Evolved User Equipment for Collaborative Wireless Backhauling in Next Generation Cellular Networks

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Abstract—In this paper, we propose a novel architecture for next generation cellular networks that enables collaborative forwarding at Layer 2 among adjacent eNBs with the aid of enhanced user equipment (UE) devices, that act voluntarily as packet forwarders. Therefore, legacy UEs are leveraged as active network elements being capable of operating simultaneously over multiple base stations (eNBs). To this end, we introduce an evolved-UE (eUE) in order to enable reliable multi-hop operation through relaying and to achieve low-latency communication through efficient L2/MAC forwarding. Through extensive experimentation with OpenAirInterface emulation platform, we evaluated the performance and also validated the feasibility of the proposed architecture. Our results show that, in certain use cases corresponding to public safety and moving/small cell scenarios, the proposed architecture achieves significant reduction in latency (up to 16.94%) and improvement on packet loss rate (up to 59.25%), as the number of the employed eUEs increases with increasing BLER up to 20%. Moreover, the proposed architecture enables eUEs to increase the aggregated data rate in downlink by exploiting data connection to multiple eNBs at the expense of extra power consumption, which calls for the appropriate incentives to enable such a cooperation.

Keywords – Cellular Networks, Wireless Mesh, Architecture, Virtual Link, Cooperation, Wireless Backhaul.

I. INTRODUCTION

A. Motivation

As the definition of 5G technologies is still in progress, the need for solutions that will bring to cellular networks improved capacity, coverage and energy efficiency render new communication trends for seamless connectivity, heterogeneous networking and interoperability more-and-more attractive [1], [2]. Those trends stipulate a combination of sophisticated techniques that have been in the foreground research promising to be the key enablers for future cellular networks, not least of which are small cell and heterogeneous network deployments, data offloading techniques, tighter 4G/Wi-Fi interworking, advanced interference coordination techniques and spectrum management, coordinated multipoint (CoMP) transmissions, relaying and multiflow techniques across small cells, private mobile radio (PMR), device-to-device (D2D) and machine-to-machine (M2M) communication. Despite their promising
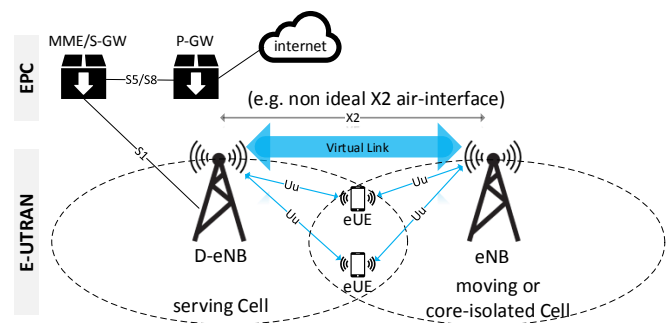
Fig. 1. Evolved UEs (eUEs) are leveraged to become active network elements, to form a virtual antenna and to interconnect core-isolated with donor eNBs.

benefits, all the above techniques call for a network architecture that can simultaneously provide lower costs, lower latency, and greater flexibility to offer improved networking, ubiquitous access and extended coverage.

In this context, a disruptive and forward-looking idea is for the future cellular networks to exploit UEs as active network elements to collaboratively convey traffic. Recent studies (e.g. see [3]–[5]) have shown that users are willing to participate in such collaboration and delay their own traffic or increase their power consumption if, for example, some incentives in terms of reduction of subscription costs are provided. Besides, the incentives from the carriers side stem from the need to reduce the cost of providing services. In the legacy PMR for example, UEs undertake packet relaying and can play the gateway role. That is, carriers provide the same services as in legacy systems by exploiting the standard operation of UEs.

In this paper, we propose a new paradigm for link virtualization through cooperative L2/MAC information (packet) forwarding enabled by a group of UEs, denoted as evolved UE (eUE). The considered architecture is depicted in Fig. 1. The gist of this architecture relies on the exploitation of a new virtual air-interface for next generation radio access network (RAN) systems that extends the classical point-to-point physical links and enables new use-cases, possibly raising the ante to create a new marketplace among users and carriers [3]. To this end, we re-establish the X2-air interface that is used to interconnect eNBs by utilizing intermediate collaborative eUEs in order to create a virtual air-interface and achieve a low-

latency yet reliable over-the-air transmission through L2/MAC packet forwarding.

Currently, solutions that are used in CoMP techniques such as Joint Transmission (JT) cannot achieve the maximum performance gain and fail to exhibit the full collaborative potential using the traditional X2-air interface due to low-latency and high bandwidth requirements [6], [7]. As dynamic coordination that is used for resource reconfiguration requires very strict time limitation on the update of the control information, the need for an advanced solution that can provide low-latency communication for CoMP techniques by forwarding packets at the MAC/L2 becomes essential.

B. Contribution

In this paper, we design and present a novel architecture which evolves UEs (eUEs) in the context of future cellular networks. The intellectual merit of this architecture is considered for certain use cases, as it enables the establishment of a new virtual air-interface that helps operators to improve network coverage and low-latency performance and accordingly helps users to benefit from their participation and improve their received throughput or bargain for beneficial data plans at an expense on their battery consumption. Particularly: *i*) In moving cell scenarios, multiple eUEs act voluntarily as relays and packet-forwarders and extend the network coverage area by building virtual links (VL), hence, eUEs re-establish backhaul access to moving and/or core-isolated eNBs by allowing end-point eNBs to exploit their functionalities as a service (see [8]), *ii*) in small and/or densified cell scenarios, network and subsequently eNBs provide multiple connectivity and data pipes to the eUEs through different radio bearers so as to increase their capacity and enable seamless handover between the connected eNBs [9], *iii*) a new type of collaborative transmission is realized as a *dual* CoMP in uplink, where eUEs form a virtual MIMO antenna for transmitting to the destination eNB, and (*iv*) a MAC scheduler for the eNBs to handle the collaborative transmissions is given.

The rest of this paper is organized as follows: In Section II we present prior related work. Subsequently, in Section III, we describe the design of the proposed architecture as an enabler of a wireless mesh operation over a cellular topology. Then, we give an overview of the procedures designed in PHY and MAC layer for enabling this architecture. In Section IV we describe representative use-cases that exploit eUE-aided L2 forwarding. Performance evaluation of our architecture is validated in Section V and Section VI concludes our work.

II. RELATED WORK

In pursuit of designing a novel architecture for future cellular networks, we differentiate from prior studies in the literature as they are summarized below.

Relaying and packet forwarding: In their seminal works [10], Sendonaris *et al.* advocate that in a multi-hop relay scenario, cooperative communication is being considered as an efficient solution for transmissions, as it provides robust and resilient forwarding by recruiting multiple intermediate relays to collaboratively transmit the source signal to the destination. Authors in [11], [12], compare different relay types and topologies in LTE-Advanced and WiMAX standards.
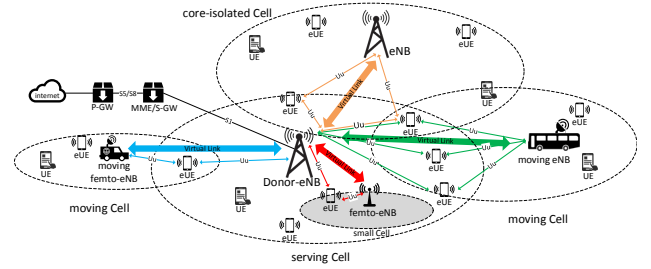

Fig. 2. Network Topology: Moving, small and core-isolated cells exploit eUE-enabled multipoint connectivity to access backhaul, when either non-ideal X2-air interfaces cannot be effectively utilized to inter-connect eNBs or wired interfaces are infeasible or too costly to be deployed.

Simulation results show that relay technologies can effectively improve service coverage and system throughput. Those works motivate the applicability of packet forwarding solutions in relay assisted networks. Our work is differentiated from the above in the sense that it rethinks the end-to-end information transfer as relays terminate the S1-AP protocol. The current practice considers relays as a part of network planning that maintain sufficient backhaul access to the core, while in our architecture eUEs adopt a light-weight design to effectively enable new use cases in small and moving cell scenarios.

Although both relays and eUEs operation requires multiple connectivities, a distinctive characteristic is that relays can play the role of UE with respect to Donor eNB and the role of eNB with respect to the UEs, while the introduced eUEs remain always UEs with respect to the connected eNBs. In [13], authors discuss the evaluation of a cooperative relaying scheme that exploits QMF for Wi-Fi infrastructure networks. A PHY layer design is presented motivating the need for a close interaction with a suitable MAC to exploit the benefits of relaying diversity either through link switching or link cooperation. Our approach considers cooperative MAC forwarding by exploiting the underlying relaying scheme.

Cooperative Communications: A novel cross-layer design is presented in [14] and exploits benefits of PHY/MAC interworking to enable cooperative relaying in a WIMAX system. Authors propose a MAC layer protocol, named CoopMAX that is in compliance with WiMAX standards to allow for leveraging intermediate relays to service cell edge users. On the contrary, our work introduces the concept of collaborative radio bearer establishment in LTE, where multiple eUEs can be leveraged to support backhaul access connectivity to core isolated or moving eNBs as well as to benefit by multiple inter-node radio aggregation. In a preliminary work in [15], we studied the throughput efficiency in the presence of two UEs when decode-nd-forward (DF) is used in system-level simulator in absence of any protocol. We enhanced this preliminary work aiming at enabling low-latency transfer in inter-cluster communications, introducing a full protocol implementation mechanism for MAC/L2 packet forwarding that exploits buffer aware scheduling.

III. ARCHITECTURE

In this Section we describe a light-weight architecture that employs eUEs to form a virtual MIMO and forward packets at L2/MAC for low-latency communication. Our approach is inline with the latest activities of 3GPP to enable multiple connectivity access for public safety [16] and enable services

to private mobile radio (PMR) systems responding to natural disaster scenarios [17].

A. LTE Mesh Network Topology

The network topology that we consider, is a wireless mesh network that is built on the top of LTE. This topology is assumed to be 2-level hierarchical or clustered, where a cluster is defined as the set of nodes which are characterized by one-hop connectivity with the eNB macro base station. Fig. 2 illustrates the network topology and the new use-cases (see Sec. IV) introduced by eUE-assisted packet forwarding. In this topology, there exist three type of nodes.

- **eNBs** are the legacy 3GPP eNBs with extended functionalities to support *i*) meshing, *ii*) the coordination of user traffic, *iii*) the management and scheduling of radio resources (i.e. time, frequency, and space) within a cell and *iv*) the routing for intra and inter cell communication. It should also be considered that user traffic is not necessarily passed to the core network through eNBs.
- **UEs** They are legacy 3GPP user equipment.
- **eUEs** are actually evolved UEs with enhanced capabilities of associating to multiple eNBs and thus interconnecting adjacent eNBs. They act as 3GPP UE terminals maintaining their initial operation and also act as a slave with respect to the eNBs perspective. As UEs do, they also interpret the scheduling messages coming from eNBs on signaling channels so as to enable traffic routing and forwarding relying on the allocated physical resource blocks RBs.

B. Virtual Overlay - Enable Mesh Networking

Consider this: In cellular networks, we have to deploy typically wires (fiber/coper) to base stations in order to access the core network and enable internet connectivity to the wireless access part. As this is the standard method in LTE and LTE-A deployments to access an internet gateway, the proliferation of relays and small cells, although it has promised to confront this problem, it actually introduces additional costs both for the operators and the users. The former need to invest and the latter are called for buying new equipment (e.g. Home-eNBs). While in LTE the X2 air-interface can be utilized for interconnecting eNBs, it has been mainly formed for exchanging control plane information between eNBs for assisting handover procedures and advanced inter-cell interference coordination (ICIC) techniques. Contrary to the above, the proposed networking approach rethinks the standard way of wireless cellular communication. It enables a virtual overlay wireless mesh on the top of cellular topology that is abstracted by the eUEs collaboration[1]. Multiple eUEs can collaboratively participate to form VLs. A VL can be perceived into two phases: a broadcast point-to-multipoint (P2MP) phase from (source) eNB to eUEs and a cooperative multi-point-to-point (MP2P) phase from eUEs to (destination) eNB.

Moreover, in order to establish a virtual link by appropriately selecting the subset of eUEs, it should be considered also the level of cooperation they are able or willing to provide to the network according to a service-level-agreement (SLA). The selected eUEs list is then provided to the corresponding eNBs so as to initiate the establishment of a collaborative virtual link [3], [5]. That is out of the scope of this work and we mainly focus on the design of the PHY and MAC operations. However, the significance of the above concept implies the need to describe the hidden potential offered.

Specifically, the interaction among the layers that is dynamically enabled by the eUEs requires a novel architecture to suggest a new type of collaborative transmission for cooperation that is realized as a CoMP in uplink where eUEs form a virtual MIMO antenna for transmitting to the destination eNB. Particularly, this architecture implies the PHY layer to present a VL as a link abstraction to the MAC layer with a given probability of packet erasure and subsequently the MAC layer to present a VL as a channel abstraction to the network layer by enabling collaborative bearers that are used for local traffic routing between eNBs and end-to-end services.

- *Signal-level Cooperation* is operated by the PHY layer, which is responsible for identifying the optimal way to cooperate at the signal-level so that the bit error probability is minimized with respect to predefined quality constraints. Signal-level cooperation presents an interesting abstraction to higher layers: that is, a VL with a given probability of packet erasure. Moreover, cooperation at signal-level implicates all eUEs regardless of the perceived link quality in TX or RX mode with the interconnected eNBs. An appropriate selection of a relaying and coding scheme e.g. Decode-and-Forward (DF) or Quantize-Map-Forward (QMF) and distributed Alamouti codes allows for independent coordination among eUEs and enables an over-the-air signal combination towards the destination eNB [13], [15].
- *Packet-level Cooperation* is operated by the MAC, or more generally Layer 2 (L2), which is responsible for packet-forwarding and scheduling. Specifically, L2 creates a virtual link by leveraging the legacy 3GPP connection establishment procedures in order to complete packet transmissions between two specific end-points. It identifies which physical links (PLs) and their respective end-points need to be activated so that end-to-end frame error rate is minimized, hence improving drastically the efficiency of the signal-level cooperation. The actual decision about VL establishment and PL activation is obtained by the higher layers and L2 from its side identifies and reports this induced relay selection to the higher layers. In addition to regular scheduling MAC performs scheduling of collaborative broadcast in DL and CoMP transmission in UL[2]. The routing path is optimized as packets do not have to traverse the whole protocol stack and when identified by the MAC they are forwarded for collaborative transmission. Reliable end-to-end packet delivery over a VL may be also handled by L2 through retransmission and/or forwarding-error-correction-codes (FEC), e.g. Hybrid-ARQ (HARQ).
- *Network-level Cooperation* The decision about local traffic routing and relay selection (control plane) over a VL can be performed either at the network or higher layers. This kind of information is passed to the MAC. Therefore, there is a need to select one or a group of eUEs that will serve as

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[1]Software-defined networking techniques can be also applied to the virtual overlay network for enabling the wireless meshing.

[2]We assume that the introduced *dual* CoMP in UL performed by users (eUEs) considers the distributed Alamouti coding as a general class for an independent yet coordinated transmission scheme.

relays to enable signal and packet level cooperation (data plane). Furthermore, the control and the data plane are decoupled as the routing decision and relay selection are performed at the higher layers while data forwarding at the MAC/PHY layer. Therefore, a sophisticated mechanism to support the cooperation by giving access to the forwarding table of the MAC is required. Such a mechanism can be implemented either locally or over the network. In the former case, the MAC/L2 forwarding table can be simply built based on the routing table in a similar way as done in the L2.5/L3 forwarding (e.g as in the multiprotocol label switching (MPLS)). In the latter case, a SDN approach can be applied to interface between the control and data plane.

C. PHY Layer Design

The course of actions that occur in the PHY are described by the following procedures:

Cell-search: Search procedures is the primary step to access the LTE network, and consists of a series of synchronization stages to determine time and frequency parameters required for correct timing in uplink and downlink. Standard LTE synchronization procedures allows a terminal to detect the primary and subsequently the secondary synchronization sequences (PSS, SSS) from at most 3 eNBs distinguished by their cell ID group (also known as physical layer identity) representing roots of the Zadoff-Chu sequences [18]. Using this property, the procedures by which an eUE is attached to the network could be activated for non-primary eNBs. The attachment procedure, that an eUE follows so as to associate with an eNB follows the standard 3GPP RRC connection reconfiguration process.

Synchronization: For core-isolated eNBs, over-the-air decentralized network synchronization can be utilized by allowing a designated (usually the *Donor* eNB) to provide a time reference synchronization within the network. Then, eUEs will propagate the signal to the core-isolated eNBs through a common synchronization channel. This approach also resolves the interference problem for scenarios with multiple transmitters and one receiver as all the core-isolated eNBs are synchronized with the same reference point as well as the cyclic prefix is able to absorb the differential propagation delay. Regular UEs will follow the standard timing advance procedure controlled by their respective eNBs, while the eUEs will select one of the available timing advance value (e.g. the minimum value or that of communicating eNB). Note that this solution does not require any coordination, and scales smoothly with the number of connected eUEs. However, if the reliability of a unique reference point cannot be assured, due to network mobility or adverse environmental conditions, the designated eNB could be dynamically elected based on parameters of interest, e.g. cell stability. Ultimately, if a common external time reference like a GPS signal is not available the fire-fly synchronization technique could be applied whenever a fully distributed approach is required [19].

Coding: The PHY layer uses orthogonal frequency division multiple access (OFDMA) in a single frequency mesh network, where all network nodes eNBs, eUEs and UEs share the same resources both in DL and UL. In DL (eNB-to-eUE) a *Decode-and-Forward* DF technique is implemented. Then

on the second hop in UL, we apply a distributed Alamouti coding scheme [20] to eUEs to form a virtual MIMO antenna. eUEs belonging on a VL can dynamically participate in the collaborative forwarding a-priori regardless their respective to eNBs link quality. The destination eNB specifies the same time-frequency resources for the framing allocation to the collaborative eUEs by sending them a scheduling grant with an additional information related to the PDUs sequence number, size and HARQ id. Next, each eUE after having correctly decoded (positive CRC check) the requested PDU during the broadcast phase, it performs Alamouti coding independently as an autonomous antenna element and transmits the codes to the destination eNB.

Notice that the selection of the antenna element can be done autonomously by each eUE. In fact, the destination eNB will be able to detect the antenna element from the pilot signal. Moreover, the Alamouti code (distributed or not) is robust to the fading or erasure of the antennas (eUEs). Hence, this technique allows for a flexible number of participant eUEs and does not require that the destination eNB signals to each active eUE the information about the antenna element.

D. MAC Layer Design

To operate effectively using collaborative packet forwarding at MAC layer and to achieve lower latency communication comparing to the L3 forwarding, apart from the legacy 3GPP procedures, the proposed architecture requires a sophisticated MAC mechanism to manage a VL and perform packet forwarding. Packets are encoded in the source eNB with DF and then are broadcasted to the eUEs, where after successfully received by the eUEs, they are decoded and stored in the eUEs buffer queues maintained at the MAC layer. The reason why the packets are not forwarded directly to the destination eNB is twofold: *i*) In legacy 3GPP LTE, eNBs schedule packet transmissions, therefore eUEs cannot autonomously decide to transmit without having received a scheduling grant request by the destination eNB [3]. *ii*) If eUEs perform packet transmissions as soon as they receive them, synchronization and over-the-air signal level combination of the packets cannot be guaranteed at the second hop (eUEs-to-eNB).

The new MAC layer that is designed to enable eUE packet forwarding for collaborative transmission is illustrated in Fig. 3 and is composed of five additional functional blocks to handle the VL between two end-points, namely:

- *queuing:* It handles packet storage using MAC layer buffers. When a packet is correctly received by eUEs, it is stored locally at MAC buffers waiting to be scheduled by the destination eNB. The buffer supports indexing mechanisms using AVL trees and hash functions for PDUs storage so as to optimize requests for PDUs that are identified by their sequence number (SN) and their PDU size.
- *reporting:* It sends periodically the MAC buffer status report (BSR) to the destination eNB indicating which MAC protocol data units (PDUs) have been correctly received and stored.
- *aggregation:* It is used to concatenate the requested MAC PDUs instructed by the destination eNB.

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[3]It should also be clarified here that the eUEs have already notified eNBs through a buffer status report (BSR) about their PDU availability.
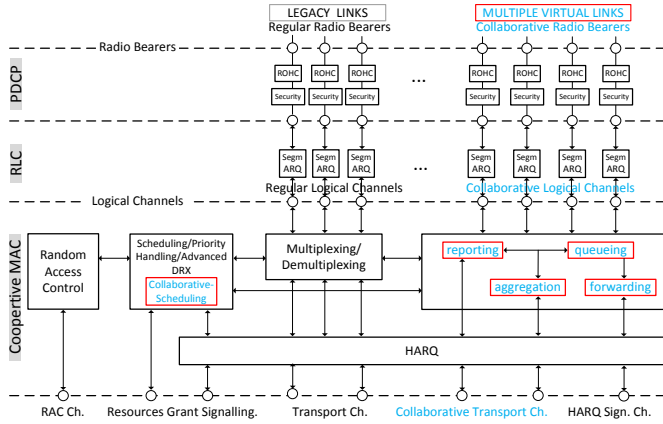
Fig. 3. eUE MAC layer architecture and collaborative logical channels: The functional blocks *aggregation*, *forwarding*, *reporting* and *queuing* and *co-scheduling* allow for buffer-aided collaborative packet forwarding to interconnect isolated eNBs.

- *forwarding:* It identifies whether an incoming PDU on the intermediate eUEs is related to a VL, in which case queuing block will be instructed to store the PDU in a buffer associated with the destination eNB.
- *co-scheduling:* It schedules the outgoing PDUs on the intermediate eUEs corresponding to a VL requested by the destination eNB.

eUE Cell Association and Initialization: eUE initialization follows the same process of a legacy UE performing "*attach*" to its serving eNB and access to the core is provided by the S-GW and P-GW functionalities. The eUE retrieves configuration parameters from this certain eNB through the control-plane messaging and also a list of other eNBs to which it is allowed to attach. Then, an additional attach procedure is triggered with respect to one of the neighboring eNBs [21]. After the completion of this establishment procedure each eNB initiates the virtual data radio bearer interfaces and the corresponding PDU buffer queues.

Virtual Link Setup: When instructed by the higher layer, a VL establishment procedure is triggered by the source eNB to setup a collaborative radio bearer (CO-RB). Through this procedure, the VL will be mapped to a set of physical links (PLs) from a source eNB to eUEs and from eUEs to a destination eNB. A VL provides an abstraction to the cooperative transmission at the MAC layer. Thus, the multiple access scheme at the higher layer perceives the lower PHY layer of the protocol stack still as a packet erasure link even though it may be decomposed into several point-to-point links. A VL is used as a means of hiding the information to higher layers: that is, a VL between two points is composed of several point-to-point links formed with the aid of intermediate forwarding eUEs. An eUE can participate at the same time in multiple VLs. (see for example Fig. 2 where a PL can be used by multiple VLs and Fig. 3, where these VLs are contemplated on the eUE side.) The MAC layer is responsible for managing the virtual/logical links. Particularly, the MAC layer is responsible for identifying the links that will be created in order to complete a single packet transmission between two specific endpoints. Moreover, it is responsible for the identification and scheduling of collaborative transmissions both in downlink and uplink direction.
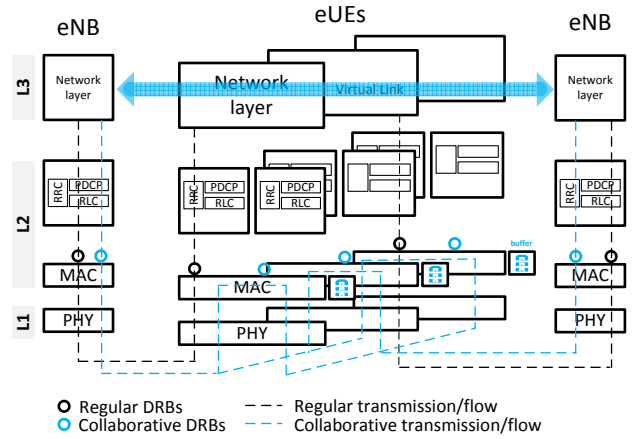

Fig. 4. Collaborative Transmission over a virtual link. eUEs adopt a dual protocol stack so as to be able to associate with two eNBs and perform efficiently L2 packet forwarding.

For that reason, we introduce the concept of the collaborative-RNTI (Radio Network Temporary Identifier) as an identification number to differentiate a regular transmission from a collaborative one and identify that a certain packet belongs to a certain collaborative transmission via a VL. The CO-RNTI is carried as a part of the MAC header of the control packets that are transmitted from an eNB to eUE in order to establish the VL. A collaborative transmission over a VL requires at least one eUE acting as packet forwarder and two CO-RNTIs that describe the point-to-point transmission on the (eNB-eUE-eNB) physical links. Two CO-RNTIs (an ingress and an egress) can participate to form a VL setup. The ingress CO-RNTI is used by the source eNB to perform a collaborative broadcast and allow the eUEs to store the received data in the destination buffers associated with the egress CO-RNTI. The destination eNB will then schedule a collaborative transmission on this CO-RNTI based on the previously reported collaborative buffer status report (CO-BSR). From the perspective of the destination eNB that needs to communicate back to the source eNB over a collaborative transmission, this design is symmetric and the ingress CO-RNTI (which is the egress CO-RNTI of the source eNB) is used to perform the opposite transmission.

Virtual Link Hybrid Automatic Repeat Request (VL-HARQ) strategy: HARQ strategy over a VL with multiple eUEs is not trivial, since the eUEs cooperate to send the same information but are physically separated. This fact creates, for example, possible loss of coherence inside the eUE HARQ buffers. To confront this problem, we propose the following HARQ strategy which tends to minimize latency and resource use while being robust [15]. During the broadcast phase, the source eNB keeps sending redundancy versions (RV) of the packet with the ingress CO-RNTI, until all the eUEs have correctly detected it. A new ACK/NACK message (in fact the one for Scheduling Requests) is used: the absence of this signal is a ACK, while the presence of it is a NACK[4].

In order to reduce latency, as soon as one of the eUEs correctly decodes the MAC PDU, it sends a BSR to the destination eNB. If the destination eNB decides to schedule the MAC

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[4]Notice that the source eNB will see a NACK as long as one eUE has not correctly received the packet (the identity of the eUEs having sent a NACK is not available to the eNB).

PDU on the egress CO-RNTI, the scheduling information will be received by all the eUEs, even to those not having correctly decoded the MAC PDU yet. Then, all the eUEs create a (virtual) HARQ process associated to the sequence number (SN) of the MAC PDU, which is contained in the scheduling information.

Hence, the eUEs having the MAC PDU with the right SN in their queue will send it to the (virtual) HARQ process, for transmission. On the other hand, the eUEs not having yet the MAC PDU with the right SN in their queues do not send anything, however, they maintain the HARQ process as if they have sent the MAC PDU. In fact, the virtual HARQ processes in the eUEs are different instances of a unique HARQ process shared among the group of eUEs participating to the VL and the destination eNB. These processes are all synchronized and follow the timing and procedures described in the standard. This mechanism allows the insertion of the eUEs, which have decoded with a delay the packet from the broadcast phase, in the HARQ transmissions of the second hop, without any additional signaling cost. In this way, robustness is increased.

Upon reception of an ACK from the destination eNB, the virtual HARQ process are released, even by the eUE which has never succeeded in receiving the packet from the source eNB. However, if none of the eUEs have successfully decoded the packet in the broadcast phase, the source eNB is still sending redundancy versions to the eUEs thus wasting resources. To reduce this wastage an explicit ACK/NACK is sent over the same resources of the implicit ACK/NACK as soon as the eUEs receive an ACK from the destination eNB.

Adaptive Modulation and Coding (AMC): In LTE, the AMC is performed according to the CQI values that UEs report back to the eNBs so as to support the highest Modulation and Coding Scheme (MCS) that can effectively decode packets with a BLER probability not exceeding 10% [22]. For a given MCS an appropriate code rate is chosen relying on the Table 7.2.3.1 of 3GPP TS36.213. Therefore, link adaptation matches the transmission parameters of MCS and coding rate to the channel conditions. It should be clarified here that UEs in LTE, and hence eUEs are not permitted to deliberately decide about an autonomous MCS and coding rate selection. This is a control information that is instructed by the eNBs so as to optimally control and configure transmissions within the cell. Moreover, all the resource blocks within a subframe that are allocated to a certain user should use the same MCS. A key issue in the design of AMC policy in the two-hop topology interconnecting two eNBs is whether the MCS assigned to a specific eUE for a collaborative transmission should be the same over the two hops or different exploiting the intermediate buffer storage at the eUEs. In the 1st case, the source eNB uses that MCS that captures a representative CQI (e.g. it can be dynamically selected using metrics i.e. average or worst over the two consecutive physical links) for the eUE configuration so as to minimize packet drops and sustain adequate end-to-end communication quality and reliability. In the 2nd case, each interconnected eNB can opportunistically use a different MCS for the transmissions with the bridging eUE relying on the fact that packets are temporarily stored in the buffers in order to be transmitted with the best possible MCS over each physical link. This feature is enabled by the packet aggregation service at the MAC layer (see Section IV-D) which concatenates multiple

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Algorithm 1: A MAC Layer CO-scheduler of an eNB for PDUs collaborative transmission.

> **Input** : $u \in \mathcal{U}$ of selected eUEs and $V \in \mathcal{V} = \{u \in U$ belonging to the Virtual links$\}$.
> **Output**: Collaborative PDUs transmission over VLs enabled by eUEs.
> **Data**: Request N PDUs
> **Result**: Grant resources for $u \in \mathcal{U}$ eUEs.
> **foreach** *TTI* t **do**
>> **foreach** $V \in \mathcal{V}$ /* Virtual Links. */ **do**
>>> **foreach** $u \in \mathcal{U} \bigcap V$ **do**
>>>> Receive a BSR for N PDUs identified by their SN, size and HARQ id.
>>>
>>> **end**
>>> **if** $\mathcal{U}' \subseteq \mathcal{U} \bigcap V$ *respond with a positive BSR for* $N' \leq N$ *PDUs* **then**
>>>> **foreach** $u \in \mathcal{U}'$ **do**
>>>>> Destination eNB grants resources for scheduling u eUE to transmit N' PDUs. and acknowledges PDU reception/failure to HARQ for transmitted PDUs in $t-1$ TTI.
>>>>
>>>> **end**
>>>
>>> **else**
>>>> Notify HARQ to manage a reschedule of $|N - N'|$ PDUs.
>>>
>>> **end**
>>
>> **end**
>> **foreach** $u \in \mathcal{U}$ **do**
>>> Provide the Channel State and CQI reports to the higher layers for the PL between u and eNB.
>>
>> **end**
>
> **end**

---

packets together which are being identified by their sequence numbers to fill the allocated transport blocks. This is further explained in the following paragraph.

eNB MAC CO-scheduler: In LTE cellular networks, packet scheduling decisions are orchestrated by eNBs. Therefore, eNBs are responsible to decide which packets should be transmitted by requesting a buffer status report (BSR) from the collaborating eUEs. A source eNB schedules the broadcast transmission in downlink, while the destination eNB schedules a CoMP transmission in uplink. Until now, eNB schedulers have aimed either at the sole optimization of a performance metric (i.e max. throughput, or min. delay) or aimed at attaining desired trade-offs for achieving a balanced compromise between different competing interests (i.e. Proportional Fairness or Min. Power vs. Delay). To effectively leverage eUEs for benefiting from a collaborative transmission at the MAC layer, we advance the eNB scheduler - apart from applying a specific policy - so as to be able to identify the common packets that are stored in eUEs' buffers and are identified by their sequence number (SN) and PDU size.

The introduced eNB CO-scheduler that is presented in Algorithm 1 is able to select the eUEs that are currently participating to a VL and grant them resources for scheduling if they reply with a positive BSR for a requested packet. However, the association of the eUEs with a certain VL

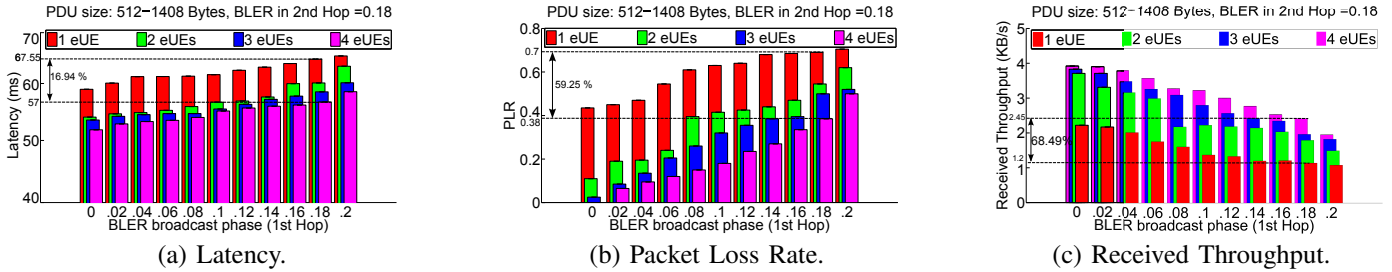(a) Latency. (b) Packet Loss Rate. (c) Received Throughput.

Fig. 5. OAI Measurement Results of a LTE wireless mesh network enabled by eUEs.

depends on on higher layer network policies and network-level cooperation instructions[5]. The selected eUEs are leveraged to store incoming packets and relay traffic when this would be instructed to them by the destination eNB.

Flexible eUE Protocol Stack: eUEs requires in L2 (RRC, RLC and PDCP sub-layers) a multiple-stack protocol in control and data-plane. This allows for eUEs to associate and communicate in parallel with multiple different eNBs and handle simultaneously regular and collaborative transmissions. Fig. 4 illustrates the protocol stack of this mechanism that enables collaborative packet forwarding at L2 and multiple DRB reception. The goal is to prevent packets that belong to a collaborative transmission from passing through the whole protocol stack aiming to reduce latency. At L1 a source eNB broadcasts packets to collaborative eUEs. If these packets are correctly received by the eUEs and belong to a Collaborative Data Radio Bearer, the L2/MAC of eEUs identifies their CO-RNTI and stores them temporarily in buffers. Then a collaborative transmission in uplink is scheduled by the destination eNB so as to activate eUEs to transmit the requested PDUs identified by their sequence numbers.[6] L2 transmission presents an abstraction to the L3 layer where the VL is established by hiding the point-to-point physical transmissions.

IV. NEW USE CASES

A. Moving Cells

In public safety or intelligent transport system (ITS) scenarios, the planning of the point-to-point wireless interface for backhaul access may often be too costly to be established between moving and/or static cells. Currently, in 3GPP an interface named X2 is used to allow meshing of neighboring eNBs so as to coordinate base stations and assist UEs' handover procedure.

Public Safety: When a major emergency situation such as an earthquake, wildfire, hurricane or warfare strikes communication networks related to civil or military purposes, need to be built rapidly and on-the-fly [17], [23]. In such tactical response cases, providing backhaul access to a rapid network deployment and core-isolated cells of communication trucks can be effectively enabled by leveraging the respond commander terminals (UEs) to convey critical control information.

Intelligent Transport Systems: In planned deployments for public transport, employing moving relays in vehicles (buses, metro, trains, etc.) is a promising solution to overcome

potential degradation issues like shadow fading that cause poor QoS/QoE to end-users [8]. Currently, solutions stemming from heterogeneous and small cell networks, relaying and offloading methods promise performance improvements and are quite attractive to immerse into future cellular networks [24].

However, what is missing is a light weight and cost effective solution for the unplanned deployments. Core-isolated eNBs of moving vehicles often fade away from the macro eNB's coverage range as they move out of the predefined trajectory which ensures communication. By exploiting the potential of eUEs to convey traffic within the network, operators expand their network coverage and provide resilient access to the core for these moving cells. This solution comes also with zero cost for network planning and infrastructure deployment.

B. Small Cells

In a dense urban area, where large physical obstacles such as buildings create a harsh communication environment, coverage holes may often occur due to volatile ambient conditions, even when network planning had been contemplatively designed. Although the solution of small cells can offer improved capacity and extended coverage to users, an UE may still experience poor performance, mainly at the cell edge or during handover, since it is only served by only one eNB regardless of the number of macro or small base stations in its vicinity.

To this end a cost-effective and resilient solution is to offer to UEs alternative paths for service to fully exploit the available resources. By allowing eUEs to communicate with multiple eNBs, thus realizing a CoMP on the downlink reception, the benefit to users is clear. "The higher the number of active alternative paths is, from which a user can be actually served, the more the number of resource blocks is, which are aggregated and allocated to the user".

V. PERFORMANCE EVALUATION

A. OpenAirInterface System Setup

To conduct experimentation, we leveraged OpenAirInterface (OAI) in order to evaluate the performance of the collaborative forwarding in a practical setting, the distributed synchronization procedures and the 3GPP protocol operations for eNBs and eUEs (full implementation code is online available [25]). OAI is an Open-source software implementation of the 4th generation mobile cellular system that is fully compliant with the 3GPP LTE standards and can be used for real-time indoor/outdoor experimentation and demonstration. OAI features a built-in emulation capability that can be used within the same real execution environment to seamlessly transition between real experimentation and repeatable, scalable emulation [26]. The behavior of the wireless medium is obtained (a) using

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[5]The eNB cannot associate eUEs to VLs autonomously, relying only on PHY layer information.

[6]The collaborative transmission realizes a distributed Alamouti coding scheme perceived as CoMP transmission.

Parameter	Value	Parameter	Value
Carrier Freq.	1.9 GHz	Traffic Type	UDP
Bandwidth	5MHz	Fading	AWGN Ch.
Frame Duration	10ms	Pathloss	-50dB
TTI	1 ms	Pathloss Exp.	2.67
UEs	$1, 2, 3, 4$	Mobility	Random

a PHY abstraction unit which simulates the error events in the channel decoder, and (b) using (real) channel convolution with the PHY signal in real-time. The platform can be run either with the full PHY layer or with PHY abstraction. The remainder of the protocol stack for each node instance uses the same implementation, as would be in the full system. Each node has its own IP interface that can be connected either to a real application or a traffic generator.

B. Experimentation

Topology Description: In our system validation scenario, there exist two eNBs and four eUEs located in an area of $500m^2$. Table I summarizes the system configuration setup. A 5MHz channel bandwidth (25 RB) is used where the maximum data rate of the collaborative link (UL) is 12 Mbps.

Efficient L2/MAC forwarding: The MAC layer performance is measured in terms of latency, packet loss rate and throughput for different number of UEs=$\{1, 2, 3, 4\}$ and for different BLER probabilities for the backhaul link ($1st$ hop: DL source eNB-to-eUEs) and for a bad channel configuration on the $2nd$ hop UL (eUEs-to dest eNB) characterized by a BLER probability equals to 0.18. The above setup captures a harsh scenario where eUEs assistance is validated. The traffic pattern is defined by a fixed packet inter-arrival time of 20ms and a uniformly distributed packet size from 512 to 1408 bytes.

Fig. 5 illustrates the obtained results for the above scenario and demonstrates clearly the eUEs contribution. As the number of employed eUEs increases, the latency and packet loss rate reduces while there is an improvement on end-to-end throughput performance. For the sake of comparison 3GPP, latency requirements for QoS Class Identifiers QCIs 1 and 4 that characterize two guaranteed bit rate (GBR) bearer types for VoIP call and Video streaming are set to 100ms and 300ms respectively [22]. Using 4 collaborative eUEs the measured latency is constantly below 60ms for all BLER probabilities, thus achieving low latency.

Collaborative Performance Rationale: In our analysis, we explicitly focus on the achieved latency and packet loss rate of the collaborative link rather than the data rate as this is very critical for the control plane information exchanged between the eNBs. An important finding is that as the number of eUEs increases the respective periodicity that the eNB receives the PDUs from the collaborative MAC actually decreases, thus reducing drastically the communication latency. Indicatively, experimentation results reveal a significant reduction in latency (up to 16.94%) and improvement on packet loss rate (up to 59.25%) for BLER equals to 18% on the first and second hop (see Fig. 5.(a) and (b)). Moreover, for the considered traffic load, we observe a significant gain (up to 68.49%) on the achievable throughput (see Fig. 5.(c)).
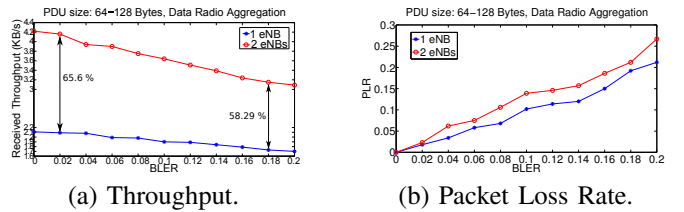

(a) Throughput.   (b) Packet Loss Rate.

Fig. 6.   OAI Measurement Results of an eUE experiencing multiple eNB communication.

The impact of queuing storage: Each eUE maintains for each VL two MAC buffers for the corresponding ingress and egress CO-RNTIs. Those buffers are utilized reciprocally in both directions to store the incoming PDUs identified by their ingress and egress CO-RNTIs. The absence of the buffers would cause all the PDUs to be lost as it would be impossible to be forwarded directly to the destination eNB without scheduling. In our experimentation we used a maximum buffer size equals to 100 PDUs. As the buffer storage capacity increases, the PLR is expected to be reduced. However, this comes at a cost of increased overhead and storage for the MAC layer that needs to be attained. Another benefit from maintaining buffers is that they used to store the PDUs until their reception will be acknowledged. As the BLER increases, the PLR grows slightly constant (see Fig. 5.(b)) as buffers aid in robust transmission and packet recovery.

The benefit of the signal level cooperation in throughput: The actual throughput benefit that is attained by the destination eNB (see Fig. 5.(c)) is due to signal-level cooperation. The more the number of collaborating eUEs is, the more the over the air signal combining allows the destination eNB to increase its received throughput (up to ∼60% using 4 eUEs) even in bad communication condition with BLER up to 20%.

eUE improves its performance by exploiting multiple eNB communication: Fig. 6 illustrates the measured results for the scenario where an eUE is benefited from receiving service concurrently by two eNBs. In this scenario, the payload size ranges from 64-128 Bytes and we measure the received throughput gain when the eUE is served by two eNBs vs. a sole eNB service for different BLER probabilities. UDP constant bit rate traffic of 2.1 KB/s is transmitted by both eNBs. The queue size has no impact at all as the eUE absorbs traffic. As it can be observed in Fig. 6.(a) the eUE improves its throughput (up to ∼65%) when experiences a dual eNB connectivity and maintains this difference slightly reduced as the BLER increases. This slight throughput reduction is due to the PLR that increases as the bad channel quality affects the communication (see Fig. 6.(b)).

VI.   CONCLUSIONS AND DISCUSSION

In this paper, we propose a novel architecture for next generation cellular networks that evolves eUEs as active network elements to form a virtual MIMO antenna and forward voluntarily packets at L2/MAC by performing packet level cooperation over a virtual air-interface. As the simmering interest for efficient solutions on public safety and moving cell scenarios grows, our cost-effective approach exploits eUEs cooperation to enable non-ideal wireless backhaul access and provide resilient and low-latency communication. The evaluation of the prototype implementation in OAI [25] demonstrates that the proposed architecture achieves tangible results for

low-latency communication (up to 16.94% reduction when using 4 eUEs) satisfying the guaranteed-bit-rate (GBR) traffic requirements, while also improves packet-loss rate (up to 59.25% improvement).

A. Discussion

The integration of the proposed architecture in today's cellular networks raises basic design and implementation challenges. Next, we outline the not least of which.

Challenge 1: Enable new use cases: Evolving UEs for enabling new use-cases such as moving cells which are required by intelligent transport systems (ITS) applications is important to future networks. Yet utilizing UEs to provide robust and public safety communications in PMR networks is essential as well. For example as illustrated in Fig. 2, network coverage extension can be realized rapidly by taking advantage of the diverse and multiple paths that eUEs create in scenarios where network planning cannot be previously contemplated or designed (PMR or ITS), while in parallel multiple eNBs provide services as in legacy systems with resiliency, which are enabled by the eUEs.

Challenge 2: Provide low-latency communications using a light-weight architecture: Extending UEs capabilities with smart protocols and advanced RF processing in order to be able to forward packets is essential for wireless mesh networking over the cellular network. Toward this direction, UEs are evolved into *on-demand* intermediate data forwarders (called eUEs) that convey voluntarily traffic among eNBs and form a virtual MIMO antenna. Thereby, eUEs are enabled as a service by the eNBs [13] for relaying traffic.

Challenge 3: Enable incentives to users and carriers: On one hand, at a cost of a more dynamic network and resource management, eNBs can leverage eUEs to assist them with cooperative forwarding so as to improve their performance and re-establish non-ideal backhaul. Besides, in use cases such like PMR, legacy UEs are considered relays, and for the carriers there is a vested interest for exploiting them as a pool of resources, since this comes at a zero cost in network planning and deployment. On the other hand, eUEs at the expense of increased battery/power consumption agree to convey traffic for the network upon proper compensation which is provided by the carriers (e.g. carriers provide users with beneficial or expedient data and cost plans). Moreover, eUEs can use multiple data flows through alternative paths for their own benefits in order to increase their throughput by (i) receiving multiple flows and (ii) selecting among multiple interfaces that are able meet their QoS requirements. Those incentives can be offered to eUEs to participate and help eNBs to re-establish the X2 air interface. As a consequence, a promising economical business model can be enabled, where operators compensate users for assisting them (see [3]–[5]).

REFERENCES

[1] J. Andrews, "Seven ways that HetNets are a cellular paradigm shift," *Comm. Magazine, IEEE*, 2013.

[2] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji, T. Luo, M. Vajapeyam, T. Yoo, O. Song, and D. Malladi, "A survey on 3GPP heterogeneous networks," *Wireless Comm., IEEE*, 2011.

[3] S. Ha, S. Sen, C. Joe-Wong, Y. Im, and M. Chiang, "TUBE: Time-dependent Pricing for Mobile Data," ser. SIGCOMM, 2012.

[4] Y. Im, C. Joe-Wong, S. Ha, S. Sen, T. T. Kwon, and M. Chiang, "AMUSE: Empowering users for cost-aware offloading with throughput-delay tradeoffs." in *INFOCOM*, 2013.

[5] S. Sen, C. Joe-Wong, S. Ha, and M. Chiang, "Incentivizing time-shifting of data: a survey of time-dependent pricing for internet access," *Comm. Magazine, IEEE*, 2012.

[6] Q. Wang, D. Jiang, G. Liu, and Z. Yan, "Coordinated Multiple Points Transmission for LTE-Advanced Systems," in *WiCom*, 2009.

[7] C.-L. I, J. Huang, R. Duan, C. Cui, J. Jiang, and L. Li, "Recent Progress on C-RAN Centralization and Cloudification," *Access, IEEE*, 2014.

[8] Y. Sui, J. Vihriala, A. Papadogiannis, M. Sternad, W. Yang, and T. Svensson, "Moving cells: a promising solution to boost performance for vehicular users," *Comm. Magazine, IEEE*, 2013.

[9] "Study on Small Cell enhancements for E-UTRA and E-UTRAN, Higher Layer Aspects, 3GPP TR 36.842 V12.0.0," .

[10] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity. part i & ii. implementation aspects and performance analysis," *Communications, IEEE Trans. on*, 2003.

[11] M. Iwamura, H. Takahasi, and S. Nagata, "Relay technology in lte-advanced," *Ongoing Evolution of LTE toward IMT-Advanced, NTT Docomo Journal*.

[12] S. W. Peters, A. Y. Panah, K. T. Truong, and R. W. Heath, "Relay architectures for 3GPP LTE-advanced," *EURASIP J. Wirel. Commun. Netw.*, Mar. 2009.

[13] M. Duarte, A. Sengupta, S. Brahma, C. Fragouli, and S. Diggavi, "Quantize-map-forward (QMF) Relaying: An Experimental Study," in *Mobihoc*, 2013.

[14] C. Nie, P. Liu, T. Korakis, E. Erkip, and S. Panwar, "Cooperative relaying in next-generation mobile wimax networks," *Vehicular Technology, IEEE Trans. on*, 2013.

[15] A. Cipriano, P. Agostini, A. Blad, and R. Knopp, "Cooperative communications with HARQ in a wireless mesh network based on 3GPP LTE," in *EUSIPCO*, 2012.

[16] "Delivering Public Safety Communications with LTE, 3GPP." [Online]. Available: http://www.3gpp.org/news-events/3gpp-news/1455-Public-Safety

[17] "Service Requirements for the Evolved Packet System (EPS), 3GPP TS 22.278, WG SA2," .

[18] "Physical layer - general description, 3GPP TS 25.201 V11.1.0," .

[19] A. Tyrrell, G. Auer, and C. Bettstetter, "Fireflies as Role Models for Synchronization in Ad Hoc Networks," in *Bio-Inspired Models of Network, Information and Computing Systems*, 2006.

[20] Y. Jing and B. Hassibi, "Distributed space-time codes in wireless relay networks," in *Sensor Array and Multichannel Signal Processing Workshop Proc.*, 2004.

[21] L. Evolved Universal Terrestrial Radio Access Network (E- UTRAN), "Radio Resource Control (RRC)," 3GPP TS 36.331 V11.5.0 (2013-09).

[22] S. Sesia, I. Toufik, and M. Baker, *LTE - The UMTS Long Term Evolution*. John Wiley & Sons, Ltd, 2009.

[23] T. Doumi, M. Dolan, S. Tatesh, A. Casati, G. Tsirtsis, K. Anchan, and D. Flore, "LTE for public safety networks," *Comm. Magazine, IEEE*, 2013.

[24] M. Bennis, M. Simsek, A. Czylwik, W. Saad, S. Valentin, and M. Debbah, "When cellular meets wifi in wireless small cell networks," *Comm. Magazine, IEEE*, 2013.

[25] "SVN repository of the OAI prototype implementation of the proposed architecture." [Online]. Available: https://svn.eurecom.fr/openairsvn/openair4G/branches/lolamesh

[26] N. Nikaein, R. Knopp, F. Kaltenberger, L. Gauthier, C. Bonnet, D. Nussbaum, and R. Ghaddab, "Demo: OpenAirInterface: an open LTE network in a PC," in *Mobicom 2014*, Maui, USA ,