance d	-	500
Uplink Data Rate	0.5-50 Mbps	0.5-15 Mbps
Downlink Data Rate	1-80 Mbps	1-40 Mbps
Simulation Time	1000 s	1000 s
Mobility speed	15 m/s	-
eNBs' Distance (d)	Based on real deployment	0.5 km
Packet size	1250 Bytes	1250 Bytes
Number of runs	5	6

The packet loss for the uplink starts at 60 Mbps and starts for the downlink at 90 Mbps. Specified data rates in the 3GPP standard are based on the rate observed in the physical channel, while it decreases in the higher layers. On the other hand, the specified rate in the standard is for peak data rate. Therefore, data rates in Figures 13 to 16 are selected up to 50Mbps and 90 Mbps for uplink and downlink, respectively, to illustrate the results better. We have investigated the decoupling impact over a scenario where UE is considered static, and the other case is mobile. Three performance metrics are applied in our investigation and are defined as follows: first, the Average Delay, calculated using the formula (1).

$$
\begin{aligned}
&Average\_Delay \\
&= \frac{total\_connection\_set - up\_time}{number\_of\_tx\_pkts} \\
&\quad + \frac{\sum_{i=1}^{i=number\ of\ tx\_pkts}(rx\_pkt\_int_i - tx\_pkt\_int_i)}{number\_of\_tx\_pkts}
\end{aligned}
\tag{1}
$$

where total_connection_set − up_time denotes the summation of all cell selection, handover, decoupling, coupling time. Also, number_of_tx_pkts indicates the total number of sent packets, $rx\_pkt\_int_i$ denotes the time of receiving the ith packet, and $tx\_pkt\_int_i$ represents the time of sending the ith packet. Second, the Number of Lost Packet is the number of packets assumed to be lost, i.e., those transmitted but not reported as received or forwarded. Third, we study the signalling overhead to show the cost of using proposed signalling mechanisms.

We examine the performance metrics for uplink and downlink traffic separately to fully investigate the impact of applying DUDe. Finally, we discuss the cost of the proposed signalling mechanisms at the end of the current section.

A. UPLINK ANALYSIS

As shown in Fig. 13.a, the number of lost packets in the uplink considering mobility in the case with DUDe 26.4% are less than the case without DUDe and in the uplink without mobility (Fig. 13.b) in the case with DUDe 27.2% are less than the case without DUDe.

This is due to connecting the uplink to the small cell which has lower pathloss than the macrocell. While using DUDe, in the without mobility case the improvements 1% are better than the with mobility case. Moreover, the total number of lost packets in the without mobility case is 7% lower than the with mobility case. This is due to the impact of mobility and the number of coupling and decoupling during the mobility duration. We should bear in mind that depending on which of the decoupling shown in Figures 3 to 6, during the up/downlinks decoupling process, uplink or downlink packets are transmitted to the target cell from the X2 link. At the end of the up/downlinks decoupling process, the sequence number of the last packet sent/received is transferred to the target cell. Results show that in these processes (when considering mobility), the total number of lost packets increases by 7% compared to those without mobility case.

In Fig. 13, the trend of the Number of Lost Packets is ascending. This is due to network crowding caused by increasing the data rates. As mentioned at the beginning of the current section, the network will be congested in the uplink direction for data rates higher than 60 Mbps. As shown in Fig. 14.a, the delay in the uplink considering mobility in the case with DUDe 30.8% are less than the case without DUDe. Also, the delay in the uplink without mobility (Fig. 14.b) in the case with DUDe 36.16% are less than the case without DUDe. When DUDe implementation is in place, the uplink flow is sent over the small cell links with lower pathloss. As a result, packet delivery delay is reduced.
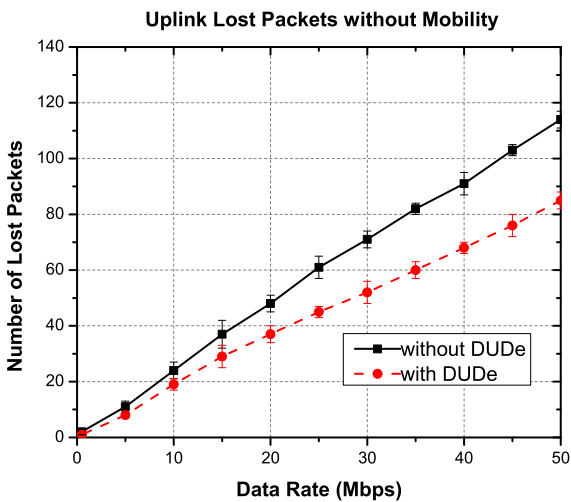
The X2 link delay also contributes to the delay results. During the DUDe process as described in Section III, depending on the decoupling types shown in Figures 3 to 6, the uplink or downlink flow is retransmitted over the X2 link (typically a wired connection) over to the target cell over decoupling time (approximately 20ms).
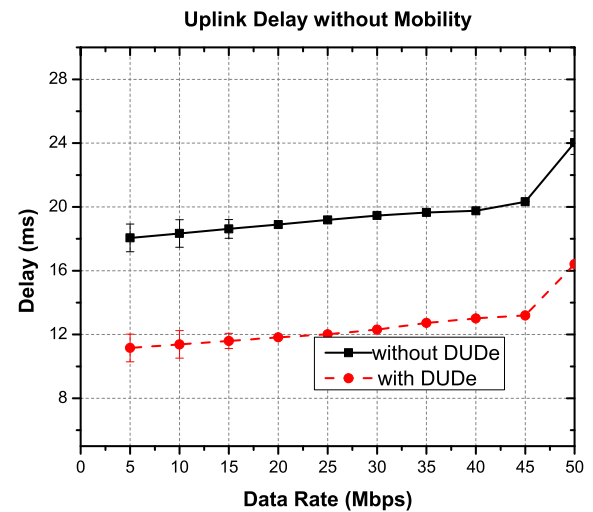
(a)
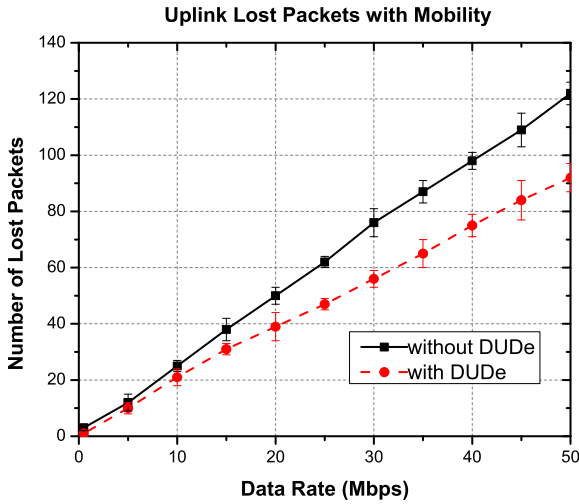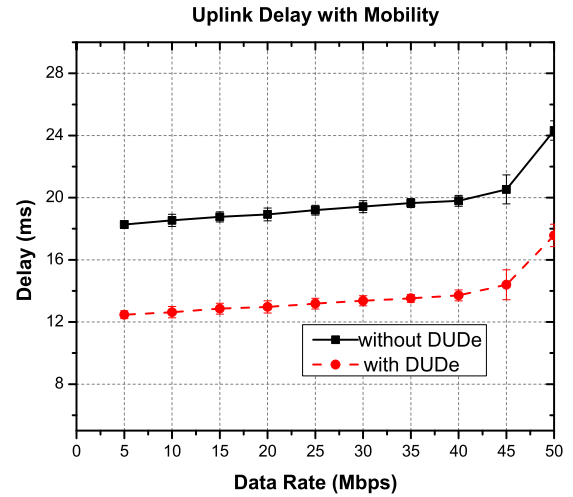
(b)

FIGURE 13. Uplink Packet Loss: a) with mobility, b) without mobility.

(a)

(b)

FIGURE 14. Uplink Delay: a) with mobility, b) without mobility.

Since the X2 link is usually wired, the observed delay is insignificant. While due to the decrease in number of lost packets in the case without mobility with DUDe (Fig. 13.b) relative to mobility-based with DUDe, the delay in the case without mobility with DUDe (Fig. 14.b) decreases. As shown in the results, the uplink delay for the data rate of more than 45Mb/s is considerably increased (Fig. 14) which can be justified due to channel saturation.

Considering the impact of DUDe on uplink performance metrics, we look at the downlink traffic scenario in the following subsection.

B. DOWNLINK ANALYSIS

As shown in Figures 15 and 16, downlink delays and the number of lost packets are not affected by using the DUDe mechanism. This is due to selecting downlink cells based on RSSI.

In Fig. 15, the trend of the figures is constant. As mentioned in formula (1), we calculate the average delay of all received packets. Increasing the data rates increases the number of packets. It should be noted that the lost packets rate does not increase. So, the ascending trend of the Number of Lost Packets caused by network crowding (as shown in Fig. 16) does not affect the Average Delay. In Fig. 16, the trends of the Number of Lost Packets are ascending. This is due to increase data rates; therefore, the network becomes crowded, and as mentioned at the beginning of the current section, in the downlink direction, the network will be congested for the data rates higher than 90 Mbps.

C. COST OF PROPOSED SIGNALLING MECHANISM

Table 2 summarises the improvement percentage in the results relative to using DUDe and without using DUDe. The gain of using DUDe case relative to the conventional scheme,

TABLE 2. Performance comparison for using DUDe solution vs. conventional scheme.

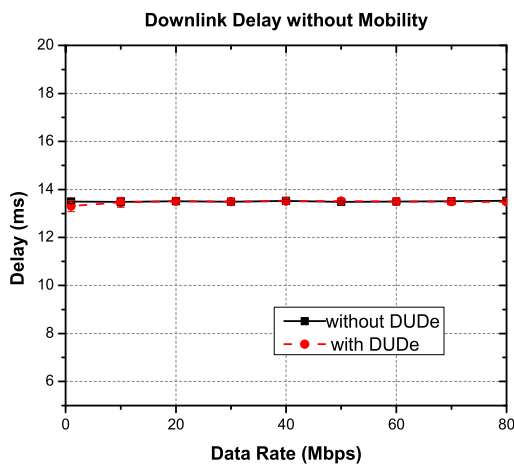| Parameter	Uplink		Downlink	
	With mobility	Without mobility	With mobility	Without mobility
Delay	-30.87%	-36.16%	-0.74%	-0.2%
Number of Lost Packets	-26.04%	-27.2 %	-1.7 %	-0.99%
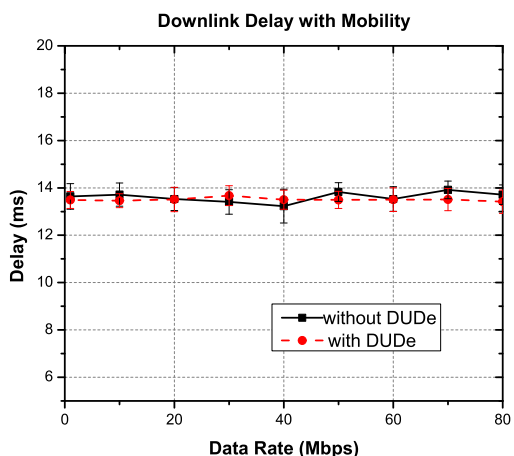
FIGURE 15. Downlink Delay: a) with mobility, b) without mobility.
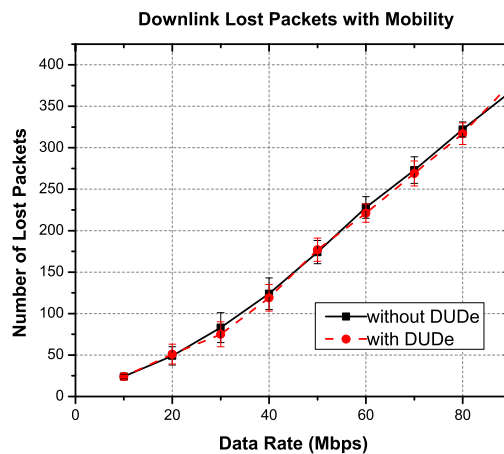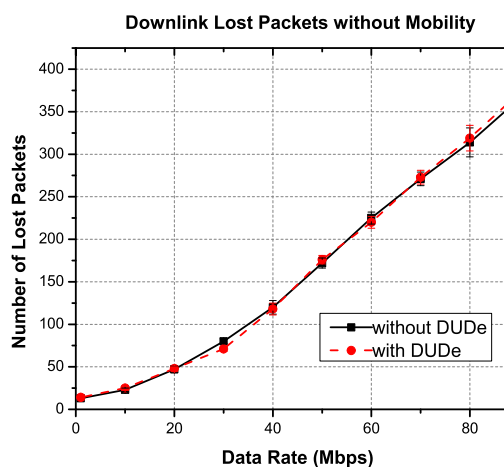

FIGURE 16. Downlink Packet Loss: a) with mobility, b) without mobility.

for data rates 0.5 to 50 Mbps for uplink and data rates 1 to 80 Mbps for downlink is presented in Table 2. It should be noted that Table 2 is derived from the results showed in Figures 13 to 16.

The impact of using the DUDe mechanism shows mainly improvements for the uplink, the delay and loss packets are reduced by 30% and 26%, respectively for considering mobility scenario. Also, for the without mobility scenario, the delay and lost packets are reduced by 36.16% and 27.2% respectively. Our observation shows similar performance in

the downlink DUDe mechanism as it is also based on RSSI decision. The cost of the improvements achieved by DUDe is that we have assumed that the UEs know the pathloss value. This has been implemented in a simulation with a public entity. Another cost of this improvement is the use of small cells, as well as the number of coupling and decoupling signalling that are added instead of handover for the with mobility case.

Fig. 17 compares the signalling overhead in the proposed signalling mechanism (with DUDe) and conventional handover (without DUDe). In this comparison, we evaluate the percent of signalling overhead relative to the data rate using formula (2), as shown at the top of the next page, where total_connection_set − up_messages_length denotes the total length of all cell selection, handover, decoupling, and coupling messages. Also, numberoftx_pkts and numberofrx_pkts indicate the total number of sent and received packets in the UE, respectively. The $rx\_pkt\_int\_l_j$ represents the length of receiving j^{th} packet, and $tx\_pkt\_int\_l_i$ denotes the length of sending i^{th} packet.

$$\text{Signalling\_Overhead\_Rate} = \frac{\text{total\_connection\_set} - \text{up\_messages\_length}}{\left(\sum_{i=1}^{i=\text{number\_of\_tx\_pkts}} \text{tx\_pkts\_l}_i\right) + \left(\sum_{j=1}^{j=\text{number\_of\_rx\_pkts}} \text{tx\_pkts\_l}_j\right)} \times 100 \qquad (2)$$
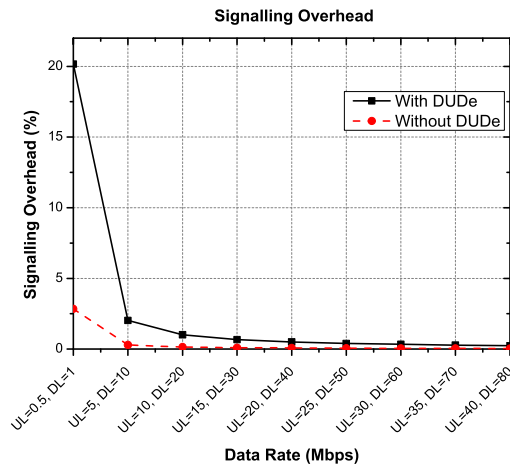

FIGURE 17. Proposed Signalling mechanism Overhead VS. conventional handover Signalling Overhead.

As it can be observed in the DUDe case, the signalling overhead is higher, since the number of couplings and decouplings are more than the conventional handovers. The trend of overheads is descending due to the increase in the data rate. As depicted in Fig. 17, the signalling overhead for the data rates higher than the 15 Mbps and downlink 30 Mbps for the up/downlinks are close to each other. Hence, the cost of using DUDe for the higher data rates is meager and similar to conventional handover.

V. CONCLUSION & FUTURE WORKS

In this paper, we have proposed the signalling mechanisms for downlink uplink decoupling and assess the gains of the DUDe with ns3 simulations. The impact of using the DUDe with proposed signalling mechanisms is compared to the conventional scheme for uplink rates in the range of 0.5 to 50 Mbps and the downlink rates between 1 to 80 Mbps.

The main improvements are reported to be for the uplink scenario the delay and the number of lost packets is reduced by 30% and 26%, respectively in with mobility scenario and 36.16% and 27.2% respectively in without mobility scenario. Our observation shows similar performance in the downlink DUDe proposed signalling mechanisms as it is also based on the RSSI decision. These improvements were achieved in return for using small cells, decoupling signalling overheads, and knowing the value of pathloss in each UE. We are working on the verification of proposed signallings with the Markov Chain.

Further analysis is required for the suggested IP level solution of the DUDe as shown in Fig. 9. If the coupling/decoupling is trigged by the congestion control or load balancing mechanisms, further analysis is required to study the gain of the proposed signalling mechanisms. Studying the

execution order of proposed signalling in the composite state (Fig. 8), which may affect the decoupling delay, can also be investigated in future studies. Further research is required to calculate the value of pathloss of each UE in the actual environment. We suggest three approaches for this aim: First, by using the pathloss prediction algorithms, second, by the actual measurement maps in the target environment, and third by using the diffraction of small/macrocell send power and UE receive power.

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