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

Apostolos Apostolaras[†,≀], Navid Nikaein[‡], Raymond Knopp[‡],
Antonio M. Cipriano[ƚ], Thanasis Korakis[†,≀], Iordanis Koutsopoulos[*,≀] and Leandros Tassiulas[§]
[†]Dept. of Electrical and Computer Engineering, University of Thessaly, Greece
[≀]The Centre for Research & Technology Hellas (CERTH), Greece
[‡]EURECOM, France
[ƚ]Thales Communications & Security, France
[*]Athens University of Economics and Business, Greece
[§]Electrical Engineering & Institute for Network Science, Yale University, USA

***Abstract*—In this work, we demonstrate and validate 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. We introduce an evolved-UE (eUE) which is capable of operating simultaneously over multiples eNBs in order to enable reliable multi-hop operation through relaying and to achieve low-latency communication through efficient L2/MAC forwarding. For the demonstration and the evaluation of this architecture, we used the OpenAirInterface emulation platform to implement it, and also to evaluate its performance. The obtained results show that, 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.**

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

I. Introduction

In this paper, we demonstrate a new paradigm for link virtualization through cooperative L2/MAC information (packet) forwarding enabled by a group of UEs, denoted as evolved UEs (eUEs). The considered architecture is depicted in Fig. 1. A virtual air-interface is being established between two eNBs with the aid of collaborative eUEs. Yet, existing techniques are expressed only at a 3GPP legacy in-band/out-band relaying level [1], [2]. Although state-of-the-art results for relaying and data forwarding have exhibited the feasibility of such approaches in LTE systems, the main disadvantage is that relays are used as a part of network planning process that is performed by the carriers. Our aim is to design a cost-effective, resilient and light-weight architecture for supporting packet-level forwarding by leveraging and evolving legacy UEs to operate as active elements of the network, to forward the traffic and to provide backhaul access to moving and core-isolated eNBs.

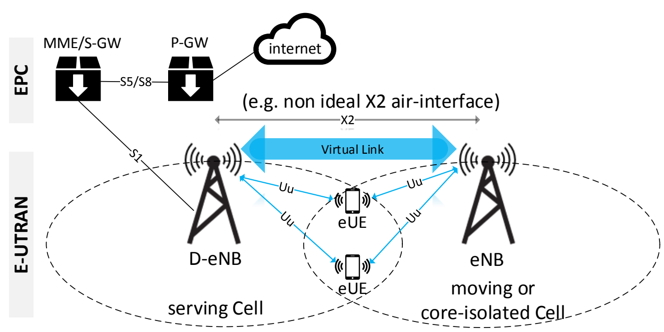


Fig. 1. Evolved UEs (eUEs) are leveraged to become active network elements, to form a virtual antenna and to interconnect core-isolated with donor eNBs.

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 private mobile radio (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 addition, there is a simmering interest about non-ideal backhaul solutions for CoMP as it is an active area under discussion in the 3GPP for integration within the LTE Rel. 12 framework [6]. A non-ideal wireless backhaul solution requires eUEs to establish multiple connections to different base stations. Such operation allows eUEs to consume a larger portion of radio resources provided by at least two different network points (master and secondary eNB) connected with non-ideal backhaul. The benefits for eUEs that motivate their participation is to experience improved aggregated throughput, mobility robustness at the cost of higher signaling load and

This paper consists a demo version of the work entitled "Evolved User Equipment for Collaborative Wireless Backhauling in Next Generation Cellular Network", which has been accepted for presentation in IEEE SECON 2015.

TABLE I. LTE-A TDD SYSTEM CONFIGURATION.

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

power consumption. Additionally, dual connectivity is under study by 3GPP to improve performance of small cell networks [7].

In this demonstration, we will showcase two different experimental scenarios that clearly demonstrate the advantages of using eUEs in the context of next generation cellular networks.

II. EXPERIMENTAL DEMONSTRATION

We leverage 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 [8]). 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 [9].

The behavior of the wireless medium is obtained (a) using 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.

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[1] and Fig. 2 illustrates the logical topology overview. Furthermore, we can use several configurations for the system setup - tailored and easily configured to the requirements of the experimentation scenarios under investigation - and retrieve accordingly the results using OAI software libraries.

Scenario 1 - Efficient L2/MAC forwarding: In this indicative scenario, we explicitly focus on the demonstration of the performance of MAC layer over the virtual collaborative link. Measurements are collected in terms of latency, packet loss rate and throughput for different number of UEs=$\{1, 2, 3, 4\}$ and for different block error rate (BLER)

[1]The capacity of this collaborative link is dominated by the capacity of the UL, which depends on the channel quality (CQI) of the involved eUEs that is mapped to an MCS. The highest MCS in UL for a 5 MHz channel is 12 Mbps (corresponding to a 16QAM).

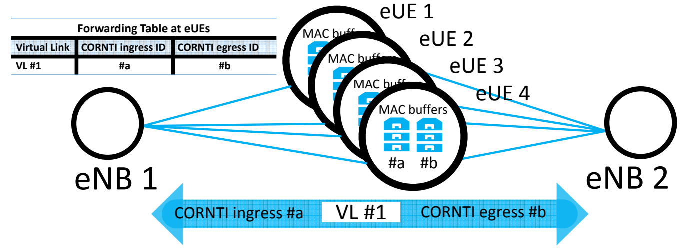
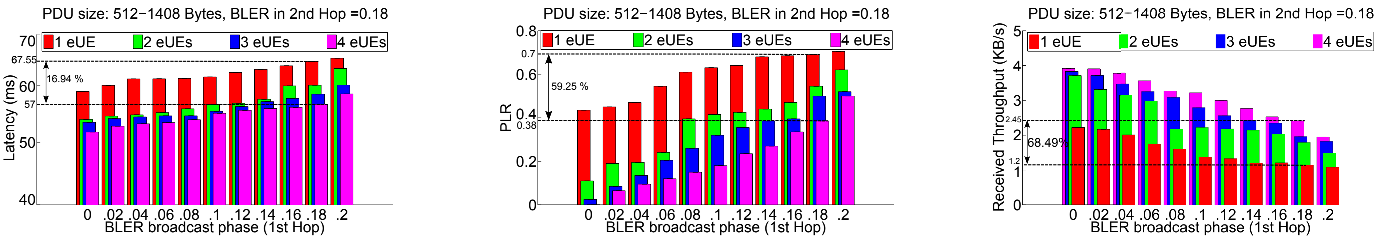


Fig. 2. Logical topology for the performance evaluation scenario: A VL is setup to interconnect two eNBs with the aid of 4 eUEs. Each eUE maintains a forwarding table of CO-RNTIs so as to identify the VL and the respective MAC buffers.

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. An important finding that stems from the results as an inference, 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.

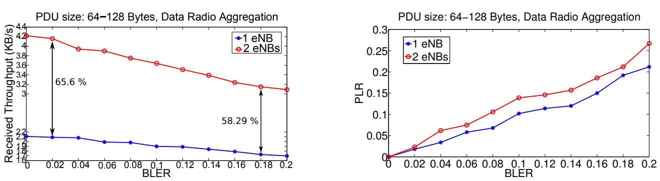
- *Collaborative Performance:* Indicatively, experimentation results reveal a significant reduction in latency (up to 16.94%) and improvement on packet loss rate (up to 59.25%) for BLER equals to 18% on the first and second hop (as it is demonstrated Fig. 3.(a) and (b)). Moreover, for the considered traffic load, we observe a significant gain (up to 68.49%) on the achievable throughput (see Fig. 3.(c)).
- *The impact of queuing storage:* This experimentation part focuses on the demonstration of the impact of using buffers to store the incoming packets on the intermediate eUEs before forwarding to their destination. Each eUE maintains for each VL two buffers at the MAC layer for the corresponding ingress and egress collaborative radio network temporary identifiers (CO-RNTIs). Those buffers are utilized reciprocally in both directions to store the incoming packet data units (PDUs) identified by their ingress and egress CO-RNTIs. As the buffer storage capacity increases, the packet loss rate (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. 3.(b), here maximum buffer size is equal to 100 PDUs) as buffers aid in robust transmission and packet recovery. 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.
- *The benefit of the signal level cooperation in throughput:* The actual throughput benefit that is attained by the destination eNB (see Fig. 3.(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 $\sim$60% using 4 eUEs) even in bad communication condition with BLER up to 20%.



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

Fig. 3. OAI Measurement Results of a LTE wireless mesh network enabled by eUEs.

Scenario 2 - eUE improves its performance by exploiting multiple eNB communication: In this scenario, we aim to demonstrate the benefits that eUEs receive when they get connected simultaneously to two eNBs. Fig. 4 illustrates the measured results in the case 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. 4.(a) the eUE improves its throughput (up to $\sim$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. 4.(b)).



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

Fig. 4. OAI Measurement Results of an eUE experiencing multiple eNB communication.

III. Conclusions and Discussion

In this demo paper, we demonstrate the operational showcase of a novel architecture, which lies in the context of future cellular networks and rethinks the standard operation of UEs, by enhancing them into active network elements called evolved-UEs. As the evolved-UEs are requested to aid in the transfer of data/traffic - which sometimes is not exclusively destined to them - and help eNBs to re-establish virtual air-interfaces, this implementation demonstration showcases the benefits that are given both to users (eUEs) and carriers in terms of tangible improvements on certain performance metrics, such as throughput, latency and packet losses. The full protocol stack implementation of this architecture has been built on the OpenAirInterface emulation platform and it is online available [8].

IV. Demo Requirements

For the purposes of this demonstration, we will bring:

- our projector and laptops
- a desk of 2 meters length to place the equipment
- power supply for all the devices.
- 30 minutes for setup and testing.

Acknowledgment

The research leading to these results has received funding from the European Community's 7th Framework Programme, FLEX under grant agreement No. 612050.

References

[1] Y. Yang, H. Hu, J. Xu, and G. Mao, "Relay technologies for WiMax and LTE-advanced mobile systems," *Comm. Magazine, IEEE*, 2009.

[2] O. Teyeb, V. Van Phan, B. Raaf, and S. Redana, "Dynamic Relaying in 3GPP LTE-Advanced Networks," *EURASIP Journal on Wireless Communications and Networking*, 2009.

[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] "Study on Coordinated Multi-Point (CoMP) operation for LTE with Non-Ideal Backhaul, 3GPP TR 36.874," .

[7] "Study on Small Cell enhancements for E-UTRA and E-UTRAN; Higher layer aspects, 3GPP TR 36.842 V12.0," .

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

[9] 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 ,