A Distance-based Study for Device-to-Device Communication Underlaying a Cellular System

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***Abstract*—The increasing demand for rich multimedia services and the scarcity of radio resources has motivated the research of technologies able to increase wireless systems' capacity without requiring additional spectrum. In this context, direct Device-to-Device (D2D) communication between User Equipments (UEs) is a promising technology. By allowing direct low-power communication among UEs, D2D communication leads to intelligent spatial reuse of radio resources, permits to offload the network and to increase its capacity and/or Quality of Service (QoS) levels. In this work, we provide a brief literature review on D2D communication, identify and discuss key issues related to the potential benefits of D2D communication within a cellular system, as well as present a distance-based study for defining scenarios in which D2D communication can increase the overall system capacity.**

I. INTRODUCTION

Multimedia services are being increasingly consumed through mobile computers such as laptops, netbooks and smartphones and these services are mainly responsible for the growing demand for high data rates in wireless systems. Providing rich multimedia services conveniently is a challenge for the mobile operators. In the context of the International Mobile Telecommunications (IMT)-Advanced initiative, future cellular networks such as 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) try to answer this demand by employing new technologies able to improve the system performance [1]. Therein, Device-to-Device (D2D) communication represents a promising technology since it allows for direct and low-power communication among devices thus contributing to reduce interference and system load and improving its overall performance.

In a cellular network, the direct D2D communication between two devices can use reserved resources for its data communication or eventually can use the same resources of the cellular communication and stays under control of the cellular network. Thereby the spectrum efficiency can be increased. Besides that, other advantages of D2D communication are: system off-loading in congestion situations, reduced battery consumption, spatial resource reuse, among others [2].

Recently, D2D communication has been a topic of intense research. An introduction to D2D communication underlaying a cellular network is provided in [2]. The authors derive analytical expressions for the probability of existence of a D2D link as long as the resource sharing does not cause the cellular link Signal to Interference-plus-Noise Ratio (SINR) to fall below a required minimum value. In addition, a clustered D2D model and a multihop scenario connecting two D2D users are also investigated. The results reveal that the D2D communication has high probability of existence in certain topologies resulting in opportunities for increasing spectral efficiency of the cellular network.

In other works, the authors evaluate the integration of the D2D communication underlaying a 3GPP LTE-Advanced network [3], [4]. The results demonstrate the feasibility of co-existence of the D2D communication and the 3GPP LTE-Advanced network with interference constraints on the cellular communication system. The feasibility analysis performed by [3] shows that D2D communication brings benefits in interference limited scenarios. In [4], it is shown that allowing D2D communications in the Downlink (DL) of a cellular system is more challenging than in the Uplink (UL) due to increases in the DL interference levels.

In [5], multiple antennas are utilized to suppress interference in the DL of a cellular network. The proposed schemes offers substantial gain in terms of SINR of D2D communications. Nevertheless, this approach can require a considerable amount of feedback, which increases the signaling overhead.

Clustering, as proposed in [6], is another interesting approach for D2D communication within cellular systems. Therein, the authors extend the system equations derived in [7] to cover D2D clustering operation. They demonstrate that with small separation of cluster members, the D2D communication can reach the optimum system performance.

Radio resource allocation schemes based on time-hopping are proposed in [8] to solve the interference problems caused by the imperfect spatial reuse. This scheme aims to randomize the near-far interference from nearby transmitting D2D and cellular users. The results reveal a trend for the optimal operation of time-hopping on scenarios comprising D2D communication as underlay of a cellular system.

In [9], the authors studied a cellular network where the Base Station (BS) can coordinate the interference between the cellular and D2D communications by assuming instantaneous Channel State Information (CSI) while in [10] a similar problem is investigated with only average CSI at the BS. More recently, the authors in [11] discuss key challenges to realize the potential gains of D2D communications in cellular networks. They use the 3GPP LTE network as baseline for D2D design and propose solution approaches to explore the

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resource sharing between D2D and cellular users.

Most of the previous works about D2D communication are dedicated towards the decision about which communication mode the user should employ: cellular or direct D2D communication. This is one of the most challenging problems in D2D communication. Therefore, this article focuses on another important area, which is the evaluation of possible scenarios where the D2D communication mode should be used to improve the system performance and so in the future, develop an algorithm for mode selection. In section II we detail the proposed scenario in which we make our study. In section III we present the main results and discuss them. Finally, section IV draws some conclusions and perspectives of this work.

II. SYSTEM MODEL

In this section, we present the proposed scenario to investigate the potential sum rates gains of having a D2D communication underlaid in a cellular system compared to conventional cellular systems without direct D2D communication.

Figure 1 illustrates our study scenario which consists of two circular cells, each one having one BS at its center. One User Equipment (UE) and one D2D pair are assigned to the first cell. This UE is called *UE1* and communicates with the BS of this cell, which is termed *BS1*. The D2D pair is composed of two UEs that can communicate with each other directly with the transmitting and receiving nodes being termed *D2D-Tx* and *D2D-Rx*, respectively. In the other cell, we model an interfering link involving one UE, termed *UE2*, and the BS of that cell, termed *BS2*. This link mainly plays the role of an external interference source. We should mention that all investigations considered in this paper assume that the communication occurs only in the UL. Moreover, we consider two communication modes, namely:

1) **D2D mode**: D2D users share the same resources than the cellular users. In this mode, *UE1* transmits to *BS1*, *D2D-Tx* to *D2D-Rx*, and *UE2* to *BS2* simultaneously and, consequently, interfere with each other. We calculate rates at the *BS1*, *BS2* and *D2D-Rx*;
2) **Cellular mode**: the D2D terminals cannot communicate with each other directly. The terminals use orthogonal resources in the same cell, but we assume co-channel interference among users of the different cells. There are two phases in this mode. In phase 1, *UE1* transmits to *BS1*. In phase 2, the *D2D-Tx* transmits to *BS1*. In both phases, the *UE2* transmits to *BS2*. Here we calculate rates at the *BS1* and *BS2* per phase.

In this work, our aim is to compare the sum rates of the D2D and cellular communication modes. In order to evaluate the rates, we need to calculate the SINR γ_i at each receiver i, which is given by

$$\gamma_i = \frac{p_i |h_{i,i}|^2}{\sum\limits_{j \neq i} p_j |h_{i,j}|^2 + \sigma^2}, \tag{1}$$

where $h_{i,j}$ is the channel coefficient between a transmitting node j and a receiving node i, which encompasses the average path loss, shadowing and fast fading, which is assumed to be flat. p_i and p_j are the transmit power of the nodes sending to and interfering with the receiver i, respectively. The first term of the denominator of (1) models the interference caused by the other links to the link of interest and σ^2 denotes the average noise power.

Figure 1(a) shows the links of interest (solid lines) and the interfering links (dashed lines) for the D2D mode, while Figure 1(b) and Figure 1(c) refer to the phase 1 and phase 2 of the cellular mode, respectively. The rates are computed considering Shannon's capacity formula as

$$R(\gamma_i) = \log_2(1 + \gamma_i) \text{ bps/Hz}, \tag{2}$$

and we assume normalized bandwidth and symbol time.

The sum rate R_{D2D} for the D2D mode can be given by

$$R_{D2D} = R(\gamma_1) + R(\gamma_{\text{D2D}}) + R(\gamma_2) \tag{3}$$

where $R(\gamma_1)$, $R(\gamma_{\text{D2D}})$ and $R(\gamma_2)$ are the rates at the *BS1*, *D2D-Rx* and *BS2*, respectively.

The sum rate R_{cell} in the cellular mode is obtained by averaging the sum rate of the two phases, i.e.,

$$R_{cell} = \frac{1}{2}(R_1 + R_2) \tag{4}$$

where

$$R_n = R_n(\gamma_1) + R_n(\gamma_2) \tag{5}$$

and $R_n(\gamma_1)$ and $R_n(\gamma_2)$ are respectively the rates at the *BS1* and the *BS2* in the phase $n = 1, 2$.

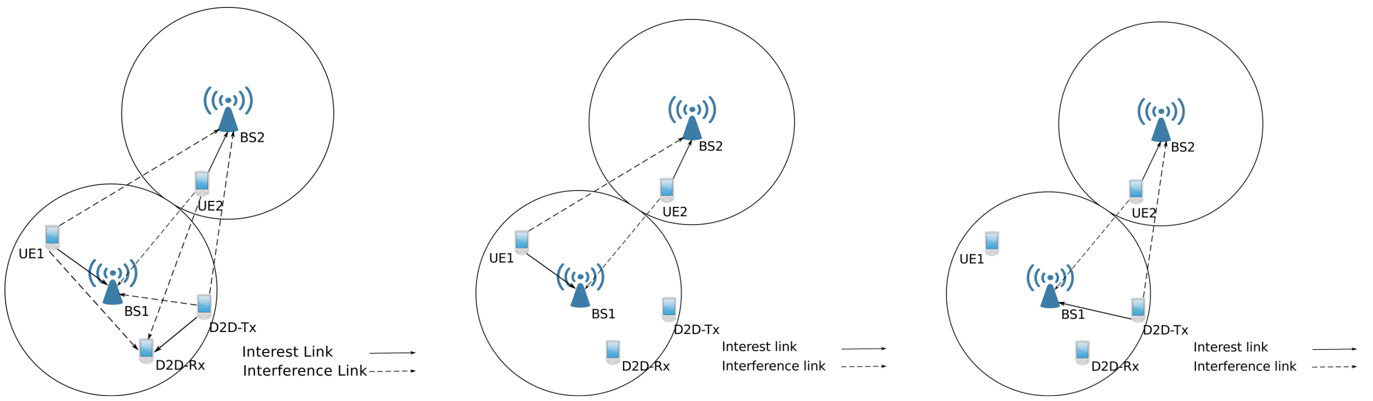
III. PERFORMANCE EVALUATION

In this section, we firstly explain our simulation setup in section III-A. Then, in section III-B we present and discuss the obtained results.

A. Simulation setup

In order to evaluate the performance of D2D and cellular modes, we considered a large number of snapshot simulations. In every snapshot, we keep fixed the positions of the two BSs, namely *BS1* and *BS2*, and of the cellular device from the interfering cell, namely *UE2*, as shown in Figure 1. The *D2D-Rx* and *D2D-Tx* nodes and the cellular device *UE1* have their positions set deterministically at points of a grid covering the cell area. In order to do this, they vary their positions in steps of 20 m in x- and y-axis directions starting from a minimum distance of 10 m from *BS1*, which is considered as reference $(0, 0)$. Additionally, we do not allow any two among *UE1*, *D2D-Rx* or *D2D-Tx* to be placed at the same position at the same time. Several possible combinations of positions for these three devices inside the cell centered in *BS1* are considered in our analysis and in this way we can sample several possible configurations of these 3 nodes within the area covered by the first cell and so characterize the performance of the D2D and cellular communication modes.

In this section, we make performance analyses conditioned to specific positions of *UE1*, *D2D-Tx* and *D2D-Rx*. In all analyses conducted in this work, we adopt 1000 realizations of Independent and Identically Distributed (IID) channel snapshots for each set of positions of *UE1*, *D2D-Tx* and



(a) D2D Mode. (b) Phase 1 cellular Mode. (c) Phase 2 cellular Mode.

Fig. 1. Study scenario with the interest and interference links for both communication modes: D2D and cellular.

D2D-Rx. Moreover, for each snapshot we calculate the sum rate for the D2D and cellular modes based on Equations 3 and 4, respectively. This approach has been chosen to help determining at which positions of *UE1* conditioned to the distance between *D2D-Tx* and *D2D-Rx* configures scenarios in which D2D communication can increase the system overall capacity. However, due to the large number of positions' combinations, channel realizations and associated memory space issues relate, we analyzed only the 10th percentile, the 50th (median) and the 90th percentile of the D2D mode and cellular mode sum rates. The main simulation parameters considered in the evaluations are those presented in Table I.

TABLE I
SIMULATION PARAMETERS

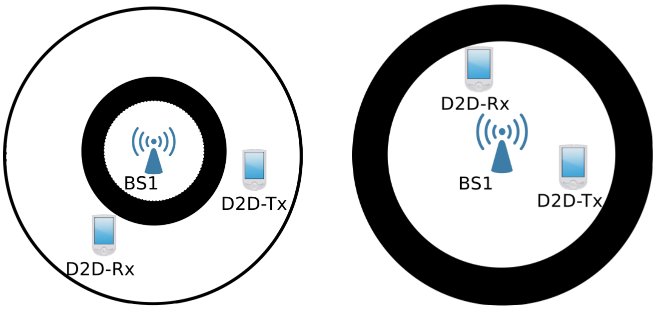
Parameter	Value
Path loss model	$128.1 + 37.6\log(d)$, with d in km
Inter site distance	500 m
Noise power	-116.4 dBm
Transmit power	24 dBm
Cell Radius	250 m
Standard deviation of shadowing	8 dB

Since we are interested at studying the gains of having D2D communication in a cellular system constrained to the positions of the communicating and interfering nodes, we define some regions regarding the allowed relative positions of *D2D-Tx* and *D2D-Rx* nodes and the allowed *UE1*'s position with respect to the *BS1*.

Let R_c denote the radius of the cell centered at *BS1*. Denoting by r the radius where *UE1* is, we define two regions represented by discs $R_i \leq r \leq R_o$ limited by an inner radius R_i and an outer radius R_o, namely a **near BS** region and a **near cell-edge** region, within which the *UE1* is placed according to the grid points that were previously explained. The two aforementioned regions are defined as:

- **Near BS region**: $0.1R_c \leq r \leq 0.15R_c$, where R_i equals $0.1R_c$ and R_o equals $0.15R_c$. Considering the value of 250 m for R_c we have $25 \leq r \leq 37.5$ m.
- **Near cell edge region** : $0.9R_c \leq r \leq R_c$, where R_i equals $0.9R_c$ and R_o equals R_c. Considering again $R_c = 250$ m we have $225 \leq r \leq 250$ m.

Considering this, Figure 2 illustrates these two regions, where the dark areas represent the areas of interest for each region. It is worth mentioning that the above values chosen for R_i and R_o have been defined based on previously performed experimental observations [12], [13].



(a) *UE1* **near BS**. (b) *UE1* **near cell-edge**.

Fig. 2. Two investigated regions.

B. Results

In order to find the specific scenarios in which D2D can increase the system overall capacity using UL resources, we have made two different analysis: without and with restriction concerning the distances between *D2D-Tx* and *D2D-Rx*.

In the case without restriction, *UE1* is placed into one of the two different regions defined in Section III-A and the distance between *D2D-Tx* and *D2D-Rx* is not restricted. In the case with restriction on the distance between *D2D-Tx* and *D2D-Rx*, *UE1* is still placed into one of the two different regions of Section III-A and we impose that the distance between *D2D-Tx* and *D2D-Rx*, termed $d_{\text{Tx-Rx}}$, must be smaller than or equal to 50 m.

Without restriction

This section shows results without restriction concerning $d_{\text{Tx-Rx}}$. In Figure 3 we can find the sum rate Cumulative Distribution Function (CDF) of the D2D and the cellular modes, both in **near BS** and **near cell-edge** regions. The median values of sum rates were considered having 1000 samples for each allowed set of *UE1*, *D2D-Tx* and *D2D-Rx* positions in the grid described in Section III-A. When *UE1* is close to *BS1*, the rates of the D2D mode still show a gain of 1 bps/Hz in about 30% of the cases and, in 10% of the cases, such a gain can reach 2 bps/Hz. On the other hand, when *UE1* is close to the cell edge, the cellular mode can reach better rates than D2D mode.

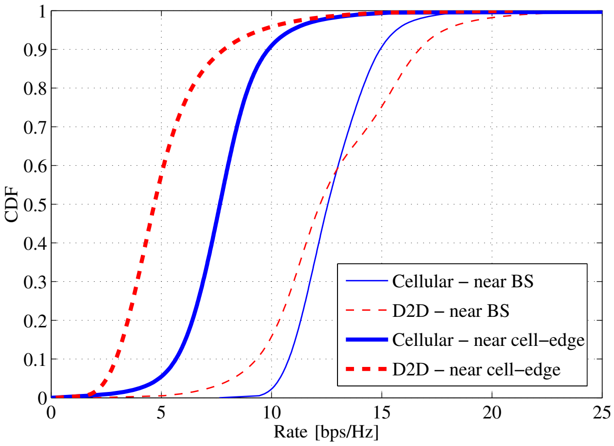


Fig. 3. Rates in D2D and cellular modes for each set of *UE1*, *D2D-Tx* and *D2D-Rx* positions - Median.

In Figure 4, we define $P(R_{D2D} > R_{cell})$ as the probability that the rate of the *D2D* mode is greater than the rate of the cellular mode. Hence, we can see how this probability varies when $d_{\text{Tx-Rx}}$ and the distance between *UE1* and *D2D-Rx*, termed $d_{\text{UE1-Rx}}$, increases.

In Figure 4(a), *UE1* is in the **near BS** region and therein the smallest probability of the rate of the *D2D* mode surpassing the rate of the cellular mode is 30%, even when *D2D-Tx* is far from the *D2D-Rx* or the *UE1* is near the *D2D-Rx*.

In Figure 4(b) we can see that when *UE1* is in the **near cell-edge** region the probability varies a lot mainly concerning $d_{\text{Tx-Rx}}$. From Figures 4(a) and 4(b), we can conclude that when the $d_{\text{Tx-Rx}}$ is smaller than 50 m, the probability that the rate of the *D2D* mode is greater than the rate of the cellular mode is at least 90%.

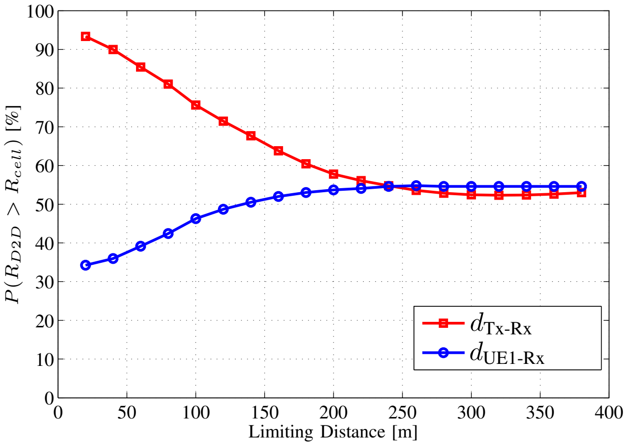
With restriction

In this section, we evaluate how much restricting the distance $d_{\text{Tx-Rx}}$ between *D2D-Tx* and *D2D-Rx* could improve the sum rates presented in the last section.

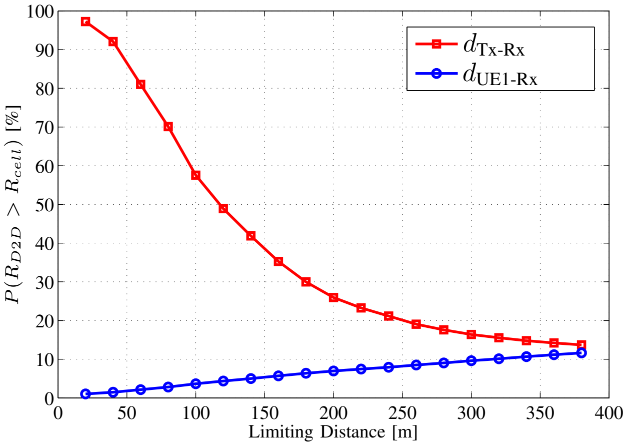
In Figures 5, 6 and 7 we compare the sum rate CDF obtained in the cellular mode with that obtained in the D2D mode for the situations in which *D2D-Tx* and *D2D-Rx* are distant from each other at most by 50 m considering the median, the 10th percentile and the 90th percentile of sum rate values, respectively.

Comparing the curves in Figure 5, we can see that when *UE1* is in the **near BS** region the rates are greater than when *UE1* is in the **near cell-edge** region. Moreover, comparing Figures 3 and 5, we have shown that not only the **near BS** region had better results, but also the **near cell-edge** region, which had not shown good results for the use of D2D in Figure 3. The **near BS** region shows a gain of at least 5.5 bps/Hz in 50% of cases, while **near cell-edge** region shows a gain of at least 4 bps/Hz in 50% of cases.

In Figure 6, the **near BS** region shows a gain of at least 3 bps/Hz in 50% of cases when D2D mode is performed, while **near cell-edge** region shows a gain of at least 2 bps/Hz in 50% of cases. The analysis of the 10th percentile aims to



(a) *UE1* **near BS**.



(b) *UE1* **near cell-edge**.

Fig. 4. Variation of the *D2D* Gain with distance.

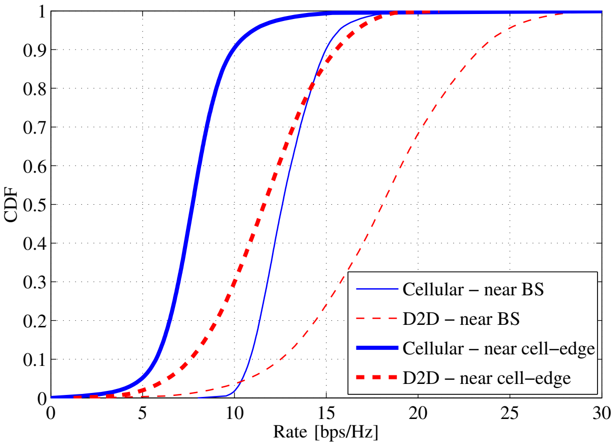


Fig. 5. Rates when *D2D-Tx* and *D2D-Rx* are distant less than 50 m from each other - Median

study the behavior of the D2D mode when we consider the worst ten percent sum rates. Even considering this, the D2D mode provides a better performance compared to the cellular mode, except for 11% of the cases in the **near BS** region, where the cellular mode outperforms the D2D mode.

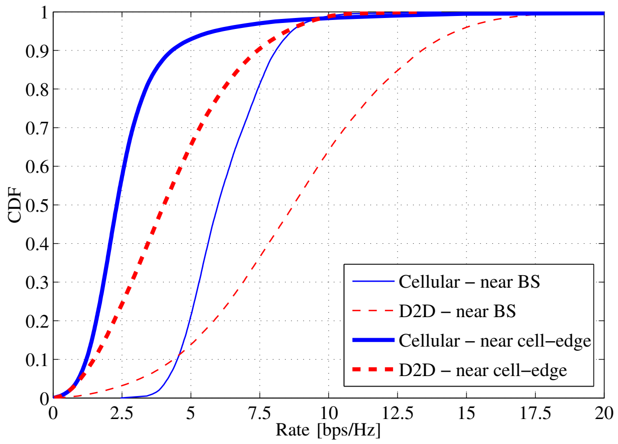


Fig. 6. The worst ten percent rates when *D2D-Tx* and *D2D-Rx* are distant less than 50 m from each other - 10th percentile.

In Figure 7, the two regions show a gain when D2D mode is performed, but the **near BS** region still shows a higher gain. The **near BS** region shows a gain of at least 7 bps/Hz in 50% of cases, while **near cell-edge** region shows a gain of at least 5 bps/Hz in 50% of cases. The analysis of the 90th percentile aims to study the behavior of the D2D mode when we consider the best ten percent sum rates. Considering these better rates, the cellular mode outperforms the D2D mode in the **near BS** region only in 1% of the cases, while in the **near cell-edge** region the D2D mode always outperforms the cellular mode.

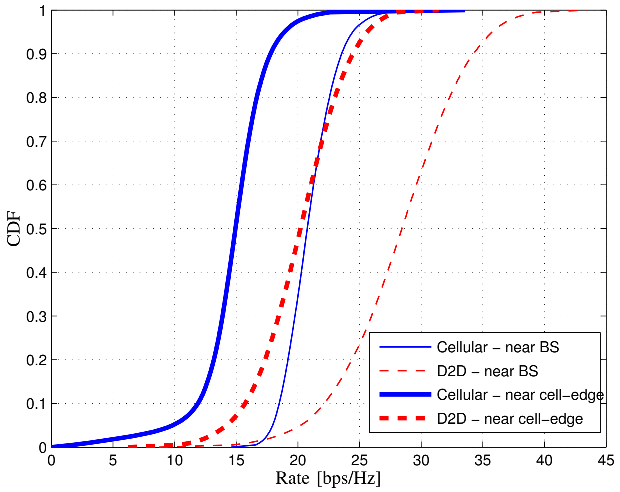


Fig. 7. The best 10 percent rates when *D2D-Tx* and *D2D-Rx* are distant less than 50 m from each other - 90th percentile.

IV. CONCLUSION

In this article we evaluated the possible scenarios where the D2D communication mode should be used to improve the system performance. We showed that when *UE1* is in the **near BS** region the rates are greater than when *UE1* is in the **near cell-edge** region. Moreover, we also showed that when we restrict the $d_{\text{Tx-Rx}}$, the rates achieved by the D2D mode are greater even in the **near cell-edge** region, where without restriction the rates were always lower than the cellular mode. As a perspective for future works, we intend to formulate a mode selection algorithm in order to increase the system data rate, but considering the requirements for power saving via power control algorithms.

ACKNOWLEDGMENT

The authors acknowledge the technical and financial support from Ericsson Research, Wireless Access Network Department, Luleå, Sweden and from the Ericsson Innovation Center, Indaiatuba, Brazil.

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