Performance analysis of a distributed RRM scheme for D2D communications underlaying cellular networks

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***Abstract*- Device-centric wireless technologies, such as Device-to-Device (D2D) communications, will provide new ways of connectivity and significant opportunities to enhance the capacity and efficiency of 5G networks. Underlaying D2D communications will share radio resources with cellular communications and novel radio resource management schemes need to be defined to control the interference between D2D and cellular nodes. This paper proposes a distributed radio resource allocation scheme for D2D communications underlaying cellular networks. The proposed scheme allows D2D nodes to select radio resources from a pool identified by the infrastructure to limit the interference caused by D2D links to cellular communications. The proposed scheme includes a control process in order to guarantee that user QoS requirements are satisfied. The conducted study demonstrates that the proposed scheme significantly improves spectral efficiency of traditional cellular systems while guaranteeing QoS requirements to both cellular and D2D communications.**

I. INTRODUCCIÓN

Cellular networks are experiencing significant traffic growth levels that will be maintained in the years to come. The massive growth in data traffic and the requirement for future wireless networks to handle and support very large numbers of connected devices with distinct QoS (Quality of Service) requirements is driving the development of next generation of 5G cellular networks. Device-centric wireless technologies, such as Device-to-Device (D2D) communications, will be one of the key components of 5G networks [1]. D2D communications allow two devices in proximity to establish a direct communication with the support and control from the network. D2D communications can operate on cellular (inband) or unlicensed spectrum (outband) [2]. Inband D2D communications can operate in overlay or underlay mode. In the overlay mode, D2D links use a dedicated portion of the cellular spectrum [3] avoiding interference between D2D and cellular communications in the same cell. In the underlay mode, D2D and cellular communications share a portion of the cellular spectrum [4]. Underlaying D2D communications can significantly increase the spectral efficiency ([4][5]) if the radio resource management can limit and control the interference between D2D and cellular communications.

The majority of proposed radio resource allocation schemes for inband D2D communications underlaying cellular networks are centralized ones where the BS takes the final resource allocation decision. Centralized schemes seek to better control interference levels. For example, the scheme proposed in [6] exploits the characteristic of a system with Fractional Frequency Reuse (FFR) to mitigate interference between D2D and cellular transmissions. FFR divides the cell area in different regions, and determines a fixed pool of radio resources to be used by cellular users in each region. This proposal uses location information to assign to each D2D transmission the radio resources used by a cellular user located in a different area. Other proposed studies seek for optimum centralized radio resource allocations ([7],[4]). For example, [7] defines an optimization problem that seeks maximizing the sum of the data rate for all D2D and cellular links constrained to all transmissions experiencing a received SINR (Signal to Interference plus Noise Ratio) level higher than a threshold. In [7], only a D2D link can reuse resources of a cellular transmission. On the other hand, [4] considers that multiple D2D links can reuse the radio resources of a cellular transmission, and defines an optimization problem that seeks minimizing the number of radio resources assigned to D2D links to maximize the spectrum utilization. Optimization problems significantly increase the computational complexity, and authors of [7] and [4] proposed alternative sub-optimum heuristic algorithms to solve the proposed problems.

The optimization proposals reported to date generally require the BS to know the channel gain of all cellular and/or D2D links, and also between cellular and D2D nodes, to estimate the SINR of each transmission. The process to measure and send this information to the network can entail a high signaling overhead that can compromise the feasibility of the proposed schemes. In this context, distributed radio resource allocation schemes can reduce such signaling overhead [4]. For example, a distributed proposal is presented in [8] that aims to maximize the total throughput of D2D links guaranteeing a maximum interference level for protecting cellular transmissions. In [8], the BS establishes prices to limit the aggregated interference caused to cellular transmissions. Based on the prices reported by the BS, D2D nodes locally take their resource allocation decision trying to maximize their data rate. The distributed proposal in [8] reduces complexity compared to centralized schemes, but still introduces overhead due to the channel state measurement for cellular links, D2D links, and links between D2D transmitters and BS.

In this context, this study presents a novel network-assisted distributed radio resource allocation scheme for D2D communications underlaying cellular networks. In the proposed scheme, the BS (or eNB in LTE) identifies first the pool of radio resources that can be used by each D2D link based on the interference that each link will generate to the cellular transmissions. D2D nodes select from their corresponding pool the available radio resources that would experience the lower interference level at the D2D receiver. The receiver of each transmission continuously evaluates if its

QoS requirements are satisfied. Whenever the requirements are not satisfied, the BS is notified and it modifies the pool identified for the corresponding D2D link. This study demonstrate the benefits of the proposed scheme in terms of spectral efficiency and system capacity.

II. Distributed Radio Resource Allocation for Inband D2D Underlaying Cellular Networks

This study focuses on scenarios where several D2D transmissions can simultaneously utilize the same radio resources as an uplink (UL) LTE cellular transmission. The study considers that all available radio resources are being used by cellular users. Cellular users are considered to be primary users of these resources. This work proposes a novel distributed radio resource allocation scheme where the network supports the allocation process, but the final resource allocation decisions are taken at the distributed D2D nodes. The proposal is hence referred to as *ADA* (network-Assisted Distributed radio resource Allocation scheme), and operates following a three stage process.

A. Identification of the pool of resources at the network side

When a D2D transmission *i* requests radio resources, the eNB identifies the pool P_i of radio resources r_j used by cellular users j ($\forall j \in [1, C]$) that can be used by the D2D transmission. The eNB knows the number of cellular users with active UL transmissions, *C*, and the number of active D2D transmissions in the cell, *D*. The EPC-level ProSe Discovery defined in the 3GPP TS 23.303 standard requires nodes to periodically inform the network about their location. In this context, this study assumes that the eNB knows the location of the cellular and D2D users present in its cell. The eNB uses all this information to identify the pool of radio resources that could be used by a new D2D link. The pool contains the resources that would result in lower interference from the new D2D transmission to the primary UL cellular users. The average received signal level, and therefore the interference, is estimated using the path loss that is a function of the distance between transmitter and receiver ($d_{Tx\text{-}Rx}$) and the path loss exponent. The selection of the pool of radio resources that a new D2D link could utilize is then done considering a set of distance conditions. In particular, a D2D transmission *i* is allowed to share the radio resources of a cellular transmission *j* if the following conditions are met:

- The distance $d_{TxDi-eNB}$ between the transmitter of a D2D link *i* (TxD_i) and eNB must be larger than the distance $d_{TxCj-eNB}$ between the uplink cellular transmitter *j* (TxC_j) and eNB (condition 1). Due to the larger distance, but also to the lower D2D transmission power levels, this condition guarantees that the signal received at eNB from TxD_i is lower, in average, than the signal received from TxC_j.
- The distance $d_{TxCj-RxDi}$ between TxC_j and the receiver of a D2D link i (RxD_i) must be larger than the distance $d_{TxCj-eNB}$ (condition 2). This condition is intended to limit the interference received by RxD_i from TxC_j.
- The resources in P_i must also satisfy $\delta_{ji} = 1$, where δ_{ji} is a binary variable equal to one if transmission D2D *i* can utilize the radio resources used by cellular user *j*, and zero otherwise (condition 3). δ_{ji} is initially set equal to one, but its value can be modified by the control process that monitors the experienced QoS levels (Section II.C).

The eNB notifies each D2D transmission *i* of the pool P_i. eNB also informs the D2D nodes of the distances $d_{TxCj-RxDi}$ between RxD_i and TxC_j for all radio resources r_j included in P_i. It is important noting that the defined process does not consider the aggregate interference caused by all D2D transmissions sharing the same radio resources simultaneously since this could significantly increase the computational complexity. Cellular transmissions potentially experiencing high aggregated interference levels from D2D transmissions will be detected at the control process (Section II.C).

B. Local resource selection

The D2D nodes select the radio resources r_{j^*} within P_i that would result in the lower interference level at the receiver from other transmissions sharing the same radio resources. A first approach is to select the radio resources r_{j^*} used by the cellular user j^* that is farther away from RxD_i, i.e., $j^* = \arg\{\max_{j|r_j \subset P_i} d_{TxCj-RxDi}\}$. The local resource selection process does not take into account at this stage the interference caused by other D2D transmissions sharing the same radio resources. Instead, the control process that is next described continuously evaluates whether such interference can have an impact on the user QoS. Overall, this alternative approach reduces the computational complexity and signaling overhead.

C. Control process

The eNB continuously evaluates the QoS for each UL cellular transmission, and determines whether the QoS of a cellular transmission *j* decreases below some predefined threshold as a result of a new D2D transmission *i* sharing its radio resources. If this is the case, the δ_{ji} variable is set to zero and the D2D transmission *i* is not allowed to share radio resources with cellular transmission *j*. For cellular transmissions, this study establishes that the throughput th_j^t experienced during the last LTE scheduling period must be higher than a threshold th_{min}, and also higher than 90% of the average throughput experienced during the last *h* LTE scheduling periods (th_j^{avg}); all configuration parameters are listed in Table I. Similarly to the control process conducted at the eNB, the D2D receivers also analyze the impact of a new D2D transmission on their QoS. For D2D transmissions, this study establishes that the throughput experienced during the last LTE scheduling period (th_j^t) must be higher than th_{min}. Then, if an ongoing D2D transmission *k* sharing radio resources with cellular user *j* sees its QoS degrade below the established threshold as a result of a new paired D2D transmission *i*, the affected D2D nodes notify the eNB. The eNB then modifies the pool of radio resources of the D2D transmission *i* by setting the δ_{ji} variable equal to 0.

The proposed network-assisted distributed radio resource allocation scheme reduces the implementation complexity and provides a lightweight solution that only requires exchanging information between the network and D2D nodes when: eNB informs a new D2D transmission *i* of P_i, P_i is modified by the control process, and a D2D transmission notifies the eNB that its QoS performance is below the predefined threshold.

III. Reference Radio Resource Allocation Schemes

The distributed radio resource allocation scheme proposed in this study for D2D communications is here compared to relevant centralized schemes reported in the literature. The first reference centralized resource allocation scheme (referred to as *Areas*) is based on the principle proposed in [6] that establishes that D2D and cellular users in the same geographical area should use orthogonal resources. In this study, the cell is then divided into three areas (D1, D2 and D3) different from the cell sectors (see Fig. 1). Following [6], D2D transmissions in D1 share the radio resources used by cellular users in S1. Within each area, radio resources are randomly assigned to each D2D transmission. The scheme considers that only one D2D transmission per cell can share the radio resources of a cellular transmission. *Areas* is a low complexity and signaling overhead resource allocation scheme.

The second reference centralized scheme is based on linear programming optimization techniques [4] (the scheme is referred to as *LP-Opt*) and seeks to maximize the spectrum utilization. The scheme is designed to minimize the transmission length of D2D links, i.e., minimize the number of radio resources allocated to D2D transmissions, by allowing multiple D2D transmissions in the same radio resources of a cellular user. The proposed scheme establishes a maximum aggregated interference for cellular transmissions. It is important noting that as the authors express in [4], there is no known polynomial-time algorithm for finding all feasible solutions since all possible combinations of concurrently active D2D links can grow exponentially with the total number of D2D links. This scheme is implemented as a reference scheme that should provide an upper bound performance.

Performance achieved when only cellular communications are allowed are also used as reference (referred to as *Cellular*).

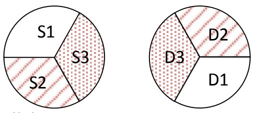


Fig. 1. Areas reference scheme: areas division and bandwidth allocation for cellular and D2D communications.

IV. Evaluation Environment

The performance of the radio resource allocation schemes are evaluated using a C++ software that models the LTE radio interface. A three-sector cell with 500m radius is considered and 3MHz are allocated to each sector for UL communications (14 Physical Radio Blocks for data). The platform estimates the path loss using the models recommended in 3GPP TR 36.843 for system simulations. In particular, the cellular path loss is computed using the ITU UMA channel model, and the D2D path loss is estimated using the outdoor-to-outdoor channel model under LOS conditions. The throughput (Th) is modeled using the expression reported in 3GPP TR 36.942:

$$Th = \begin{cases} 0 & \text{for } SINR < SINR_{min} \\ \delta \cdot S(SINR) & \text{for } SINR_{min} < SINR < SINR_{min} \\ Th_{max} & \text{for } SINR < SINR_{max} \end{cases} \quad (1)$$

Th is expressed in bits per seconds per Hertz (bps/Hz). *SINR* is the value of SINR measured at the receiver. $S(SINR)$ is the Shannon bound ($S(SINR) = log_2(1 + SINR)$), and δ is an attenuation factor. Values for $\delta, SINR_{min}, SINR_{max}$ and Th_{max} are reported in Table I.

Each cellular and D2D user transmits a 20Mb file with a transmission deadline ($t_{deadline}$) of 60s [5]. When a cellular user ends its transmission, a new one starts. This results in that there are always *C*/3 active cellular users per sector (users are uniformly distributed across the cell). The arrival rate of D2D transmissions is modeled with a uniform distribution with an average time between sessions (*tbs*) equal to 1s or 0.5s for medium or high D2D load conditions. 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. D2D receivers are apart from their corresponding D2D transmitter with distance *x*, (*x* is a uniform random variable in [0, d_{d2d}^{max}]). All cellular and D2D users demand 2 radio resources. D2D transmissions cannot utilize simultaneously radio resources from two different cellular users. Cellular and D2D users transmit with constant power, P_{max}^{cel} and P_{max}^{d2d} (Table I).

TABLE I
Configuration Parameters

Parameter	Description	Value
h	Number of LTE scheduling periods considered to calculate th_i^{avg}	10
th_{min}	Minimum required throughput	512 kbps
$SINR_{min}$, $SINR_{max}$	SINR limits in (1)	-6.5 dB, 17 dB
Th_{max}	Maximum throughput in (1)	4.8 bit/s/Hz
δ	Attenuation factor in (1)	0.75
C	Number of active cellular users	21
D_{max}	Maximum number of active D2D users	100
d_{d2d}^{max}	Maximum D2D distance	100m
P_{max}^{cel}	Maximum transmission power for cellular nodes	20 dBm
P_{max}^{d2d}	Maximum transmission power for D2D nodes	14 dBm

V. Performance Evaluation

Fig. 2 compares the average spectral efficiency achieved with the different D2D radio resource allocation schemes under medium and high D2D load conditions. The spectral efficiency is expressed in terms of the data sent per second and Hertz in the cell. Fig. 2 differentiates between the data sent by cellular and D2D users. The obtained results show that D2D transmissions increase the total average spectral efficiency in the cell. The higher increases are experienced with the *LP-Opt* and *ADA* schemes that augment the spectral efficiency by 99% and 101% respectively under high D2D load conditions compared to *Cellular*. These two schemes are also the ones that experience the lower cellular degradation when D2D transmissions are allowed into the system. It is important remembering that *LP-Opt* is a centralized scheme and *ADA* a distributed one. In addition, *LP-Opt* is challenged by the time needed to find solutions in real-time as highlighted in [4].

Areas is the resource allocation scheme that experience higher cellular degradation (Fig. 2). Although cellular and D2D transmissions sharing radio resources are located in different geographical regions with *Areas*, it randomly assigns resources to D2D transmissions within each area. Such random assignment can result in that D2D transmissions close to the eNB are paired with cellular transmissions near the cell edge, with the consequent SINR degradation at the eNB. This results in low throughput levels for cellular transmissions as

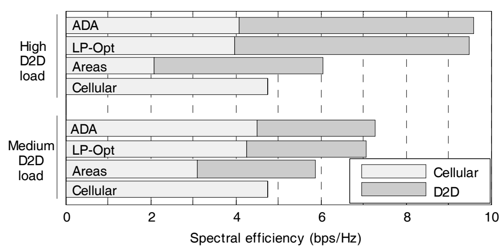
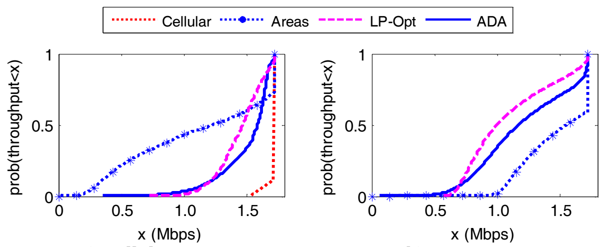


Fig. 2. Average spectral efficiency.

shown in Fig. 3. Fig. 3 depicts the cumulative distribution function (cdf) of the throughput experienced by cellular and D2D transmissions under high D2D load conditions. *LP-Opt* and *ADA* guarantee better QoS levels to cellular users than *Areas* as they take into account the interference between D2D and cellular transmissions when allocating resources. *Areas* guarantees lower interference levels to D2D transmissions as only one D2D transmission is allowed to share at a given time the radio resources with a cellular user. This explains higher D2D throughput experienced with *Areas* compared to *LP-Opt* and *ADA* (Fig. 3.b). However, *Areas* does not take advantage of the spatial diversity of D2D transmissions to increase its spectral efficiency. Fig. 4 depicts the average number of paired D2D transmissions per cellular transmission as a function of the distance between the cellular node and the eNB. Fig. 4 shows that cellular users are paired with more than one D2D transmission simultaneously with *LP-Opt* and *ADA*; in fact, more than 85% and 53% of cellular transmissions are paired with two or more D2D transmissions simultaneously under high D2D load conditions with *LP-Opt* and *ADA* respectively. As a result, *LP-Opt* and *ADA* increase the D2D spectral efficiency with respect to *Areas* by more than 40% under high D2D load conditions (Fig. 2).

LP-Opt and *ADA* are then capable to maintain high spectral efficiency and throughput conditions to cellular users while providing good QoS levels to D2D transmissions. The performance achieved with *LP-Opt* and *ADA* results from their better ability to exploit spatial diversity of D2D transmissions. Although both schemes achieve similar performance in terms of spectral efficiency, *LP-Opt* and *ADA* results in different resource allocation to D2D transmissions. As shown in Fig. 4, *LP-Opt* results in a more homogeneous number of paired D2D transmissions per cellular transmissions and independent on the distance $d_{TxC-eNB}$. On the other hand, *ADA* pairs a higher number of D2D transmissions with cellular users close to the eNB. Considering the lower power received at the eNB from cellular users further from the eNB, cellular users near the cell edge do not share radio resources with D2D transmissions when *ADA* is applied. The differences between both allocation schemes result in higher cellular and D2D throughput levels when *ADA* is applied, as shown in Fig. 3.

Finally, Table II shows the capacity increase achieved with the different D2D radio resource allocation schemes in comparison with the scenario in which D2D transmissions are



a) Cellular users   b) D2D users

Fig. 3. CDF of the throughput under high D2D load conditions.

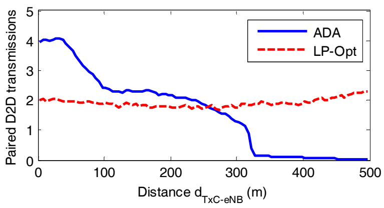


Fig. 4. Average number of paired D2D transmissions per cellular transmission as a function of $d_{TxC-eNB}$ under high D2D load conditions.

not allowed. The capacity is measured in terms of the number of completed transmissions (cellular and D2D) before the established deadline (60 seconds). Table II shows that *LP-Opt* and *ADA* increase system capacity in a 99.3 and 99.7% respectively under high D2D load conditions. However, *Areas* reduces the system capacity in a 33% mainly due to the cellular performance degradation. In addition, it is important to highlight that *ADA* achieves slightly better capacity performance than *LP-Opt* under medium and high D2D load conditions as a result of the better throughput levels experienced by cellular and D2D transmissions.

TABLE II
CAPACITY INCREASE (%)

Scheme	Medium D2D load	High D2D load
Areas	22.7	-33.1
LP-Opt	48.2	99.3
ADA	52.1	99.7

VI. CONCLUSIONS

This paper has presented and evaluated a novel distributed radio resource allocation scheme for D2D communications underlaying cellular networks. The proposed scheme distributes the resource allocation decisions to the D2D nodes, but incorporates a control mechanism so that the eNB assists the D2D nodes in their decisions in order to guarantee good cellular QoS levels and control the interference among D2D transmissions. The proposed distributed scheme achieves performance levels close to that obtained with a centralized scheme that utilizes optimization techniques and exploits the knowledge of the channel gains of all cellular and D2D links. The proposed scheme significantly reduces the complexity and signaling overhead compared to the centralized scheme.

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