Reuse of Multiple Channels by Multiple D2D Pairs in Dedicated Mode: A Game Theoretic Approach

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***Abstract*— Device-to-device communication (D2D) is expected to accommodate high data rates and to increase the spectral efficiency of mobile networks. The D2D pairs can opportunistically exploit channels that are not allocated to conventional users in a dedicated mode. To increase the sum capacity of D2D pairs in the dedicated mode, we propose a novel solution that allows the reuse of multiple channels by multiple D2D pairs. In the first step, the bandwidth is split among D2D pairs so that each pair communicates at a single channel that guarantees a minimal capacity for each pair. Then, the channel reuse is facilitated via a grouping of the D2D pairs into coalitions. The D2D pairs within one coalition mutually reuse the channels of each other. We propose two approaches for the creation of the coalitions. The first approach reaches an upper-bound capacity by optimal coalitions determined by the dynamic programming. However, such approach is of a high complexity. Thus, we also introduce a low-complexity algorithm, based on the sequential bargaining, reaching a close-to-optimal capacity. Moreover, we also determine the transmission power allocated to each reused channel. Simulations show that the proposed solution triples the sum capacity of the state-of-the-art algorithm with the highest performance.**

***Index Terms*— Device-to-device, dedicated mode, game theory, resource allocation, channel reuse.**

I. Introduction

HIGH data rates and low latencies are required to enable new services and to increase the number of connected devices in the future mobile networks. To accommodate these demands, a direct communication between two user equipments (UEs) in proximity of each other, known as Device-to-Device (D2D) communication, is considered as a promising technology [1]–[3]. Two D2D UEs (DUEs), a transmitter (DUE_T) and a receiver (DUE_R), create a single D2D pair, within which the data is transmitted directly, i.e., without being relayed through a base station (in this paper, denoted as gNB in line with 3GPP terminology for 5G mobile networks) [4].

The D2D communication enables two possible modes: 1) a *shared mode* in which the D2D pairs reuse the resources allocated to common cellular UEs (CUEs) communicating via the gNB and 2) a *dedicated mode* in which the D2D pairs use dedicated resources that are not assigned to the CUEs [5], [6]. Although, the shared mode offers a higher spectral efficiency than the dedicated one, the higher efficiency is usually at the cost of highly complex solutions for the resource allocation and management. Moreover, the shared mode leads to a mutual interference among the CUEs and the DUEs. This interference can be too high and can vary frequently and significantly, especially in the case with a dense presence of the UEs. Consequently, the reliability of the communication cannot be easily guaranteed and overall quality of services (QoS) can be impaired due to the interference in the shared mode [7]. Thus, the DUEs with strict requirements on QoS should prefer the dedicated mode, which is suitable for the services that require highly reliable communication with a minimum risk of an unexpected interference from the CUEs. Concrete and up-and-coming examples of the use cases for the dedicated mode are the direct communication of vehicles or public safety communication. Then, an ultra-reliable communication with a guaranteed minimum communication capacity should be ensured. In the shared mode, however, interference might lead to the situations when such guarantee is simply not possible and the unreliability in the communication can have grievous consequences. Hence, the dedicated resources are commonly considered for the vehicular or public safety communications. Thus, in this paper, we focus on the dedicated mode for D2D communication.

One of the key challenges in the dedicated mode is the allocation of the available bandwidth to the D2D pairs. The authors in [8] and [9] present channel allocation schemes dividing a dedicated bandwidth to channels with different bandwidths so each D2D pair gets exactly one channel. In both [8] and [9], the optimal allocation is achieved for the case when the interference from other neighboring cells is nonexistent. However, in real networks, the interference from other cells always exists and we can expect the level of interference will even increase in the future due to the densification of mobile networks. Such inter-cell interference impacts the optimal channel allocation for the D2D pairs in the dedicated mode. Moreover, neither [8] nor [9] assume the reuse of each channel by more than one D2D pair resulting in a low spectral efficiency.

A simplified channel reuse in the dedicated mode is presented in [10]–[12]. Although all these studies consider that either two D2D pairs [10] or multiple D2D pairs [11], [12] can access the same channel, each D2D pair is allowed to occupy

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just one channel at any time. The papers [13]–[15] exploit the reuse of multiple channels by multiple D2D pairs to guarantee a minimal SINR for every D2D pair while using the minimal possible number of channels. In these works, however, the D2D pairs do not benefit fully from the reuse, as only a limited number of channels is used and the sum capacity is not maximized. In [16], the authors maximize the sum capacity of D2D pairs in the dedicated mode considering that the D2D pairs reuse all available channels. Nevertheless, the authors do not consider the constraint on the minimal capacity C_{min} that should be guaranteed to the individual D2D pairs. Thus, the solution proposed in [16] can lead to the situation when some D2D pairs end up with zero capacity as these are forbidden to transmit at any channel due to the interference caused to other D2D pairs. Note that the ideas presented in [13]–[16] cannot be easily extended to maximize the sum capacity and, at the same time, to guarantee C_{min}, since the capacity maximization under the constraint on C_{min} for every D2D pair requires completely different solutions.

In summary, the existing resource allocation methods for the dedicated mode either restrict the number of D2D pairs reusing a single channel (e.g., [8], [9]) or limit the number of channels that can be occupied by a single D2D pair (e.g., [10]–[12]). As an exception, the papers [13]–[16] allow the reuse of multiple channels by multiple D2D pairs in the dedicated mode. These papers target either the sum capacity maximization ([16]) or the individual minimal capacity (C_{min}) satisfaction ([13]–[15]). However, none of these papers maximizes the sum capacity while guaranteeing C_{min} to every D2D pair.

Despite our focus on the dedicated mode in this paper, we survey also research targeting the shared mode and we also summarize related works on the channel reuse not considering D2D communication at all in order to justify the novelty of our solution from a broader perspective. Most of the existing channel allocation algorithms in the shared mode assume a restriction on either the number of D2D pairs that can reuse a single channel [17]–[21] or the number of channels that can be occupied by each D2D pair [22]–[30]. An exception to these restrictions is represented by [31] and [32]. These papers allow the reuse of multiple channels by multiple D2D pairs in the shared mode. Nevertheless, the channel allocation approaches from [31] and [32] depend on the presence of the CUEs. In other words, the optimized utility function in [31] is convex only if the interference caused to the CUEs by the D2D pairs is taken into account. The utility function becomes non-convex if the dedicated mode is considered and the presented solution becomes infeasible. Similarly, in [32], the presented solution adds the D2D pairs sequentially to the channels, which are already occupied by the CUEs. Hence, the decision of the D2D pairs whether to communicate over the given channel or not is based on the interference from/to the CUEs. Moreover, when the D2D pair reuses the channel according to [32], the D2D pair sets its transmission power at this channel based on the allowed interference imposed by this D2D pair to the corresponding CUE. Considering this, the channel and power allocations in [32] essentially depend on the existence of the CUEs that are completely absent in the dedicated mode and can be absent even in the shared mode with (very realistic) situation when the CUEs do not occupy all channels.

Besides the work addressing the reuse of channels for D2D communication, ongoing research is focused also on multiple links communicating over multiple channels for other scenarios and concepts. For example, in [33], many-to-many matching game is exploited to allocate multiple channels to multiple cellular links (i.e., links from multiple UEs to the gNB) in non-orthogonal multiple access-based networks. Since the matching games generally fall into the category of non-cooperative games, every link aims to selfishly maximize its own capacity. Consequently, the matching approach does not guarantee any C_{min} to individual links. Although the cooperative "coalitions' formation games" are also used widely for the channel reuse problem, e.g., in cognitive femtocell networks [34] or in cloud radio access networks [35], these approaches allow the users in the coalition to reuse a single channel only. Moreover, both [34] and [35] cannot be simply extended to the case where the UEs can access multiple channels, because [34] considers the coalitions' creation problem in the partition form (different problem compared to channel reuse problem in D2D communication) and [35] solves the coalitions' formation problem with a predefined final number of coalitions, but this number is usually not known in advance as it should be an output of the optimization.

In our paper, we focus on the resource allocation in D2D dedicated mode and we propose a solution that allows the reuse of multiple channels by multiple D2D pairs to maximize the sum capacity while guaranteeing C_{min} to individual D2D pairs. The major contributions of the paper are summarized as follows:

- We present and solve the problem of reusing multiple channels by multiple pairs as a coalition structure generation problem in order to put the D2D pairs into disjoint coalitions in a way that all D2D pairs in the same coalition can reuse the channels of each other. We derive the optimal coalitions by means of the dynamic programming reaching a theoretical maximum sum capacity while each D2D pair is still guaranteed to receive at least C_{min}.
- Since the dynamic programming is of a high complexity, we also propose a sequential bargaining game to determine the coalitions of the D2D pairs mutually reusing multiple channels. The heuristic sequential bargaining-based approach is of a low complexity and reaches a close-to-optimal performance.
- In order to facilitate the channel reuse in an efficient way, we analytically derive the optimal initial channel bandwidth allocation for the D2D pairs in the dedicated mode if interference from other cells is considered.
- Furthermore, we analytically determine the optimal allocation of the DUEs' transmission power over the reused channels within the coalitions. Since the defined optimization problem for power allocation is not convex, we approximate the problem to the convex one and we discuss the assumptions under which this approximation is realistic.

- We demonstrate that the proposed solution combining the initial allocation of the bandwidth available to the D2D pairs, the novel reuse of multiple channels by multiple D2D pairs exploiting sequential bargaining game, and the proposed power allocation significantly outperforms state-of-the-art solutions and reaches close-to-optimal sum capacity of the D2D pairs. Moreover, we show that our proposed algorithm is of a low complexity and exhibits very short convergence time. This allows its implementation in real networks.

Note that a basic idea of the sequential bargaining solution for the coalitions' creation in its simplified version and without any optimization of bandwidth and power allocations is presented in our prior conference paper [36].

The rest of the paper is organized as follows. In Section II, the system model is described and the targeted problem is formulated. In Section III, the proposed resource allocation scheme for D2D communication in the dedicated mode is presented. The simulations results are discussed in Section IV. Last, Section V concludes the paper and outlines possible future research directions.

II. System Model and Problem Formulation

In this section, we first describe the system model and, then, we formulate the problem, which is solved later in the next sections of this paper.

A. System Model

In our model, N D2D pairs are uniformly deployed within an area. Each D2D pair is composed of one DUE_T and one DUE_R. The DUE_T and the DUE_R in a single D2D pair are fixed for a specific time interval (such as, e.g., a communication session during which the transmitter sends data to the receiver). This consideration is in line with the common purpose of the D2D communication when a high amount of data is transmitted from one device to another, as in, e.g., [37].

The whole bandwidth B dedicated for D2D communication is split into $K = N$ channels (as in [8] and [9]) to serve all N D2D pairs. The capacity of the n-th D2D pair at the k-th channel ($C_{n,k}$) is defined as:

$$\begin{aligned} C_{n,k} &= B_k log_2\left(1+\gamma_{n,k}\right) \\ &= B_k log_2\left(1+\frac{p_{n,k}\, g_{n,n}}{\sigma_o B_k + \sum_{\substack{t\in N_k \\ t\neq n}} p_{t,k} g_{t,n} + I_d}\right) \end{aligned} \tag{1}$$

where B_k is the bandwidth of the k-th channel, $\gamma_{n,k}$ is the signal to interference plus noise ratio (SINR) of the n-th D2D pair at the k-th channel, $p_{n,k}$ is the transmission power of the n-th DUE_T at the k-th channel, $g_{n,n}$ is the channel gain between the n-th DUE_T and the n-th DUE_R, $p_{t,k}$ is the transmission power of the t-th DUE_T at the k-th channel, $g_{t,n}$ is the channel gain between the t-th DUE_T and the n-th DUE_R, N_k represents the set of D2D pairs communicating at the k-th channel, σ_o is the white noise power spectral density [38], and I_d stands for the background interference received from adjacent cells. The background interference is measured by the receiver of each D2D pair and reported to the gNB. As this interference represents the sum interference from all sources (namely the interference from neighboring gNBs and UEs in other cells), it can be derived from RSRP/RSRQ reported even in a conventional network according to 3GPP. Note that we focus on the dedicated mode, where the D2D pairs experience no interference from the CUEs in the same cell. Consequently, the CUEs are not considered.

Without loss of generality, we define C_{min}, based on [8] and [9], as the minimal capacity that can be guaranteed to the D2D pair with the worst SINR if the total bandwidth is split among N D2D pairs proportionally to $g_{n,n}$ (i.e., $B_n = \frac{g_{n,n}}{\sum_{n=1}^{n=N} g_{n,n}}$). Taking this into consideration, C_{min} is defined as:

$$C_{min} = \frac{g_{n,n}^{min}}{\sum_{n=1}^{n=N} g_{n,n}} B\ log_2\left(1+\frac{P_{max}\, g_{n,n}^{min}}{\sigma_o \frac{g_{n,n}^{min}}{\sum_{n=1}^{n=N} g_{n,n}} B + I_d}\right) \tag{2}$$

where $g_{n,n}^{min}$ is the minimal channel gain among all D2D pairs, i.e., $g_{n,n}^{min} = min\{g_{i,i}\},\ \forall i = 1,\ldots,N$, and P_{max} is the maximal transmission power that can be used by the D2D pair over all channels. Note that P_{max} in (2) is considered in order to achieve the highest possible C_{min} that can be guaranteed to each D2D pair. The value of C_{min} decreases if the number of D2D pairs increases in order to serve all D2D pairs with at least C_{min}.

In our system model, we adopt the following assumptions:

Assumption 1: We consider that the distance d between the DUE_T and the DUE_R creating one D2D pair is at most equal to a maximal distance d_{max} (i.e., $d \leq d_{max}$) to guarantee a reliable D2D communication.

Assumption 2: We consider a fully controlled D2D communication, where the gNB is aware of the devices under its coverage and manages them. This is in line with the implementation of the D2D communication expected in 3GPP-based mobile networks, see, e.g., [42].

Assumption 3: We assume full knowledge of channel state information (CSI) in our system. Although full CSI knowledge can imply a high signaling overhead, such assumption is commonly adopted in many recent papers, e.g., [17], [18], [43]–[45]. Moreover, there are already works that relax this problem and allow to determine the channel gains among all D2D pairs at a very low cost, see for example, [46], where deep neural networks are exploited to predict the D2D channel gains with a very high accuracy with almost no additional overhead.

Assumption 4: We focus on a common interference-limited mobile network [47]–[49], where the interference is a key limiting factor and overrules the impact of noise. This allows to adopt the approximation $\sigma + I_d = I_d$ later in Appendix A.

B. Problem Formulation

The objective of this paper is to maximize the sum communication capacity of the D2D pairs in the dedicated mode while the minimum capacity is guaranteed to each D2D pair. The sum capacity is maximized by an efficient allocation of the communication channels and their reuse in such a way that multiple channels can be reused by multiple D2D pairs. We denote the set of L coalitions of the D2D pairs as $\mathbf{CS} = \{cs_1, cs_2, \ldots cs_L\}$. Each coalition cs_l includes all D2D pairs that mutually reuse all channels allocated to all D2D pairs in cs_l. The coalitions are formed so that the sum capacity of the D2D pairs is maximized while the minimal capacity C_{min} of each D2D pair is still guaranteed. To improve the sum capacity, we also determine a vector $\mathbf{B}$ of the communication channels bandwidths for all N D2D pairs, i.e., $\mathbf{B} = \{B_1, B_2, \ldots, B_N\}$. To exploit the overall bandwidth allocated to each D2D pair (including reused channels) efficiently, we further find a set of vectors $\mathbf{P} = \{P_1, P_2, \ldots, P_N\}$, where every vector P_n contains the transmission powers of the n-th D2D pair at all channels allocated to this pair. Note that every vector P_n is of $|K_n|$ length, where K_n is the subset of channels allocated to the n-th D2D pair. Hence, K_n contains all channels of all D2D pairs, which are in the same coalition with the n-th pair. The optimization problem over $\mathbf{B}$, $\mathbf{CS}$, and $\mathbf{P}$ is then formulated as:

$$\begin{aligned}
&\mathbf{B}^*, \mathbf{CS}^*, \mathbf{P}^* \\
&= \underset{\mathbf{B},\mathbf{CS},\mathbf{P}}{\operatorname{argmax}} \sum_{n=1}^{n=N} \sum_{k\in K_n} B_k log_2 \left(1+\gamma_{n,k}\right) \\
&\quad \text{s.t.} \sum_{k\in K_n} B_k log_2 (1+\gamma_{n,k}) \geq C_{min} \quad \forall n \in \{1,2,\ldots N\} \ (a) \\
&\quad\quad 0 < B_n \leq B \quad \forall n \in \{1,2,\ldots N\} \quad (b) \\
&\quad\quad \sum_{n=1}^{n=N} B_n = B \quad (c) \\
&\quad\quad \sum_{k\in K_n} p_{n,k} = P_{max} \quad \forall n \in \{1,2,\ldots N\} \quad (d)
\end{aligned} \tag{3}$$

where $\mathbf{B}^*$, $\mathbf{CS}^*$, and $\mathbf{P}^*$ are the optimal $\mathbf{B}$, $\mathbf{CS}$, and $\mathbf{P}$, respectively. The constraint (a) ensures that the sum capacity of any D2D pair over all the channels allocated to this pair (including the reused channels within the coalition) is not below C_{min}, (b) limits the size of each channel with respect to the maximum available bandwidth B, (c) guarantees that the sum of all channel bandwidths is equal to B (i.e., that the dedicated spectrum is fully utilized to maximize the capacity), and (d) limits the sum transmission power of each D2D pair over all channels to the maximal allowed transmission power P_{max}.

The problem defined in (3) is a non-convex mixed integer non-linear programming (MINLP) as the coalitions' formation represents an integer programming problem [53] while the bandwidth allocation and the power allocation represent continuous non-integer variables. The MINLP problems are known to be NP-hard. Nevertheless, theoretically, the joint solution of problem (3) is numerically derivable via the common approach for solving MINLP problems, i.e., optimizing the continuous variables ($\mathbf{B}$ and $\mathbf{P}$) at all feasible settings of the discrete variables ($\mathbf{CS}$). The optimization of both continuous variables is an NLP problem that is solvable via the interior point method. However, the joint numerical solution is not practical due to its very high complexity and its feasibility only for very few D2D pairs, as previously mentioned. Therefore, in the next section, we solve the optimization problem from (3) by determining, sequentially, the bandwidth allocation, the coalitions' formation and the power allocation. However, later in Section IV, we still derive the joint numerical solution when few pairs are present, in order to prove that the proposed sequential solution introduces only minor losses in the performance compared to the joint solution.

III. The Proposed Resource Allocation Scheme

To solve the optimization problem from (3), we separate it into three sub-problems. First, we analytically derive the channel bandwidth allocated to each D2D pair in the initial phase (i.e., determination of $\mathbf{B}$). Second, we solve the coalitions' creation problem allowing the reuse of multiple channels by multiple D2D pairs (i.e., determination of $\mathbf{CS}$). The channel reuse problem is solved by the dynamic programming, which composes the optimal coalition structure and demonstrates an upper bound performance. However, the dynamic programming is of a high complexity, which makes it impractical for real networks. Thus, we propose also a low-complexity algorithm based on the sequential bargaining to handle the reuse. Third, we determine the power allocation for the D2D pairs at each channel (i.e., determination of $\mathbf{P}$). Note that, in the following subsections, the solutions solving the sub-problems of bandwidth allocation, coalitions' formation, and power allocation are denoted as $\mathbf{B}^{**}$, $\mathbf{CS}^{**}$, and $\mathbf{P}^{**}$, respectively.

A. Initial Allocation of Channel Bandwidth for Individual D2D Pairs

Before the channel reuse by D2D pairs takes place, each D2D pair is allocated with a dedicated channel of a certain bandwidth to guarantee the required channel capacity C_{min} for all D2D pairs. This channel can be then reused by other pairs in the main phase of the proposed approach (described in the next subsections). The sub-problem of optimizing $\mathbf{B}$ from the problem defined in (3) is reformulated as:

$$\begin{aligned}
\mathbf{B}^{**} &= \underset{\mathbf{B}}{\operatorname{argmax}} \sum_{n=1}^{n=N} B_n log_2 \left(1+\gamma_{n,n}\right) \\
&\quad \text{s.t.} \ C_{n,n}^{nr} = B_n log_2 \left(1+\gamma_{n,n}\right) \geq C_{min} \\
&\quad\quad \forall n \in \{1,2,\ldots N\} \quad (a) \\
&\quad\quad (b),(c) \quad \text{taken from (3)}
\end{aligned} \tag{4}$$

where $\gamma_{n,n} = \frac{p_{n,n}\, g_{n,n}}{\sigma_o B_n + I_d}$ is the SINR of the n-th D2D pair at the n-th dedicated channel with no-reuse and the constraint (a) ensures that the capacity of every n-th D2D pair at the n-th dedicated channel with no-reuse ($C_{n,n}^{nr}$) is, at least, equal to the minimal required capacity C_{min}. It is worth to mention that each D2D pair can transmit with P_{max} (i.e., $p_{n,n} = P_{max}$) at its allocated channel in this initial phase, because only one channel without reuse is exploited by each D2D pair and the interference among the D2D pairs is absent in this phase.

The solution of (4) for the case with no interference from the adjacent cells (i.e., with $I_d = 0$) is derived in [8] and [9]. However, in a realistic case with a dense deployment of cells and a high density of communicating UEs, the interference I_d

is significant with respect to the noise and cannot be neglected. In such case, the solution proposed in [8] and [9] is not optimal. Thus, we determine the optimal allocation of the bandwidth for the channel assigned to each D2D pair initially (without channel reuse) in the following proposition.

Proposition 1: Considering the background interference from the adjacent cells I_d, the optimal allocation of the bandwidth B_n to the n-th channel assigned to the n-th D2D pair guaranteeing the fulfillment of C_{min} for all D2D pairs is:

$$B_n = \frac{C_{min}}{log_2\left(1 + \frac{P_{max} g_{n,n}}{\sigma_o \frac{g_{n,n}^{min}}{\sum_{n=1}^{n=N} g_{n,n}} B + I_d}\right)} \tag{5}$$

Proof: The proof of Proposition 1 is in Appendix A. ■

If $\sum_{n=1}^{n=N} B_n < B$ after the channel allocation, the rest of the bandwidth is added to the channel of the D2D pair with the highest $g_{n,n}$ in order to maximize the sum capacity of the D2D pairs as defined in (4). Consequently, the highest capacity in the initial allocation phase is achieved by the D2D pair with the best channel quality similarly like in [8] and [9]. Then, with a high probability, this particular D2D pair forms a coalition with other pairs during the generation of the coalition structure (as described in the next subsection). Thus, the above-mentioned assignment of the rest of the bandwidth is beneficial for other D2D pairs as their capacity can be significantly enhanced as well by joining the coalition, which contains the D2D pair with the highest $g_{n,n}$.

The initial resource allocation is centrally managed by the gNB based on the knowledge of the channel quality of all D2D pairs in a similar way as assumed, e.g., in [17], [18], or [43].

B. Optimal Coalition Structure Generation for Channel Reuse

After the initial channel bandwidth allocation to the D2D pairs, the reuse of channels is implemented. To determine which D2D pairs should mutually reuse their channels, we formulate the problem of coalitions' formation. The problem is understood as a coalition structure generation problem in game theory [51]–[53]. For any set of players, the coalition structure is a set of coalitions $\mathbf{CS}= \{cs_1, cs_2, \ldots, cs_L\}$ such that each element $cs_l \in \mathbf{CS}$ is the set of players composing one coalition. Note that each player can belong only to a single coalition. For our channel reuse case, the problem is to find the coalition structure over N D2D pairs in such a way that the D2D pairs in each coalition mutually reuse the channels of each other. Based on this, our goal is to find the coalition structure that maximizes the sum capacity of D2D pairs while guaranteeing the minimal capacity required by each pair. Consequently, the sub-problem of optimizing $\mathbf{CS}$, from the problem defined in (3), is written as:

$$\mathbf{CS}^{**} = \underset{\mathbf{CS}}{\operatorname{argmax}} \sum_{n=1}^{n=N} \sum_{k \in K_n} B_k log_2 \left(1 + \gamma_{n,k}\right)$$
$$\text{s.t.} \ (a) - (d) \text{ taken from } (3) \tag{6}$$

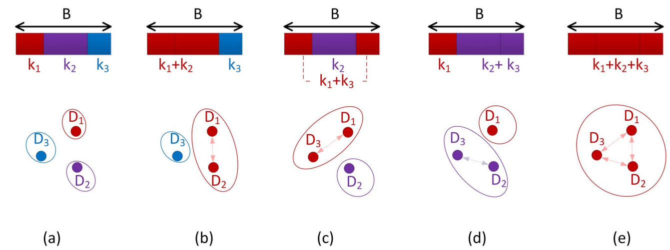


Fig. 1. The possible coalitions' creation for three D2D pairs. Note that the dashed arrows represent the interference introduced by the channel reuse.

Fig. 1 illustrates the channel reuse problem presented as a coalition structure generation with an example of three D2D pairs (i.e., three players' coalition structure game). The example represents all possible coalitions created for the problem of three D2D pairs. Note that the D2D pairs within the same coalition transmit at the same time over all channels of all D2D pairs in the same coalition. For example, if three D2D pairs create one coalition (as in Fig. 1e), all these D2D pairs transmit over all three channels simultaneously and mutually interfere with each other. The D2D pairs in different coalitions are supposed to transmit at the same time, but at different channel(s), thus no interference occurs among the different coalitions.

To find the optimal solution for the problem defined in (6) and to determine the optimal structure of the coalitions, the dynamic programming [53], [54] is a suitable solution. In the dynamic programming, the values of a gain function V for each possible coalition cs_x composed of X D2D pairs (where $X \in \{1, 2, \ldots, N\}$) should be calculated. However, the problem defined in (6) is different from the general coalition structure generation problems due to the constraint (a). Therefore, in order to solve (6), the gain function should take the constraint (a) into account to guarantee C_{min} for each D2D pair even after the channel reuse. Thus, we build up the gain function $V(cs_x)$ of the coalition cs_x, which is composed of X D2D pairs, as follows:

$$V(cs_x) = \begin{cases} C_{cs_x} & \text{if } C_{D_y} > C_{min}, \ \forall D_y \in cs_x \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where C_{cs_x} is the sum capacity of all D2D pairs in the coalition cs_x mutually reusing the channels of all D2D pairs in cs_x, and C_{D_y} is the sum capacity of the D2D pair D_y over the communication channels, including the reused channels, in cs_x (note that D_y represents the y-th D2D pair from the coalition cs_x). Note that to calculate (7), the transmission powers of the D2D pairs over the reused channels are optimized based on subsection III-D presented later in this paper.

The dynamic programming-based solution is of a high complexity as the general complexity of dynamic programming is $\mathcal{O}(3^N)$, where N is the number of D2D pairs. Thus, such solution is not practical for the real networks and we propose a low-complexity algorithm in the next subsection to solve the coalitions' creation problem.

C. Low-Complexity Channel Reuse Based on Sequential Bargaining

In this subsection, we describe the proposed low-complexity algorithm for the channel reuse to solve (6). The proposed solution is based on the sequential bargaining allowing multiple D2D pairs to reuse multiple channels simultaneously. This reuse is enabled by the fact that all D2D pairs in the same coalition always use all channels allocated to them previously during the initial allocation phase (as shown in Fig. 1e). Moreover, all channels in the coalition are used simultaneously by all D2D pairs in that particular coalition.

Before the proposed sequential bargaining process is initiated, we calculate the utilities for all possible coalitions of any two D2D pairs (D_i and D_j) in the system. The utility function is defined as:

$$U_{i,j} = \begin{cases} -\infty & \text{if } C_{i,i} + C_{i,j} < C_{min} \\ -\infty & \text{if } C_{j,i} + C_{j,j} < C_{min} \\ G_{i,j} & \text{otherwise} \end{cases} \tag{8}$$

where $C_{i,i}$ ($C_{j,i}$) and $C_{i,j}$ ($C_{j,j}$) are the capacities of the i-th (j-th) D2D pair at the i-th and j-th channels, respectively. If the reuse would lead to a decrease in the capacity below C_{min} for any of the D2D pairs, the coalition is not allowed and the utility function $U_{i,j}$ is set to $-\infty$, see (8). In contrast, if both D2D pairs keep the capacity at least at C_{min}, a gain $G_{i,j}$ introduced by the new coalition of the pairs D_i and D_j, even if it is negative, is calculated as:

$$G_{i,j} = (C_{i,i} + C_{i,j} + C_{j,i} + Cj, j) - (C^{nr}_{i,i} + C^{nr}_{j,j}) \tag{9}$$

where $C^{nr}_{i,i}$ and $C^{nr}_{j,j}$ correspond to the capacities of the i-th and j-th D2D pairs without channel reuse (see Section III-A). Note that from the structure of the utility function $U_{i,j}$ and from (9), we observe that $U_{i,j} = U_{j,i}$.

Remark 1: If the D2D pairs D_i and D_j form togther one coalition, the communication channel k_i is reused by the pair D_j while the pair D_i reuses the channel k_j. In other words, both D_i and D_j communicate over both channels k_i and k_j at the same time.

Remark 2: Since the utility $U_{i,j}$ in (8) is calculated for any two D2D pairs D_i and D_j creating one coalition and accessing the two shared channels k_i and k_j assigned originally to each of them, the transmission powers $p_{i,i}$, $p_{i,j}$, $p_{j,i}$, and $p_{j,j}$ that are required to derive $U_{i,j}$ are calculated as $p_{x,y} = \frac{B_y}{B_x+B_y} P_{max}$, where x and y stand for either i or j to represent all four powers $p_{i,i}$, $p_{i,j}$, $p_{j,i}$, and $p_{j,j}$. For more details on the power allocation, please refer to the proposed power allocation derived later in Section III-D).

After obtaining the individual utilities $U_{i,j}$, these are inserted into a bilateral utility matrix $\boldsymbol{U}$:

$$\boldsymbol{U} = \begin{bmatrix} -\infty & \dots & U_{1,N} \\ \vdots & \ddots & \vdots \\ U_{N,1} & \dots & -\infty \end{bmatrix} \tag{10}$$

where the diagonal elements are set to $-\infty$ (i.e., $U_{i,i} = -\infty$). The reason for setting $U_{i,i} = -\infty$ is that the diagonal elements contain the utilities of the i-th D2D pair making a coalition with itself. Such coalition is automatically disregarded as, in principal, a D2D pair cannot make any new coalition with itself. The reason why we do not set the diagonal values simply to "0" is that in some special cases even the coalitions with slightly negative utilities can be initially created as long as C_{min} is guaranteed. In contrast, the elements $U_{i,j}$ equal to $-\infty$ (i.e., the elements for which C_{min} is not guaranteed as well as all diagonal elements) are omitted in the reminder of the process, because these should not lead to the creation of any coalition. This way, the complexity of the whole bargaining process is significantly decreased, as the search space (i.e., the number of the possible coalition structures among the D2D pairs) is reduced.

After all the entries in $\boldsymbol{U}$ equal to $-\infty$ are removed, the rest of the elements are sorted in a descending order taking into account that every couple of symmetric elements is considered as one element ($U_{i,j} = U_{j,i}$). The sorting serves further to indicate the priorities for coalitions' creation so that the coalitions yielding the highest capacity gains are created preferentially. This ordering is motivated by the fact that a higher bilateral utility represents, in our case, a lower interference among two D2D pairs. Thus, these D2D pairs are expected to end up in the same coalition also in the case of optimal coalitions created by the dynamic programming. Hence, it is likely that the proposed low-complexity solution leads to a close-to-optimal performance.

The sorted elements $U_{i,j}$ from $\boldsymbol{U}$ represent a vector of sub-games (denoted as $\boldsymbol{U}^*$) that are played sequentially over time in the way that one sub-game is played in every time step. Consequently, when the sub-game s is played, the coalition structure $\mathbf{CS_s}$ is created resulting in the sum capacity $C_{\mathbf{CS_s}}$. At the beginning of the algorithm, the sub-game is played only between two D2D pairs (e.g., D_i and D_j) over their respective channels (k_i and k_j) allocated in the initial phase. In this case, the coalition is simply created if both D_i and D_j agree to reuse their dedicated channels among each other. However, when some coalitions already exist, the sub-game is extended to all members of all related coalitions. Thus, if the pair D_i wants to join the coalition cs_x composed of two or more other D2D pairs, the sub-game s is played between the pair D_i and all the D2D pairs already included in the coalition cs_x. The pair D_i joins the coalition cs_x if and only if the pair D_i as well as all pairs in cs_x agree. Each D2D pair D_j agrees to accept the pair D_i into cs_x if the capacity of the pair D_j is not lower than C_{min} and if the sum capacity of the D2D pairs composing $\mathbf{CS_s}$ is higher than the sum capacity of the D2D pairs composing $\mathbf{CS_{s-1}}$ (i.e., if $C_{\mathbf{CS_s}} > C_{\mathbf{CS_{s-1}}}$); where $\mathbf{CS_{s-1}}$ is the coalition structure created in the previous sub-game $s-1$ with the sum capacity of $C_{\mathbf{CS_{s-1}}}$.

Furthermore, to get closer to the creation of the optimal coalitions, we enhance the proposed sequential bargaining process by testing to create larger coalitions even if the coalitions of two pairs are not beneficial (i.e., $C_{\mathbf{CS_s}} < C_{\mathbf{CS_{s-1}}}$). Thus, we try the coalitions of three pairs even if the previous coalitions with two pairs can lead to a decreased performance. In other words, if the creation of the coalitions with any two pairs leads to a negative gain (all bilateral utilities are negative), the two D2D pairs playing the first sub-game in the sorted utilities are forced to test the reuse of their channels even if the sum capacity is decreased. Then, the rest of the sub-games are played out normally as described before and the D2D pair is added only if the sum capacity of D2D pairs is increased. This way, we keep the possibility of making coalitions with more than two D2D pairs and we prevent the possibility that the algorithm gets stuck in local optima.

In the last step, the formed coalition structure $\mathbf{CS_s}$ is compared with two other coalition structures: i) $\mathbf{CS_{all}} = cs_1$ where all D2D pairs create one coalition cs_1 and reuse all the channels; ii) $\mathbf{CS_0} = \{cs_1, \ldots, cs_N\}$ where each D2D pair represents a stand-alone coalition and no channel reuse is exploited (i.e., the initial allocation from Section III-A). Among the three coalition structures $\mathbf{CS_s}$, $\mathbf{CS_{all}}$, and $\mathbf{CS_0}$, the one that reaches the highest sum capacity of D2D pairs is chosen. Note that the sum capacity of $\mathbf{CS_{all}}$ is set to zero if $\mathbf{CS_{all}}$ does not guarantee C_{min} for all D2D pairs. There are two reasons for the inclusion of this last step. The first reason is a potential consequence of the special case (described in previous paragraph) when all elements of (10) are negative and the sum capacity decrement is acceptable in the first sub-game. This sum capacity decrement makes it necessary to compare the sum capacity in the final formed coalition structure $\mathbf{CS_s}$ with the sum capacity achieved by the initial allocation (i.e., $C_{\mathbf{CS_0}}$), in order to guarantee that $C_{\mathbf{CS_s}} > C_{\mathbf{CS_0}}$. The second reason is, generally, the very low probability of reaching the coalition structure where all D2D pairs reuse all of the available channels (i.e., $\mathbf{CS_{all}}$) through the played sub-games. Nevertheless, with a very low density of D2D pairs, the probability that the D2D pairs can reuse all the channels and compose one coalition is higher. Thus, selecting the best-performing coalition structure among $\mathbf{CS_s}$ and $\mathbf{CS_{all}}$ can further improve the performance.

Algorithm 1 Sequential Bargaining Algorithm to Solve Channel Reuse Problem for N D2D Pairs

1: Estimate utility matrix $\boldsymbol{U}$ with size $N \times N$
2: Eliminate utilities equal to $-\infty$ from the matrix $\boldsymbol{U}$
3: Sort remaining utilities in descending order into vector $\boldsymbol{U}^*$
4: Initialize $\mathbf{CS_0} = \{cs_1, \ldots, cs_N\}$; $cs_i = \{D_i\}$, $\forall i \in \{1, \ldots, N\}$
5: **for** $s = 1 : \text{length}(\boldsymbol{U}^*)$ **do**
6: Sub-game is played between pairs $D_i \in cs_x$ and $D_j \in cs_y$ where $U_{i,j} \equiv \boldsymbol{U}^*(s)$
7: Update $\mathbf{CS_s}$ (i.e., merge cs_x and cs_y into one coalition cs_z)
8: Estimate all $\sum_{k\in K_n} B_k log_2(1+\gamma_{n,k})$ $\forall n \in \{1, ...N\}$ and corresponding $C_{\mathbf{CS_s}}$
9: **if** $\exists n \in \{1, ...N\} : \sum_{k\in K_n} B_k log_2(1+\gamma_{n,k}) < C_{min}$ **or** $C_{\mathbf{CS_s}} < C_{\mathbf{CS_{s-1}}}$ **then**
10: **if** $\exists s$: $\boldsymbol{U^*(s)} > 0$ **or** $s \neq 1$ **then**
11: $\mathbf{CS_s} = \mathbf{CS_{s-1}}$
12: **end if**
13: **end if**
14: **end for**
15: **if** in $\mathbf{CS_{all}}$ $\exists n \in \{1, ...N\} : \sum_{k\in K_n} B_k log_2(1+\gamma_{n,k}) < C_{min}$ **then** $C_{\mathbf{CS_{all}}} = 0$
16: **end if**
17: $\mathbf{CS_s} = \{\mathbf{CS_s} \in \{\mathbf{CS_s}, \mathbf{CS_{all}}, \mathbf{CS_0}\} : C_{\mathbf{CS_s}} = max(C_{\mathbf{CS_s}}, C_{\mathbf{CS_0}}, C_{\mathbf{CS_{all}}})\}$

The above-described algorithm for the sequential bargaining-based channel reuse is summarized in Algorithm 1. The algorithm is supposed to run centrally at the gNB (as explained in Section II.A). Thus, no special synchronization between the D2D links is needed with respect to the common D2D communication fully controlled by the network [2], because all the D2D pairs within the coalition use all the channels of each other at the same time. Note that within every step from the previously described coalitions' formation solution, the capacities are calculated (line 8 from Algorithm 1) with the optimized transmission power allocation derived in the following subsection III-D.

D. Power Allocation to Channels

In this subsection, we aim to optimize the power allocation and set the transmission power of every D2D pair at every channel allocated to this pair based on the created coalition structure. We take into account the maximum power budget for each D2D pair to fulfill the constraint (d) in (3) and (6). The problem of power allocation is non-convex. Thus, an iterative method is required to solve such problem. However, any iterative method would increase the time complexity of the overall resource allocation scheme. Thus, we relax the problem from the maximization of the sum capacity to the maximization of individual capacity of each D2D pair. In other words, the transmission power of each D2D pair at each individual channel allocated to this pair is set in a selfish way so that the sum capacity of every single D2D pair is maximized.

The problem of maximizing the sum capacity of the D2D pair D_n over all $|K_n|$ channels reused by this pair D_n is formulated as:

$$\begin{aligned} \max(C_n) = \max \Bigg(\sum_{k\in K_n} B_k log_2 \Big(1 \\ + \frac{p_{n,k} g_{n,k}}{\sigma_o B_k + \sum_{\substack{t\in N_k \\ t\neq n}} p_{t,k}\, g_{t,k} + I_d}\Big)\Bigg) \\ \text{s.t.} \sum_{k\in K_n} p_{n,k} = P_{max} \quad (a) \end{aligned} \tag{11}$$

The optimization problem (11) is, still, unsolvable analytically as the transmission power setting of other pairs is not known. However, the DUE$_T$ and the DUE$_R$ of the same D2D pair are typically close to each other and, consequently, the channel between the DUE$_T$ and the DUE$_R$ is of a high quality (i.e., high SINR). Moreover, the coalitions' formation algorithm is interference-aware and, hence, minimizes the mutual interference among the D2D pairs. These reasons allow to expect $\gamma_{n,k} \gg 1$ and, hence, to adopt the approximation $log_2(1+\gamma_{n,k}) \approx log_2(\gamma_{n,k})$ for the derivation of the analytical solution of the previous optimization problem (11). Note that this approximation is very common for the scenarios with a "high SINR regime" (as considered in this paper), see for example [8]. Thus, the problem of maximizing C_n is simplified to:

$$\max(C_n) = \max\left(\sum_{k\in K_n} B_k log_2 \left(\frac{p_{n,k} g_{n,k}}{\sigma_o B_k + \sum_{\substack{t\in N_k\\ t\neq n}} p_{t,k}\, g_{t,k} + I_d}\right)\right)$$
$$\text{s.t.} \sum_{k\in K_n} p_{n,k} = P_{max} \quad (a) \tag{12}$$

The maximization problem in (12) is a convex constrained optimization problem and its solution is determined using the Lagrangian method as:

$$p_{n,k} = \frac{B_k}{\sum_{k\in K_n} B_k} P_{max} \tag{13}$$

This sub-optimal solution maximizes the individual capacity of every D2D pair selfishly. The relaxation from maximizing the sum capacity to maximizing the individual capacity of individual pairs is justified by the fact that the coalitions are formed to suppress the interference among the D2D pairs belonging to one coalition and interfering to each other. This interference suppression allows to perform the power allocation for every D2D pair independently with only minor losses in terms of the sum capacity, as confirmed via simulations in Section IV. In addition to the sum capacity maximization, C_{min} is guaranteed to be satisfied by Algorithm 1 via lines 9-11, where C_{min} satisfaction is continuously checked.

By deriving the transmission powers of all D2D pairs over all the corresponding channels based on (13), a sub-optimal power allocation ($\mathbf{P}^{**}$) is reached. The transmission power $p_{n,k}$ defined in (13) is inserted to (9) for the determination of the gains $G_{i,j}$ and to derive the bilateral utilities $U_{i,j}$ in (8) (see *Remark 2* in Section III-C).

IV. Performance Evaluation

The simulations are carried out in Matlab to evaluate the performance of the proposed resource allocation scheme and to compare it with the competitive algorithms. To this end, the simulation scenario and parameters are presented in the next subsection. Then, the competitive algorithms and performance metrics are defined. Last, the simulation results are presented and discussed.

A. Simulation Scenarios

We consider an area of $500\times500\ m^2$. The simulation results are averaged out over 1000 simulation drops. For each drop, N DUE_T are uniformly distributed within the area. The position of the DUE_R for each D2D pair is generated with respect to the position of the DUE_T to guarantee that the distance between the transmitter and the receiver is not higher than d_{max}. The distance between the transmitter and the receiver is randomly generated with the uniform distribution between 0 and d_{max}. The angle of the receiver with respect to the transmitter is also uniformly generated between 0° and 360°. The number of D2D pairs remains the same for all 1000 drops, but we run different 1000 drops for every tested value of N from 5 to 50.

TABLE I
SIMULATION PARAMETERS

Parameter		Value
Carrier frequency	f_c	2 GHz
Bandwidth	B	20 MHz
Noise power spectral density	σ_o	−174 dBm/Hz
Interference level from neighboring cells	I_d	$\mathcal{N}$(−80, 15) dBm
Number of D2D pairs	N	5 – 100
Maximal transmission power of D2D pair	P_{max}	20 dBm
Default maximal distance between DUE_T and DUE_R	d_{max}	50 m ([39]–[41])

Note that the CUEs are not considered as these operate in a different band in case of the dedicated mode as explained in Section II-A.

For the modeling of radio channel, we follow 3GPP recommendation for D2D communication defined in [42]. Hence, the path loss model is defined as $PL = 89.5 + 16log_2(d)$, where d is the distance between the transmitter and the receiver. The maximal transmission power for every D2D pair is set to $P_{max} = 20$ dBm. The background interference from neighboring cells I_d is modeled randomly for each drop following a normal distribution with a mean value of -80 dBm and a standard deviation of 15 dB. This level of interference from neighboring base stations represents a high interference scenario, which can be expected in future mobile networks with dense small cells deployment [50]. The detailed parameters of the simulations are summarized in Table I.

B. Competitive Algorithms and Performance Metrics

To the best of our knowledge, there is no solution targeting the reuse of multiple channels by multiple D2D pairs in the dedicated mode with the goal of maximizing the sum capacity of D2D pairs and guaranteeing the minimal capacity for each individual D2D pair. Nevertheless, we compare our proposed algorithm with the schemes that target similar objectives or address similar problem. Thus, the proposed resource allocation algorithm, encompassing the initial channel bandwidth allocation (derived in Section III-A), the channel reuse algorithm (Section III-B and III-C), and the proposed power allocation (Section III-D), is compared with the following state-of-the-art schemes:

1) *No reuse* [8], [9]: This scheme, designed for the dedicated mode, distributes the whole available bandwidth B among the D2D pairs in the way that communication capacity is maximized while C_{min} is guaranteed to each D2D pair. However, the channels cannot be reused by the D2D pairs and each channel is occupied by just one pair. Note that the channel allocation in [8] and [9] is not optimal if there is background interference I_d as considered in our case.
2) *Single reuse* [10]: In this algorithm, the total bandwidth is divided into several channels with equal bandwidths (we consider six channels as in [10]). Every channel is allocated to a single D2D pair, i.e., six D2D pairs are served. The Hungarian algorithm is implemented to solve a matching problem between the six channels and the unserved D2D pairs to enable the D2D channel reuse. As defined in [10], up to two D2D pairs can

reuse each channel. Thus, the solution allows twelve ($2\times$number of channels) D2D pairs to be served, while the rest of the D2D pairs are provided with no resources. Even if this leads to an unfairness among the D2D pairs, it also yields a high capacity for the served D2D pairs as only those having a high channel quality between DUE_T and DUE_R access the available channels.

3) *Empty channel protocol (ECP)* [11]: For this case, the total bandwidth is also divided into several channels with equal bandwidth (in our case six channels as in [11]). First, every channel is allocated to a single D2D pair (i.e., six D2D pairs are served). Then, empty channel protocol adds the unserved D2D pairs to the channels so that all unserved D2D pairs reuse the channels already assigned to other D2D pairs. Note that the D2D pairs are not allowed to exploit multiple channels simultaneously and only one channel can be used by every D2D pair. Still, each channel can be reused by multiple D2D pairs at the same time.

The performance of the proposed and competitive algorithms is assessed by means of the sum capacity of D2D pairs defined as $C = \sum_{n=1}^{n=N} \sum_{k \in K_n} C_{n,k}$. We also investigate the percentage of satisfied D2D pairs, that is, the D2D pairs for which the minimal capacity is granted (i.e., the percentage of the D2D pairs with $C \geq C_{min}$).

C. Simulation Results

In this section, we first compare the performance of the proposed resource allocation scheme with the competitive state-of-the-art algorithms. Then, we analyze thoroughly the proposed scheme and we show the added value of the individual sub-parts of the proposal.

1) Comparison of the Proposed Scheme With Competitive Algorithms: In this subsection, we compare the performance of the full proposed resource allocation scheme, containing the initial bandwidth allocation, channel reuse based on sequential bargaining (SB), and proposed power allocation (denoted as "Proposal with SB (Alg. 1)"), with all above-mentioned competitive algorithms. Additionally, we derive the optimal sequential solution, where the optimal bandwidths are allocated to the channels, the optimal channels are allocated to the D2D pairs via the dynamic programming (i.e., the optimal coalitions are created) (Section III-B), and finally, the transmission powers are allocated to the D2D pairs based on (13) (denoted as "Proposal - optimum"). Although the optimal solution is not practical due to the high complexity of the dynamic programming, it is used as a benchmark for our scheme as it achieves the maximal possible sum capacity. In addition, we also test the performance of the sub-optimal greedy algorithm for the creation of the coalitions with a complexity equal to $\mathcal{O}(N^3)$. The greedy algorithm outlined for a general coalitions' creation in [55] is modified to guarantee C_{min} and we combine it with the initial channel allocation and the power allocation of our proposed scheme. Hence, we denote the algorithm as "Proposal with m-greedy").

Fig. 2 illustrates the impact of the number of D2D pairs on the sum capacity of all D2D pairs. The capacity is increasing for the proposed as well as competitive algorithms with more D2D pairs in the system despite the fact that the interference among D2D pairs increases. The reason for this is the fact that C_{min} naturally decreases with the increasing number of D2D pairs (as explained in Section II-A), such that C_{min} can be always guaranteed. The decrease in C_{min} with the increasing number of D2D pairs allows all pairs to contribute to their sum capacity and, hence, increase it. This is, however, expected as the coalitions are created in a way that decreases the interference among pairs.

We see that the sum capacity of all three competitive schemes saturates quickly and reaches approximately 223 Mbps (ECP), 297 Mbps (Single reuse), and 294 Mbps (No reuse) for 50 D2D pairs. The proposal with sequential bargaining leads to a significant gain with respect to all competitive algorithms. The gain ranges from 20% to 200%, from 55% to 297%, from 55% to 295%, when compared to the No reuse, Single reuse, ECP algorithms, respectively. The gain of the proposal with respect to the existing solutions increases with the number of D2D pairs, since a higher number of D2D pairs leads to more opportunities for the multiple reuse in case of our proposed scheme. Note that the proposal with m-greedy, also, outperforms the existing solutions, but its sum capacity is from 2% to 13% below the sequential bargaining approach. Besides, Fig. 2 also shows the performance of the proposal with the optimal coalitions' creation by the dynamic programming. Due to the very high complexity, we cannot show results for more than ten D2D pairs as the results cannot be obtained in a realistic time frame. The difference between the optimal coalition structure derived by dynamic programming and the low-complexity sequential bargaining approach is negligible (1.2% for 10 D2D pairs) and the low-complexity solution reaches almost optimal performance. Note that such a good performance of the proposed sequential bargaining with respect to the optimum is thanks to the sorting of the bilateral utilities in descending order and, also, allowing the creation of the coalitions with negative utilities if no bilateral utility is positive, see Section III.C. Fig. 2 also proves that our proposed sequential solution reaches a sum capacity very close to the joint numerical solution (derived as explained in Section II-B for up to eight D2D pairs only due to its very high complexity). The sum capacity of the "Proposal - Optimum" and the "Proposal with SB (Alg. 1)" is only less than 3% and 4%, respectively, below the provided joint numerical solution.

Furthermore, we investigate the impact of the maximum distance between the DUE_T and DUE_R (i.e., d_{max}) on the sum capacity in Fig. 3 for $N = 10$. It is obvious that the longer d_{max} is, the lower sum capacity is observed. The reason for such behavior is that the signal between the DUE_T and the DUE_R is more attenuated for a larger d_{max} and the D2D communication becomes less efficient. Figure 3 also shows that the proposal with sequential bargaining outperforms all competitive algorithms significantly and also overcomes the proposal with m-greedy. The gain introduced by the proposed algorithm with sequential bargaining ranges from 16.4% to 180%, from 53% to 166%, and from 73% to 187% in comparison to the No reuse, Single reuse, and ECP algorithms,

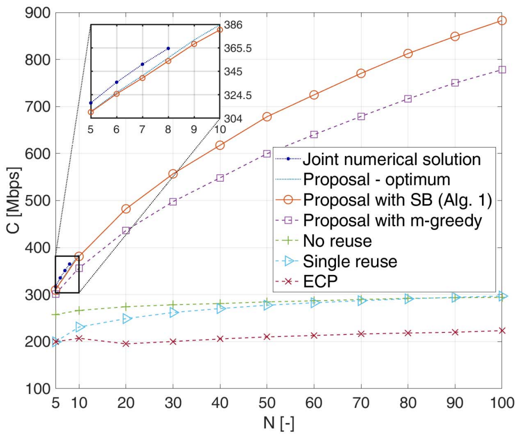


Fig. 2. Sum capacity of D2D pairs over number of D2D pairs for $d_{max} = 50$ m.

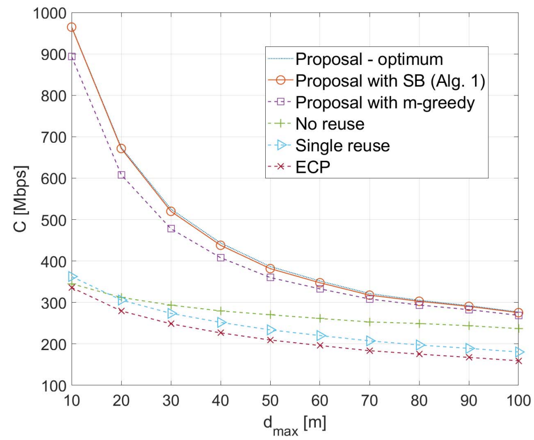


Fig. 3. Sum capacity of D2D pairs over maximum distance between transmitting and receiving device within D2D pair and for $N = 10$.

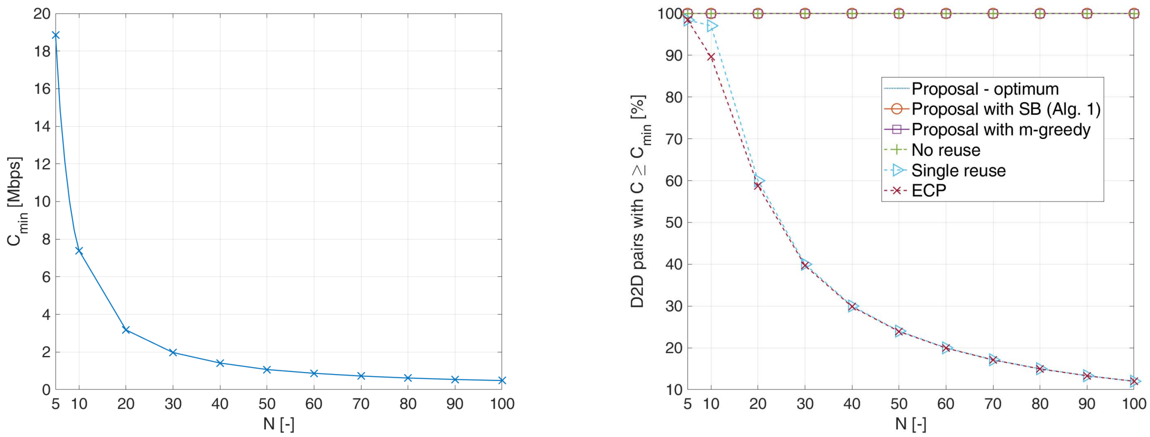
respectively. The proposal with m-greedy reaches from 2% to 10% lower sum capacity with respect to the sequential bargaining. The gain is less significant for a larger d_{max} as the interference among D2D pair is more significant with respect to the useful signal and the possibility of sharing communication channels decreases. From Fig. 3, we further see that the proposed low-complexity algorithm with sequential bargaining reaches almost the optimal capacity obtained by the dynamic programming disregarding d_{max}.

The proposed algorithm is designed to guarantee the minimal capacity C_{min} to all D2D pairs (see (3)). The minimal capacity C_{min} is derived as the capacity that is guaranteed to all D2D pairs in the case of no reuse (according to [8] and [9] as explained in (2) in Section II-A). The minimal capacity C_{min} decreases with the number of D2D pairs N, since the bandwidth B is divided among a higher number of D2D pairs (see Fig. 4a). In Fig. 4b, we verify the fulfillment of the constraint on C_{min}. The proposals with optimal coalitions, sequential bargaining as well as with m-greedy guarantee C_{min} for every D2D pair over all investigated numbers of D2D pairs in all simulation drops. Thus, although every D2D pair is exposed to interference from other D2D pairs in the same coalition, there is no D2D pair that experiences a capacity below C_{min}. Note that there is no difference between the percentage of the satisfied D2D pairs for the proposed algorithm with optimal coalitions' creation and sequential bargaining-based coalitions' creation. Also No reuse algorithm (proposed in [8] and [9]) satisfies C_{min} for all D2D pairs. In contrast, the Single reuse algorithm and the EPC do not guarantee C_{min} to all D2D pairs due to the equal channel bandwidth allocation and limited channel reuse.

2) Analysis of the Proposed Resource Allocation Scheme: In this subsection, we analyze the impact of individual sub-parts of the proposed scheme on the sum capacity of D2D pairs and the contribution of individual sub-parts to the gains achieved with respect to the competitive algorithms. To that end, we show the impact of the following individual sub-parts of the proposed algorithm:

1) *Proposal - opt. BW*: Illustrates the gain of stand-alone proposed initial channel bandwidth allocation for scenario with the background interference (Section III-A) while no channel reuse is considered. This way we show the impact of interference on the bandwidth allocation with respect to [8] and [9], where the authors neglect this interference.
2) *Proposal - reuse only*: Performance of the stand-alone proposed channel reuse (Section III-C) is demonstrated on the top of the channel bandwidth allocation according to [8], [9], i.e., if the n-th D2D pair has the bandwidth $B_n = \frac{g_{n,n}}{\sum_{n=1}^{n=N} g_{n,n}} B$ while the transmitting power among all channels is distributed equally.
3) *Proposal - reuse with opt. BW*: One can expect that the consideration of interference for the bandwidth allocation can influence also the efficiency of the reuse phase. Thus, we present this scheme in order to demonstrate the contribution of the derived initial bandwidth allocation (i.e., combined Section III-A and Section III-C). As this algorithm also assumes the equal power allocation over all channels, the gain of the proposed power allocation over channels is illustrated by the difference between this algorithm and the proposal with sequential bargaining.

For the sake of Fig. 5 clarity, we do not show the performance of the optimal coalitions' creation and we depict only the No reuse algorithm [8], [9], which serves as a basis for the bandwidth allocation performance. We see that a high gain ranging from 19.5% to 106% with respect to No reuse algorithm is introduced by the reuse of multiple channels by multiple D2D pairs (as proposed in Section III-C, in Fig. 5 labeled as "Proposal - reuse only"). The gain is a result of the proposed reuse of channels by the D2D pairs whenever it is beneficial. In addition, Fig. 5 also shows that the gain introduced by the proposed initial bandwidth allocation considering the background interference (in Fig. 5 depicted as "Proposal - opt. BW" and derived in Section III-A) with respect to the same approach disregarding the interference (i.e., No reuse according to [8] and [9]) introduces only a gain of up to 8.1% for $N = 50$. However, if the proposed



(a) (b)

Fig. 4. Minimum capacity C_{min} that can be guaranteed to all D2D pairs according to (2) (a), and percentage of D2D pairs for which C_{min} is guaranteed (b).

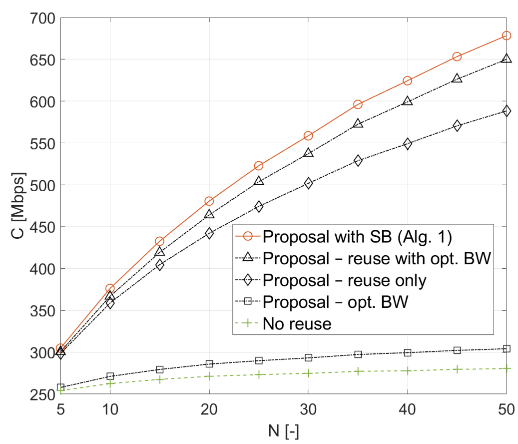


Fig. 5. Impact of individual subparts of proposed algorithm (bandwidth allocation, channel reuse, power allocation) on sum capacity of D2D pairs ($d_{max} = 50\,m$).

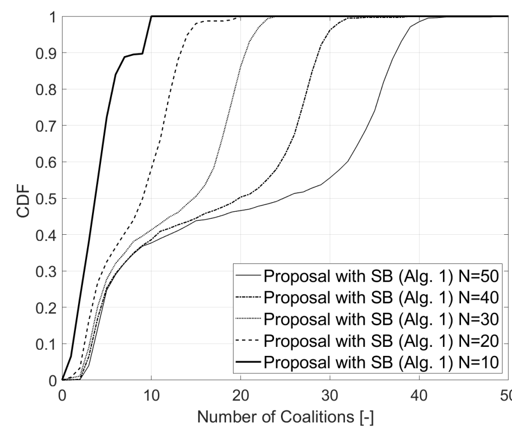


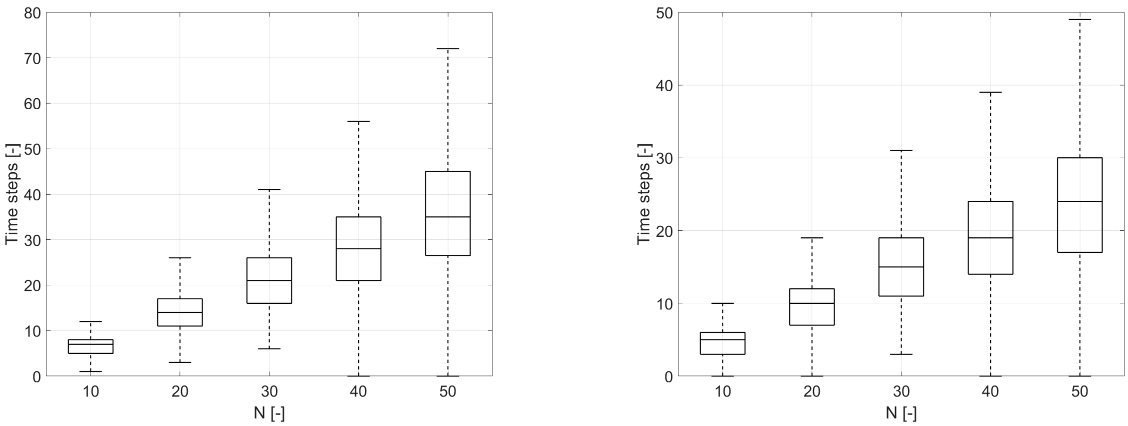
Fig. 6. CDF of number of coalitions created by the sequential bargaining for different numbers of D2D pairs.

initial bandwidth allocation considering interference is applied together with the proposed reuse ("Proposal - reuse with opt. BW" in Fig. 5), the synergy effect of both leads to an additional gain of up to 22.5% added on the top of the reuse gain. The reason for such gain of the proposed initial bandwidth allocation applied together with the reuse is that the bandwidths of the individual channels are derived with respect to the background interference. If the interference from the adjacent cells is neglected for the bandwidth allocation, the reuse phase is impaired by the non-optimal bandwidth allocation and, consequently, some well-performing coalitions are not established.

The impact of the proposed power allocation (determined in Section III-D) is represented by the difference between two top lines in Fig. 5 ("Proposal with SB (Alg. 1)" and "Proposal - reuse with opt. BW"). The additional gain with respect to No reuse (up to 8.6%) is a result of the power allocation over the channels assigned to each D2D pair taking into account the inequality among the bandwidths of these channels.

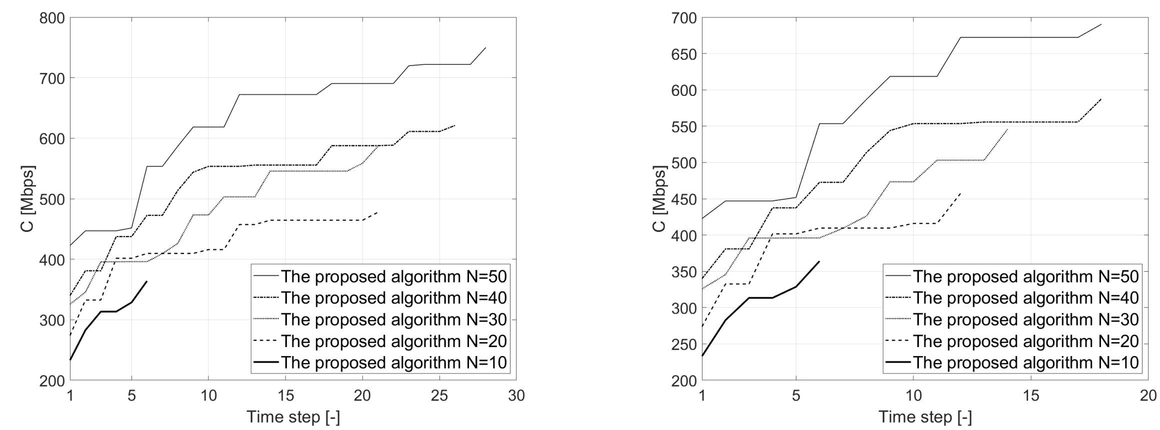
In addition to the analysis of the impact of individual subparts of the proposed algorithm, we also give more insight into the size of the resulting coalitions. Cumulative distribution function of the number of coalitions resulting from the proposed sequential bargaining game (see Section III-C) is depicted in Fig. 6. In roughly 40% of the cases, less than ten coalitions are created disregarding the number of pairs. This relatively low number of coalitions indicates that there is a high probability that multiple D2D pairs reuse the channels of other D2D pairs. The figure shows that at least one coalition is composed of more than one D2D pair (i.e., the channel(s) are reused) in 90%, 99%, and 100% of the cases for $N = 10$, $N = 20$, and $N > 20$, respectively. In other words, almost always, the number of created coalitions is lower than the number of D2D pairs N, thus, multiple D2D pairs reuse multiple channels. Note that each D2D pair represents one coalition if this D2D pair communicates only at its dedicated channel without reuse.

3) Feasibility of the Proposed Scheme: The worst case time complexity of Algorithm 1 is $\mathcal{O}(N^2 log N)$, since the bilateral utility matrix $\boldsymbol{U}$ in (10) is of $N \times N$ size and its entries



(a) (b)

Fig. 7. Number of time steps corresponding to number of bargaining sub-games required to reach 95% (a) and 90% (b) of the sum capacity of D2D pairs.



(a) (b)

Fig. 8. Example of evolution of sum capacity over time steps in one drop for different number of D2D pairs N. The endpoint for each line illustrates the step when 95% (a) and 90% (b) of sum D2D capacity is reached.

are sorted in descending order (sorting of n elements results in the complexity $\mathcal{O}(nlog(n))$. Nevertheless, the proposed algorithm is based on the bargaining sub-games that are played sequentially over time. Thus, we investigate also the feasibility of the proposed scheme for real networks by analyzing the convergence of the proposed algorithm. The number of time steps of the proposed algorithm over the number of D2D pairs N to reach 95% and 90% of the maximum capacities is illustrated in Fig. 7a and Fig. 7b, respectively. The figures confirm that reaching 95% and 90% of the maximum capacity is quick even for a high number of D2D pairs. For realistic scenarios with, for example, 20 D2D pairs, only 14 and 10 steps (bargaining sub-games) are performed in average to reach 95% and 90% of the maximum sum D2D capacity, respectively. Even for 50 D2D pairs (which is rather an extreme case for an area of 500×500 m), only 35 and 24 time steps in average are carried out to reach 95% and 90% of the maximum capacity. Note that the complexity of dynamic programming is 3^N, thus, the complexity of the sequential bargaining-based solution is negligible.

We also show a step-by-step increase in the sum capacity of D2D pairs after each sub-game is played out for selected samples of results in Fig. 8. The capacity is increasing steeply during the first steps and promptly converges close to the maximum. Even after very first steps, the gain with respect to the best performing competitive solution is significant (up to 281.5 Mbps in average for No reuse [8], [9] as shown in Fig. 2). The low number of time steps and the steep growth of the sum capacity over the time steps, demonstrated in Fig. 7 and Fig. 8, confirm the feasibility of the proposed solution for the real-world mobile networks.

V. Conclusion

In this paper we have proposed a new resource allocation scheme allowing multiple pairs to reuse multiple channels for the D2D communication in the dedicated mode. The proposed resource allocation scheme encompasses an initial bandwidth allocation, channel reuse, and power allocation over the reused channels. The channel reuse is presented as a coalition structure generation problem, where the D2D pairs composing one coalition reuse the channels dedicated to each other. The coalition structure generation problem is optimally solved by the algorithm based on dynamic programming. As the dynamic programming is of a high complexity, we also develop a low-complexity sequential bargaining algorithm solving the reuse problem while reaching close-to-optimal sum capacity of D2D pairs. The performance analysis shows that the sum capacity of D2D pairs is significantly increased by the proposed resource allocation scheme compared to the existing algorithms. In addition, although the interference is imposed among D2D pairs reusing the same channel, the minimal required capacity for each D2D pair is still guaranteed after the channel reuse.

A potential future direction should aim at a power control among D2D pairs in every coalition in order to further increase the spectral efficiency. Another topic for further study is the allocation of resources when the multiple channels are used by multiple D2D pairs without the requirement on forcing the D2D pairs to reuse their channels only mutually while still guaranteeing the minimal capacity to each D2D pair.

Appendix A

To solve the problem of channel bandwidth presented in (4), we adopt the approximation $log_2(1+\gamma_{n,n}) \approx log_2(\gamma_{n,n})$ like in Section III-D and under the same assumptions. By applying this approximation into sub-problem (4) and after several simple mathematical operations, the objective function from (4) is rewritten as:

$$\begin{aligned}\sum_{n=1}^{n=N} B_n log_2\left(1+\frac{p_{n,n}\, g_{n,n}}{\sigma_o B_n + I_d}\right) &= \sum_{n=1}^{n=N} log_2\left(\frac{p_{n,n}\, g_{n,n}}{\sigma_o B_n + I_d}\right)^{B_n}\\ &= log_2 \prod_{n=1}^{n=N}\left(\frac{p_{n,n}\, g_{n,n}}{\sigma_o B_n + I_d}\right)^{B_n} \qquad (14)\end{aligned}$$

We target an interference-limited network, see Section II-A, allowing us to assume that $\sigma_n + I_d \approx I_d$. Hence, the objective function of (4) presented in (14) is simplified to:

$$log_2 \prod_{n=1}^{n=N}\left(\frac{p_{n,n}\, g_{n,n}}{I_d}\right)^{B_n} \qquad (15)$$

By the integration of (15) into (4) and by substituting $p_{n,n}$ by P_{max} in the objective function according to the constraint (d) in (4), the sub-problem (4) is presented as:

$$\begin{aligned}\mathbf{B}^{**} &= argmax\, log_2 \prod_{n=1}^{n=N}\left(\frac{P_{max}\, g_{n,n}}{I_d}\right)^{B_n}\\ \text{s.t. } & B_n log_2\left(\frac{P_{max}\, g_{n,n}}{I_d}\right) \geq C_{min}\\ & \forall n \in \{1,2,\dots N\} \quad (a)\\ & 0 < B_n \leq B \quad \forall n \in \{1,2,\dots N\} \quad (b)\\ & \sum_{n=1}^{n=N} B_n = B \quad (c) \qquad (16)\end{aligned}$$

The constraint (a) ensures that the approximated capacity of every n-th D2D pair on the n-th dedicated channel with no-reuse is higher than the minimal capacity C_{min}. The constraints (b) and (c) are the same constraints as described in (4).

The maximization of any function $f = log_2(f')$ can be solved by maximizing f'. The problem (16) is in a form of argmax$[(a_1)^{B_1}(a_2)^{B_2}\dots(a_N)^{B_N}]$, where $a_1, a_2, \dots, a_N$ are constants. Thus, taking into account the constraints (b) and (c), maximizing (16) is achieved by assigning the maximum possible part of the bandwidth to the D2D pair with the maximal a_n. In other words, the D2D pair with the highest $g_{n,n}$ is granted with the maximal allowed part of the dedicated bandwidth. However, the constraint (a) should be also satisfied. We are able to guarantee C_{min} if any n-th D2D pair is allocated with a channel of a bandwidth equal to $B_n = \frac{C_{min}}{log_2\left(1+\frac{P_{max} g_{n,n}}{\sigma_{max}+I_d}\right)}$, where σ_{max} is the highest possible expected noise at the channel with the bandwidth B_n. The noise σ_{max} is, then, estimated as follows. The D2D pair with the lowest channel quality (i.e., the pair with $g_{n,n}^{min}$) is allocated with a channel of a bandwidth $\frac{g_{n,n}^{min}}{\sum_{n=1}^{n=N} g_{n,n}} B$ to guarantee C_{min}. Thus, any other n-th D2D pair requires less bandwidth to guarantee C_{min}, since the channel gain of the n-th D2D pair is always higher than $g_{n,n}^{min}$. Thus, the noise at the channel of the n-th D2D pair with the bandwidth B_n is at most equal to the noise at the channel dedicated to the D2D pair with the lowest channel quality (i.e., $\sigma_n = \sigma_n B_n \leq \sigma_o \frac{g_{n,n}^{min}}{\sum_{n=1}^{n=N} g_{n,n}} B = \sigma_{max}$). Hence, the bandwidth of the channel dedicated for any n-th D2D pair always guaranteeing C_{min} is:

$$B_n = \frac{C_{min}}{log_2\left(1+\frac{P_{max} g_{n,n}}{\sigma_o \frac{g_{n,n}^{min}}{\sum_{n=1}^{n=N} g_{n,n}} B + I_d}\right)} \qquad (17)$$

This concludes the proof.

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