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Distributed Radio Resource Allocation for Device-to-Device Communications Underlaying Cellular Networks

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***Abstract*— Underlaying Device-to-Device (D2D) communications can increase the spectral efficiency of cellular networks when sharing part of the spectrum with cellular users. This requires radio resource allocation policies capable to limit and control the interference between D2D and cellular communications. Many of the proposed policies are centralized, and require the base station to decide which resources should be allocated to each D2D transmission. Centralized schemes can efficiently control interference levels, but their feasibility can be compromised by their complexity and signaling overhead. To address this constraint, this paper proposes DiRAT, a distributed radio resource allocation scheme for D2D communications underlaying cellular networks. With DiRAT, the D2D nodes locally select their radio resources from a pool created by the cellular network in order to control the interference generated to the primary cellular users. DiRAT includes a control mechanism to ensure that the user QoS requirements are satisfied. This study demonstrates that DiRAT can increase the network capacity while avoiding or limiting the degradation of the performance of the primary cellular users. DiRAT also significantly reduces the complexity and overhead compared to existing centralized and distributed schemes.**

***Index Terms*— Device-to-Device, D2D, underlaying, radio resource management, radio resource allocation, distributed, centralized, network-assisted, cellular networks, 5G.**

1. INTRODUCTION

The design of future 5G cellular networks is driven by the massive growth in data traffic, and the requirement to handle and support very large numbers of connected devices with distinct QoS (Quality of Service) requirements. Device-to-device (D2D) communications will be one of the key technological components of 5G. D2D allows 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 (outband) spectrum. Inband D2D communications include underlay and overlay modes. The overlay mode results in that a fixed portion of the cellular spectrum is dedicated only to D2D links. This eliminates the interference between D2D and cellular communications, but also limits the spectral efficiency gains that D2D communications can provide. In the underlay mode, D2D and cellular communications[1] share a portion of the cellular spectrum. Underlaying D2D communications can significantly increase the spectral efficiency (especially under high traffic loads [1]) if the radio resource management can limit and control the interference between D2D and cellular communications.

Many of the proposed radio resource allocation schemes for inband D2D communications underlaying cellular networks consider a centralized approach where the BS (Base Station) or eNB (enhanced Node B) takes the final resource allocation decision [2]. Centralized schemes can better control interference levels, but their signaling overhead and complexity can compromise their feasibility. This was actually highlighted in [1] where the authors formulate a centralized proposal as an integer linear programming problem, and show that 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. The complexity and overhead

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[1] The terms ‘cellular communications’ or ‘cellular transmissions’ are used in this paper to refer to conventional cellular links between a mobile station and a base station.

can be reduced with distributed schemes, although the implementation of existing solutions can be still compromised by the signaling overhead or by the time required to achieve a solution to the problem. In addition, any reduction of overhead or complexity should not come at the expense of a significant reduction of the gains that can be achieved with D2D communications, or at the expense of degrading the performance of primary cellular users. In this context, this study proposes DiRAT, a novel network-assisted Distributed Radio resource AllocaTion scheme for D2D communications underlaying cellular networks. The proposed scheme has been designed with the objective to increase the network capacity without degrading the performance of the cellular users, and to significantly reduce the computational complexity and signaling overhead. To this aim, the D2D nodes locally select their radio resources from a pool of resources that has been previously created by the eNB in order to control the interference generated to the primary cellular users. DiRAT implements an additional control process at the eNB and D2D receivers that continuously evaluates if their QoS requirements are satisfied. If they are not, the eNB modifies the pool of resources that interfering D2D transmissions can utilize. This control process reduces the need for nodes to continuously exchange channel state information for their resource allocation decisions. The paper presents and evaluates two implementations of the DiRAT proposal. In the first one, the eNB and D2D nodes base their decisions on distance information. The second implementation uses locally measured received signal and interference levels. The performance achieved with DiRAT is compared against that obtained with reference centralized and distributed schemes. The obtained results demonstrate that the proposed network-assisted distributed radio resource allocation scheme is the only scheme capable to increase the network capacity without significantly degrading the performance of cellular users. In addition, DiRAT significantly reduces the complexity and overhead compared to existing centralized and distributed resource allocation schemes. The main contributions of this paper can be summarized as follows:

- The proposal of a novel network-assisted distributed radio resource allocation scheme for D2D communications in underlaying cellular networks. The scheme reduces some of the existing performance, complexity and overhead shortcomings by distributing the decisions in the network, while relying on the assistance from the infrastructure and implementing a distributed QoS control process that monitors the quality of the resource allocation decisions.
- The presentation of two different implementations of the proposed scheme that follow the same operation but differ on the metrics used for the resource allocation decisions.
- The demonstration that the proposed distributed scheme can increase the network capacity and QoS without degrading the performance of the primary cellular users. The study also demonstrates the reduced complexity and overhead of the proposed scheme.

2. RELATED WORK

The 3GPP standards (from Release 12 [3]) allow for the centralized or distributed allocation of radio resources to D2D communications. Many of the proposals reported to date for inband D2D communications underlaying cellular networks are centralized schemes. Centralized schemes are particularly suitable to control interference levels. For example, [4] defines an optimization problem to maximize 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. The authors proposed a sub-optimum greedy heuristic algorithm to solve the optimization problem given its computational complexity. Another optimization process is proposed in [2]. The process computes the optimum transmission power for each D2D link, and the radio resources are assigned to the D2D link that could achieve the highest data rate with the identified transmission power levels. The proposals in [4] and [2] consider that a single D2D link can reuse the resources of a cellular transmission. On the other hand, [1] allows multiple D2D links to reuse the radio resources of a cellular transmission, and defines an optimization problem to maximize the spectrum utilization by minimizing the number of radio resources assigned to D2D links. The authors propose a column generation method to solve the optimization problem and reduce the computational complexity.

The optimization-based centralized proposals generally require the eNB to know the channel gain of all cellular and/or D2D links, as well as the channel gain between cellular and D2D nodes. The process to measure and send all this information to the network can entail a high signaling overhead that can compromise the feasibility of the proposed schemes[2]. Distributed radio resource allocation schemes can reduce the overhead. This is for example the case of the proposal reported in [5], where the authors present a joint mode selection and resource allocation scheme. The authors propose an optimization problem to maximize the sum of the data rate of all D2D links, and a two-step approach to solve it. This approach reduces the overhead by dividing the original problem into smaller ones. The smaller problems are then directly solved by the D2D nodes. [5] considers that only one D2D link can share at any given point in time the radio resources of a cellular transmission. This constraint reduces the interference experienced by cellular and D2D users, and the complexity of the optimization problem. However, it also negatively impacts the spectral efficiency as it limits the spatial reuse of resources among D2D users. [6] proposes the use of stable matching, message passing, or auctions to design distributed schemes capable to maximize the sum of the data rate of D2D transmissions; the interference to cellular users must also be kept below a maximum threshold. The proposed schemes require D2D nodes to estimate the achievable D2D data rate and the interference channel gains between cellular

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[2] The studies do not generally indicate how to obtain the channel gain information. Obtaining such information can require additional signaling messages and overhead, in particular for non-active links.

and D2D nodes (part of this information is also reported to the eNB). The eNB is in charge of the final resource allocation decision for the schemes based on stable matching and message passing[3]. In the case of the auction-based scheme, the eNB calculates and broadcasts parameters needed for the auction subroutine carried out locally at each D2D node. [6] does not present performance or capacity results, but the authors show analytically that the different schemes provide interesting trade-offs between optimality, computational complexity, convergence, and overhead. The proposals in [6] can reduce the computational complexity and overhead compared to centralized schemes, but they still require nodes to exchange the CSI (Channel State Information) of interfering links from other D2D and cellular nodes.

Game theory has been proposed to implement distributed resource allocation ([7]-[10]) and power control ([11]-[12]) schemes for D2D communications. We focus the discussion on the radio resource allocation challenge that is the objective of this work. Game theory is particularly interesting in distributed decision problems where nodes seek to maximize their own benefit. Song et al. propose in [7] the use of Stackelberg-type games, non-cooperative games, or combinatorial auctions to model the allocation of radio resources to D2D communications. A two-stage Stackelberg game is fully developed in [8] to model the allocation of resources to D2D communications. The proposed distributed scheme is designed with the objective to maximize the total throughput of D2D links while protecting cellular transmissions from excessive aggregate interference. In the Stackelberg game, each D2D link selfishly tries to maximize its transmission rate using local information about the CSI of its D2D link, and of the link between the D2D transmitter and the eNB. During this process, the D2D links also use information about prices broadcasted by the eNB. The eNB adapts the prices in order to limit the aggregate interference caused to cellular transmissions. The results in [8] show that the proposed scheme provides a significant gain in total throughput compared to the case in which there are no D2D transmissions. In addition, the average rate of cellular links also improves compared to the case in which there is no interference management, i.e. all links are active. Sun et al. propose to jointly address the mode selection[4] and the allocation of radio resources to D2D communications using a non-cooperative game [9]. The objective of the proposed scheme is to maximize the overall spectral efficiency, and the authors propose a three stage distributed process to solve the game. At the first stage, each D2D node selects randomly its communication mode and radio resources using a vector of probabilities for each possible combination of communication mode and radio resources. A many-to-many matching process is applied for the nodes that selected the conventional cellular communication mode. The process decides with which base stations each node will communicate with using CSI values collected for all possible links. During the third stage, the D2D nodes update the vector of probabilities based on the spectral efficiency. The three-stage process is executed iteratively until a stable solution is achieved (i.e., the same solution is obtained in consecutive iterations). The conducted simulations show that the proposed scheme can improve the spectrum efficiency, and that the gains depend on the distance between D2D transmitters and base stations. Katsinis et al. also proposed the use of a non-cooperative game [10], but in this case the objective is to minimize the total interference in the cell. The solution to the non-cooperative game is also achieved by an iterative process that ends when a stable solution is reached. At each iteration, each D2D node identifies the radio resource that minimizes the sum of the interference created by its D2D link to other transmissions (cellular and D2D) sharing the same radio resource, and the interference perceived by its D2D link from other transmissions sharing the same radio resource. The D2D nodes can estimate the interference levels from cellular users using their location that is broadcasted by the eNB. Using this information and locally measured received interference levels, the D2D nodes can estimate the interference contribution from other D2D links. Once the D2D nodes select their radio resources, they also adjust their transmission power by means of a non-cooperative game-based control process in order to reduce the interference. The conducted evaluation shows that the proposed scheme reduces the power consumption and achieves higher transmission data rates compared with other schemes. The proposals based on game-theory can reduce the computational complexity and signaling overhead[5]. However, solving the games require iterative processes. The studies in [8]-[10] showed that the proposed iterative processes converge to stable solutions after a limited number of iterations in scenarios with limited variability. It is still necessary to demonstrate that the processes will converge quickly under more variable scenarios (in terms of propagation, mobility and traffic sessions). In addition, some of the proposed iterative processes (e.g. [10]) require measuring the interference levels after each iteration. Such measurements can only be available if transmissions are allowed between each iteration, which can compromise the feasibility of the proposals.

This paper contributes to the existing state of the art by proposing a novel network-assisted distributed radio resource allocation scheme that reduces some of the shortcomings of existing distributed schemes. In particular, the proposed scheme reduces the computational complexity and signaling overhead, and protects the primary cellular users while augmenting significantly the network capacity. This is achieved by: 1) distributing the resource allocation decisions among the network nodes; 2) exploiting the network infrastructure to limit the amount of information exchanged in the network and the computations at the D2D nodes; and 3)

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[3] Although the final resource allocation decision is taken at the eNB, the authors consider these two schemes as distributed ones because they distribute the computational load among the D2D nodes.

[4] The mode selection scheme decides whether a transmission should be done using a conventional cellular link or a D2D one. For conventional cellular communications, the study considers that each node can communicate with several base stations simultaneously.

[5] The decisions in [8]-[10] are based on local CSI or interference measurements.

implementing a reactive distributed QoS control process that monitors the quality of the resource allocation decisions.

3. SYSTEM MODEL

This study models a sectorized LTE cellular network, in particular, seven three-sector cells. Inter-cell interference is modelled, but the schemes are evaluated only at the center cell. Cellular and D2D users coexist in every cell and share the available spectrum (see Fig. 1). Following the 3GPP recommendations [13], D2D communications utilize uplink (UL) cellular spectrum. This reduces the interference generated by D2D transmissions to cellular links (at the eNB), and the interference generated by UL cellular transmissions to D2D links as a result of the low transmission power of cellular devices. Cellular users are considered primary users of the spectrum, and hence their performance should not be degraded by D2D transmissions. D2D users cannot simultaneously utilize radio resources assigned to two different primary cellular users. However, several D2D transmissions can simultaneously utilize the radio resources assigned to an active primary cellular user.

The users modelled in the system are either cellular or D2D users, and they cannot change their transmission mode during the complete simulation[6]. Cellular and D2D users are always assigned 2 PRBs (Physical Radio Blocks) to conduct their transmissions. This is the maximum assignment suggested by 3GPP TR 36.877 for D2D communications. We have considered the same assignment for the primary cellular users since this study focuses on the impact of inband D2D communications in underlaying cellular networks, and not on the QoS of cellular users as a function of the assigned radio resources.

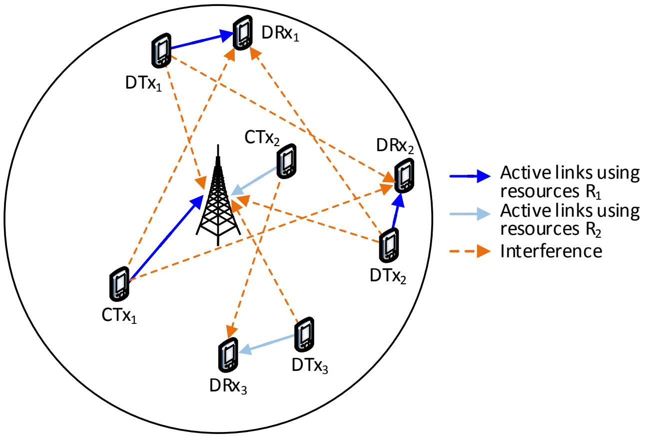

Fig. 1. Cellular network with underlaying D2D communications.

Cellular and D2D users are homogeneously distributed across the cell. However, D2D transmitters are located at a minimum distance to the eNB equal to 150m. Several studies (e.g. [14] and [15]) suggest that cellular transmissions or overlay D2D links are preferred when D2D users are close to the eNB. The distance between paired D2D transmitters and receivers is a uniform random variable in the range [0, d_{max}] (expressed in meters).

4. DIRAT

The DiRAT proposal has been designed with the objective to increase the network capacity (while limiting the QoS degradation suffered by primary cellular users) and reduce the complexity and overhead of the resource allocation process for D2D communications underlaying cellular networks. To this aim, DiRAT identifies suitable radio resources for D2D links with the assistance of the cellular infrastructure. However, the final resource allocation decisions are taken by the D2D nodes. DiRAT operates following a three stage process. When a D2D user i wants to start a new transmission ($i \in [1, D]$, and D is the number of active D2D transmissions), it will request radio resources to the eNB. The eNB will not select the resources for this D2D user, but will identify instead the pool P_i of radio resources r_j ($\forall j \in [1, C]$) that the D2D user could utilize. The variables r_j and C represent the radio resources used by cellular user j and the number of cellular users with active UL transmissions respectively. The pool P_i includes all the radio resources that have not been assigned to a primary cellular user, and the radio resources (already used by cellular users) that if utilized by the D2D user i would not degrade the QoS of the primary cellular user below a pre-defined threshold. The process to establish P_i at the eNB is referred to as *Pool Assignment*. The selection of the pool takes into account the QoS experienced by the primary cellular users, but not the QoS that D2D transmissions would experience if assigned any of the radio resources included in the pool. The QoS of D2D transmissions is taken into account during the *Local Selection* process that is executed at the D2D nodes after receiving the selected pool from the eNB. The D2D node selects from this pool the radio resources r_{j^*} that it estimates will experience the lowest interference. DiRAT also includes a distributed QoS control process (referred to as *QoS Control*) to continuously monitor the impact of local decisions. In particular, the receivers of active cellular and D2D transmissions continuously monitor their QoS. If a cellular or D2D link degrades its QoS below a minimum QoS threshold, the interfering D2D link must pause its transmission, and the eNB will modify its pool of radio resources. The eNB notifies the interfering D2D link of its new pool, and the D2D transmitter selects new radio resources from the modified pool. Fig. 2[7] illustrates the operation of DiRAT with an event-driven process chain diagram.

The three DiRAT processes are explained in detail in the following sections. Different parameters can be utilized in DiRAT in order to identify the pool of resources at the eNB and to locally select radio resources. This paper presents and evaluates two implementations of DiRAT. The D-DiRAT implementation uses as parameter the distance between nodes.

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[6] The design of mode selection schemes is out of the scope of this study.

[7] The hexagons represent events, and the rectangles represent processes. CTx and DTx refer to a cellular and D2D transmitter respectively. DRx refers to a D2D receiver.

The distance information is already available at the network level, and therefore its use reduces the overhead of the resource allocation process. In addition, studies such as [16] and [17] (centralized schemes) have shown that the use of location or distance information can significantly reduce the outage probability of inband D2D communications underlaying cellular networks. The S-DiRAT implementation uses as parameter locally measured received signal and interference levels that do not require signaling exchange between nodes.

4.1. DiRAT Pool Assignment

4.1.1. D-DiRAT

The eNB is in charge of identifying the pool of resources that each D2D transmission can utilize. To this aim, the eNB utilizes information available at the network: the number of cellular users with active UL transmissions (*C*), the position of active cellular nodes, and the position of D2D nodes. The Evolved Packet Core (EPC)-level ProSe Discovery defined in the 3GPP TS 23.303 standard [18] 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[8].

The eNB includes in the pool the radio resources that are not utilized by a primary cellular user, and the radio resources (already used by cellular users) that if utilized by the D2D user would not generate excessive interference levels to the primary cellular user. In particular, a D2D transmission *i* is allowed to share the radio resources of a cellular transmission *j* if the following conditions are met:

- Condition D.1. The distance $d_{DTxi-eNB}$ between the D2D transmitter of link *i* (DTx$_i$) and the eNB must be larger than the distance $d_{CTxj-eNB}$ between the uplink cellular transmitter (CTx$_j$) and the eNB. This condition guarantees that the interference generated by DTx$_i$ at the eNB is lower in average than the signal received from CTx$_j$. This is a result of the larger distance and the lower D2D transmission power levels.
- Condition D.2. The distance $d_{CTxj-DRxi}$ between CTx$_j$ and the D2D receiver of 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$_j$.

The eNB notifies each D2D transmission *i* of the pool P_i of resources that it can use. Together with P_i, the eNB also sends to *i* the set of distances $d_{CTxi-DRxj}$ between DRx$_i$ and CTx$_j$ for the radio resources r_j included in P_i (only for those currently used by cellular users). The distance information is used by the D2D nodes to locally select their resources from P_i.

4.1.2. S-DiRAT

S-DiRAT identifies the pool of radio resources P_i for a D2D transmission *i* using information about received signal and interference levels at the eNB. We denote as S_j the received signal level at the eNB from the UL cellular transmission *j* that uses resources r_j. The variable I_j represents the interference level experienced by r_j at the eNB[9], and N the noise power level. The variables S_j, N and I_j represent average levels experienced during the last *f* LTE frame periods. The eNB also estimates the interference $\hat{I}_{ji}$ that a new D2D transmission *i* could generate if assigned the resources r_j. This interference can be estimated using the Sounding Reference Signals (SRSs)[10] that are defined in the 3GPP standards [19]. The eNB can then compute the SINR (Signal to Interference Noise Ratio) $\hat{\sigma}_{ji}$ that the cellular transmission *j* would experience if a D2D link *i* is assigned the same radio resources r_j:

$$\hat{\sigma}_{ji} = \frac{S_j}{N + I_j + \hat{I}_{ji}} \qquad (1)$$

Using (2), the eNB can estimate the throughput $\widehat{th}_{ji}$ (in bps)

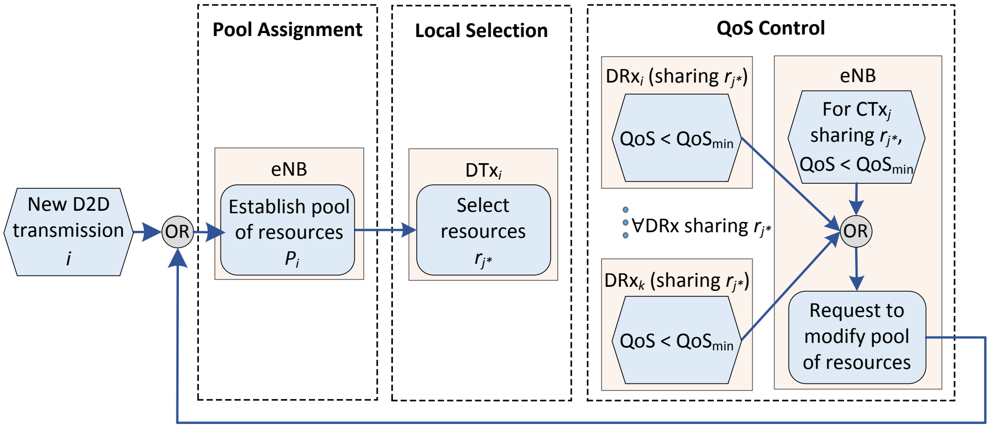

Fig. 2. DiRAT operation.

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[8] If such information was not available at the network, it would be sufficient if users send their position information (after being polled by the eNB) when DiRAT is executed.

[9] I_j includes the interference generated by D2D transmissions sharing the resources r_j, and the inter-cell interference.

[10] The SRSs are reference signals transmitted by the UE, and that are used by the eNB to estimate the uplink channel quality.

that the cellular transmission j would experience if the new D2D transmission i is assigned the resources r_j. The throughput is estimated using the expression reported in 3GPP TR 36.942 (Annex A) [15]:

$$\widehat{th}_{ji} = \begin{cases} 0 & if\ \hat{\sigma}_{ji} < \sigma_{min} \\ B \cdot \delta \cdot S(\hat{\sigma}_{ji}) & if\ \sigma_{min} < \hat{\sigma}_{ji} < \sigma_{max} \\ Th_{max} & if\ \hat{\sigma}_{ji} > \sigma_{max} \end{cases} \tag{2}$$

In (2), B is the transmission bandwidth, σ_{min} the SINR value under which the throughput is considered to be null, and σ_{max} the SINR value at which the maximum throughput (Th_{max}) is achieved. Function $S(\cdot)$ is the Shannon bound ($S(\hat{\sigma}_{ji}) = log_2(1 + \hat{\sigma}_{ji})$), and δ is an attenuation factor. The eNB also computes the average throughput th_j^f experienced by the cellular transmission j during the last f LTE frames (i.e. prior to the new D2D transmission i requesting resources). It is important to highlight that the eNB only estimates throughput values for the primary cellular users and not for the D2D transmissions. The QoS of the D2D transmissions is directly estimated at the D2D nodes. S-DiRAT includes in the pool P_i of the new D2D transmission i the radio resources that are not assigned to cellular users, and the radio resources r_j used by cellular user j if the following conditions are satisfied:

- Condition S.1. The throughput $\widehat{th}_{ji}$ that the cellular user j would experience if D2D transmission i is allowed to share its radio resources r_j is not degraded by more than a given percentage (Δ_{th}) with respect to th_j^f :

$$\frac{th_j^f - \widehat{th}_{ji}}{th_j^f} < \Delta_{th} \tag{3}$$

- Condition S.2. The throughput $\widehat{th}_{ji}$ must be higher than a predefined minimum threshold:

$$\widehat{th}_{ji} > th_{min} \tag{4}$$

The values of Δ_{th} and th_{min} must be established to increase the capacity while guaranteeing that the performance of the primary cellular users is not degraded. Conditions S.1 and S.2 guarantee that if a D2D transmission uses any of the radio resource r_j included in its pool P_i, the primary cellular user of r_j will not see its throughput degrade by more than Δ_{th} compared to th_j^f, and the throughput will always be above th_{min}.

4.2. DiRAT Local Selection

4.2.1. D-DiRAT

The D2D transmitter i selects resources from P_i that are not used by any primary cellular transmission. If all the resources in P_i are already used by a cellular transmission, then it will select the resources r_{j^*} from P_i that are used by the cellular user j^* that is farther away from DRx$_i$:

- Condition D.3. $j^* = arg\left\{\max_{j|r_j\subset P_i} d_{CTxi-DRxj}\right\}$ (5)

It is important noting that D-DiRAT does not take into account the transmission power of users, or the aggregate interference caused by all D2D transmissions simultaneously sharing the same resources, when identifying P_i or locally selecting resources. The impact of these two factors is considered within the *QoS Control* process. This approach reduces the computational complexity since nodes do not need to exchange information to estimate the aggregate interference caused by other cellular and D2D transmissions.

4.2.2. S-DiRAT

The D2D transmitter i selects resources from P_i that are not used by any primary cellular transmission. If all the resources in P_i are already used by a cellular transmission, the D2D receiver senses during N_s frames the received interference level I_{ij} in each of the resources r_j included in P_i[11]. S-DiRAT takes into account the aggregate interference levels during the process to locally select resources from P_i. As a result, I_{ij} includes contributions from the respective primary cellular user, other D2D users sharing the same resources r_j, and the inter-cell interference. The D2D transmitter i selects the radio resources r_j included in P_i that experience the lowest I_{ij}, as long as I_{ij} is smaller than a predefined maximum threshold $I_{i,max}$:

- Condition S.3. $j^* = arg\left\{\min_{j|r_j\subset P_i} I_{ij}\ \middle|\ I_{ij} < I_{i,max}\right\}$ (6)

The threshold $I_{i,max}$ is the maximum interference level that results in a throughput equal or higher than th_{min}. $I_{i,max}$ can be derived from (1) and (2). Since S-DiRAT locally selects the radio resources based on interference levels, it does take into account the impact of the transmission power of each user. It is important to emphasize the distributed nature of S-DiRAT since the resource allocation decisions are made by the D2D nodes with information they locally measure. This approach reduces the overhead compared to centralized schemes that require measuring and sending to the eNB the channel gain of all links.

4.3. DiRAT QoS Control

The same *QoS Control* process is implemented for D-DiRAT and S-DiRAT. The eNB continuously monitors the QoS of each UL cellular transmission j. The QoS is here expressed in terms of throughput. If the average throughput experienced by the cellular user j during the last s LTE frames (th_j^s) decreases below a minimum acceptable threshold (th_{min}) as a result of a D2D transmission i sharing its radio resources, i is not allowed to use these resources anymore, and the eNB creates a new pool P_i for the D2D transmission i. This condition is expressed in the following equation:

$$th_j^s < th_{min} \tag{7}$$

The eNB will also create a new pool P_i for the D2D transmission i if the throughput th_j^s is degraded more than Δ_{th} percent with respect to the throughput th_j^f experienced during

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[11] [20] also proposed to use carrier sensing mechanisms to select cellular or D2D transmission modes. Detection techniques such as those used in cognitive radio systems [21] can be used to sense the interference signals on each radio resource.

the last f LTE frames (where $f = k \cdot s$ and $k > 1$, i.e., th_j^f is calculated over a longer time period than th_j^s) as a result of the D2D transmission i sharing the resources of the cellular user j. This condition is expressed in the following equation:

$$\frac{th_j^f - th_j^s}{th_j^f} > \Delta_{th} \tag{8}$$

The D2D receivers also continuously monitor their QoS. D2D transmissions are not primary users of the radio resources, and therefore the *QoS Control* process only requests changing the pool of a D2D transmission if the average throughput experienced by a D2D transmission i during the last s LTE frame periods (th_i^s) is smaller than th_{min}:

$$th_i^s < th_{min} \tag{9}$$

In (9), th_i^s is the average throughput experienced by the D2D transmission i during the last s LTE frame periods. This condition prevents D2D transmissions experiencing poor QoS levels to interfere other cellular or D2D users. An active D2D transmission will notify the eNB if its QoS degrades below th_{min}. If the degradation is due to a new D2D transmission, the *QoS Control* process requests the eNB to modify the pool of resources of the new D2D transmission. If the degradation is not due to a new D2D transmission, the eNB modifies the pool of the D2D link that experiences the QoS degradation. The new pool will not contain the previously used radio resources. The operation of the *QoS Control* process is explained in Algorithm I.

The eNB and the D2D nodes use the *QoS Control* process to dynamically adapt their resource allocation decisions in order to guarantee the QoS requirements of the primary cellular users. D2D transmissions are provided with the highest possible QoS. Overall, DiRAT results in a low complexity and low overhead solution that only requires exchanging information between the network and the D2D nodes when: 1) the eNB informs a new D2D transmission i of its pool P_i, 2) a D2D node notifies the eNB that its QoS performance is below the predefined minimum threshold, and 3) P_i is modified by the *QoS Control* process.

Algorithm I: DiRAT QoS Control Process

```
For each active cellular transmission $j$, $1 \le j \le C$ do
  If minimum cellular QoS condition not satisfied for $j$ then
    Identify the last D2D transmission paired with $j$: D2D transmission $i*$
    Modify the pool of resources for D2D transmission $i*$ by excluding the resources used by $j$
  End If
End For
For each active D2D transmission $i$, $1 \le i \le D$ do
  If minimum D2D QoS condition not satisfied for $i$ then
    Identify the cellular transmission paired with D2D transmission $i$: cellular transmission $j$
    Identify the last D2D transmission paired with cellular transmission $j$: D2D transmission $i*$
    Modify the pool of resources for D2D transmission $i*$ by excluding the resources used by $j$
  End If
End For
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5. REFERENCE SCHEMES

The performance of DiRAT is compared in this study against that obtained with reference centralized and distributed schemes. The selected centralized scheme was proposed in [1] and is referred to as CentLP. The scheme searches for the optimum resource allocation solution that maximizes 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 and hence maximize the spectrum utilization. This is achieved by allowing multiple D2D transmissions in the same PRB (Physical Radio Block) of a cellular user. The scheme is executed at the network, and it assumes that the eNB has always complete and exact knowledge of the channel gain for all (cellular and D2D) active links, and for all interfering links between cellular and D2D users as well as between D2D users sharing the same radio resources. This information is used by the network to calculate the exact interference level and throughput that each cellular and D2D user will experience. The scheme includes constraints to limit the aggregate interference suffered by primary cellular users from D2D transmissions to a maximum threshold I_{max}^c, and to guarantee a minimum SINR (γ_{min}) to D2D transmissions. The resource allocation problem is expressed in [1] as an optimum integer linear programming problem. The formulated problem is NP (Non-deterministic Polynomial time)-complete [1], and 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. CentLP represents the optimal case in terms of maximizing the spectrum utilization and the system capacity when introducing inband underlaying D2D communications in cellular networks. It is then implemented in this study as the reference scheme that provides the upper bound capacity performance.

The selected reference distributed resource allocation scheme was proposed in [6], and is referred to in this paper as DiSM. This scheme has been selected given its good trade-off between optimality, computational complexity, convergence, and overhead compared to other proposals. DiSM is based on a stable matching process that matches distinct agents following their preferences. The matching process is iterative until a stable solution is found. In DiSM, the D2D transmissions and the radio resources are the agents that need to be matched. D2D transmitters estimate the channel gain of the links with other cellular or D2D nodes, and send this information to the eNB. The eNB estimates and sends to the D2D nodes the interference level experienced by each cellular transmission j over its assigned radio resources r_j. Using this information, the D2D transmitters and the radio resources establish their matching preferences through an ordered list of radio resources and D2D transmitters respectively. The D2D transmitters identify their preferred radio resources as those that would provide the highest data rates. The radio resources identify their preferred D2D transmitters based on the interference they generate to the primary cellular transmissions. The eNB uses the identified preferences to match D2D transmitters and radio resources. The matching process has the constraint that the aggregate interference level to cellular transmissions cannot exceed a threshold I_{max}^{c}. After finding a matching solution, the eNB computes the aggregate interference level experienced by each cellular transmission, and sends this information to the D2D nodes. The D2D transmitters and the radio resources update their preferences that are sent back to the eNB for a new iteration of the matching process. The process ends when the same solution is obtained in two consecutive iterations.

6. EVALUATION ENVIRONMENT

The performance of the radio resource allocation schemes is evaluated using a C++ simulator that models the LTE radio interface. The simulator implements a scenario with seven three-sector cells, and the performance of the different schemes is evaluated at the center cell. Each cell has a radius of 500m. All cells share the same spectrum, and each sector is allocated 1.4 MHz of spectrum (6 PRBs of 180kHz each for data transmissions) for UL communications.

The simulator models the path-loss, shadowing and multi-path fading. The path-loss and shadowing are estimated using the models recommended in 3GPP TR 36.843 [13] for system level simulations. In particular, the simulator implements the ITU UMA channel model to estimate the cellular path-loss, and the outdoor-to-outdoor channel model under LOS conditions to estimate the D2D path-loss. The shadowing is modelled as a log-normal distribution with standard deviation equal to 4 and 7 for cellular and D2D communications respectively. The multi-path fading is modelled using a Rayleigh fading channel with the Rayleigh coefficient set equal to one.

The LTE open loop power control scheme (defined in 3GPP TR 36.213 [19]) is implemented for both cellular and D2D communications [22]. The transmission power P is hence computed as:

$$P = \min\{P_{max}, P_0 + 10 \cdot \log_{10} M + \beta \cdot PL\} \quad (10)$$

where P_{max} represents the maximum transmission power (P_{cell} and P_{d2d} for cellular and D2D nodes respectively), P_0 is a UE (User Equipment)-specific parameter, M is the number of assigned PRBs, and β is a path-loss compensation factor. For cellular transmissions, PL is the downlink path-loss measured at the cellular node. In the case of a D2D link, PL represents the path-loss measured at the D2D transmitter.

Active cellular and D2D users are requested to transmit a 20Mb file with a transmission deadline ($t_{deadline}$) of 60s [23]. To do so, all cellular and D2D users demand 2 PRBs (i.e. M in (10) is set equal to 2) independently of the resource allocation scheme under evaluation. Simulations have been conducted for two different cellular loads that represent an average occupancy of radio resources by primary cellular users equal to 75% (L_1) and 87% (L_2). The average time between sessions for D2D users is equal to 3s. Δ_{th} has been set equal to 10% following a previous simulation analysis that showed that this value provides a good compromise between augmenting the total capacity and guaranteeing the performance of the primary cellular users. Table I reports the main simulation parameters.

TABLE I
SIMULATION PARAMETERS

Parameter	Description	Value
f, s	Number of LTE frame periods considered to estimate average signal and throughput values	10, 100
th_{min}	Minimum required throughput	512 kbps
Δ_{th}	Maximum tolerable throughput degradation in (3) and (8)	10%
N_s	Number of frames during which D2D receivers sense the received interference level	5
$\sigma_{min}, \sigma_{max}$	SINR limits in (2)	-6.5dB, 17dB
Th_{max}	Maximum throughput in (2)	1.7Mbps
B	Bandwidth in (2)	360kHz
δ	Attenuation factor in (2)	0.75
I_{max}^{c}	Maximum tolerable interference to cellular transmissions in *DiSM* and *CentLP*	10^{-6} mW
γ_{min}	Minimum SINR threshold for D2D transmissions in *CentLP*	2.8dB
$t_{deadline}$	Transmission deadline	60s
d_{max}	Maximum D2D distance	100m
P_{cell}, P_{d2d}	Maximum transmission power for cellular and D2D nodes	20dBm, 14dBm
P_0	UE-specific parameter in (10)	-78dBm
β	Path-loss compensation factor in (10)	0.8
M	Number of assigned PRBs in (10)	2

7. PERFORMANCE EVALUATION

This section compares the performance achieved with the DiRAT proposal to that obtained with the reference schemes. The performance is also compared to that obtained when only cellular transmissions are allowed (referred to as NoD2D). We define the cell capacity as the number of transmissions (cellular, or cellular and D2D) that are completed before the established deadline. Fig. 3 represents the ratio between the cell capacity of each resource allocation scheme and the cell capacity with NoD2D. The results differentiate the performance obtained for cellular and D2D transmissions. The obtained results clearly show that accepting D2D transmissions significantly increases the total cell capacity independently of the resource allocation scheme. However, there are significant differences between the schemes under evaluation. DiSM results in the lowest increase in total cell capacity with respect to NoD2D (89% compared to 101% for CentLP under L_1). DiSM also results in the largest degradation of the cellular capacity with respect to the scenario in which D2D transmissions are not allowed. For example, DiSM reduces by 31% the number of completed cellular transmissions with respect to NoD2D under L_1. CentLP achieves the largest increase in total cell capacity (101% under L_1 and 82% under L_2). However, this is achieved at the expense of decreasing the performance of the primary cellular users. In particular, CentLP reduces by 11% (L_1) and 25% (L_2)

the number of completed cellular transmissions with respect to NoD2D. S-DiRAT is the only scheme capable to augment the total cell capacity without degrading the performance of the primary cellular users. This is achieved at the cost of a slightly lower total cell capacity increase than CentLP. For example, CentLP can serve in total 12% and 12.1% more transmissions (D2D and cellular) under L_2 than D-DiRAT and S-DiRAT respectively. However, it decreases by 21% and 25% the number of served cellular users with respect to D-DiRAT and S-DiRAT under L_2. It is also important to remember that CentLP is a centralized scheme while DiRAT is a distributed one. In addition, CentLP can be challenged by the time needed to find solutions in real-time as highlighted in [1]. The results depicted in Fig. 3 are a consequence of the impact of the different allocation policies on the QoS of cellular and D2D transmissions. Such impact is explained next.

Fig. 4.a shows that S-DiRAT is the scheme that better protects the QoS of the primary cellular users when D2D transmissions are allowed to share their radio resources. In fact, the figure shows that the cellular transmissions experience with S-DiRAT nearly the same average throughput as when no D2D transmissions are allowed (NoD2D). This result is shown to be independent of the cellular load. On the other hand, Fig. 4.a shows that DiSM and CentLP reduce the average throughput of cellular transmissions by 23% and 12% with respect to NoD2D for L_1. All the resource allocation schemes under evaluation take into account the interference generated by D2D transmissions to the primary cellular users, but clearly with different outcomes. Fig. 4.a clearly shows that the control process introduced in DiRAT is more capable to protect the performance of the primary cellular users than the mechanisms included in DiSM and CentLP for this objective. DiSM and CentLP limit the maximum aggregate interference level that cellular transmissions can tolerate[12], but differ in how they allocate radio resources. DiSM seeks to maximize the throughput of D2D transmissions, while CentLP seeks to minimize the number of radio resources assigned to D2D transmissions and guarantee them a minimum SINR. This results in that DiSM pairs a higher number of D2D transmissions per primary cellular transmission than CentLP (Fig. 5). This approach increases the interference, and decreases the throughput of the primary cellular users with DiSM (Fig. 4.a). Reducing the cellular throughput results in that users need to utilize their radio resources for a longer time in order to transmit their file. As a consequence, DiSM augments the time cellular users need to wait in order to be assigned radio resources (Fig. 6.a), which explains the larger cellular capacity degradation experienced with DiSM (Fig. 3).

CentLP assigns radio resources with the constraint of guaranteeing a minimum SINR to D2D transmissions. This augments the average waiting time of D2D users with respect to DiSM (Fig. 6.b), but reduces the number of D2D

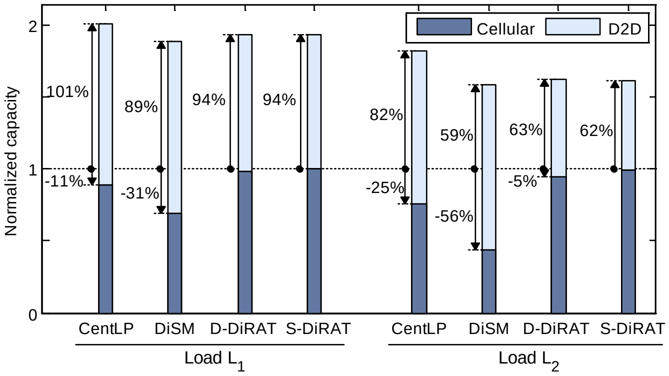
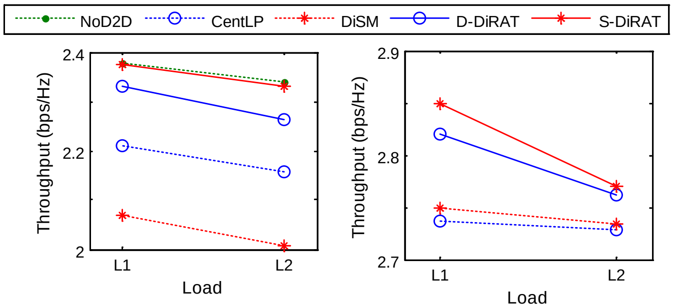


Fig. 5. Normalized cell capacity with respect to NoD2D.



a) Cellular throughput
b) D2D throughput

Fig. 6. Average throughput (bps/Hz).

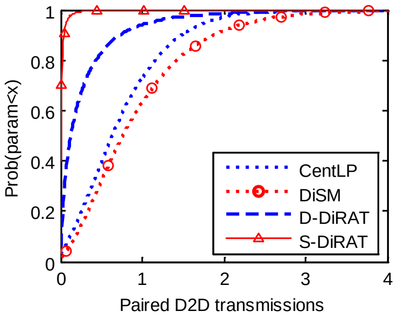
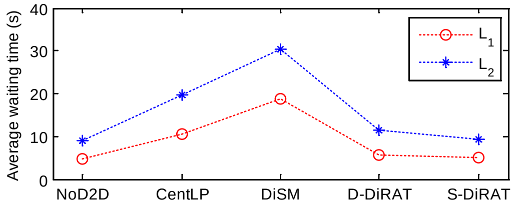
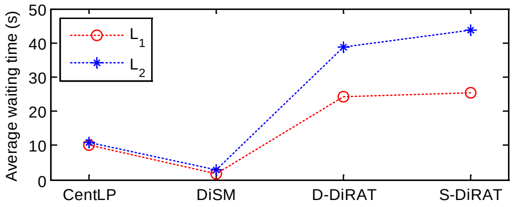


Fig. 3. Cumulative distribution function of the average number of paired D2D transmissions per primary cellular user (load L_2).



a) Cellular users.



b) D2D users.

Fig. 4. Average waiting time to access radio resources.

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[12] Fig. 4.a shows that this does not necessarily guarantee high throughput levels.

transmissions paired with primary cellular users (Fig. 5). As a result, CentLP increases the cellular performance (capacity and throughput in Fig. 3 and Fig. 4.a) with respect to DiSM. However, the interference from D2D transmissions reduces the average CentLP cellular throughput (Fig. 4.a) and augments the average waiting time of cellular users (Fig. 6.a) with respect to NoD2D. These two factors explain why CentLP cannot maintain the cellular capacity achieved when D2D transmissions were not allowed (Fig. 3).

Fig. 3, Fig. 4.a and Fig. 6.a demonstrate that S-DiRAT can increase the system capacity without degrading the cellular performance; i.e. cellular users experience the same QoS when executing S-DiRAT and when no D2D transmissions are allowed (NoD2D). S-DiRAT is designed to protect the primary cellular users. As a result, S-DiRAT tends to assign to D2D transmissions the radio resources that are not being utilized by cellular users. In fact, Fig. 5 shows that nearly no D2D transmissions are paired with primary cellular links when executing S-DiRAT in the scenarios under evaluation[13], which explains its larger D2D average waiting time (Fig. 6.b). However, S-DiRAT augments the capacity by allowing multiple D2D transmissions to share the same radio resources. Fig. 7 shows that 37% of D2D transmissions are paired on average with seven or more transmissions when executing S-DiRAT in the scenarios under evaluation. This percentage decreases to 8%, 3% and 12% when executing CentLP, DiSM and D-DiRAT respectively (Fig. 7). Despite sharing the resources among more D2D transmissions, S-DiRAT results in higher D2D throughput levels than CentLP and DiSM (Fig. 4.b) due to its *Local Selection* process. CentLP augments though the D2D capacity (Fig. 3) thanks to its lower D2D waiting time (Fig. 6.b). In a sense, the obtained results show that S-DiRAT can adapt its operation based on the experienced interference levels in order to exploit the advantages offered by overlay and underlay communications. Under high interference levels, S-DiRAT can operate like an overlay resource allocation scheme to protect the performance of the primary cellular transmissions. However, when the interference decreases, S-DiRAT can pair D2D transmissions with cellular ones in order to exploit the advantages offered by underlay schemes (higher capacity and spectral efficiency).

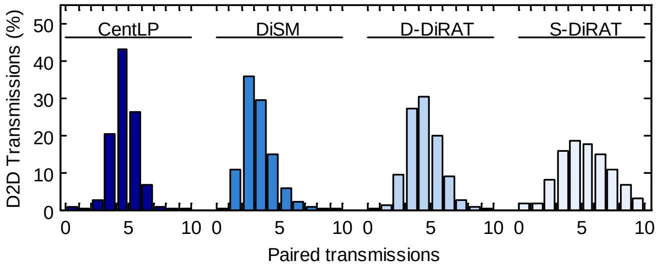

Fig. 7. Discrete probability density function of the average number of D2D transmissions sharing radio resources under L_2.

The depicted results show that S-DiRAT and D-DiRAT achieve similar results. D-DiRAT slightly decreases the cellular throughput and capacity, and the D2D throughput (Fig. 3 and Fig. 4.a). However, the latter is compensated by a lower D2D average waiting time to finally achieve D2D capacity levels similar to S-DiRAT. D-DiRAT and S-DiRAT have been designed with the same objective (increase the capacity while protecting the performance of the primary cellular users), but utilize different information to implement the *Pool Assignment* and *Local Selection* processes. D-DiRAT utilizes distance information, and S-DiRAT local received signal and interference levels. The use of distance information reduces the computational complexity, but also the capacity to precisely guarantee the QoS of cellular and D2D transmissions. To overcome this limitation, D-DiRAT relies on the *QoS Control* process to modify resource allocation decisions that do not adequately guarantee the cellular and D2D QoS requirements. Table II represents the average number of pool assignments required per D2D transmission (denoted as p). This number includes the initial pool assignment as well as the pool changes that might be requested by DiRAT's *QoS Control* process. Table II shows that the use of distance information results in that D-DiRAT requires more frequent changes of the pool P_i than S-DiRAT in order to achieve similar performance levels. This entails a larger signaling exchange and overhead.

TABLE II
AVERAGE NUMBER OF POOL ASSIGNMENTS PER D2D TRANSMISSION

Allocation scheme	L1	L2
D-DiRAT	5.7	6.1
S-DiRAT	3.9	3.9

8. SIGNALING OVERHEAD AND COMPLEXITY

The previous results have demonstrated that S-DiRAT is the only scheme capable to increase the capacity while preserving the performance of the primary cellular users. CentLP augments the total capacity, but at the expense of the primary cellular users. CentLP is an optimization-based centralized scheme. It is then also relevant to compare the complexity and overhead of the evaluated resource allocation schemes.

The authors state in [1] that CentLP formulates the radio resource allocation dilemma as a mixed-integer programming NP-complete problem. This implies that there is no known polynomial-time algorithm for finding all feasible solutions. The computational complexity of CentLP grows fast with the number of active D2D transmissions since the possible combinations of D2D transmissions that can simultaneously share radio resources with a cellular user (and hence the order of the computational complexity) increases exponentially with the number of active D2D transmissions. CentLP also requires channel gain information to be measured and sent to the eNB. This information is used to calculate the SINR experienced by D2D transmissions, and the interference caused by D2D transmissions to cellular users. This information needs to be constantly transmitted to the eNB, which results in a very high signaling overhead. In particular, each D2D receiver has to

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[13] Additional simulations were conducted for scenarios with lower interference levels. In this case, S-DiRAT allowed pairing some D2D transmissions with primary cellular links as long as the cellular and D2D QoS conditions were satisfied, and in particular as long as the QoS of the primary cellular users was not degraded.

send a message to the eNB that includes the channel gain of the links between the D2D receiver and the C active cellular transmitters. A total of D messages are then sent to the eNB, one for each active D2D transmission. Each message also includes the channel gain of the links between the D2D receiver and the D active D2D transmitters. The 3GPP 36.133 standard [24] considers that the received interference power and reference signal received power (RSRP) can be reported using 7 and 9 bits respectively. We then consider that the channel gains and interference data can be reported using a single byte. The amount of information exchanged between the D2D nodes and the eNB (or overhead) is then equal to $D \cdot (C+D)$ bytes for CentLP.

DiSM distributes the computational load between the nodes. The process executed at the D2D transmitters has a complexity of $\mathrm{O}(nC \cdot \log(C))$[14], while the process executed at the eNB has a complexity of $\mathrm{O}(nCD)$ [6]. DiSM has a complexity significantly smaller than CentLP. To estimate its overhead, we have to take into account that DiSM needs to iteratively exchange information between the D2D nodes and the eNB in order to allocate the radio resources. In particular, a total of D messages are sent to the eNB (one per D2D receiver). Each message includes the channel gain of the links between the D2D receiver and the C active cellular transmitters, and the channel gain of the links between the D2D receiver and the D active D2D transmitters. At each iteration of the resource allocation process, the eNB broadcasts to the D2D nodes the aggregate interference experienced on each resource. To this aim, a single message is transmitted, and the message contains the aggregate interference experienced by each one of the C active cellular transmissions. At each iteration, the D2D nodes also send their preference profiles to the eNB. This results in a total of D messages that include an ordered list of the radio resources used by the C active cellular transmissions. We consider that 1 byte is sufficient to identify the radio resources in the preference profiles[15]. DiSM requires then the exchange of $D \cdot (C+D) + n \cdot C + n \cdot C \cdot D$ bytes (overhead) between the D2D nodes and the eNB.

S-DiRAT and D-DiRAT have a lower complexity ($\mathrm{O}(C)$) than DiSM, and also reduce the signaling overhead. D-DiRAT only requires the eNB to know the location of active cellular nodes, and the location of the transmitter and receiver of the D2D link for which radio resources need to be assigned. This requires a total of $C+2$ messages with location information. The location information can be coded using 6 bytes (3GPP TS 36.355 [25]). It is important to highlight that this location information is already available at the eNB when implementing Proximity Services (ProSe), and hence the transmission of these $C+2$ messages would not be necessary. The eNB also needs to inform D2D users about their pool of resources and about the distance between the D2D receiver and the cellular transmitters that use the resources in the pool. In the worst case scenario, the pool will contain the radio resources utilized by all active cellular transmissions. In this case, the length of the message sent by the eNB will be equal to $C \cdot (1+2)$ bytes. One byte is used to identify each resource, and two bytes are used to identify the distance between each cellular transmitter and the D2D receiver[16]. This information is sent before a D2D transmission starts, or when resources need to be reassigned because the cellular or D2D QoS requirements are not satisfied. The number of times that this information is exchanged during a D2D transmission is equal to the variable p previously defined as the average number of pool assignments required per D2D transmission. The overhead of D-DiRAT is then equal to $[(C+2) \cdot 6 + C \cdot 3] \cdot p$ bytes. The overhead of D-DiRAT is reduced to $(C \cdot 3) \cdot p$ bytes when location information is already available at the eNB. S-DiRAT requires the eNB to identify the pool of radio resources using information that is locally sensed at the eNB. The eNB then notifies D2D users of their pool. In the worst case scenario, the pool will contain the radio resources utilized by all active cellular transmissions. In this case, the length of the message sent by the eNB is equal to $C \cdot 1$ bytes. This message is also sent when resources need to be reassigned because cellular or D2D QoS requirements are not satisfied. The overhead of S-DiRAT is then equal to $C \cdot p$ bytes. Table III summarizes the computational complexity and signaling overhead of all the schemes.

TABLE III
COMPLEXITY AND SIGNALING OVERHEAD

Allocation scheme	Computational complexity	Signaling overhead (bytes)
CentLP	NP-complete	$D \cdot (C+D)$
DiSM	$\mathrm{O}(nC \cdot log(C))$ at the D2D transmitters, $\mathrm{O}(nCD)$ at the eNB	$D \cdot (C+D) +$ $n \cdot C + n \cdot C \cdot D$
D-DiRAT	$\mathrm{O}(C)$	$[(C+2) \cdot 6 + C \cdot 3] \cdot p$
S-DiRAT	$\mathrm{O}(C)$	$C \cdot p$

To compare the overhead of the different schemes, let's consider the best case scenario for DiSM (it finishes the resource allocation after just 2 iterations, i.e. $n=2$) and the worst one for D-DiRAT and S-DiRAT. In the worst case scenario for D-DiRAT, ProSe is not implemented, and the location information is not available at the eNB by default. Let's consider that there are 9 active cellular transmissions, and 30 active D2D transmissions. In this scenario, p is equal to 5.6 and 3.6 for D-DiRAT and S-DiRAT respectively. D-DiRAT reduces the overhead by 64.5% with respect to DiSM, and by 47.5% with respect to CentLP. The reduction would be equal to 89.7% (with respect to DiSM) and 84.8% (with respect to CentLP) if ProSe was implemented and the location data was available at the eNB by default. S-DiRAT reduces even more the overhead with respect to DiSM (97.6%) and to CentLP (96.5%). We should also note that the overhead of CentLP and DiSM has been estimated without taking into account the messages that would have to be transmitted to

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[14] n is the number of iterations executed to achieve a stable solution.

[15] One byte is sufficient to identify all PRBs even when considering a 20MHz band that contains 100 PRBs.

[16] 2 bytes can code distances up to 65km with a 1m granularity.

estimate the channel gain between two nodes that do not have an active transmission. Such overhead would not be negligible, so D-DiRAT and S-DiRAT would reduce even more the overhead.

9. CONCLUSIONS

This paper has presented and evaluated DiRAT, a novel network-assisted distributed radio resource allocation scheme for D2D communications underlaying cellular networks. The proposed scheme has been designed with the objective to increase the network capacity and limit any possible degradation of the performance of the cellular users. To do so, the D2D nodes locally select their radio resources from a pool of resources that has been previously created by the cellular network in order to control the interference generated to the primary cellular users. The proposed scheme includes a low complexity and low overhead control mechanism that continuously evaluates whether the cellular and D2D QoS requirements are satisfied. If they are not, the control process triggers the modification of the pool of resources that interfering D2D transmissions can utilize. This study has evaluated two implementations of the proposed distributed scheme. In the first one, the eNB and D2D nodes base their decisions on distance information. The second implementation uses locally measured received signal and interference levels.

This study has demonstrated that the proposed S-DiRAT scheme can significantly improve the total capacity without degrading the throughput and capacity of cellular users. Higher total capacity gains could be achieved using an optimization-based centralized scheme, but these gains are obtained at the expense of reducing the performance of the cellular users and significantly increasing the complexity and overhead. Such complexity and overhead are significantly reduced by the proposed distributed scheme. The low complexity and overhead of DiRAT result from the distribution of the decision process between the eNB (implements the *Pool Assignment* process) and the D2D nodes (implement the *Local Selection* process), and the introduction of a distributed *QoS Control* process that monitors the impact of any resource allocation decision. This *QoS Control* process reduces the need to estimate the interference that other users would experience as a result of a resource allocation decision. The highest overhead reductions are achieved when DiRAT bases its resource allocation decisions on locally measured received signal and interference levels (S-DiRAT implementation).

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