Uplink System Capacity of a Cellular Network with Cooperative Mobile Relay

Kiran Vanganuru, Matthew Puzio, Gregory Sternberg, Kandarp Shah, Samian Kaur

InterDigital Communications LLC, King of Prussia, Pennsylvania, 19406, USA

{Kiran.Vanganuru , Matthew.Puzio , Gregory.Sternberg , Kandarp.Shah, Samian.Kaur}@InterDigital.com

***Abstract*— This paper studies the performance of a hybrid cellular network with cellular controlled direct radio links between multiple mobile User Equipments (UEs). The main focus is on the uplink of the proposed system with multiple idle UEs acting as relays to assist the communication of any given UE with an active connection. In the presence of multiple UEs as relays, the Base Station (BS) dynamically chooses the best relay to maximize the throughput of each radio link. We present system capacity results using Monte Carlo system simulation techniques. Further, we compare results with and without the use of distributed beam forming techniques. Our results indicate that cell edge capacity could be improved by more than 99% by using idle UEs in the system as mobile relays. The performance improvement at cell edge is achieved while improving the mean cell throughput by more than 50%.**

***Index Terms*— Mobile Relays, Cooperative Communications, D2D communications, Hybrid Cellular Network, Opportunistic Relays, Decode and Forward, LTE**

I. Introduction

Next generation broadband cellular communication networks are being designed to provide seamless coverage and quality of service comparable to today's broadband infrastructure networks. Examples of such networks include LTE Advanced and the evolutions of WiMax standards. These networks are designed to provide greater than 1Gbps data rates, while using a wideband radio channel of up to 100MHz bandwidth. However, such high data rates can only be provided over a relatively short range, which limits coverage. This is because the total BS transmit power is spread over a much wider bandwidth. This in turn requires a high density deployment of infrastructure base station (BS) nodes in any given coverage area. In order to improve coverage, these standards also have support for infrastructure relay nodes. In addition, relays act like small cells, which may be further used to improve system throughput.

We propose direct radio communication links between any two mobile user equipments (UEs). These communication links are used to enable idle UEs to serve as relays to assist the uplink communication of any given UE with an active connection (referred to as a terminal UE or T-UE). At any given point of time, a large fraction of the UEs in a typical system will be idle, which allows us to assign multiple helper UEs (H-UEs) acting as relays to any given T-UE. This is quite different from an infrastructure relay, which typically has multiple T-UEs assigned to it.

The idea of enabling direct UE to UE communications within a cellular system is not an entirely new concept and it was discussed in 3GPP under the name "Opportunity Driven Multiple Access" (ODMA) as a means to improve the efficiency of UMTS TDD systems [1]. In [2], the authors studied the performance of an ODMA system using various radio resource management schemes. More recently in [3], the authors bring the concept of direct UE to UE links within an OFDMA framework, with a maximum of two hop relays. In [4], the authors have proposed direct UE to UE links to enable short range local source and sink traffic. It should be noted that in all these studies, only one H-UE is assigned for each T-UE, and it transmits or receives all its data through the H-UE.

In this paper, we introduce multiple novel concepts including the allocation of sets of potential helper UEs to any given T-UE with dynamic helper selection, which uses the best transmission path during any transmit time interval (TTI). In addition, we also propose and study the performance of the systems with distributed beam forming schemes. Spectral re-use is maximized in the direct UE-UE communications links in that all T-UEs transmit on the same resources, each acting as a separate low power cell for its associated H-UEs. This paper is primarily concerned with the uplink performance and interested readers are referred to [7] for discussion on the downlink.

In Section II, we describe the proposed relay mechanisms. Section III describes the system simulation model. In Section IV, we present the system simulation results.

II. Opportunistic Mobile Relay Mechanisms

In the proposed cellular system with direct UE to UE communications, there are two kinds of radio links. The first is the communication link between the Base Station (BS) and the UE, while the second is a direct link between two mobile UE's. We make the assumption that each UE is operating in half duplex mode. In other words, a mobile UE is never simultaneously involved in both BS-UE and UE-UE link in any transmission time interval (TTI).

At any given time, a typical cellular system consists of both active state and idle state UEs. In the proposed system, idle UEs are chosen as candidates to help active UEs. Henceforth, we designate UEs with an active connection T-UEs and UEs which have been chosen as candidates to help a T-UE are referred to as Helper UEs or H-UEs. Further, any T-UE could be assigned multiple H-UEs for the duration of its connection. The set of H-UEs assigned to a T-UE is referred to as its Helper Active Set or HAS. The two kinds of radio links and the HAS is illustrated in Fig 1. We further discuss the proposed relaying mechanisms in the following subsections.

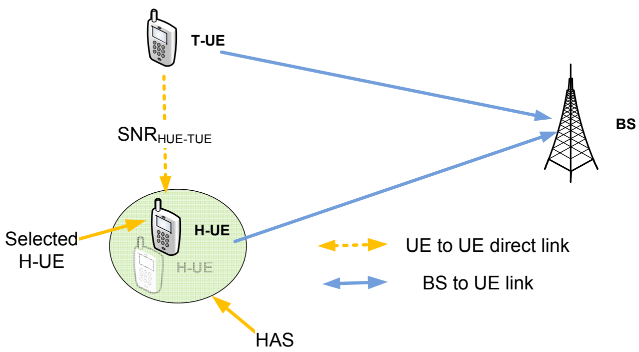

Fig. 1. Two kinds of Radio links

A. Decode and Forward

In the proposed system, we restrict ourselves to a maximum of two hops, wherein the first hop is composed of a T-UE to H-UE transmission, and the second hop is a joint H-UE, T-UE to BS transmission or direct H-UE to BS transmission, which is illustrated in Fig 2. Although each T-UE's HAS consists of multiple H-UEs, only a single H-UE would be transmitting in any given TTI. In addition, we restrict ourselves to decode and forward relay, wherein the complete codeword has to be decoded by the relay before forwarding the whole message. The T-UE may choose not to take help from H-UE at all if it does not give any throughput gains.

First Hop T-UE to H- UE Transmission	Second Hop H-UE -> BS or Joint H-UE T-UE ->BS Transmission
TTI → N	TTI → N+1

Fig. 2. Two Hop Relay Mechanism

Whenever a T-UE is scheduled in the uplink, the BS could also choose to schedule a H-UE with the highest capacity among the T-UE's HAS if it's likely to improve the performance of the end to end link.

In the event an H-UE is scheduled, the T-UE would transmit the data to the H-UE in the first hop. We study both joint transmission and simple relay mechanisms for the second hop, which are discussed in more detail in Sections II.C and II.D. In the event an H-UE is not scheduled, T-UE directly transmits to the BS during the second hop.

The T-UE benefits from selection diversity gain resulting from selecting the best relay path. This gain is a combination of diversity gain against independent Rayleigh fading and shadow fading from the spatial separation of the H-UEs.

B. Uplink Power control of T-UEs

Open loop fractional power control is used to obtain the transmit power of the T-UEs. The transmit power of T-UEs is guided by the long term channel gain of the BS - T-UE link. The objective of employing power control is to minimize the near far effect and to guarantee a certain amount of fairness throughout the whole system. The uplink transmit power of a T-UE after power control is given by equation (1).

$$P_{T-UE} = P_{offset} - \beta * G_{T-UE} \text{ dBW/MHz} \qquad (1)$$

where P_{T-UE} is the power controlled transmit power for a given T-UE, P_{offset} is the open loop power control offset, β is the open loop power control slope and G_{T-UE} is the long term gain of the BS- T-UE link in dB, which includes path loss and shadow fading. In our simulations, P_{offset} is set to -80 and β to be equal to 0.875, which we found to provide a good tradeoff between cell edge and cell center performance.

C. Dynamic Helper Selection

In this relaying mechanism, whenever a T-UE is scheduled, the BS chooses the best transmission path either through an H-UE or a direct transmission to the BS. If a H-UE is selected, it uses all the transmit power assigned to the T-UE as given by equation (1) for the second hop transmission. In our studies, we assume the use of capacity achieving codes and so use the Shannon capacity formula to calculate the throughput. We also assume that full channel state information is available at the base station and that the channel is static for a minimum of 2 TTIs, which would allow for the BS to select the best path of transmission from each scheduled T-UE. We define the capacity of a radio link $C(W, SNR) = W log_2(1 + SNR)$, where W is the bandwidth and SNR is the signal to noise and interference ratio for any given radio link. The end to end throughput using the i^th H-UE as a decode and forward relay is given by

$$TP_{simple\_relay(i)} = Min\begin{Bmatrix} C\left(W_{BS\_UE}, SNR_{HUE(i)\_BS}\right), \\ C\left(W_{UE\_UE}, SNR_{TUE\_HUE(i)}\right) \end{Bmatrix} \qquad (2)$$

Where W_{BS_UE} is the bandwidth of BS-UE link, W_{UE_UE} is the bandwidth of the UE-UE link, $SNR_{TUE\_HUE(i)}$ is the SNR of the T-UE to H-UE link for the i^{th} H-UE. $SNR_{HUE(i)\_BS}$ is the SNR of the i^{th} H-UE to BS link. With dynamic relay selection, the BS chooses the best transmission path, for which the end to end throughput is given by

$$TP_{dynRelSel} \text{ (bits/2TTI)} = Max\{ C(W_{BS\_UE}, SNR_{BS\_TUE}), TP_{simple\_relay}(1), TP_{simple\_relay}(2), ..TP_{simple\_relay}(i) .. TP_{simple\_relay}(maxHelpers) \} \quad (3)$$

D. Dynamic Helper Selection and Transmit Beam forming

In a joint transmission scheme, both the T-UE and the selected H-UE would jointly transmit to the BS during the second hop using transmit beamforming. Further, the total transmit power assigned to the T-UE is shared between the T-UE and the selected H-UE.

Whenever a T-UE is scheduled, the BS chooses the best H-UE from a T-UE's HAS. In case the end to end throughput estimate using the best H-UE is not better than direct transmission from the T-UE, a helper is not selected for this scheduling interval and the T-UE is scheduled to directly transmit to the BS.

Let $H_i = [h_0, h_i]^T$ be the effective channel using i[th] H-UE. Where $h_0$the channel between T-UE and BS is, h_i is the channel between i[th] H-UE and BS. The transmit beamforming weight vector Wt is given as $Wt = [wt_0, wt_i]^T$, where wt_0 is the weight applied at the T-UE and wt_i is the weight applied at the i[th] H-UE. Further, the individual transmit beamforming weights are given as

$$wt_0 = \frac{h_0^*}{||H_i||} * \sqrt{P_{T-UE}}$$
$$wt_i = \frac{h_i^*}{||H_i||} * \sqrt{P_{T-UE}} \quad (4)$$

Where P_{T-UE} is the transmit power obtained from (1). It should be noted that this form of transmit weight computation effectively shares the total transmit power proportional to the respective channel strengths. The effective SNR with transmit beamforming is given by

$$SNR_{HUE(i)\_BS}^{txbf} = \frac{\|H_i^T Wt\|^2}{Noise\ Power} \quad (5)$$

The end to end throughput achievable using a decode and forward relay with transmit beamforming is given by

$$TP_{txbf\_relay(i)} = Min \begin{Bmatrix} C\left(W_{BS\_UE}, SNR_{HUE(i)\_BS}^{txbf}\right), \\ C(W_{UE\_UE}, SNR_{TUE\_HUE(i)}) \end{Bmatrix} \quad (6)$$

With dynamic relay selection, the BS schedules the best transmission path, which involves either the selection of the best H-UE or direct transmission between T-UE and BS. The end to end throughput with transmit beamforming is given by

$$TP_{TxBfDynRelSel} \text{ (bits/2TTI)} = Max\{ C(W_{BS\_UE}, SNR_{BS\_TUE}), TP_{txbf\_relay}(1), TP_{txbf\_relay}(2), ..TP_{txbf\_relay}(i) .. TP_{txbf\_relay}(maxHelpers) \} \quad (7)$$

III. System Simulation Model

The proposed concept has been implemented in a Matlab based system simulator using Monte Carlo methods. The system parameters have been chosen to be representative of a typical system deployment. Most of the system parameters are based on the recommendations in the IEEE 802.16m Evaluation Methodology document [5].

We have simulated a 19 site hexagonal topology with an inter-site distance of 1500 meters, wherein each site is further composed of three sectors with a 70 degree 3dB beam width; 14dBi bore sight antenna gain and a 20dB front to back ratio. The Base station antenna height is set to 15 meters which is above the rooftop, and the UE's height is set to 1.5 meters for the purpose of determining path loss. The system consists of a total uplink bandwidth of 10MHz with the carrier frequency set to 2.5GHz. The total bandwidth is split into 10 equal sub channels of 1MHz each. We define a resource block (RB) as being equivalent to a time frequency resource of 1MHz sub channel spanning a TTI of 1ms. A resource block (RB) is the minimum level of granularity for scheduling of radio resources in our system simulations.

In the proposed cellular system with direct UE to UE links, 1 RB is dedicated for all UE-UE links in each TTI, while the remaining 9 RBs are used for BS-UE links. In the baseline cellular system configuration without UE-UE links, all the 10 RBs in each TTI would be used for BS-UE communications. The UE transmits at a fixed 10dBm transmit power for all UE-UE links over the dedicated RB used for UE to UE links. The transmit power for BS-UE links is determined according to an open loop power control mechanism specified in equation (1). Note that many UE-UE links may be simultaneously scheduled (one for each T-UE where the best TP is achieved via a H-UE) in the same RB within any given sector. This high reuse is possible because of the spatial separation between the various scheduled short range UE-UE links.

We make the assumption that the Rayleigh fading channel coefficient stays constant for at least 2 TTIs, which is equal to 2ms in our simulator model. This is a reasonable assumption for low mobility environments, which is the primary focus of the proposed system. Further, we assume that the Rayleigh fading channel coefficient for each UE is independently and identically distributed. We also assume that full channel state information is available at the BS to facilitate the selection of the best transmission path to all the scheduled T-UEs.

A. Simulation Overview

The overall system simulation procedure is described using flow charts. The major steps in the flow charts shown in Fig. 3 and Fig. 4 are described in more detail in the following subsections.

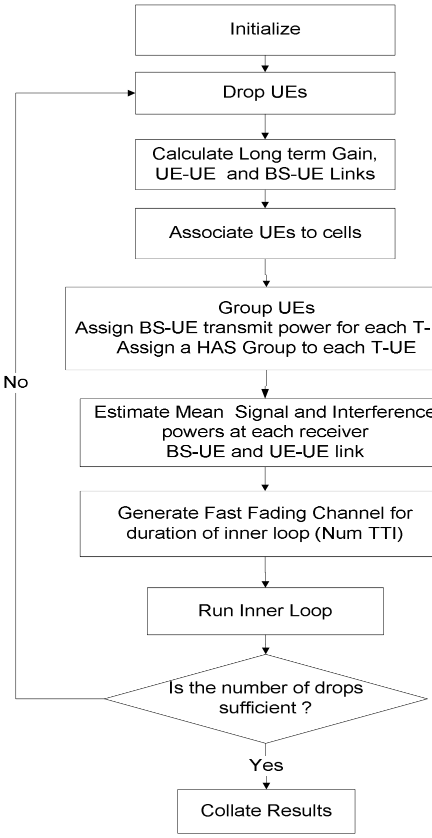

Fig. 3. System Simulation Flow Chart Overview

The inner loop in more detail

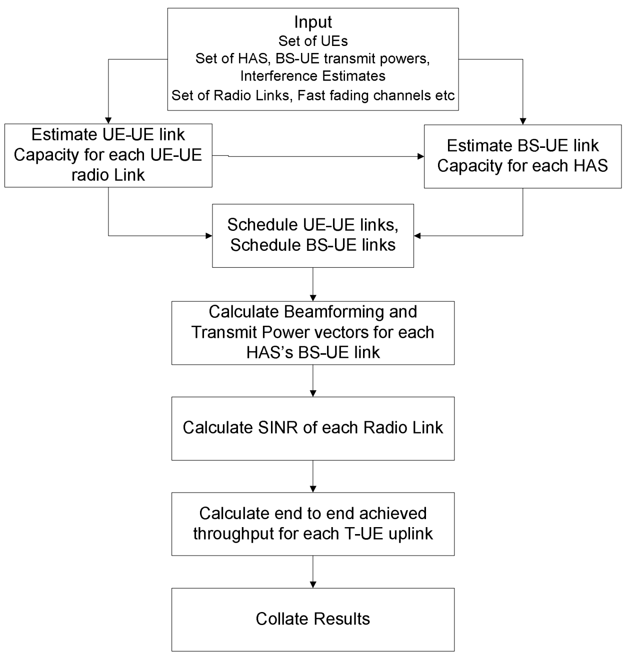

Fig. 4. System Simulation Flow Inner Loop

B. Path loss and Shadowing Model

We used the path loss model for UE-BS links defined in Section 3.2.3.8 of the 802.16m Evaluation Methodology Document [5]. Specifically we used the baseline test model defined for an urban/suburban environment. The path loss for all UE-BS links is calculated according to equation (8).

$$PL(dB) = 40(1 - 4 \times 10^{-3} h_{BS}) log_{10}(R) - 18 log_{10}(h_{BS}) + 21 log_{10}(f_{carrier}) + 80 \quad (8)$$

The path loss model for UE to UE links is as defined in the 802.16j type F path loss model, which is described in Section 2.1.2.4 of reference [6]. This model is applicable for below roof top relay to UE links. We specifically used the LOS model for system studies. If the distance between the transmitter and receiver is below a break out distance, the path loss is based on the free space path loss model with a minimum path loss exponent of 2. If the distance is greater than the break out distance, the minimum path loss exponent is 4. Further the path loss exponent increases with distance by a visibility factor, which is an exponent of distance ($e^{0.002d}$) . The path loss model with transmit antenna height of 1.5 meters and receiver antenna height of 1.5 meters and a carrier frequency of 2.5GHz is given by equation (9).

$$PL(dB) = \begin{cases} 40.4 + 20 log_{10}(d e^{0.002d}) \ for\ d \leq 8.3\ meters \\ 22.0 + 20 log_{10}(d^2 e^{0.002d}) \ for\ d > 8.3\ meters \end{cases} \quad (9)$$

The shadow fading for UE-BS links is modeled according to the description given in Section 3.2.4 of the 802.16m Evaluation Methodology document [5]. It has a log-normal distribution with a standard deviation of 4dB and a spatial correlation distance of 50 meters. Further, inter-site shadow fading correlation for any given UE is equal to 0.5. The shadow fading for UE-UE links has log-normal distribution as well as a standard deviation of 10dB. UE-BS and UE-UE links experience correlated shadowing with normalized correlation of 0.25.

C. Grouping of T-UEs

In our proposed system, we group the T-UEs in any given sector into two groups, Group A and Group B. There are two main motivations for this grouping operation. The first motivation naturally results from the relay operation, which consists of two hops. The UE-BS links and UE-UE links for Group A and Group B are scheduled in a pipeline fashion, such that all the RBs are completely utilized in any TTI. This is illustrated in Fig. 5. It should be noted that if the cell is lightly loaded with very few number of T-UEs, there may not be any need to group the UEs into two groups as the BS is not resource constrained and it could afford to stay silent during the first hop UE-UE link TTI.

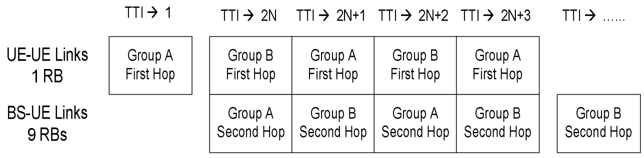

Fig. 5. Pipeline Scheduling of T-UE Groups

The second motivation for grouping the T-UEs is to maximize the spatial reuse of the dedicated RB used for all UE-UE communications. If two T-UEs are located close to each other, transmissions from their respective H-UEs are likely to strongly interfere with each other. This motivates the separation of closely located T-UEs into two separate groups. In the system simulator, we used the interference power at T-UEs assuming that all the other T-UEs in its group are transmitting as the metric to minimize while determining the grouping of the T-UEs. T-UEs are grouped into Group A and Group B such that the maximum interference within any group is minimized. We note that this grouping mechanism is not necessarily an optimum solution, however it has been found to be a simple mechanism yielding sufficient spatial separation to maximize spatial spectrum reuse for UE-UE links.

D. Helper Active Set Assignment

After grouping the T-UEs into two separate groups, the next step is to assign a set of H-UEs to make up its HAS. In a practical system, this operation is likely to be performed during the establishment of connections and periodically, e.g., every few hundreds of TTIs. Therefore we use long term channel statistics including the path loss and shadowing to assign H-UEs to each T-UE's HAS.

As described in Section II, only idle UEs associated to the same cell as the T-UE would be considered as helper candidates. As part of the helper assignment process, one requirement is the received power at a candidate H-UE from the T-UE is greater than -95dBm. This roughly corresponds to a range of 110 meters using the path loss formula given in equation (9) assuming that the T-UE transmits at 10dBm. This receive power threshold has been chosen such that shadowing diversity and UE-UE link spatial reuse is maximized while allowing for sufficient protection above the thermal noise.

All idle UEs within the range of a T-UE (received power greater than -95dBm) are its potential candidate H-UEs. The helper assignment process tries to assign the best of the candidate H-UEs to each T-UE's HAS. An estimate of the end to end throughput using either equation (3) or equation (7) depending on the chosen relay mechanism is used to rank the candidate H-UEs. The SNR estimates for the BS-UE links are obtained using the path loss and shadow fading channel matrix, under the assumption that all the T-UE's are transmitting at their respective transmit power. Similar to the grouping mechanism described in Section III-C, we use the total interference power from the T-UEs within the same group as an estimate of interference power to calculate SNR of each UE-UE link.

Among the candidate H-UE's, each T-UE is assigned the strongest set of H-UEs ranked according to their estimates of the end to end throughput. Further, each T-UE is restricted to a maximum number of H-UEs in its HAS, which is a parameter of the simulator.

E. Round Robin Scheduler

In the system simulator studies we assume an infinite buffer traffic model for each of the T-UEs. Further, all the T-UEs are assigned an equal amount of radio resources for the duration of the simulation run using a round robin scheduler.

In the proposed system, 9 RB's are available for UE-BS links and 1 RB is available for UE-UE links. In each TTI, 9 UE-BS links are simultaneously scheduled. This means that each of the T-UEs is assigned at most 1 RB in each TTI for its BS-UE radio link. All the T-UE to H-UE links are simultaneously scheduled on the single dedicated RB used for UE-UE communications.

In the baseline system model, all of the 10 RBs are available for UE-BS links, therefore 10 UE-BS links are simultaneously scheduled during any TTI.

F. Helper Selection mechanism

As we discussed in Section II-A and Section II-B, the best transmission path from the T-UE needs to be determined whenever a T-UE is scheduled. The data is transmitted either through a selected H-UE or it is directly transmitted by the T-UE to the BS.

Once again, we use an estimate of the end to end throughput for each of the possible transmission paths using the formulae given in equation (3), equation (7) based on the relay selection mechanism. The SNR estimates for all UE-BS links and UE-UE links include the effect of the Rayleigh fading channel. While both the signal and interference powers can be readily calculated for all UE-UE links, the same cannot be said about all UE-BS links. This is because the interference power on the UE-BS links depends on the selected H-UEs for other T-UEs, which obviously cannot be known until the H-UEs are selected. We solve this chicken and egg problem by using the average received power from other H-UEs within the HAS of other T-UEs as an estimate of the interference on each UE-BS link.

The transmission path with the highest end to end throughput estimate is scheduled for transmission. If a H-UE is selected, a T-UE to H-UE link is scheduled for the current TTI and a H-UE to BS link is scheduled for the next TTI. If a H-UE is not selected, only the T-UE to BS link is scheduled for the current TTI.

IV. Simulation Results

We evaluate the system level performance of the proposed system with direct UE-UE communication using Monte Carlo methods and compare it with the baseline system without direct UE-UE links. In Fig. 6, we compare the cumulative distribution function of the average throughput per T-UE for both the baseline system and the proposed system with direct UE-UE links and a maximum of 4 H-UEs per T-UE. In Table 1, we compare the percentage improvement of the proposed system with direct UE-UE links over the baseline system.

Table 1.
Percentage improvement over Baseline System

	Dynamic Helper selection	Dynamic Helper selection + Transmit Beamforming
	Max 4 H-UEs	Max 4 H-UEs
10^{th} %-tile	72%	99%
50^{th} %-tile	37%	53%
99^{th} %-tile	49%	52%
Mean	40%	54%

As shown in Fig. 6, the average throughput of each T-UE for the baseline system is about 0.62 Mbps, while the proposed system with a maximum of 4 H-UEs, dynamic helper selection and transmit beamforming is about 0.96 Mbps. This represents an improvement of about 54%. It should be noted that the total sector throughput is 26 times the average T-UEs throughput, because the time frequency resources are equally split between the 26 T-UEs per sector. While the improvement in the mean T-UE throughput is substantial, the improvement at cell edge is even greater. The 10^{th} percentile throughput with dynamic helper selection and transmit beamforming improves from 0.22 Mbps to 0.44 Mbps, which is an improvement of about 99%. It is also observed that with just dynamic helper selection and no transmit beamforming, the mean throughput improves by 40%, while the cell edge 10^{th} percentile throughput improves by about 72%.

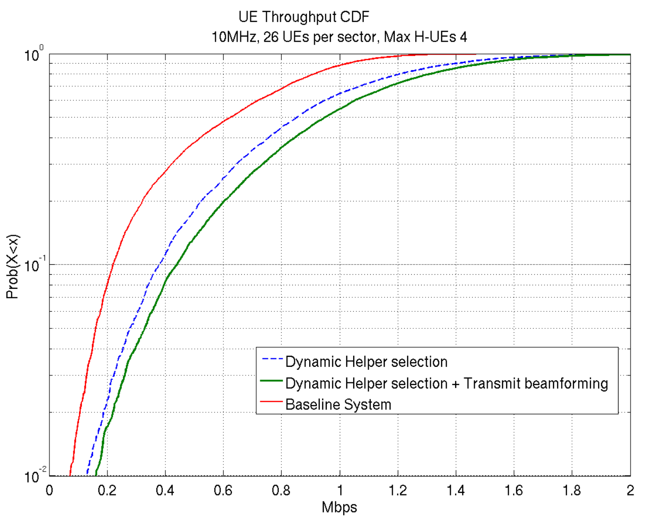

Fig. 6. Cellular System with direct UE-UE communications, Maximum of 4 H-UEs

Comparing the two proposed systems with and without transmit beamforming, it appears that dynamic helper selection provides most of the gains, and transmit beamforming improves results only marginally. This is fairly intuitive if we observe that if the selected H-UE has a significantly higher channel quality than the T-UE channel quality, the benefits of transmit beamforming are only marginal.

V. Conclusions and Future Work

In this paper, we analyze the uplink performance of a cellular system that allows the use of mobile terminals as relays by enabling direct UE-to-UE communication. We propose two relaying mechanisms, the first one uses dynamic helper selection, while the second relaying mechanism makes use of both dynamic helper selection and transmit beamforming. We have shown that relays using direct UE-to-UE communication not only improve the cell edge throughput by around 99%, but also improve the mean throughput of the uplink by more than 50%.

This work focused on using Helper UE's to improve the diversity of the end to end radio link. In our future work, we will focus on bringing in elements of multi-user spatial multiplexing using multiple antenna techniques to further improve the system.

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