On the Performance of Device-to-Device Communication: a Distance-based Analysis

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***Abstract*— Allowing a Device-to-Device (D2D) communication mode in a cellular network is a feature that might improve the system performance due to a better (re)use of radio resources and a reduced congestion when several users located at the same area want to communicate with each other. The design of an efficient D2D communication mode with minimal interference to the cellular network is a key problem for future communication systems. In this work, we study the impact of the distance between communicating and interfering nodes and illustrate the benefits of D2D communication in a cellular network by comparing its performance in terms of total rate with that of a conventional cellular communication mode. The obtained results show that the use of D2D communication might provide considerable gains, but strongly depends on the distances among the involved nodes.**

***Keywords*— Device-to-device communication, distance-based analysis**

I. Introduction

Device-to-Device (D2D) communication represents a promising technique concerning system off-loading in congestion situations in cases in which a group of people is placed near from each other and a couple of devices want to communicate with each other. This short distance allows for direct communication among devices with low transmit power and so contributes to reduce interference and load levels in the system improving its performance. This kind of communication can happen in a rock concert, in an enterprise building, in a revival meeting or even in a political rally. In these kind of situations the distance between two different User Equipments (UEs) is not expected to be large. However, it is important to investigate until which distance between a potential pair of nodes, namely a potential D2D pair, should use D2D communication or the common cellular network.

D2D communication can use reserved resources for its data communication or eventually can use the same resources of the cellular system. Thereby the system spectral efficiency can be increased. Other advantages of D2D communication are reduced battery consumption, spatial resource reuse, increased rates, and more [1].

A big challenge is to determine under which conditions the D2D communication underlaying a cellular network enables local services with limited interference to the cellular network. Simple mode selection procedures between D2D or cellular communication lead to unsatisfactory results. Instead, a communication mode selection procedure should be proposed that takes into account the D2D link quality and the different interference situations resulting from sharing cellular uplink or downlink resources. Some works discuss these mode selection procedures for D2D communication underlaying a cellular network. In general, three D2D communication modes are described: a reuse mode, a dedicated mode and the cellular mode [2], [3], [4].

In [2], by allowing D2D communication to underlay the cellular network, the overall throughput in the network may increase up to 65 % compared to a case where all D2D traffic is relayed by the cellular network. In [3], semi-analytical studies showed that D2D communication sharing the same resources as the cellular network can provide higher capacity (sum rate) than pure cellular communication. In [4], the Base Station (BS) decides whether the underlaying D2D pair should reuse cellular resources, get dedicated resources or communicate via BS. It concludes that the optimal communication mode selection strategy does not only depend on the quality of the D2D link and the quality of the link between D2D terminals and the BS, but also on the interference situation. In a multi-cell scenario also the interference from other cells will affect the decision. In other words, it largely depends on the position of the D2D receiver relative to the cellular terminal when reusing uplink resources and to the BS when reusing downlink resources.

In [5], means for getting optimal communication mode for all devices in the system are derived in terms of equations that capture network information such as link gains, noise levels, and Signal to Interference-plus-Noise Ratios (SINRs). According to the results, the main factors affecting the performance gain of D2D communication are local communication probability and maximum distance between communicating nodes, as well as the communication mode selection algorithm. Thus, the design of an efficient D2D communication mode with minimal interference to the cellular network becomes also a key problem.

The communication mode selection problem is basically guided by chosen metrics used to determine if D2D communication will provide some gain to the cellular network or if the cellular network is already the best way to communicate. In this work, we choose the distance as a possible metric that could help in the communication mode selection decision. We present results that show the impact of the significant distances between the communicating nodes in the comparison of system sum rate when using either D2D or cellular modes in the uplink. In section II we detail the proposed scenario in

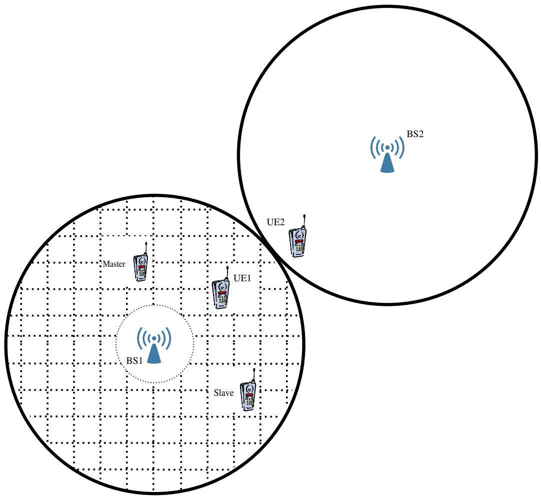

Fig. 1. Study scenario for the distance-based analysis.

which we make our study. In section III we present the main results and discuss them. Finally, in section IV we draw some conclusions and perspectives concerning D2D communication underlaying cellular network.

II. System Model

Our study scenario consists of two circular cells, where each cell has a BS at its center, as illustrated in Figure 1. One UE and one D2D pair are assigned to the first. 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 *Slave* and *Master*, respectively. In the other cell, we model a link involving one UE, termed *UE2*, and the BS of that cell, termed *BS2*.

All or some of these links will interfere with each other depending on the adopted communication mode. In this work, we consider two communication modes:

- D2D: the D2D pair uses the same resources as the UEs in both cells, causing interference to each other. We assume that the communication occurs only during the uplink frame when *UE1* transmits to *BS1*, *UE2* transmits to *BS2* and *Slave* transmits to *Master*.
- Cellular: in this kind of communication there are two orthogonal phases. In phase 1, only *UE1* transmits to *BS1*. In the second phase, only *Slave* transmits to *BS1*. However, in both phases the interfering link is modeled as *UE2* transmitting to *BS2*.

In the considered scenario, we should take care on the interference created by the communication between *Slave* and *Master*. In this work, our aim is to compare the sum rates of the D2D and cellular communication modes when the same resources are shared.

In the D2D mode, the SINR $\gamma_{d2d}^{(i)}$ is measured at each BSs and at the *Master*, being computed as

$$\gamma_{d2d}^{i} = \frac{p_i \cdot g_{i,i}}{p_j \cdot g_{i,j} + p_k \cdot g_{i,k} + \eta} \qquad (1)$$

where the index i stands for the link of interest and j, k for the two interfering links, $g_{m,n}$ is the channel gain between a receiving node m and a transmitting node n, p_n is the transmit power of node n, and η is the noise power.

In the cellular mode, the simulation is divided into two phases and we only calculate the SINRs and rates at the *BS1* and *BS2*. The SINR is obtained as in (1). The difference here is that in each phase we have just one interfering link (*UE2* transmiting to *BS2*).

Shannon's capacity formula is used to calculate the rates of the D2D and cellular connections. The sum rate C_{d2d} in the D2D mode is calculated as

$$C_{d2d} = \log_2(1+\gamma_{BS1}) + \log_2(1+\gamma_{Master}) + \log_2(1+\gamma_{BS2}), \qquad (2)$$

where γ_{BS1}, γ_{Master} and γ_{BS2} are the SINRs at the *BS1*, *Master* and *BS2*, respectively, which are computed using (1).

In the cellular mode, the sum rate C_{cell} is calculated as

$$C_{cell} = \frac{1}{2}(C_{cell}^{1} + C_{cell}^{2}), \text{ where} \qquad (3a)$$

$$C_{cell}^{i} = \log_2(1+\gamma_{BS1}^{i}) + \log_2(1+\gamma_{BS2}^{i}), \; i = 1, 2. \qquad (3b)$$

where C_{cell}^{i} is the sum rate in the phase i. Note that the sum rate in the cellular mode is obtained by averaging sum rate of the two phases.

III. Performance Evaluation

In this section, we explain firstly 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 simulations. Our simulation tool is developed in Matlab^{TM}. In every run, 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 pair, namely the *Master* and *Slave* nodes, and the cellular device *UE1* are not placed randomly. They 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 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*, *Master* or *Slave* to sit at the same position at the same time. All 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 over the whole area covered by the first cell and characterize the performance of the D2D and cellular communication modes.

The channel model considers only path loss. We do not consider in this work shadowing nor fast fading. The main parameters used in this work are described in the Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Path loss model	128.1+37.6log(d), with d in km
Inter site distance	500 m
Noise power	-116.4 dBm
Transmit power	24 dBm

B. Results

The first main result shows the percentage of cases in which the system sum rate is larger when D2D is performed. To obtain this result, we compare the sum rate when either D2D or cellular mode are performed considering all the simulations. In almost 22% of the cases (possible position combinations) the sum rate obtained by operating in D2D mode is higher than that obtained when operating in the cellular mode. This value seems to be small, but when a gain is obtained, it can be impressive as shown in the sequel.

In Figures 2, 3 and 4 we show results for cases in which the D2D mode outperforms the cellular mode in terms of sum rate keeping the exact same positions of the nodes for both modes.

In Figure 2 we show the Cumulative Distribution Function (CDF) of the percentage gain of the D2D mode sum rate over the sum rate obtained with the cellular mode. Therein, we take all cases in which the sum rate obtained with the D2D mode is larger than that obtained with the cellular one. We can see that in about 40% of the cases the gain is around 25% and this gain can reach 150% in a few cases, mainly when the distance between the D2D pair is small.

In Figure 3 we show the CDF of the sum rate for those cases in which the D2D mode performs better than the cellular mode and vice-versa. In more details, the dashed curve is the CDF of the sum rate obtained when the D2D is performed in the cases where the sum rate of the D2D mode is larger than that obtained by cellular mode. On its turn, the solid curve is the CDF of the sum rate obtained by the cellular mode in the cases where its sum rate is larger than that obtained by the D2D mode. We can observe that when the D2D mode wins compared to cellular mode, the obtained sum rates are higher than in the dual situation in which the cellular wins. This result is a contribution of this work and gives support to the benefits of D2D communication to enhance the efficiency of cellular networks.

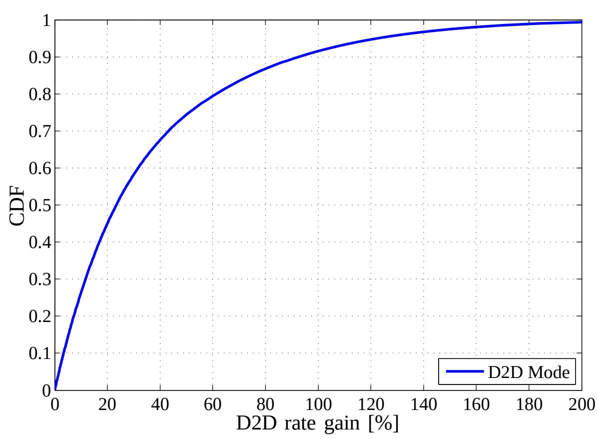

Fig. 2. Percentage gain of D2D mode rates over the cellular mode rates.

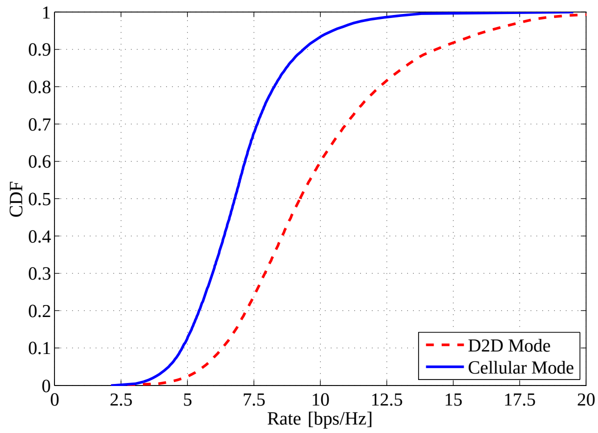

Fig. 3. Best rates of D2D mode outperforms best rates of cellular mode.

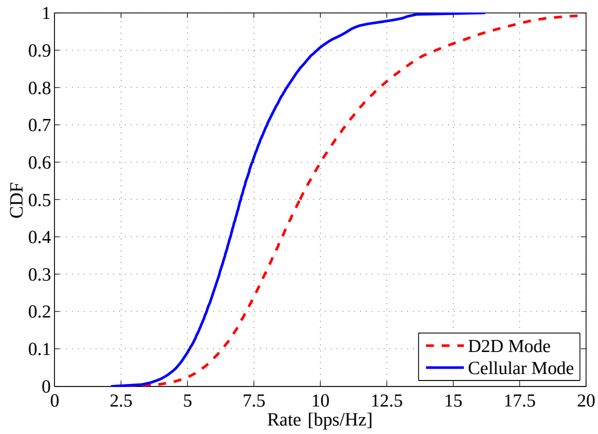

Fig. 4. Rates of D2D mode when it outperforms cellular mode at the same positions.

In Figure 4 we show CDFs of the sum rates when the D2D mode outperforms the cellular mode. In this case, it is possible to measure how much the D2D can really improve the spectral efficiency of the system. The dashed curve is the CDF of the sum rate obtained when the D2D is performed in the cases where the sum rate of the D2D mode is larger than that obtained by cellular mode. On the other hand, the solid curve is the CDF of the sum rates obtained when the cellular mode is performed. We can observe that close to 50% of cases show a gain of $\approx$2.25 bps/Hz when D2D communication is performed. This gain can be converted in different ways by the operators, e.g., in more users sharing the free resources or even higher data rates for the users.

The result expressed in Figure 5 shows the CDF of the sum rate when the rates of cellular mode outperforms those obtained in the D2D mode. In this case, the dashed curve is the CDF of the sum rate obtained when the D2D is performed in the cases where the sum rate of the cellular mode is larger than that obtained by D2D mode. The solid curve is the CDF of the sum rate obtained when the cellular mode is performed. We

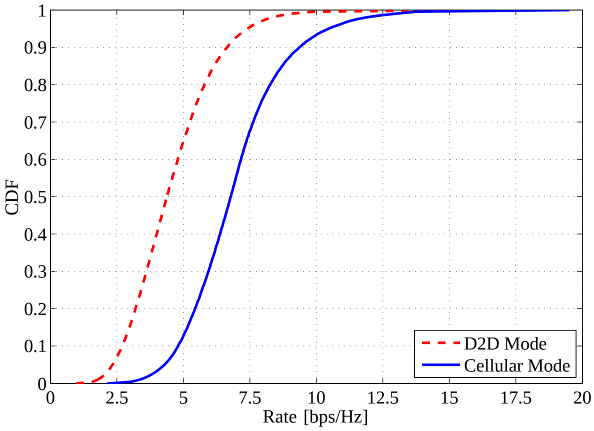

Fig. 5. Rates of D2D mode when cellular mode outperforms it at the same positions.

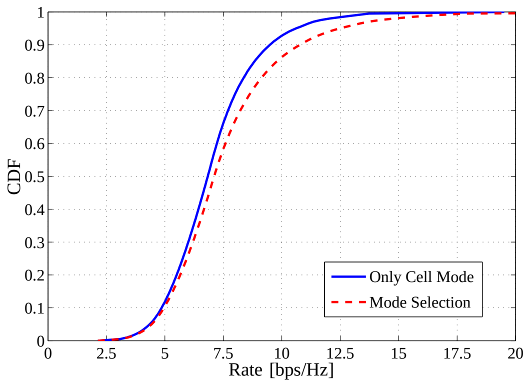

Fig. 6. Comparison between rates considering only cellular mode and mode selection.

can observe that close to 50% of cases when D2D is performed the gain of the cellular mode is around 3 bps/Hz. This result just illustrates that the D2D communication should not be applied all the time, but only in some favorable conditions. Otherwise, its utilization can bring losses to the sum rate.

Thus, in Figure 6 we show a result concerning the rates obtained when only the cellular mode is performed and also another curve illustrating the rates if a mode selection algorithm were apllied. This mode selection curve represents the best rates found in each case, considering cellular and D2D modes. We can conclude that if the D2D is chosen in some occasions, it will be a gain in the system capacity.

In order to take some conclusions concerning distances, we investigate in which possible cases the D2D mode brings a gain in the sum rate as function of the main distances involved in the problem. In Figure 7 we can see the frequency of occurrences among all simulations performed concerning the distance between the *Slave* and the *BS1*. It is possible to see the more distant the *Slave* is from the *BS1* the more often D2D mode is used. In this case, the extreme possible distance between *BS1* and any device located inside a cell centered at *BS1*' position is 250 m.

On its turn, Figure 8 shows the histogram of the frequency of occurrence when D2D mode outperforms the cellular mode for a limiting distance between the *Slave* and *Master*. This figure considers the case in which the sum rate of the D2D mode is higher than that of the cellular mode. As expected, the more distant the *Slave* is from the *Master* the less is the frequency of occurrence of D2D gain in the system capacity.

Finally, to complement the histogram analysis, we have the Figures 9 and 10. These figures show to some distances the percentage of cases in which D2D mode outperforms the cellular mode. The main distance to be analyzed is that between *Slave* and the *Master*. It is important to remember that the larger possible distance between them happens when they are diametrically opposed, in this work, 500 m. Figure 9 shows that when this distance is less around than 150 m, the percentage of cases in which D2D mode outperforms the cellular mode is larger than 50%. It is important to observe that this distance can substantially influence this result. As an example, when this distance is less than around 50 m, the percentage of cases in which D2D mode outperforms becomes larger than 80%.

The distance of *UE1* from *BS1* should be also analyzed. A similar behavior is expected once this link is also a link of interest in the calculation of the system sum rate. In Figure 9 is also possible to see that when this distance is around 100 m the percentage of success of the D2D mode is larger than 50%.

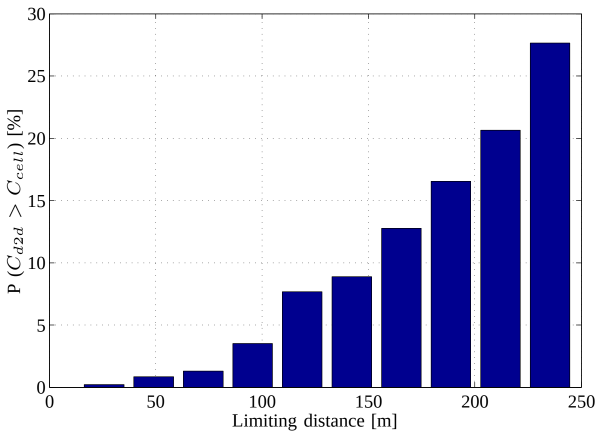

Fig. 7. Limiting distance: *Slave*-to-*BS1*.

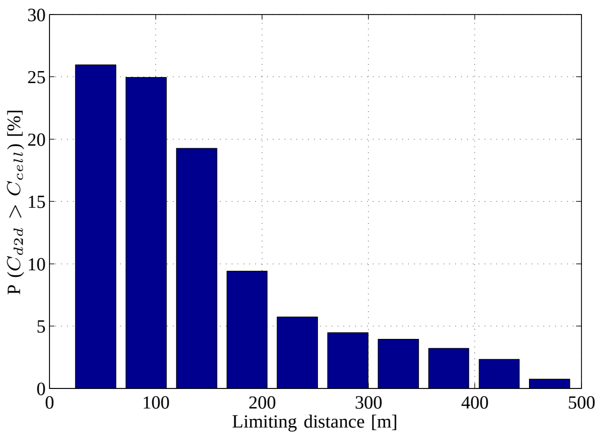

Fig. 8. Limiting distance: *Slave*-to-*Master*.

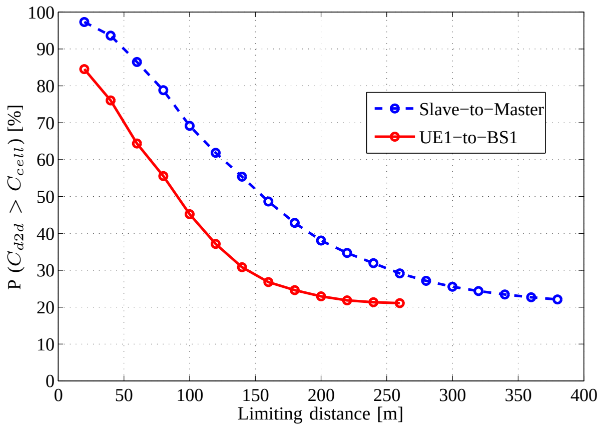

Fig. 9. Limiting distance between *Slave*-to-*Master* and *UE1*-to-*BS1*.

It is important to remember that the extreme possible distance between *BS1* and any device located inside a cell centered at *BS1*'s position is 250 m. The more distant *UE1* is from *BS1* the lower is the probability of the D2D mode outperforming the cellular mode.

On the other hand, Figure 10 analyzes the case of an interfering link. The impact of the distance between *Slave* and *BS1* and also the distance between *UE1* and Master are analyzed. Both results show that the probability of the D2D mode outperforming the cellular mode is almost zero when the respective distances are very small. Although, we can not take an strong conclusion when these distances increase since the highest probability verified is less than 25%, we can still observe that the more distant the *Slave* is from *BS1* the larger is the percentage of cases in which D2D mode outperforms the cellular mode.

IV. Conclusion

In this work, we present a detailed study of the effect of the main distances on Device-to-Device (D2D) communication when using either D2D or cellular mode by means of a large number of simulations.

In almost 22% of the considered cases, the sum rate obtained by operating in D2D mode is higher than that obtained when operating in the cellular mode and in about 40% of the cases the D2D increases the capacity by ≈25%. However, gains can reach 150% in a few cases.

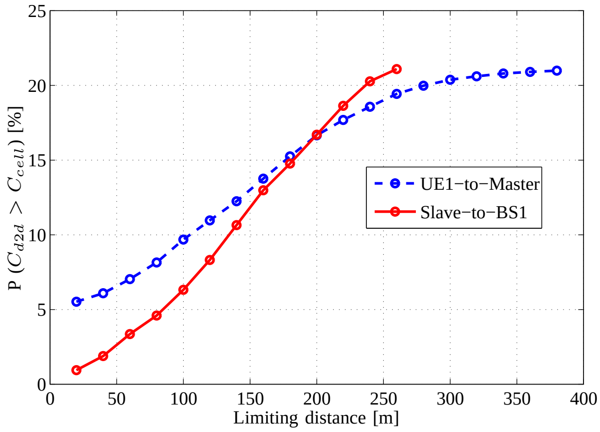

Fig. 10. Limiting distance between *UE1*-to-*Master* and *Slave*-to-*BS1*.

As expected, the key distance in D2D communication analysis is that from *Slave* to *Master*. It is possible to say that when the this distance is less than ≈50 m, the percentage of cases in which D2D mode outperforms the cellular mode becomes larger than 80%. Another strong result (not presented in this work) is when the *UE1* is near from the *BS1* associated to the cases when the distance from *Slave* to *Master* is less than ≈50 m. The gain obtained in such situation can be considerable. The first perspective of this work is another study concerning how we can potentialize the D2D gain, finding certain scenarios where the D2D is better than the cellular mode helping in a possible mode selection algorithm.

The interference is a key problem when we consider D2D communication underlaying a cellular network. We have also made a study about the distance between *Slave* and *BS1* and the distance between *UE1* and *Master*. Both results show that the percentage of success is almost zero when these distances are close to zero, thus illustrating the D2D communication should not be applied all the time, but only in some favorable conditions. As perspectives of this work, we intend to extend it to a scenario considering shadowing and fast fading in a set of fixed positions and so perform a stochastic analysis. As no power control strategy is adopted in this paper, a power control algorithm helping a communication mode selection algorithm is also foreseen.

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