Distance-based Radio Resource Allocation for Device to Device Communications

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***Abstract*— Device-to-Device (D2D) communications can increase the spectral efficiency of future cellular networks when sharing part of the cellular spectrum. Radio resource allocation mechanisms are then necessary to control the interference that D2D and cellular transmissions can generate to each other. Most of the existing allocation schemes rely on the knowledge of the channel gain of all possible links between cellular and D2D nodes. This paper proposes to reduce the complexity cost and signalling overhead of the allocation process by using location information available at the network level. Using this information, the base station assigns radio resources to new D2D transmissions with the objective to control and limit the interference to the primary cellular users and existing D2D transmissions. The proposed radio resource allocation scheme continuously monitors that the user QoS requirements are satisfied. If it is not the case, it dynamically modifies the resource allocation to the interfering D2D transmissions. The proposed scheme achieves performance levels similar to that obtained with an optimized centralized allocation scheme, but with a significantly lower complexity cost and signaling overhead.**

Keywords—Device-to-Device; D2D; 5G; radio resource allocation; radio resource management; underlay mode; distance-based; cellular networks.

I. INTRODUCTION

5G networks will need to address the continuous growth in mobile data traffic with distinct QoS (Quality of Service) requirements. An approach to do so is by offloading part of the traffic to Device-to-device (D2D) communications that have already been identified as a key component of 5G [1]. D2D communications allow two devices in proximity to establish a direct communication with the support and control from the cellular infrastructure. D2D communications can operate in overlay or underlay mode. In the overlay mode, a part of the spectrum is reserved for D2D transmissions in order to avoid interfering primary cellular users. On the other hand, D2D communications share the spectrum of primary cellular users in the underlay mode [2]. The underlay mode can increase the spectral efficiency as long as the radio resource allocation mechanism can control or limit the interference that D2D and cellular transmissions can generate to each other.

Different centralized radio resource allocation schemes have been proposed for D2D communications underlaying cellular networks. For example, [3] defines an optimization problem to maximize the sum of the data rate for all D2D and cellular links in scenarios where a single D2D link can reuse the resources of a cellular transmission. The optimization problem must guarantee that all transmissions experience a Signal to Interference plus Noise Ratio (SINR) level higher than a pre-defined threshold. To reduce the computational complexity, the authors propose a sub-optimum greedy heuristic algorithm. The proposal in [4] defines an optimization problem with the objective to maximize the spectrum utilization by minimizing the number of radio resources assigned to D2D links. A column generation method is used to solve the problem and provide near-optimal solutions with lower complexity. The method is applied in scenarios where multiple D2D links can reuse the radio resources of a cellular transmission. A distributed radio resource allocation scheme is presented in [5]. The scheme is designed to maximize the total throughput of D2D links while protecting cellular transmissions from excessive interference. To do so, the BS sends information to the D2D nodes that is used to limit the aggregate interference caused to cellular transmissions.

Most of the proposals reported to date generally require cellular and/or D2D devices to measure and/or exchange channel gain information of interfering links. This can generate a significant signaling overhead that could decrease the benefits of D2D communications underlaying cellular networks. The signaling overhead can be reduced using distance information in the process to allocate radio resources. For example, the radio resource allocation scheme presented in [6] estimates the outage probability of a D2D transmission that shares uplink radio resources with a cellular user as a function of the distance between the cellular and D2D nodes. This outage probability is then used to design a distance-constrained resource-sharing criteria that pairs each D2D transmission with a cellular user located at a distance sufficiently large so that its interference to the D2D link is under control. The same outage probability is utilized in [7] to design a centralized radio resource allocation scheme that pairs the D2D link with the cellular transmission that minimizes the outage probability. [6] and [7] demonstrated that the use of location or distance information can significantly reduce the outage probability of D2D communications. However, they focus on D2D links located at the cell edge, and consider that the interference created to primary cellular users by a D2D transmission can be neglected. In addition, both studies consider scenarios where only one D2D link can share radio resources with a cellular transmission. This study considers a more realistic and challenging scenario where D2D and cellular transmissions can interfere to each other, and where several D2D transmissions can share the same cellular resources. The latter case requires considering the aggregate interference generated by the multiple D2D transmissions that share the same resources. This scenario requires the design of novel resource allocation schemes that take into account, and control, the interference experienced by both cellular and D2D transmissions and its impact on their respective QoS levels. In this context, this paper proposes and evaluates a novel distance-based radio resource allocation scheme for D2D communications in underlay cellular networks. Following the conclusions obtained in [6] and [7], the proposed scheme exploits the location information to reduce the complexity and overhead of the resource allocation for D2D communications underlaying cellular networks. In the proposed scheme, the base station (BS or eNB) assigns to each D2D transmission the radio resources that can limit the interference suffered by the primary cellular and D2D users. This decision is taken based on the distance information between D2D and cellular users. The decision taken by the eNB does not initially take into account the aggregate interference caused by other D2D transmissions sharing the same radio resources. This is done to reduce the complexity and signaling overhead. The impact of such aggregate interference is monitored and controlled at the eNB and D2D receivers that continuously evaluate if their QoS requirements are satisfied. If such requirements are not satisfied, the eNB modifies the resource allocation to the interfering D2D link. The obtained results demonstrate that the proposed distance-based radio resource allocation scheme can achieve spectral efficiency and capacity levels at least as high as those obtained with optimized centralized schemes, but with a significantly lower complexity and signaling overhead.

II. Distance-based Radio Resource Allocation

Following 3GPP TR 36.843 [8], this work assumes that D2D communications utilize uplink (UL) LTE cellular spectrum. The use of UL cellular spectrum reduces the impact of the interference generated by D2D transmissions at the eNB. In addition, UL cellular users generate less average interference levels to D2D links since the average transmission power of mobile terminals is significantly lower than that of a BS. Cellular users are considered to be primary users of the spectrum. This study considers that several D2D transmissions can simultaneously utilize the same radio resources of a cellular user.

This paper proposes to use information about the distance between nodes for the resource allocation process in order to reduce the complexity and signaling overhead. This information is available at the network level. The EPC-level ProSe Discovery defined in the 3GPP TS 23.303 standard [9] requires nodes to periodically inform the network about their location. It can then be assumed that the eNB knows the location of the cellular and D2D users present in its cell[1]. The eNB also knows the number of users with active UL cellular transmissions (C). The eNB uses all this information to allocate the radio resources to a D2D transmission. In particular, the eNB allocates the resources that will guarantee acceptable average interference levels between cellular and D2D users considering their respective QoS requirements. The eNB estimates the average received signal levels, and therefore the average interference levels, using the path loss (PL) that is a function of the distance between transmitter and receiver (d_{Tx-Rx}) and the path loss exponent (α). In particular, the eNB assigns to a D2D transmission i the radio resources that satisfy the following conditions:

- The distance $d_{DTxi-eNB}$ between the transmitter of a D2D link i (DTx_i) and the eNB must be larger than the distance $d_{CTxj-eNB}$ between an uplink cellular transmitter (CTx_j) and the eNB. This condition guarantees that the average signal received at the eNB from DTx_i is lower than the signal received from CTx_j. This also results from the lower D2D transmission power levels.
- The distance $d_{CTxj-DRxi}$ between CTx_j and the receiver of a D2D link i (DRx_i) must be larger than the distance $d_{CTxj-eNB}$ between CTx_j and the eNB. This condition is intended to limit the interference received by DRx_i from CTx_j.

If several radio resources satisfy these conditions, the eNB selects the radio resources used by the cellular user $c*$ that is further away from DRx_i. This user should generate on average the lowest interference level at the D2D receiver. It is important to highlight that the previous conditions do not consider the aggregate interference caused by all D2D transmissions simultaneously sharing the same radio resources. This reduces the computational complexity. However, the eNB and D2D receivers do take into account the impact of the aggregate interference levels from multiple D2D transmissions sharing the same radio resources by continuously monitoring the QoS of their respective transmissions. If such QoS decreases below minimum pre-defined levels as a result of the interference generated by a D2D transmission[2], the eNB will change the resources allocated to the interfering D2D link. The following minimum QoS levels have been defined:

- The throughput experienced during the last LTE scheduling period th must be higher than a minimum threshold th_{min}. This condition applies to both cellular and D2D users.
- Primary cellular users must be protected from excessive interference generated by D2D transmissions sharing their radio resources. A second minimum QoS condition defined for primary cellular users is that th must be higher than at least 90% of the average throughput experienced during the last h LTE scheduling periods (th_{avg}).

III. Evaluation Environment

A. Simulation scenario and parameters

The performance of the proposed radio resource allocation scheme is evaluated using a discrete-event system level simulator implemented in C++ that models the LTE radio interface The simulation platform has been configured to emulate a three-sector cell with 500m radius. 3MHz are allocated to each sector for UL communications (14 Physical

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[1] If such information was not available at the network, it would be sufficient if cellular users send their location information (after being polled by the eNB) when the proposed scheme is executed.

[2] If the degradation is experienced at a D2D node, it will inform the eNB.

Radio Blocks or PRBs). The path loss is estimated using the models recommended in 3GPP TR 36.843 [8] for system simulation. In particular, the cellular path loss is estimated using the ITU UMA channel model expressed in (1). The D2D path loss is estimated using the outdoor-to-outdoor channel model under LOS conditions presented in (2). In (1) and (2), d is the distance between the eNB and the cellular user in meters, f_c is the center frequency in GHz, h_{BS}=24m, $h_{UT} = 0.5m$, and $d_{BP} = 4 \cdot h_{BS} \cdot h_{UT} \cdot f_c \cdot 10^9/c$, where c is the propagation velocity in free space (c= 3.0×10^8 m/s).

$$PL_{cel} = \begin{cases} 22\log_{10}(d) + 28 + 20\log_{10}(f_c), & \text{if } d < d_{BP} \\ 40\log_{10}(d) + 7.8 - 18\log_{10}(h_{BS}) & \text{if } d_{BP} < d \\ \quad -18\log_{10}(h_{UT}) + 2\log_{10}(f_c) & \text{and } d < 5\text{km} \end{cases} \tag{1}$$

$$PL_{D2D} = \begin{cases} 22.7\log_{10}(d) + 27 + 20\log_{10}(f_c), & \text{if } d < d_{BP} \\ 40\log_{10}(d) + 7.56 - 17.3\log_{10}(h_{BS}) & \text{if } d_{BP} < d \\ \quad -17.3\log_{10}(h_{UT}) + 2.7\log_{10}(f_c) & \text{and } d < 5\text{km} \end{cases} \tag{2}$$

The throughput (th) is estimated using the expression reported in 3GPP TR 36.942 (Annex A) [12]:

$$th = \begin{cases} 0 & \text{if } \sigma < \sigma_{min} \\ B \cdot \delta \cdot S(\sigma) & \text{if } \sigma_{min} < \sigma < \sigma_{max} \\ th_{max} & \text{if } \sigma > \sigma_{max} \end{cases} \tag{3}$$

th is expressed in bits per seconds (bps). B is the bandwidth assigned to the transmission. σ is the value of the SINR measured at the receiver. σ_{min} represents the SINR value under which the throughput is null. σ_{max} represents the SINR value at which the maximum throughput (th_{max}) is achieved. $S(\cdot)$ is the Shannon bound ($S(\sigma) = log_2(1+\sigma)$), and δ is an attenuation factor. The expression in (3) models the effect of implementing an Adaptive Modulation and Coding (AMC) scheme that provides a throughput level equal to the Shannon bound attenuated by a factor equal to δ over the range of SINR over which it operates.

Each cellular and D2D user transmits a 20Mb file with a transmission deadline ($t_{deadline}$) of 60s [13]. We consider a worst case scenario in which there are always C and C/3 active cellular users per cell and sector respectively (users are uniformly distributed across the cell). Two different D2D load levels are emulated considering an average time between sessions (*tbs*) equal to 1s (high D2D load) or 0.5s (medium D2D load). The number of simultaneous active D2D transmissions D is limited to D_{max}. D2D transmitters are also homogenously distributed across the cell, but their minimum distance to the eNB is 150m. The distance between paired D2D transmitters and receivers is a uniform random variable in the range [0, d_{d2d}^{max}] (in meters). All cellular and D2D users demand 2 PRBs[3] (Physical Resource Block); this is independent of the resource allocation scheme. D2D transmissions cannot utilize simultaneously radio resources from two different cellular users. However, the resources from one cellular transmission can be shared by several D2D transmissions. Cellular and D2D users transmit at a constant power P_{max}^{cel} and P_{max}^{d2d} respectively. All simulation parameters are reported in Table I.

TABLE I. SIMULATION PARAMETERS

Parameter	Description	Value
h	Number of LTE scheduling periods	10
th_{min}	Minimum required throughput	512 kbps
σ_{min}, σ_{max}	SINR limits in (3)	-6.5 dB, 17 dB
Th_{max}	Maximum throughput in (3)	1.7 Mbps
B	Bandwidth in (3)	360 kHz
δ	Attenuation factor in (3)	0.75
$t_{deadline}$	Transmission deadline	60s
C	Number of active cellular users	21
C_{max}	Maximum number of active cellular users	60
D_{max}	Maximum number of active D2D users	100
d_{d2d}^{max}	Maximum D2D distance	100m
P_{max}^{cel}	Transmission power for cellular nodes	20 dBm
P_{max}^{d2d}	Transmission power for D2D nodes	14 dBm
I_{max}	Maximum aggregate interference threshold	10^{-6} mW
γ_{min}	Minimum SINR threshold for D2D transmissions	2.8 dB

B. *Reference schemes*

Several reference schemes have been implemented for comparison purposes. The aim of this study is to design a radio resource allocation scheme that can achieve the highest possible system performance with low computational and signalling cost. In this context, we have selected as reference schemes a low complexity scheme (referred to as *Areas*) and an optimum scheme (referred to as *LP*) that provides an upper bound of the system performance (at the expense of overhead). *Areas* is based on [10]. It assigns orthogonal resources to D2D and cellular users in the same geographical area. To this aim, the cell is divided into three areas (Dx) that are different from the cell sectors (Sx) (Fig 1). D2D transmissions in D1 share the radio resources used by cellular users in S1, and so on. Within each area, radio resources are randomly assigned to each D2D transmission [11]. *Areas* seeks minimizing the interference between cellular and D2D transmissions with low complexity cost and signaling overhead.

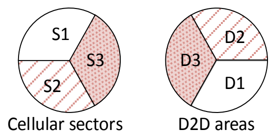


Fig.1. *Areas* reference scheme.

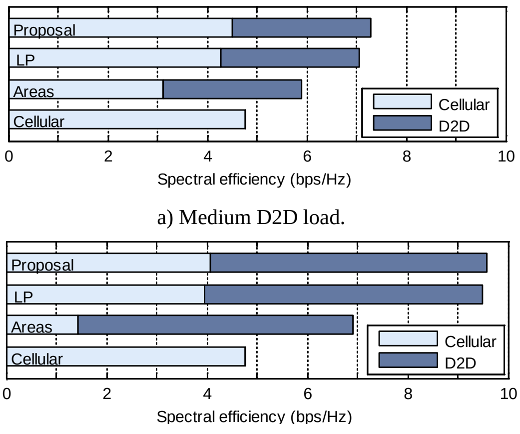
[3] 3GPP TR 36.877 suggests this maximum assignment for D2D communications. The same assignment has been considered for cellular transmissions since the objective of this study is not to evaluate the QoS of cellular users as a function of the assigned radio resources but the impact of D2D communications underlaying cellular networks.

The *LP* reference scheme was presented in [4], and is designed to maximize the spectrum utilization by allowing multiple D2D transmissions in the same PRB of a primary cellular user. *LP* includes constraints to: 1) limit the aggregate interference suffered by cellular users from D2D transmissions to a maximum threshold I_{max}, and 2) guarantee a minimum SINR (γ_{min}) to D2D transmissions. The resource allocation problem is formulated as an integer linear programming problem. *LP* has been implemented in this study to provide an upper-bound performance since there is no known polynomial-time algorithm for finding all feasible solutions [4][4].

IV. Performance Evaluation

Fig. 2 compares the average spectral efficiency achieved by the different radio resource allocation schemes under medium and high D2D load conditions. The figure includes the performance obtained when only cellular transmissions are allowed (referred to as *Cellular*). The spectral efficiency is shown for cellular and D2D users, and is expressed in terms of bps/Hz. As expected, D2D transmissions increase the total average spectral efficiency in the cell, but decrease the cellular spectral efficiency. The degradation is particularly important for the *Areas* scheme. This scheme allows D2D users to share the radio resources of a primary cellular transmission located in a different geographical region. The resources assigned to the D2D transmissions are selected randomly among the candidate resources [11]. Such random selection can result in that D2D transmissions close to the eNB are paired with cellular users at the cell edge. In this case, the D2D transmission can degrade the SINR at the eNB and hence the cellular QoS performance (Fig. 3); the degradation increases with the cell load.

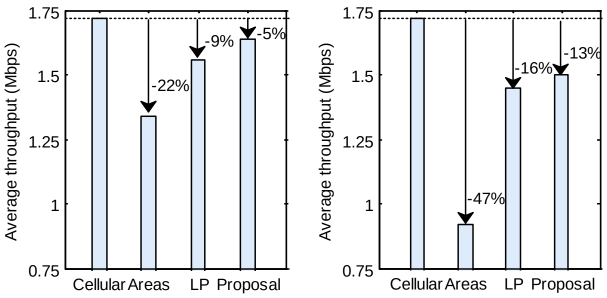
Fig. 2 shows that *LP* and the proposed scheme result in the largest increase of the total average spectral efficiency compared to *Cellular*; e.g. 99% and 101% respectively under high D2D load conditions. These schemes also result in the lowest reduction of the cellular spectral efficiency (Fig. 2) and throughput (Fig. 3) when D2D transmissions are allowed. This is due to the fact that both schemes take into account during the resource allocation process the interference between D2D and cellular transmissions. This results in that both schemes are capable to maintain high spectral efficiency and throughput levels to cellular users while increasing the spectral efficiency and throughput of D2D transmissions (Table II). Fig. 2, Fig. 3 and Table II show that the proposed scheme achieves a slightly higher performance (spectral efficiency and throughput) than *LP*. In addition, the complexity of the proposed scheme is significantly lower than *LP* which can be challenged by the time needed to find solutions in real-time [4].



a) Medium D2D load.

b) High D2D load.

Fig. 2. Average spectral efficiency.



a) Medium D2D load. b) High D2D load.

Fig. 3. Average throughput (Mbps) per cellular transmission.

TABLE II. Average Throughput (Mbps) per D2D Transmission

Allocation scheme	Medium D2D load	High D2D load
Areas	1.44	1.18
LP	1.16	1.10
Proposal	1.31	1.22

The gains obtained with *LP* and the proposed scheme result from their ability to better exploit the spatial diversity of D2D transmissions. For example, the proposed scheme takes advantage of the distance between D2D and cellular nodes to allow for various D2D transmissions (sufficiently separated) to simultaneously share the same radio resources. However, both schemes differ on how they allocate the resources. *LP* avoids pairing a high number of D2D transmissions to the same cellular transmission. For example, with *LP* only 1.3% of cellular transmissions are paired with more than 4 D2D transmissions, while this percentage increases to 10% for the proposed scheme. On the other hand, the proposed scheme reduces the percentage of cellular transmissions that simultaneously share its radio resources with more than one D2D transmission with respect to *LP*. This percentage is equal to 85% for *LP* and 53% for the proposed scheme. Decreasing this percentage reduces the average interference for both D2D and cellular transmissions, and this reduction is at the origin of the higher average throughput levels achieved with the proposed scheme (Fig. 3 and Table II). However, decreasing this percentage also resulted in that 20% of D2D transmissions had to wait for being allocated radio resources with the proposed scheme (under high D2D load conditions). On the other hand, *LP* achieved a null waiting time for all D2D transmissions. In this case, *LP* always achieved a

[4] All possible combinations of concurrently active D2D links can grow exponentially with the total number of D2D links.

solution that was capable to allocate resources for all D2D transmissions while guaranteeing the established interference restrictions. Despite the waiting time experienced by some D2D transmissions, Fig. 4 shows that the proposed scheme achieves a slightly higher capacity than *LP*. The capacity is here expressed in terms of the number of completed transmissions (cellular and D2D) before the established deadline (60 seconds). The proposed scheme compensates the waiting time with higher throughput levels (between 3.5% and 12% higher than for *LP*, see Table II), which explains why it can achieve slightly better capacity levels than *LP*.

The evaluation results have shown that the proposed scheme achieves similar (or slightly higher) performance levels to that obtained by the *LP* scheme that utilizes optimization techniques. These performance levels are obtained at a significantly lower complexity cost and signaling overhead. [4] formulates the allocation process as a mixed-integer programming NP (Non-deterministic Polynomial time)-complete problem. The computational complexity of *LP* hence grows fast with the number of active D2D transmissions since the possible combinations of D2D transmissions that can simultaneously share resources with a cellular user increases exponentially with the number of active D2D transmissions. On the other hand, the complexity of the proposed scheme is O(*C*). In addition, *LP* requires sending to the eNB the channel gain information of all possible links between cellular and D2D nodes. The signaling overhead of the proposed scheme is significantly lower as it just requires D2D receivers to notify the eNB when their QoS degrades below the pre-defined minimum threshold level. If location information is not available at the network level (e.g. if the EPC-level ProSe Discovery defined in 3GPP TS 23.303 [9] is not implemented), the proposed scheme would also require cellular and D2D nodes to notify the eNB of their location when radio resources need to be assigned to a new D2D link. However, the signaling overhead resulting from these notifications is still significantly lower compared to sending channel gain information for all possible links.

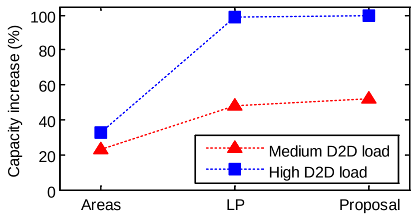


Fig. 4. Increase in capacity with respect to *Cellular* (%).

V. Conclusions

This paper has presented and evaluated a novel radio resource allocation scheme for D2D communications in underlay cellular networks. The proposed scheme has been designed for scenarios where several D2D transmissions can simultaneously share the radio resources of a primary cellular user. The scheme utilizes location information to decide at the network level the radio resources to be assigned to a new D2D link. The assignment process seeks to guarantee acceptable interference and QoS levels for the primary cellular users and other D2D transmissions. The eNB and D2D nodes continuously monitor the QoS of their transmissions to evaluate the impact of the aggregate interference. If such QoS degrades below minimum pre-defined levels, the eNB is notified to modify the radio resources of the interfering D2D link. The results demonstrate that the proposed distance-based scheme achieves performance levels similar (or slightly higher) to that obtained with an optimization-based scheme that requires the knowledge of the channel gain for all cellular and D2D links. However, the proposed scheme significantly reduces the complexity cost and signaling overhead.

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