System Architecture for a Cellular Network with UE Relays for Capacity and Coverage Enhancement

Balaji Raghothaman, Ravikumar Pragada, Gregory Sternberg, Eric Deng, Tao Deng, Kiran Vanganuru
InterDigital Communications LLC, King of Prussia, Pennsylvania, 19406, USA
{Balaji.Raghothaman, Ravikumar.Pragada, Gregory.Sternberg, Eric.Deng, Tao.Deng, Kiran.Vanganuru}@InterDigital.com

Abstract— **The wireless data explosion has been addressed with increased spectrum, better bandwidth efficiency, cell size reduction and small cell topologies. We offer an additional approach, namely the use of direct mobile-to-mobile communication. A unified solution for capacity and coverage enhancement is presented together with a system architecture that is an extension of LTE-Advanced and retains complete cellular control while enabling secure communications between mobiles and eNBs, using other UEs as relays. In the capacity scenario there is a direct link between the end user (termed terminal UE or T-UE) and the eNB, and another link through a UE relay (termed helper UE or H-UE). In the coverage scenario, the helper UE provides the only path between the terminal UE and the eNB. We present procedures essential to system operation, for example, neighbor discovery through which UEs find and associate with each other. Changes to the LTE-A control plane and data plane architectures in order to enable both modes are outlined. Mechanisms to establish an active connection between the eNB and the T-UE are described. Different mobility procedures such as a T-UE's transition to a different H-UE or the transition from capacity to coverage modes are outlined. Finally, simulation results that demonstrate the effectiveness of this solution in a Manhattan grid deployment are provided.**

Keywords- Mobile Relays, Cooperative Communications, Device-to-Device (D2D) communications, Hybrid Cellular Network, Opportunistic Relays, Decode and Forward, LTE

I. INTRODUCTION

The explosion of demand for wireless mobile data, driven by a surge in smart-phone and tablet usage, has pushed the wireless industry to invest in better spectral efficiency. Techniques such as improved multiple access, modulation, coding and multi-antenna techniques, as well as denser deployments and heterogeneous topologies using small cells (micro/pico/femto) all promise additional capacity.

This paper examines an alternative solution using direct mobile-to-mobile communications as an extended topology that can co-exist with the conventional cellular network. It allows us to harness the power of the mobiles themselves, by enabling them to communicate directly with each other under the control of the network. As mobile data demand increases, the number of available devices also increases, providing a natural mechanism for scaling capacity.

Direct mobile communications can be used in several real-world scenarios. In the capacity-enhancement scenario (RCap) [3][4][5], the network can provide a UE (terminal UE or T-UE) that has poor connectivity to the network with additional throughput by using another nearby UE (helper UE or H-UE) that has a better connection. In our previous work, simulation results have shown a significant capacity improvement (50% overall, and 100% at cell edge). In the coverage enhancement (RCov) scenario [11], the T-UE does not have any eNB coverage whatsoever, and the H-UE is its only means of reaching to the network.

II. RELAYS IN WIRELESS COMMUNICATION

While amplify and forward relays have been used in wireless communications for a long time, there has been a recent revival of interest in standardizing relays that operate at a higher protocol layer in several wireless forums, including 3GPP and WiMax [1][2][6]. In 3GPP Release 10, relays were classified into two categories - Type 1 and Type 2 [7][8]. Type 2 relays are those that only relay traffic and do not create new cells, and are suitable for capacity enhancement to UEs that already are in the coverage of a regular eNB. Type 1 relays, which act similar to cellular base-stations and are useful for providing coverage extension to legacy UEs, transmit synchronization, reference, broadcast, control, and traffic signals similar to an eNB. They forward packets at the IP layer. Type 1 is further classified into Type 1 (inband), 1a (outband) and 1b (inband with antenna isolation), on the basis of the frequency/spatial separation between the access and backhaul links. 3GPP has also considered the case of mobile relays, which are relay nodes mounted on moving platforms such as trains and buses. In the WiMax community, relays have been standardized as part of 802.16j [6] and 802.16m. The 802.16m architecture includes a relay with its own physical cell ID, similar to Type 1 discussed above. Mobile relays with group handover mechanisms have also been designed into 802.16m.

The relay architectures discussed thus far are all dependent on infrastructure-like relay nodes without constraints on power. In contrast, we propose a relay architecture using UEs as relays, and provide a system design that takes into consideration the power and form factor limitations of UEs. Relaying has been mentioned as one of the potential use cases as part of the recent 3GPP SA1 study item ProSe for D2D communication [9] .

III. PROBLEM DEFINITION

In the current LTE cellular system, a UE is considered to be in coverage if it is able to camp on an eNB and read the system information broadcast and the paging messages, and is able to transmit and receive certain minimum data rates to/from the cell. Even if a UE is in coverage, it might still suffer from low throughput. In the RCap solution, additional throughput can be provided to such a UE (terminal UE or T-UE) through another UE (helper UE or H-UE) acting as a relay. On the other hand, the RCov solution is designed to help UEs that are out of coverage by providing coverage through an H-UE. For the RCov solution, we focus on UEs that still have frequency and timing synchronization with the network, i.e., have recently lost coverage.

IV. ARCHITECTURE

We propose a solution that is based on modifying the existing Release 10 of the 3GPP LTE standard. For the RCap mode, all signalling between the T-UE and the eNB is done through the direct path, while data can flow through either the direct or the relay path. Separate data radio bearers (DRBs) can be setup to carry the data through the two paths, as shown in Figure 1. An alternative, not shown here, is to use a common DRB for both paths, and split the PDCP PDUs between the two paths. This paper focuses on the former approach.

For the RCov solution, the H-UE is used both for signalling and data transfer, and hence access stratum (AS) security will have to be established via the H-UE. As LTE R8/R10 supports mutual authentication [10] and replay protection along with usage of temporary identifiers, establishing AS security via the H-UE does not introduce any new security concerns. The PDCP layer is responsible for ciphering and integrity protection [10]. The H-UE operates at MAC/H-ARQ level and cannot interpret encrypted T-UE data. Ciphered and/or integrity protected T-UE data is tunnelled through the H-UE. **Error! Reference source not found.** shows the protocol architecture explained above, with the separate DRB approach for RCap. For RCov, since all the data flows through the relay path, only the lower path in the figure (labeled UE-Relay Path) is needed. It is noted that a partial RLC implementation is shown at the H-UE, which is used for buffering, discarding, and re-segmenting RLC PDUs.

In both the RCap and RCov modes, the H-UE operates as a decode-and-forward relay. The system assumes MAC layer protocol termination at the H-UE, i.e., there are two independent MAC protocols at the H-UE, one for the traditional link (TRL) to the eNB, and another for the crosslink (XL) to the T-UE. This eliminates the need for end-to-end propagation of ACK/NACKs which would result in an overall increase in hybrid ARQ (HARQ) latency. However, for the RCap mode, if there is a necessity to perform cooperative transmission on the physical layer, such as joint beamforming/MIMO from the eNB and H-UE to the T-UE on the DL, then the HARQ has to be end-to-end, and also necessitates the use of a single radio bearer across both paths. In this paper, we focus on the former approach involving HARQ termination at the H-UE.

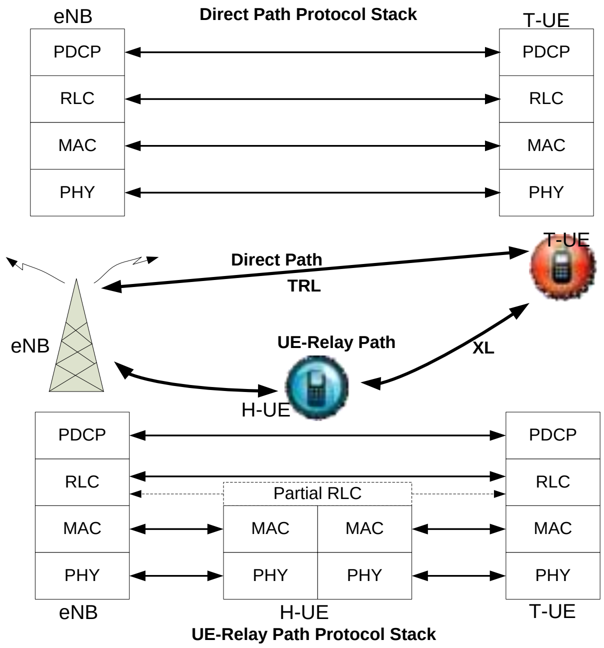

Figure 1. Protocol Architecture for UE-Relay

Our design also calls for a decoupled approach to data transfer on the relay path, where the resource allocation and scheduling for the crosslink is done by the eNB in a coarse manner by granting resources for a length of time much greater than a TTI, while the per-TTI link adaptation for the XL has to be done by the H-UE or the T-UE. This achieves an efficient modulation and coding scheme (MCS) selection based on near real-time channel conditions without the overhead of feeding back channel measurement reports to the eNB at frequent intervals. Note that the eNB is in complete control of resource allocation for the XL, allowing the network to extract the maximum benefit from this system through efficient interference co-ordination. Both the H-UE and T-UE send periodic measurement reports to the eNB to facilitate XL scheduling. The H-UE also has the ability to buffer data it receives from either end nodes (eNB or T-UE), and to re-segment the data for the XL. Buffering and re-segmentation enable XL transmissions to be tailored to the instantaneous XL capacity, without being limited by the eNB to H-UE link capacity.

At the physical layer, a separate band is used for all crosslink (XL) communications. All cross links in a certain geographic area or a cell reuse the same XL band, although the eNB's RRM might allocate a subset of the frequency resources in order to perform interference management. The basic information regarding the time/frequency location of the XL has to be known to the UE either through the system information from the cell, or through per-UE configuration.

V. NEIGHBOR DISCOVERY AND ASSOCIATION

The neighbor discovery (ND) process, analogous to peer discovery in adhoc networks, is a prerequisite for direct communication between mobiles, including UE relays. The network imposes policies on the mobiles which determine the conditions under which the mobiles participate in neighbour discovery, either initiating Neighbor seeking UEs (NSUEs) or as responding Neighbor Present UEs (NPUEs). One possible set of neighbor discovery policies could be

- In the RCap mode, it is sufficient if UEs attempt to discover helper UEs upon entering the RRC-CONNECTED state.
- In the RCov mode, UEs would perform neighbor discovery when they are out of coverage, or when they perceive a degradation of eNB coverage
- NPUEs respond to neighbor discovery requests depending upon the type of request (RCap, RCov, Emergency call, etc.), which is encoded in the transmitted PHY sequence.

The proposed neighbor discovery scheme involves transmission of beacons or preambles in the Neighbor Discovery Zone (NDZ), which is a set of resources that are pre-defined to be dedicated in each radio frame, and are common for all UEs in a cell or PLMN. A NSUE transmits a Neighbor Discovery Initiation Transmission (NDIT) sequence that identifies its sender. All NPUEs in the system that are not in DRX (discontinuous reception) mode monitor the NDZ. When they detect an NDIT, they compute a suitability index that is derived from factors such as XL and TRL radio conditions, battery status, etc. If the NDIT meets certain minimum requirements for suitability, the NPUEs respond with a Neighbor Discovery Response Transmission (NDRT), which has characteristics similar to the NDIT.

The NSUE performs helper selection based on received NDRTs from NPUEs. A two-way handshake, wherein physical layer association Tx/Rx signals are exchanged between the NSUE and the selected NPUE, confirms this association. The selected NPUE provides the NSUE with basic system information (BSI) including the PLMN ID, Tracking Area (TA), cell ID, and XL operation parameters. The NSUE verifies that the selected NPUE's PLMN is on its equivalent PLMN list, and that it is not located in one of its forbidden TAs. The NSUE then takes on the role of a T-UE and informs the selected NPUE using a SELECT H-UE RRC message and this NPUE now takes on the role of H-UE. If verification is not successful, the NSUE selects the next NPUE in its list and repeats the steps above. In RCap, the T-UE seeks association only with H-UEs in the same eNB, while in RCov, there is no such constraint.

If this T-UE has moved to RCov mode from LTE infrastructure mode or if it is not registered in the TA provided in BSI, it informs the Mobility Management Entity (MME) in the network using an ASSOCIATION REQ message. The MME provides the T-UE and H-UE with configuration information required for AT paging and idle mode DRX such as AT-IMSI, AT-S-TMSI, common DRX cycle length and paging offset. AT-IMSI is used in determining UE-ID (AT-IMSI mod 1024) for Paging Frame (PF) and Paging occasion (PO) calculations. The network will use the H-UE's S-TMSI to page the H-UE and AT-S-TMSI to page the T-UE. The H-UE monitors the paging channel on behalf of the T-UE using AT-S-TMSI along with its own S-TMSI. A common DRX cycle length is configured for both the T-UE and H-UE so that they are awake at the same time to communicate with other. Their wake up periods may be offset by a few sub-frames, as configured using a paging offset, to allow for the H-UE to process the received page and transmit in time on the XL for the T-UE's reception. After receiving the configuration information, the T-UE and H-UE go back to RRC-IDLE.

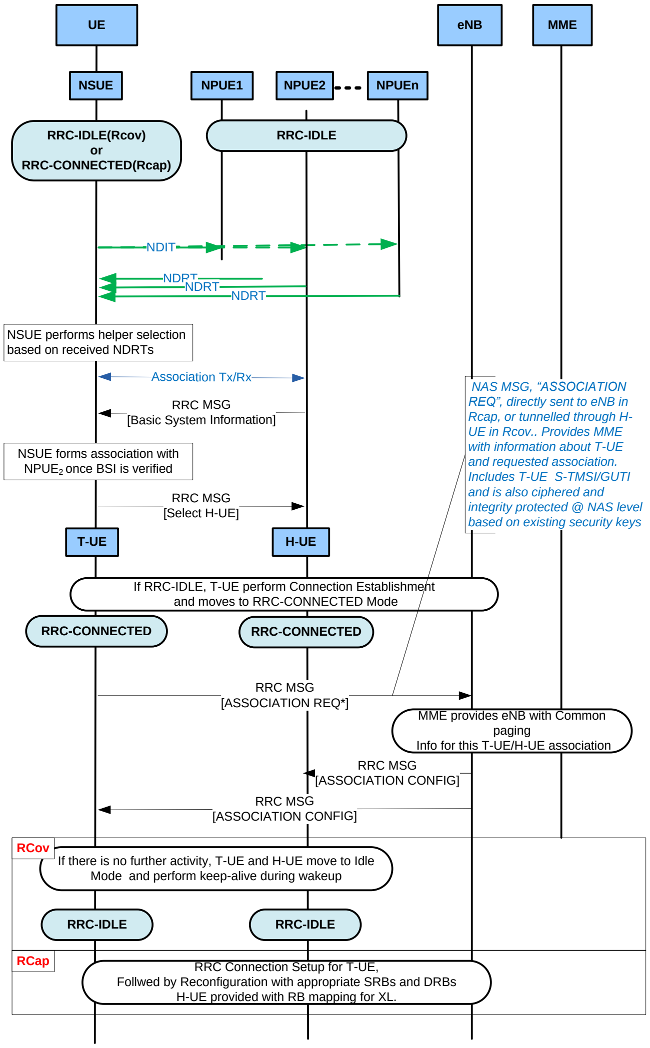

Figure 2. Neighbor Discovery and Association

In RCap mode, the T-UE and H-UE stay in RRC_CONNECTED state, and the eNB provides the configuration necessary to include the additional path to the T-UE through the H-UE. This process is explained in the next section as part of the Connection Establishment procedure for the RCov mode.

In RRC-IDLE mode, or in RRC-CONNECTED DRX for RCap, at every wake up the T-UE and H-UE check to make sure that their association is still valid by exchanging keep-alive signals to reaffirm the association. If either the H-UE or T-UE does not receive a keep-alive message, the association is voided. The T-UE then triggers ND to look for a different H-UE.

In RCov, if the H-UE belongs to a TA that is part of the TA list at the T-UE, no information is conveyed to the network. Instead, the T-UE provides the target H-UE with its current AT-IMSI, AT-S-TMSI and common paging and DRX information that it received from the MME. This new H-UE starts monitoring AT-S-TMSI on the T-UE's behalf. The original H-UE clears its association related information and may optionally convey this information to the network. With the procedure above, there is no additional signalling between the network and H-UE or T-UE due to mobility in RRC-IDLE mode. **Error! Reference source not found.** provides a condensed message sequence that depicts the neighbor discovery and association procedure described above.

VI. CONNECTION ESTABLISHMENT

In RCap mode, Connection Establishment occurs as per baseline LTE on the direct path. In RCov, when the T-UE needs to establish a connection (response to page, or mobile-originated call), it transmits a Scheduling Request (XSR) on the XL. The H-UE acknowledges the SR and proceeds to establish a connection with the eNB using a new cause code in its own RRC Connection Request ("T-UE Service Request").

The eNB sets up a default connection to the H-UE, consisting of SRB1. The T-UE's RRC Connection Request is constructed as in the current LTE system, with the appropriate Establishment cause, such as "Mobile Originating Data." The H-UE relays the T-UE's Connection Request through a newly defined RRC message called the AT Information Transfer Message. The eNB can now configure the RRC for the T-UE. The eNB configures the T-UE with one or more additional Data Radio Bearers (DRB) for the XL. It also reconfigures the RRC connection with the H-UE, by setting up new RBs that carry the XL transmissions, and provide the mapping to corresponding DRBs to the T-UE on the XL. For example, the H-UE data bearers DRB5-DRB8, may map to the T-UE bearers SRB1, SRB2, DRB0, DRB1 respectively. Note that, for the RCap mode, only one or more DRBs (and none of the SRBs) to the T-UE are tunnelled through the H-UE. The XL bearers for the H-UE, namely DRB5-8 are provided with configuration required for PHY, MAC, and partial RLC to support the protocol architecture. These XL bearers may be configured with NULL encryption, since the tunnelled T-UE bearers are already encrypted with T-UE information. As part of the RRC configuration, the H-UE and T-UE are also provided with a common wake-up slot for connected mode DRX operation. The eNB then configures the T-UE connection with a RRC Connection Setup message.

This message is transmitted over a DRB to the H-UE, which then relays it over SRB1 to the T-UE. AS Security is established between the T-UE and the eNB using the security mode command (SMC) message. A condensed message sequence for the connection establishment procedure in RCov for a Mobile Originated Data call, where both the H-UE and T-UE are initially idle, is shown in Figure 3. In cases when the H-UE is already in connected mode for its own services, the H-UE does not need to go through its initial Connection Setup before relaying the T-UE's Connection Request. A similar procedure as above applies when the T-UE is responding to a mobile terminated call.

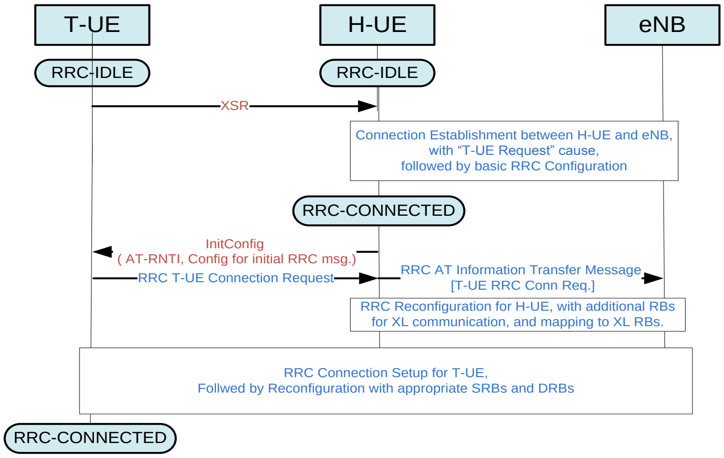

Figure 3. Connection Establishment in RCov - Mobile Originated Call, Idle H-UE

VII. MOBILITY

In order to support seamless mobility as part of both the RCap and RCov solutions, a backup H-UE may be configured. While in RRC-CONNECTED mode, the T-UE performs neighbor discovery and selects a candidate backup H-UE. As part of the association procedure, it obtains this UE's BSI and its temporary identity (S-TMSI). The T-UE then sends an RRC message to the eNB, requesting for a backup H-UE assignment, and includes the cell ID and S-TMSI. This RRC message is sent on the direct path in RCap, and tunnelled through the active H-UE in RCov. The cellID and S-TMSI is required in order to assist the eNB in uniquely identifying the candidate H-UE, and also ensure that this H-UE is not attached to a different eNB in the case of RCap. The eNB can then page the selected backup H-UE and move it to RRC-CONNECTED mode, configure its RBs and its XL RB mapping in the same way as explained previously for the active H-UE. Once the reconfiguration is complete, the eNB informs the T-UE about the assignment of the backup H-UE for mobility using an RRC message. The backup H-UE can go into connected mode DRX, for which it is configured with the same DRX configuration as that of T-UE and the current H-UE, so that the T-UE will be aware of the backup H-UE's DRX cycle. T-UE and backup H-UE will exchange physical layer keep-alive signals to periodically verify the validity of this association.

Handover (HO) to the backup H-UE may be triggered for several reasons such as current H-UE battery below threshold, measurement event indicating that the current H-UE is below a threshold, etc. If handover is triggered, the T-UE will wait for the backup H-UE's wakeup cycle, and will transmit an XSR addressed to the backup H-UE, which then transmits an XL UL grant request on behalf of the T-UE. Once the T-UE receives the XL grant, it transmits a HO INDICATION RRC message to the eNB. This message indicates to the eNB that the backup H-UE has taken the role of current H-UE. The current H-UE may release its connection and execute the required clean up procedures. The eNB can command the T-UE to perform ND in order to find a new backup H-UE.

There can also be seamless handover between the RCov mode and infrastructure mode if a T-UE moves back into eNB coverage during a connection, triggered by measurement reports from the T-UE to the eNB. Conversely, a T-UE can be seamlessly handed over from RCap mode to RCov mode if it perceives a degradation of its current eNB signal. In this case, its active H-UE will be reconfigured to be able to relay the T-UE's SRBs and direct path DRBs in addition to the relay path DRBs that it was already tunnelling.

VIII. SIMULATION RESULTS

In this section, results are presented from a Matlab based system simulator using Monte Carlo methods in order to demonstrate the advantages of using UE as a relay. A typical Manhattan grid with the eNBs deployed at intersections and a high density of UEs is simulated. Results are collected and averaged over multiple independent drops. The simulation parameters are as shown in TABLE I. Multiple XLs are simultaneously scheduled within each cell, multiplexed in the spatial domain. The XLs, are separated only in the spatial domain, and hence experience both intra and inter cell interference, while the TRLs use OFDMA and hence experience only the latter.

All idle UEs within the range of a T-UE (path loss less than 105dB) are potential candidate H-UEs. The helper assignment process tries to assign the best of the candidate H-UEs to each T-UE using an estimate of the end to end throughput based on the long term path loss measurements. Each H-UE decodes and forwards the transport blocks without any resegmentation, and is assumed to have a maximum buffer size of one transport block. A round robin scheduler is assumed for all TRLs, while multiple XLs are simultaneously scheduled in any given transmit time interval. It is assumed that the eNB has full knowledge of the channel conditions for link adaptation purposes. The CDF of the throughput results for the downlink and uplink are shown in Figure 4 and Figure 5 respectively. The percentile throughput gain for both uplink and downlink are summarized in TABLE II.

TABLE I. SIMULATION PARAMETERS

Parameter	**Value**
Street Width	30 m
Building block size	200mx200m
Channel Model	ITU/3GPP Urban Micro Manhattan / Indoor Hotzone
UE Density	1025 UEs/Km^2
# Active UEs/eNB	26
Traffic model	Full Buffer
UE Antenna config	Omni 0 dB gain, 1.5m height, 1Tx, 2 RX
eNB Antenna config	Omni 0 dB gain, 10m height, 4 Tx, 4 Rx
Carrier freq	2 GHz
Total BW in baseline	10 MHz
TRL/XL BW	9MHz/1MHz
Tx Beamforming	Ideal,Rank-1,Closed loop
Link Adaptation	Shannon formula + 2dB penalty
Max Spec. Eff.	6 b/s/Hz
eNB Tx Power	37 dBm (fixed)
UE TRL power	Max 23 dBm (power controlled)
UE XL Tx Power	10 dBm (fixed)
Max XL pathloss	105 dB

The downlink and uplink show a 10th percentile throughput gain of 100% and 250% respectively. The mean throughputs show a marginal increase (2% and 3%). However the peak throughput in the DL is reduced by 10%, corresponding to the loss of XL bandwidth to those UEs with very good radio conditions to the eNB that have no gain from the H-UEs. Improvements in coverage could also be observed, with the elimination of zero throughput (no coverage) condition for the almost 3% of the users in baseline by using our system design. Further performance improvements are possible with several additional techniques, such as for example, independent adaptation on the XL through segmentation at the H-UE.

IX. CONCLUSIONS

A consolidated system architecture for capacity and coverage enhancement using UEs as relays was presented. Several salient features of the proposed architecture were discussed, including resource allocation and multiplexing for the direct mobile links, data plane architecture, protocol termination and security. Detailed descriptions of how the UEs find and associate with neighboring UEs were provided. Idle mode and connected mode procedures were enumerated. Various mobility scenarios and associated message sequences were discussed. Performance improvements were demonstrated with simulation results. Further work involves the extension of direct UE to UE communications to other scenarios such as local traffic offloading.

REFERENCES

[1] Yang et.al., Relay Technologies for WiMax and LTE-Advanced Mobile Systems, IEEE Communications Magazine, Oct 2009

[2] Balakrishnan et.al., Mobile Relay and Group Mobility for 4G Wimax Networks, WCNC 2011

[3] Vanganuru et.al., Uplink System Capacity of a Cellular network with Cooperative mobile relays, WTS 2011

[4] Vanganuru et.al. Downlink System Capacity of a Cellular network with Cooperative mobile relays, WWRF 2010.

[5] Raghothaman et.al., System Architecture for Cellular network with Cooperative mobile relays, VTC Fall 2011-11-03

[6] IEEE 802.16j, “Draft Amendment to IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed and Mobile Broadband WirelessAccess Systems: Multihop Relay Specification”

[7] 3GPP 36.814, Further Advancements for EUTRA: Physical Layer Aspects

[8] 3GPP 36.216, 3GPP TS RAN; Physical layer for relaying operation (Release 10)

[9] 3GPP TDoc S1-120084, “Public Safety Use Cases”, NEC, Feb 2012

[10] Sankaran C.B., Network Access Security in Next Generation 3GPP Systems: A Tutorial

[11] Pragada et.al., System Architecture for LTE based Coverage Solution using UE Relays, to be presented at Future Mobile and Network Summit 2012, Berlin, July 2012.

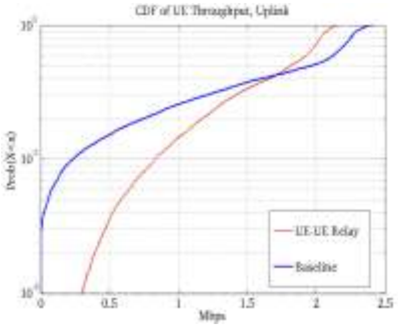

Figure 4. Downlink System Throughput CDF

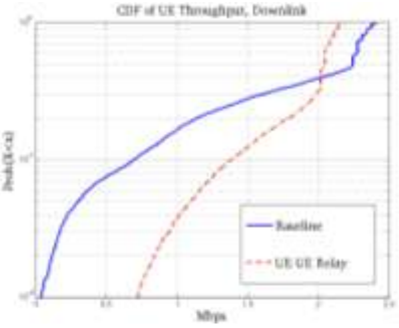

Figure 5. Uplink System Throughput CDF

TABLE II. THROUGHPUT GAIN %

	DL	UL
10% tile	96%	253 %
50% tile	-9%	-8%
99 %tile	-10%	-10%
Mean	2%	3%