A Constrained Coalition Formation Game for Multihop D2D Content Uploading

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***Abstract*—This paper investigates relay-based schemes in cellular systems, where multihop Device-to-Device (D2D) communications are exploited for content uploading toward the eNodeB. All User Equipments (UEs) are sources of their own content and form a "multihop D2D chain", with the head of the chain being in charge of uploading all the generated contents to the eNodeB. By pooling the cellular radio resources assigned to the D2D chain and by using high-quality short-range radio links, the proposed *cooperative content uploading* scheme guarantees lower upload delays than in the traditional cellular mode operation. To model the D2D chains formation in a cell and to best characterize self-interested users concerned about their own payoff, a *constrained coalition formation game* is defined, where each UE is a *player* whose cost is identified as the content upload time. The solution of the game determines the *stable feasible partition* for the UEs in the cell. We demonstrate through simulations that with this solution the content uploading time is reduced by 52% with respect to the traditional cellular mode.**

***Index Terms*—D2D communications; Constrained Coalition Formation Game; Content Uploading; LTE-A.**

I. Introduction

Device-to-Device (D2D) communications between User Equipments (UEs) in mutual proximity is a promising technology to enhance the performance of cellular systems in terms of, among others, improved spectrum utilization, higher throughput, and lower energy consumption [1], [2]. The focus of this paper is on the design of D2D-based schemes for efficient *content uploading* in future cellular systems. Scenarios of interest are crowded places, where groups of UEs gather at an aggregation place like a stadium to attend a sport or a music event, or they approach a touristic attraction and intend to upload their own-generated multimedia content (e.g., photos or videos of the points of interest). Public safety and disaster recovery are additional scenarios of interest, where first responders gather and need to upload some content from the incident area timely and reliably to a control center. Clearly, the mentioned scenarios have different service quality requirements and constraints, e.g., in terms of content upload latency and reliability, which must be met by any designed content uploading solution.

In a traditional cellular system, end-user devices do not cooperate, so each of them separately uploads its own content to the eNodeB, with the risk of spectrum crunch and poor service quality in crowded places. In this "non-cooperative" case, a UE located far from the eNodeB could suffer from low channel quality and not be able to upload a high-quality video flow within a time frame that is considered as "acceptable". This may be of high concern in an emergency scenario, for example. To cope with this issue, the UE far from the base station may use another UE in the proximity, with a higher-quality uplink, as a *relay*.

Along this line, the basic idea proposed in this paper is that a set of UEs "cooperate" to upload their contents to the eNodeB by forming a "multihop D2D chain", where the UEs located farther from the base station relay their content to a nearby UE and only the UE at the head of the chain, the so-called *gateway*, is in charge of uploading all the contents received from the other UEs to the eNodeB. The UEs in the chain are all sources of their own content and cooperate to forward the content generated by the preceding nodes in the chain toward the gateway, thus benefiting of the higher quality of the short D2D links w.r.t. the direct cellular link. The gateway is the UE with the highest link quality in the chain; it may receive, if needed, all the radio resources that would have been separately allocated by the eNodeB to the UEs in the D2D chain. We will demonstrate that all the UEs in the chain can upload their content to the eNodeB at the quality required by the application while also saving time w.r.t. the traditional cellular mode. The focus will be on video content uploaded at a wished target quality, but the proposed solution has a general validity and can be easily extended to any content type and any "acceptable" latency required by the specific application. The main factors with a positive effect on the content upload performances are: (i) the "multihop D2D chain" exploits the node with the best uplink toward the eNodeB for final content upload; (ii) short-range D2D links are used that have higher quality than the corresponding cellular uplinks; (iii) the allocated resources for all devices in the multihop D2D chain are pooled to the single gateway. The necessary condition for the cooperative relaying solution to bring benefits compared to the non cooperative one is that the quality of the multihop chain to the eNodeB is higher than the quality of the separate links, which is more likely to occur in non-isotropic propagation environments with obstacles [3].

In the remainder of the paper, we consider *self-interested* UEs, which are aware of the fact that cooperation can reduce their content uploading time, but they are concerned about their own *payoff*. This is a fundamental difference from typical multihop routing problems [4], where the objective is to achieve optimal performance disregarding the *rationality* of the involved entities. For this reason, we will resort to game theory for modeling the problem of chain formation.

The main contributions of this paper can be summarized as follows:

- We define a *constrained coalition formation game* that forms the multihop D2D chains in a cell under the constraint of reciprocal UEs visibility for the direct links activation.
- We model the uploading time through a multihop D2D chain as a function of the number of UEs forming the chain, the quality of each generated video content, and the links status.
- We analyze the stability of the proposed game, and demonstrate that the algorithm converges to a stable coalition structure, where all players are happy to join the formed network partition and do not have incentives to leave the coalition they are part of.
- We evaluate the effect of some networking parameters, such as the scheduling policy and the number of UEs in the cell, on the proposed game and on the system performance. The average gain in terms of uploading time w.r.t. the traditional cellular mode is up to 52%.

In the remainder of the paper, after scanning the main related works in Section II, the reference system model is presented in Section III; in Section IV the constrained coalition formation game is presented with the uploading time modeling, whereas in Section V the performance evaluation is discussed. Conclusive remarks are given in the last section.

II. Related Work

The number of recent papers addressing D2D communications is wide [5], and the potential applications range increases, from mobile data offloading [6], to cell coverage extension [7], to content sharing/dissemination [8], [9], [10]. Moreover, D2D has been recently considered for wearable devices [11], for multimedia content dissemination [12], [13], and for social-aware video multicasting [14]. The focus so far has been mainly on downlink services; notwithstanding, uplink direction scenarios are of undoubted interest as witnessed by recent publications, such as [15], where relaying by smartphones is proposed to send out emergency messages from disconnected areas. Multihop D2D communications have been investigated in a very few recent works. In [16] network-assisted D2D communication is addressed with an analysis on power control and mode selection. However, this refers to a traditional two-hop scenario, with a UE or the eNodeB as the last hop node. Similarly, multihop D2D communication is considered in [17] for end-to-end Machine-to-Machine connectivity. Differently from our proposal, resources dedicated to cellular and D2D links are orthogonal either in time or in frequency (i.e., *overlay* resource allocation), thus co-channel interference is avoided.

Another feature of our approach that makes it different from traditional multihop routing problems [4], where the objective is to optimize a given path metric (e.g., minimize the number of hops, the links cost, etc.), is that the multihop path selection has to considers the presence of *self-interested* UEs that are concerned about their own *payoff* when they act cooperatively (i.e., in our case, reducing the upload time). We exploit a coalition formation game to form *stable* D2D chains in a cell coverage area. Stability implies that all players interested in their own payoff do not find motivations to leave the coalition they are part of. The same type of game theoretic model has found applications in several wireless networking problems [18], such as in vehicular networks [19], virtual MIMO systems [20], ad-hoc networks [21], for Cloud providers federation [22] and [23]. Only recently, game theory and coalitional games have been successfully applied also to a few D2D communication problems. In particular, in [24] game-theoretic models are applied to D2D radio resource allocation and numerous open issues are identified. In [25] the uplink radio resource allocation is studied when multiple D2D pairs and cellular users share the available resources. In [26], game theory is applied to ensure energy-efficient D2D resource allocation; in [27] a simple coalitional game is studied for energy-efficient D2D communications in public safety networks. The main difference of the cited works compared to our proposal is the transferable utility for the proposed game. In fact, in our work the cost for the players in a coalition, expressed as the content uploading time, cannot be apportioned arbitrarily among the players. Furthermore, we use a *constrained* coalition formation model to include the coverage constraints for the D2D links so that only *feasible* coalitions are formed. Finally, the above mentioned D2D-related works focus their attention to pairs of directly connected UEs, and the coalitions typically include D2D pairs and cellular users. Differently, in our paper the attention is on multihop consecutive D2D links within a single coalition.

III. System Model and Problem Formulation

We consider a single cell in the Long Term Evolution-Advanced (LTE-A) network, with multiple UEs interested in uploading their own content to the Internet. In the traditional *cellular-mode*, separate links are activated from each UE to the eNodeB for content upload over the allocated uplink radio resources. With the proposed *cooperative upload* instead, some UEs in reciprocal proximity may establish D2D links and form what we call a “coalition” so that a UE with a poor uplink channel quality can utilize a nearby UE with a better link conditions as a relay for content upload toward the eNodeB. Under the control of the eNodeB, the UEs in a coalition organize themselves to form a “logical multihop D2D chain” and cooperate in uploading the content generated by *all* of them to the eNodeB. Each UE in the chain, but the last one, behaves as a content *source* and as a *relay*, as illustrated in Fig. 1. In particular, the UE at the end of the chain only transmits its own generated content but has no content to forward on behalf of other nodes; all the other nodes in the chain *also* act as relays for the contents received from the upstream UEs. They manage two active D2D links: an *incoming* link to receive data from the previous source in the logical chain and an *outgoing* link to relay data (its own and the received one from the incoming link) to the subsequent UE in the chain. The source at the head of the chain is the UE with the best uplink channel conditions and acts as a *gateway*; it receives all the relayed contents from the chain and is in charge of uploading it to the eNodeB.

We assume network-assisted D2D chains formation under the control of the eNodeB. In general, only the UEs in the

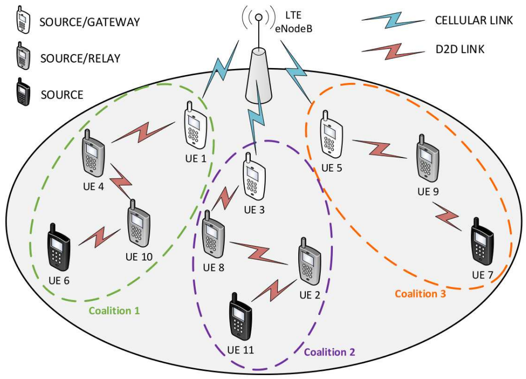


Fig. 1. Multihop D2D-based content uploading.

cell that are in mutual coverage can establish direct links, and this needs to be carefully modeled as a constraint for the multihop D2D chain formation. Uplink resources are allocated to D2D links in Time Division Duplex (TDD) mode[1]. Devices in the same coalition may share the same resources, whereas devices in different coalitions are always allocated to orthogonal frequency resources by the scheduler at the eNodeB, so that no mutual interference is caused by different coalitions (this is a reasonable assumption, used in other works [25]). Cellular links are modeled as a Rayleigh fading channel and D2D links as a Rician fading channel [29]. We refer to the *type 2 configuration 0* LTE frame structure [30] composed of six out of ten subframes (or Transmission Time Intervals, TTIs) of 1 ms duration dedicated to uplink (U). At each frame beginning, the eNodeB executes the Radio Resource Management (RRM) policy during the $2ms$ duration of a downlink (D) and a special (S) subframes preceding the first U subframe. Each UE operates in half-duplex mode; thus, it either receives or transmits in a given TTI (U subframe).

We consider a reasonable assumption for *rational* self-interested devices, that each UE uploads its own generated content first, and then the content received by the preceding UEs in the chain, but only after having received the whole content (in other words, UEs use the decode-and-forward relaying protocol). In each U subframe, the half-duplex UEs may either receive from the previous UE in the chain or relay data to the next node in the chain. By numbering the position of the nodes in the chain progressively starting from the gateway, when a generic node i transmits to node $(i-1)$, the nodes $(i-1)$ and $(i+1)$ are in receiving mode. Consequently, in a given subframe, the first UE in a chain can transmit simultaneously with all the UEs in odd positions (i.e., the third, the fifth, the seventh, and so on), while the UEs in an even position (i.e., the second, the fourth, the sixth UE and so on) receive data. Similarly, when the even UEs transmit, the odd UEs receive in a given U subframe. In particular, simultaneously transmitting UEs within the same coalition can use either the same or different frequencies, based on the decision of the eNodeB according to the interference level experienced on each direct link. There are two extreme cases that we will consider in this paper: the *best-case* that corresponds to "no interference", where the same radio resources can be reused on the D2D links, and the *worst-case*, where simultaneous transmissions interfere and so orthogonal resources have to be used. In this latter case, to avoid interference on simultaneous D2D transmissions, we assume that the radio resources used on the D2D links are only those ones allocated to the specific D2D pair in the uplink toward the eNodeB by the scheduler.

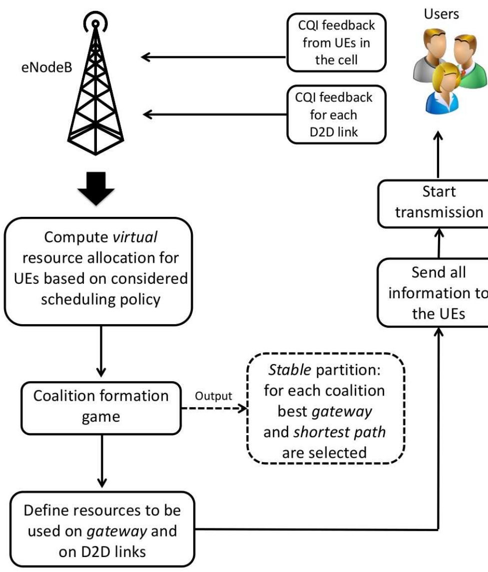


Fig. 2. Flowchart of the proposed solution.

The RRM algorithm implemented by the eNodeB is summarized in the flow chart in Fig. 2. Preliminarily, the eNodeB measures the *Channel Quality Indicators* (CQIs) of the uplink from all UEs in the cell and collects from each UE the CQIs relevant to the direct links with all its neighbors[2]. Then, the eNodeB assists the users in the chain formation process by implementing the proposed solution as illustrated in the following. In the first step the eNodeB computes the radio resources allocated to the UEs as if they were transmitting separately on the uplink according to the scheduling policy detailed in Section III-A. These resources are "virtual" in the case the UEs will form a coalition and will be used as the *pool* of resources allocated to the gateway[3]. Based on this initial information, the eNodeB implements the coalition formation algorithm (see Section IV). As a result, stable coalitions are formed in the cell, the roles of each node in the coalition is identified, and routing path is defined.

Focusing on a feasible coalition, a step-wise decision algorithm determines the *best path* that covers all the nodes in

[1]Assigning uplink resources to D2D links guarantees a more efficient reuse w.r.t. a downlink allocation [28]. The TDD mode poses less issues than the Frequency Division Duplex (FDD) mode in terms of terminal design, cost and complexity [1].

[2]We assume ideal channel feedback and do not study the impact of errors in the CQI estimation.

[3]We assume that the eNodeB assigns to the gateway of each coalition a *pool* of uplink resources, which can reach up to the sum of the radio resources separately requested by the UEs in the coalition (if less resources are needed for the coalition, then the eNodeB will not allocate the whole sum of separately allocable resources).

the chain. In particular, the eNodeB first sorts the devices in a decreasing order of uplink CQI (first those with better channel quality) and then selects the first node in the list as the *gateway* for the coalition. This is important, so that the resource pooling will produce the highest throughput toward the eNodeB for the whole multihop chain. Once the gateway is selected, the *best path* over the set of nodes is computed with focus on the D2D link qualities. We consider a simple *greedy* approach where the next hop from the gateway is selected as the one in the one-hop vicinity with the best D2D link quality. Similarly, each node in the chain will select its neighbor based on the best CQI of the direct link to the remaining nodes in the coalition. Once the coalitions are formed in the cell, the eNodeB determines the radio resources assigned to the gateway and to each D2D link and transmits all the information to the UEs so that the transmissions can start.

A. Virtual resources allocation and data rate computation

The eNodeB manages the available radio spectrum in terms of *Resource Blocks* (RBs)[4]. It assigns the scheduled number of RBs to each UE and selects the modulation and coding scheme (MCS) for each RB. The scheduled resources are based on the relevant CQI computed by the eNodeB according to the measured signal to interference plus noise ratio (SINR) on each UE-to-eNodeB link. Let us define the following sets: $\mathcal{N} = \{1, \ldots, n \ldots, N\}$, the set of UEs in the cell; $\mathcal{M} \subseteq \mathcal{N} = \{m_1, \ldots, m_M\}$, the set of UEs operating in cellular mode; $\mathcal{D} \subset \mathcal{N} = \{d_1, \ldots, d_D\}$, the set of UEs operating in D2D mode; $\mathcal{W} = \{1, \ldots, w, \ldots, W\}$, the set of RBs in the system; and $\mathcal{G} = \{1, \ldots, g, \ldots, G\}$ the set of MCSs in the system [31]. To compute the "virtual" radio resource allocation, the eNodeB determines the RB assignment $\rho_{w,n}$ and the power allocation $Pt_{n,w}$ $\forall w \in \mathcal{W}$ and $\forall n \in \mathcal{N}$, so that a utility U is maximized:

$$\max_{\rho_{w,n}, Pt_{n,w}} U, \text{ subject to: } \begin{cases} \sum_{w=1}^{W} Pt_{n,w} \le P_{\max_n},\ Pt_{n,w} \ge 0 & \forall n \in \mathcal{N} \\ \sum_{n=1}^{N} \rho_{w,n} = 1 & \forall w \in \mathcal{W} \\ \rho_{w,n} \in \{0,1\} \end{cases} \quad (1)$$

where the first constraint limits the transmitted power, with $P_{\max_n}$ being the maximum power for UE n; the second constraint states that all RBs should be allocated, and the last constraint shows that no subcarrier can be allocated for uplink transmission from multiple UEs. Function U can have different definitions in terms of the specific objectives. For instance, for the case of Maximum Throughput (MT) we have: $U = \sum_{n=1}^{N} \sum_{w=1}^{W} \rho_{w,n} log_2(1+\gamma_{n,w})$, for the case of Proportional Fair (PF) we have: $U = \sum_{n=1}^{N} \sum_{r=1}^{W} ln[\rho_{w,n} log_2(1+\gamma_{n,w})]$ where $\gamma_{n,w}$ is the SINR on the cellular link from UE n in RB w. In the performance evaluation section, we will compare the results for the MT and the PF schedulers with those achieved by the Round Robin (RR) policy and a MaxMin fair scheduler (MM) proposed in [32].

[4]The RB corresponds to the smallest time frequency resource (12 subcarriers) that can be allocated to a UE in LTE. For example, a channel bandwidth of 20MHz corresponds to 100 RBs.

The computational complexity of the joint subcarrier and power allocation problem for the multi-user Orthogonal Frequency-Division Multiple Access (OFDMA) system as LTE has been demonstrated in [33] to be NP hard, which is computationally prohibitive (the second formulation proposed in the cited paper corresponds to our problem). A possible way to solve it is through a two-step approach with lower complexity as proposed, e.g., in [34], so that an acceptable suboptimal performance can be achieved. In the first step, the RBs are allocated according to the specific scheduler rules (MT, PF, MM, or RR), based on the assumption of *equal power allocation for all UEs, uniformly distributed over the available RBs*. In the second step, the power level is decided on the performed RB assignment [35].

According to the free space propagation loss model, the power received by a generic UE j in RB w on the direct link $i \rightarrow j$ can be written as: $Pr_{j,w} = Pt_{i,w} \cdot \left|h_{i,j}\right|^2 = Pt_{i,w} \cdot Pl_{i,j}^{-\alpha} \cdot |h_0|^2$, where $Pt_{i,w}$ is the transmitted power from UE i in RB w, $h_{i,j}$ is the length of the link $i \rightarrow j$, h_0 is the channel coefficient, $Pl_{i,j}$ is the path loss on the link $i \rightarrow j$, and α is the path loss compensation factor computed by the eNodeB based on the operation environment (in the [0,1] range). Assuming that all subcarriers in an RB experience the same channel conditions, the SINR $\gamma_{j,w}$ in RB w for the generic user j on a link $i \rightarrow j$ is: $\gamma_{j,w} = \frac{Pt_{i,w} \cdot Pl_{i,j}^{-\alpha} \cdot |h_0|^2}{\mathcal{I}_{j,w} + N_0}$, where N_0 is the thermal noise density level at the receiver, and $\mathcal{I}_{j,w}$ is the set of interfering signals received by user j on RB w, which has different values in case of either a D2D or a cellular transmission. In particular, the interference on a transmission from a cellular user m to the eNodeB denoted by bs is given by the power signals of all the UEs transmitting in D2D mode on the same RB UE m is transmitting in cellular mode [25]. Given the RBs allocated to the single UEs and the transmission power level for each RB, the SINR value determines the MCS g to be used for the uplink and the corresponding spectral efficiency eff_w (*bits/symbol*). Thus, the bit rate $R_{m,g,w}$ and the throughput $TP_{m,g,w}$ of an uplink cellular transmission from UE m, when using MCS g in RB w, is defined as in [36]:

$$R_{m,g,w} = \Theta \cdot eff_w = \frac{CS_{ofdm} \cdot SY_{ofdm}}{T_{subframe}} \cdot eff_w \quad (2)$$

$$TP_{m,g,w} = R_{m,g,w} \cdot (1 - BLER(w, \gamma_{m,w})) \quad (3)$$

where Θ is a fixed parameter depending on the network configuration, CS_{ofdm} and SY_{ofdm} are the number of subcarriers and symbols per RB respectively, $T_{subframe}$ is the time duration of an RB, and $BLER(w, \gamma_{m,w})$ is the BLock Error Rate suffered by RB w. When focusing on a D2D link, the interference at the receiver d' is given by the power signals of all the D2D UEs $d'' \in \mathcal{D} \setminus \{d, d'\}$ and the cellular user m that are reusing the same RB as the receiver d'. Similar to the cellular links, the SINR value determines the MCS level g to be used for the direct link and the corresponding spectral efficiency eff_w (*bits/symbol*) in RB w. The bit rate $R_{d,g,w}$ and the throughput $TP_{d,g,w}$ for a D2D link transmission follow the formulations given in (2) and (3).

IV. A Constrained Coalition Formation Game for the Cooperative D2D Content Uploading

A non transferable utility (NTU) coalitional game in cost form is defined by the pair $(\mathcal{N}, C)$ where $\mathcal{N} = \{p_1, \ldots, p_N\}$ is the set of N players and C is a set valued function such that for every coalition $\mathcal{S} \subseteq \mathcal{N}$, $C(\mathcal{S})$ is a closed convex subset of $\mathbb{R}^{|\mathcal{S}|}$ that contains the cost vectors the players in $\mathcal{S}$ can achieve ($|\mathcal{S}|$ is the number of members in coalition $\mathcal{S}$). In our problem, the players are the single UEs forming a cooperative D2D chain. The objective for the players is to minimize their cost which is measured as the time required to upload their content to the eNodeB. Since this cost cannot be arbitrarily apportioned among the players in a coalition, we have an NTU game. Moreover, the game is in characteristic form because the cost of each player only depends on the players forming the coalition it is part of and not on the other players in the network. In particular, this is because players in different coalitions are not causing mutual interference as orthogonal RBs are allocated by the scheduler.

A *collection* of coalitions $\mathcal{K}$ is defined as a set $\mathcal{K} = \{\mathcal{S}_1, \ldots, \mathcal{S}_k\}$ of mutually disjoint coalitions $\mathcal{S}_i \subset \mathcal{N}$ such that $\mathcal{S}_i \cap \mathcal{S}_{i'} = \emptyset$ for $i \neq i'$. If the collection contains all players in $\mathcal{N}$, i.e., $\bigcup_{i=1}^{k} \mathcal{S}_i = \mathcal{N}$, then the collection is a *partition* Π or *coalition structure (CS)*. The set of all possible *coalition structures* is identified by $\Pi(N)$. A cost game is said *subadditive* when, given any two disjoint coalitions $\mathcal{S}_1$ and $\mathcal{S}_2$, if coalition $\mathcal{S}_1 \cup \mathcal{S}_2$ forms, then it can give its members any allocations they can achieve when acting in $\mathcal{S}_1$ and $\mathcal{S}_2$ separately [18]. Intuitively, if the game is subadditive, then it is always convenient that players cooperate and join larger coalitions. However, in many real problems this is not always true as there may be inherent constraints on *feasible coalitions* which should be taken into consideration. The motivations behind these constraints are linked to the specific problem and can derive from technological, social, historical or reputation aspects. For instance, from prior experience it may be known that in order to successfully execute a given task certain alliances of players are indispensable, thus the corresponding coalition is useful, or, on the contrary, specific combinations of players are known to under-perform, so they are to be excluded because considered as harmful. Similarly, constraints may exist on the size of the coalitions to be formed.

In our problem setting some pairs of UEs may not be in reciprocal visibility to set up a D2D link. This indeed introduces a constraint on the *feasible* coalitions that can be formed. To characterize the *feasible* coalitions and coalition structures, we formally define the constraints to the problem with a set of *positive constraints* $\mathcal{P} \subseteq 2^N$ such that a coalition $\mathcal{S}$ satisfies a constraint $P \in \mathcal{P}$ if $P \subseteq \mathcal{S}$, a set of *negative constraints* $\mathcal{Q} \subseteq 2^N$ such that a coalition $\mathcal{S}$ satisfies a constraint $Q \in \mathcal{Q}$ if $Q \nsubseteq \mathcal{S}$, and a set of *size constraints* $\mathcal{Z}$ that defines the constraints on the coalitions size [37]. We formally define the *cooperative D2D-uploading game* in cost form as a tuple $G =< \mathcal{N}, \mathcal{P}, \mathcal{Q}, \mathcal{Z}, C >$ where $\mathcal{N}$ is the set of UEs in the cell and $\mathcal{S} \subseteq \mathcal{N}$ is any multihop D2D chain, C is the set of cost vectors the players can achieve in all coalitions $\mathcal{S} \subseteq \mathcal{N}$, $\mathcal{P}$ and $\mathcal{Q}$ subsets of $\mathcal{N}$, and $\mathcal{Z} \subseteq \mathbb{N}$. We say that coalition $\mathcal{K} \subseteq \mathcal{N}$ is *feasible* for $G =< \mathcal{N}, \mathcal{P}, \mathcal{Q}, \mathcal{Z}, C >$ if: (i) $P \subseteq \mathcal{K}$ for some $P \in \mathcal{P}$; (ii) $Q \nsubseteq \mathcal{K}$ for all $Q \in \mathcal{Q}$; and (iii) $|\mathcal{K}| \in \mathcal{Z}$. The set all feasible coalitions is denoted by $f(\mathcal{N}, \mathcal{P}, \mathcal{Q}, \mathcal{Z})$. For a locally constrained game, we say that a coalition structure CS is feasible if and only if $CS \subseteq f(\mathcal{N}, \mathcal{P}, \mathcal{Q}, \mathcal{Z})$. In this paper, we only consider negative constraints that are a consequence of bad channel conditions on the D2D links and we set $\mathcal{P} = \emptyset$, $\mathcal{Z} = \emptyset$. For the exact definition of $\mathcal{Q}$ the eNodeB considers the D2D CQI feedback from the UEs. In particular, those coalitions for which a path cannot be constructed are considered *not feasible* and thus stored in $\mathcal{Q}$. When $\mathcal{Q} \neq \emptyset$, it is implicitly said that the grand coalition is not formed as it is certainly not a *feasible* coalition. Nevertheless, also when $\mathcal{Q} = \emptyset$, that is when all UEs are in mutual coverage for a D2D link, the game can be demonstrated to be *non-subadditive* in general. To solve the so-defined game we take inspiration from traditional coalitional game formation solutions and apply them to the feasible coalitions only.

A. Coalition cost for the content uploading game

For the considered game, we define $C : \mathcal{S} \rightarrow \mathbb{R}^{|\mathcal{S}|}$ such that $C(\emptyset) = \emptyset$, and for any coalition $\mathcal{S} \subseteq \mathcal{N} \neq \emptyset$ it is a singleton set $C(\mathcal{S}) = \{\mathbf{c}(\mathcal{S}) \in \mathbb{R}^{|\mathcal{S}|}\}$ where each element of the vector $\mathbf{c}(\mathcal{S})$ is the cost $c_i(\mathcal{S})$ associated to each player $i \in \mathcal{S}$. This cost is defined as the uploading time needed for the data generated by node i to reach the eNodeB. Similarly, the cost $c(\mathcal{S})$ of any coalition $\mathcal{S} \subseteq \mathcal{N}$ is computed as the total uploading time needed for all data generated in the coalition to reach the eNodeB. In particular, the cost for any singleton coalition is equal to the content uploading time in the cellular mode for the single player i. This is computed when the UE uploads its content b_i over its cellular link (i.e., directly to the eNodeB) having a data rate r_i^c: $c(\{i\}) = \frac{b_i}{r_i^c}$. For any coalition $\mathcal{S} \subseteq \mathcal{N}$ with cardinality $|\mathcal{S}| > 1$ instead, the associated cost is defined as $c(\mathcal{S}) = UT(\mathcal{S})$, where $UT(\mathcal{S})$ is the data uploading time modeled in the rest of this Section. If the multihop D2D chain cannot be formed due to coverage constraints, then we define: $c(\mathcal{S}) = \sum_{i \in \mathcal{S}} c(\{i\})$.

Let each UE $i \in \mathcal{N}$ have a video file of a given time duration and a predetermined quality ready to upload to the eNodeB. These two parameters determine the data size $b_i \neq 0$ of the content to upload. We know that the "virtual" radio resources for the UEs in a multihop D2D coalition are available to the gateway if needed. As a result of having more resources available, a higher uplink data rate $r_i^{c'}$ is obtained for the gateway-to-eNodeB link. Then, we say r_i^d the data rate for UE i on the D2D outgoing link to the next UE in the multihop chain. To define the $c(\mathcal{S})$ term we will compute the number of LTE frames required to transfer all the content from the UEs in the coalition to the eNodeB. To do this, we proceed to quantify the time intervals and the TTIs needed for data transmission on the D2D links, by following the listed steps:

1) Compute the channel occupation time for a generic UE i in the multihop D2D chain; this is the time spent by the UE to transmit to the next hop its own data and the data received from the previous UE in the chain.

2) Compute the time to upload the contents of the entire chain; to this aim compute the number of U subframes used by the gateway and the second UE in the chain to relay the received data to the eNodeB and to the gateway, respectively.
3) Based on the data frame structure, compute the number of data frames according to the time in terms of TTIs required for uploading all data in the chain.

Regarding the first step, let us consider UE N, the last UE in the chain. For the sake of notation simplicity, once the best path over the UEs in a coalition is computed (i.e., the multihop chain is identified), we consider the N-hop path with $i = 1$ being the gateway and $i = N$ being the last UE in the path. UE N will occupy the channel for a time $T_N = b_N/r^d_N$ to forward its data of size b_N to UE $N-1$ over the D2D link having data rate r^d_N. Considering UE $N-1$, to send its own data of size b_{N-1} and the data received from the previous UE which is of size b_N the channel will be occupied for a time $T_{N-1} = b_{N-1}/r^d_{N-1} + \left(b_N/r^d_N + b_N/r^d_{N-1}\right)$. By repeating this reasoning for all UEs in the chain, and considering that the gateway, UE 1, transmits to the eNodeB with a data rate $r^{c'}_1$, we compute the channel occupation time $T_1(N)$ for the gateway to upload all data from the D2D chain to the eNodeB as a function of the number of UEs in the chain:

$$T_1(N) = \frac{b_1}{r^{c'}_1} + \left(\frac{b_2}{r^d_2} + \frac{b_2}{r^{c'}_1}\right) + \left(\frac{b_3}{r^d_3} + \frac{b_3}{r^d_2} + \frac{b_3}{r^{c'}_1}\right) + \dots + \left(\frac{b_N}{r^d_N} + \frac{b_N}{r^d_{N-1}} + \dots + \frac{b_N}{r^{c'}_1}\right) = \sum_{i=1}^{N}\left(\frac{b_i}{r^{c'}_1} + \sum_{j=2}^{i}\frac{b_i}{r^d_j}\right). \quad (4)$$

The formulation can be generalized to the channel occupation time for any UE $n = \{1, \dots, N\}$ in the multihop chain. This includes the time to forward to the next hop in the chain all data generated by UE n and the data from its previous UEs in the chain as given below.

$$T_n(N) = \begin{cases} \sum\limits_{i=n}^{N}\left(\frac{b_i}{r^{c'}_1} + \sum\limits_{j=2}^{i}\frac{b_i}{r^d_j}\right) & n = 1 \\ \sum\limits_{i=n}^{N}\sum\limits_{j=n}^{i}\frac{b_i}{r^d_j} & n > 1 \end{cases} \quad (5)$$

Considering step 2, since all UEs in a cooperative multihop D2D chain generate data, and given the decode-and-forward relaying assumption, the total uploading time $T(N)$ will be determined by the sum of the occupation time of the first two UEs in the chain: $T_1(N)$ and $T_2(N)$. Hence, we can compute the corresponding number of uplink subframes. Given the *type 2 configuration 0* LTE frame structure, when relaying data from previous UEs toward the eNodeB, the gateway will use all six available U subframes when all the data from the previous UEs have been received. Only at that time, no subframe is used to receive additional data. Before that moment, only three U subframes per LTE data frame can be used by the gateway to transmit to the eNodeB, since the other three are used to receive data from the previous UEs. On the other hand, on all the D2D links the UEs will use three U subframes per frame to transmit and three subframes per frame to receive data. Based on these considerations, we can split the $T_1(N)$ term into two contributions (see (6)), namely one contribution (i.e., $T'_1(N)$) where three subframes per frame are used by UE 1 to upload data, and a second term (i.e., $T''_1(N)$) where six subframes per frame are used by UE 1 to upload data. In particular, the second term has a different value according to the relation between $\frac{b_{N-1}}{r^{c'}_1}$ and $\frac{b_N}{r^d_N}$. The first case refers to the situation where the data from UE N reaches the gateway only after all data from the other UEs in the chain have already been uploaded to the eNodeB. In this case, six subframes are used to upload the data from UE N only. In the other cases, besides the data from UE N, also a portion of data from UE $N-1$ will be uploaded using six subframes.

$$T'_1(N) = T_1(N) - T''_1(N)$$
$$T''_1(N) = \begin{cases} \frac{b_N}{r^{c'}_1} & \frac{b_{N-1}}{r^{c'}_1} \leq \frac{b_N}{r^d_N} \\ \frac{b_N}{r^{c'}_1} + \frac{b_{N-1} - (b_N/r^d_N)\cdot r^{c'}_1}{r^{c'}_1} & \frac{b_{N-1}}{r^{c'}_1} > \frac{b_N}{r^d_N} \end{cases} \quad (6)$$

The number of U subframes $F(N)$ required to transmit all data is computed by simply dividing the occupation time of the first two UEs in the chain by the U subframe duration (TTI=1ms): $F'_1(N) = T'_1(N)/TTI$, $F''_1(N) = T''_1(N)/TTI$ and $F_2(N) = T_2(N)/TTI$.

In step 3, the total number of data frames required for uploading data from all the UEs in the D2D chain can be determined as: $\left\lceil \frac{F'_1(N)}{3} + \frac{F''_1(N)}{6} + \frac{F_2(N)}{3} \right\rceil$. Being ten the total number of TTIs in the LTE data frame, the total content uploading time to the eNodeB, i.e., the cost in coalition $\mathcal{N}$, is given by the number of data frames needed:

$$c(\mathcal{N}) = UT(N) = 10 \cdot TTI \cdot \left\lceil \frac{F'_1(N)}{3} + \frac{F''_1(N)}{6} + \frac{F_2(N)}{3} \right\rceil. \quad (7)$$

Finally, the uploading time of a specific UE in the D2D chain can be computed according to the UE position in the chain that determines the priority order for data transmission. The data delivery time from the last UE in the chain, UE N, is equal to the total time: $UT^N(N) = UT(N)$. The data delivery time from a generic UE i is computed by repeating the same reasoning on the sub-chain from n to the gateway, so the cost for player i in the coalition is $c_i(\mathcal{N}) = UT^i(N) = UT(i)$.

B. Feasible coalition formation algorithm

The set of all possible partitions of $\mathcal{N}$ has a total number of B_N, where B_N is the N-th Bell number [38], and it grows exponentially with the number of UEs N. Thus, finding the optimal partition via exhaustive search through all possible partitions is not feasible, as it is an NP-complete problem [39]. To characterize the *feasible coalitional structure* to form for the game, we propose simple merge-and-split rules [40]. The key mechanism is to enable players to join or leave a coalition based on well-defined preferences so that each player is able to compare and order its potential coalitions based on which coalition it prefers to be a member of [41].

Definition 1 (Preference order): The preference order $\succ_i$ for any player $p_i \in \mathcal{N}$, is defined as a complete, reflexive, and transitive binary relation over the set of all feasible coalitions that player p_i can possibly form, i.e., the set Π_i of coalitions containing p_i.

A UE can decide to join or leave a coalition according to its preference order. In particular, for each player p_i, if $C \succ_i C'$, p_i prefers being a member of coalition C more than coalition C'. A less restrictive preference order is $C \succeq_i C'$, whereby player p_i prefers coalition C at most as much as coalition C'. In this paper, the preference order is defined according to its *individual cost*. Thus, for each UE $p_i \in \mathcal{N}$ and for all $C, C' \in \Pi_i$, we say that:

$$C \succ_i C' \Leftrightarrow c_i(C) < c_i(C') \wedge c_j(C') \leq c_j(C' \backslash \{i\}), \forall j \in \{C' \backslash \{i\}\} \wedge \\ c_j(C) \leq c_j(C \backslash \{i\}), \forall j \in \{C \backslash \{i\}\}. \quad (8)$$

In words, any UE i prefers being a member of coalition C over C' if it obtains a lower individual cost $c_i(C)$, without causing an increase in the cost for any other player in C and C' (*Pareto order* preference). The preference order is at the basis of the two rules for the coalition formation game.

Definition 2 (Merge rule): Merge any pair of coalitions C and C' into a unique *feasible* coalition $\{C \bigcup C'\} \Leftrightarrow [(\exists\, k \in C$ s.t. $\{C \bigcup C'\} \succ_k C) \vee (\exists\, k \in C'$ s.t. $\{C \bigcup C'\} \succ_k C')] \wedge \{C \bigcup C'\}$ *is feasible*.

Definition 3 (Split Rule): Split any coalition $\{C \bigcup C'\}$ in *feasible* coalitions $\{C, C'\} \Leftrightarrow [(\exists\, i \in C$ s.t. $C \succ_i \{C \bigcup C'\}) \vee (\exists\, j \in C'$ s.t. $C' \succ_j \{C \bigcup C'\})] \wedge \{C, C'\}$ *are feasible*.

The merge rule implies that two coalitions join to form a larger *feasible coalition* if operating all together strictly reduces the cost of at least one player, while all the other involved players do not experience a higher cost. The split rule implies that a coalition splits only if there exists at least one player that obtains a lower cost, under the constraint that this has no negative effect on the cost of the other players and the resulting coalitions are both *feasible*.

The game is implemented by the eNodeB, as summarized in Algorithm (1). The objective of a UE is to find a coalition that guarantees the lowest uploading time through an iterative application of the merge and the split rules. By starting from an initial partition $\Pi^{ini}(N) = \mathcal{N} = \{p_1, p_2, \ldots, p_N\}$, the eNodeB iteratively applies the merge and split rules to any pair of coalitions in the partition. In particular, the merging process stops when no couple of coalitions exists in the current partition $\Pi^{cur}(N)$ that can be merged. Thus, the split rule is applied to every coalition in the partition, by updating $\Pi^{cur}(N)$ if a split is applied. When no split occurs, the algorithm considers again the merging function. The algorithm terminates when no merging or splitting occurred in the last iteration. In this case, the final resulting partition $\Pi^{fin}(N)$ will be adopted by the eNodeB. Moreover, the network structure is adapted to environmental changes by periodically repeating the solution computation. In particular, in a dynamic environment, the period of time for the update should be chosen depending on how rapidly the conditions change.

Considering the finite number of partitions, it can be proved by contradiction that the proposed merge and split coalition formation algorithm converges to a *stable* final partition of disjoint coalitions of UEs (for more details see, e.g., [40]).

Algorithm 1: Coalition formation for cooperative D2D multihop data uploading

Data: Set of UEs $\mathcal{N}$
Result: Coalition structure Π^{fin}
Phase I - Neighbor Discovery:
- Each UE discovers neighboring UEs and sends feedback to the eNodeB about the CQI on the corresponding D2D links.
- Partition the network by $\Pi^{ini}(N) = \mathcal{N} = \{p_1, p_2, \ldots, p_N\}$.
- Set the current partition as $\Pi^{cur}(N) = \Pi^{ini}(N)$.

Phase II - Coalition Formation:
In this phase the eNodeB performs the coalition formation using merge-and-split.
repeat
  repeat
    For every UE $i \in \mathcal{N}$ in the current partition $\Pi^{cur}(N)$:
    - UE i investigates possible *merge* operation using the preference order given in (8).
    - If a *merge* operation is performed update the current partition $\Pi^{cur}(N)$.

  until *no merge occurs*;
  repeat
    For every UE $i \in \mathcal{N}$ in the current partition $\Pi^{cur}(N)$:
    - UE i investigates possible *split* operation using the preference order given in (8).
    - If a *split* operation is performed update the current partition $\Pi^{cur}(N)$.

  until *no split occurs*;
until *no merge nor split occur*;
Phase III - Cooperative content uploading:
- The network is partitioned using $\Pi^{fin}(N) = \Pi^{cur}(N)$.
- The eNodeB informs the UEs how to operate using the multihop D2D relaying.

Adaptation to network changes (periodic process): Periodically the algorithm is repeated to allow the network topology configuration to adapt to environmental changes.

C. Complexity analysis

The complexity of the proposed algorithm is related to the iterative implementation of merge-and-split operations. Let us consider the worst case for the merge operation, where each coalition needs to make a merge attempt with all the other coalitions in the partition. At the beginning, all UEs act non-cooperatively and form N singleton coalitions. In the worst case, the first merge occurs after $\frac{N(N-1)}{2}$ attempts, the second requires $\frac{(N-1)(N-2)}{2}$ attempts and so on [42], [43]. The total worst case number of merge attempts is $O(N^3)$ [23]. However, in practical settings, the merge process requires a significantly lower number of attempts. In fact, after the first run of the algorithm, the initial N singleton coalitions will merge to form larger coalitions.

As regards the split rule, splitting can imply finding all the possible partitions of size two for each coalition in the current network partition. However, the split operation is restricted to the already formed coalitions, which are typically not the grand coalition. This reduces the complexity. Moreover, complexity is further reduced by the fact that, in a practical setting, it is not required to go through all the split forms. As soon as a coalition finds a split form, the UEs in this coalition will split, and the search for further split forms is not required.

In any case, it is important to underline that solving the proposed merge-and-split based algorithm has a complexity far lower than optimally solving the coalition formation problem (which is unfeasible, due to its NP-complete nature [39]). The actual reduction in the merge-and-split complexity w.r.t. to the worst case will also become evident in the performance evaluation in Section V. For instance, in case of 26 UEs in the network, the observed average number of coalitions will be in the order of 5, which means a reduction of a factor of 5.2 in the maximum number of the future merge attempts. Similarly, the average number of UEs per coalition is also of a few UEs per coalition, which means that the split attempts are also reduced w.r.t. worst case.

D. Possible model extensions

A possible extension of the proposed model implies to consider alternative topologies for the cooperative D2D coalitions to form. For instance, a tree topology can be formed where, any intermediate UE can receive content from multiple branches of cooperative D2D UEs. In a generic configuration, a relay (or the gateway) will have one or more links active to receive data from the preceding sources in the tree topology, and one single link active to forward data (its own generated traffic and the traffic from the incoming D2D links) to the subsequent UE in the topology. This has two main consequences for the model we considered: (i) an alternative game model should be considered, where one or more UEs may be part of multiple coalitions; (ii) the uploading time computation should consider that at the merging points of the tree, where multiple branches converge into a single UEs, the available radio resources are shared.

For what concerns the first point, a tree topology could be nicely modeled with an *overlapping coalitions* model [44], [45], where the coalitions may overlap with each other so that one or more UEs may at the same time be part of multiple coalitions. The remainder of the proposed model with the constraint coalition formation algorithm based on merge and split iterations could be similarly applied. For the uploading time modeling instead, the main considerations made for the chain topology still hold. In particular, when the gateway transmits to the eNodeB, the second UE in the topology will not be able to send its data to the gateway (as the gateway cannot receive its data) during the same uplink subframes. Thus, the third node in the coalition topology can transmit and, similarly, the fifth UE, the seventh UE, and so on. In particular, these UEs will transmit on either the same or on separate RBs, according to the interference level experienced on each link. A small difference is introduced on the resource utilization method adopted on the D2D links, since when a UE has two or more incoming links, then the available RBs on the D2D link should be shared among the incoming D2D links. This leads to a lower data rate on the D2D links and, consequently, the gains may be reduced.

V. Performance Evaluation

A numerical evaluation is conducted by using Matlab® to assess the performance of the proposed solution. We focus on scenarios where the end-users are willing to upload a video to Youtube, which is mostly comprised of short video clips and 97.9% video lengths are within 600 seconds [46]. We assume that the end-users define the video quality to upload beforehand according to the MPEG-2 encoding possibilities [47]. The selected video quality implicitly determines also the amount of data to be uploaded. In fact, MPEG-2 supports different video quality levels with a corresponding maximum bitrate and frame size for each video resolution. In our case, we consider the following bitrate values to characterize the video quality: $[3, 6, 10, 20]$ *Mbps*. As a side note, differences in the data amount mean also differences in the "acceptable" uploading time for the UEs. This parameter can be tuned according to the constraints set by the specific service scenarios in which the proposed solution is applied.

The assessment campaign is conducted by following the system model guidelines in [31]. The main simulation parameters are listed in Table I. A single cell with available radio resources $RB = 50$ is considered, wherein up to 26 UEs are uniformly distributed. Channel conditions for the UEs are measured by the SINR experienced over each subcarrier [48] when path loss and fading phenomena affect the signal reception. As discussed earlier in the paper, the radio resources that can be used on a single D2D link of the multihop chain depend on the frequency reuse efficiency. We consider the two extreme cases: the so-called *best-case*, in which all radio resources can be reused on the D2D links since there is no interference between D2D and uplink transmission, and the *worst-case*, where the transmissions in the multihop D2D chain interfere on all radio resources. In this latter case, the radio resources that can be used on a D2D transmission are limited to the virtual resources allocated by the eNodeB to the involved pairs of UEs. Only results relevant to the two cited cases are reported in the performance analysis, as these represent the lower and upper bounds and all other cases of radio resource re-use on the D2D links fall in-between them. The performance evaluation focuses on: (i) *the UE average data uploading time gain*, (ii) *the multihop D2D chain configuration*, and (iii) *the UE average energy consumption gain*. Here gain is intended as the improvement in the delay and in the energy consumption that is achieved by a cooperative upload w.r.t. a pure cellular upload modality. The analysis also evaluates the effects of the RRM policy implemented by the eNodeB, i.e., *maximum throughput (MT)*, *proportional fair (PF)*, *maxmin fair(MM)*, and *round robin (RR)* schedulers.

Although the main focus is on the data uploading time reduction, we also want to monitor the impact of the proposed scheme on the UEs' energy consumption. In the cellular mode, the energy consumption for a generic UE i is a function of the transmitted amount of data b_i and it is equal to the power consumption on the uplink toward the eNodeB multiplied by the time where the UE is active to transmit: $E_i^c(b_i) = (P_{tx}^c + P_0) \cdot \frac{b_i}{r_i^c}$. In particular, the power consumption of UEs includes two contributions, the transmission power P_{tx}^c and the circuit power P_0, being this latter the power consumed by all the circuit blocks along the signal path that cannot be ignored. When considering the cooperative data uploading, we have three cases: (1) the UE is the gateway; it consumes energy in receiving data from the second UE and in transmitting data to the eNodeB; (2) the UE is the last UE in the chain; it only consumes energy in transmitting its own data to the next UE in the D2D chain; (3) the UE is an intermediate UE in the chain; it consumes energy to receive data from the previous UE and to transmit data to the next UE in the chain. In all three cases, energy is also spent during the idle times on the channel. However, according to [49] the power consumption in idle times is as low as $-50dbm$; therefore, this contribution can be neglected and only the transmitting and receiving power on the D2D links, P^d_{tx} and P^d_{rx}, are considered. The energy consumption for a generic UE i in the D2D chain will be the sum of the energy spent for transmission and for reception: $E_i(N) = Etx^d_i(N) + Erx^d_i(N)$.

$$Etx^d_i(N) = \begin{cases} (P^c_{tx} + P_0) \sum_{j=1}^{N} \frac{b_j}{r^{c'}_1} & i = 1 \\ (P^d_{tx} + P_0) \sum_{j=i}^{N} \frac{b_j}{r^d_i} & 1 < i \le N \end{cases}$$

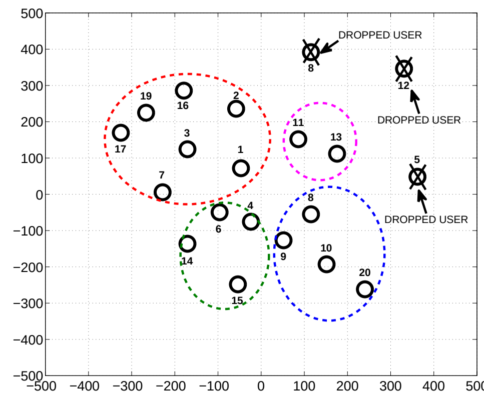
$$Erx^d_i(N) = \begin{cases} (P^d_{rx} + P_0) \sum_{j=i+1}^{N} \frac{b_j}{r^d_{i+1}} & 1 \le i < N \\ 0 & i = N \end{cases} \tag{9}$$

TABLE I
Main Simulation Parameters

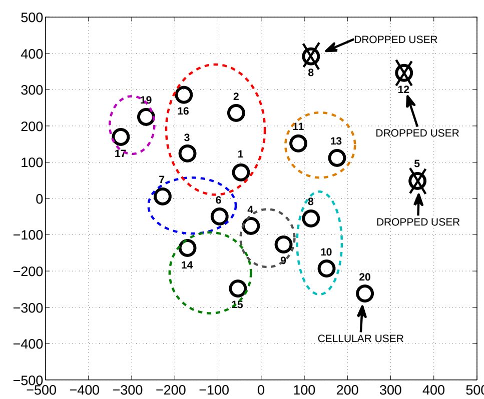
Parameter	Value
Cell radius	500 m
Maximum D2D link coverage	100 m
Frame Structure	Type 2 (TDD)
TTI	1 ms
Cyclic prefix/Useful signal frame length	16.67 μs / 66.67 μs
TDD configuration	0
Carrier Frequency	2.5 GHz
Cellular transmission power consumption	23 dBm
D2D power consumption	-19 dBm
CQI-MCS mapping for D2D links	[50]
Noise power	-174 dBm/Hz
Path loss (cell link)	128.1 + 37.6 log(d), d[km]
Path loss (D2D link, NLOS)	40 log(d) + 30 log(f) + 49, d[km], f[Hz]
Path loss (D2D link, LOS)	16.9 log(d) + 20 log (f/5) + 46.8, d[m], f[GHz]
Shadowing standard deviation	10 dB (cell mode); 12 dB (D2D mode)
Sub-carrier spacing	15 kHz
BLER target	1%
# of Runs	500

A. Analysis of a sample study case

We first focus on a sample study case with the MT resource allocation policy implemented at the eNodeB (similar analysis can be done with the PF, MM and RR schemes). The objective is to investigate the coalition formation process for the case with $N = 20$ UEs in the cell, and to compute the gains for each UE in the cooperative D2D chain. In Fig. 3 the resulting coalitions are shown for the best and worst case analysis. As it can be observed, differences in terms of length and number of coalitions are obtained as a consequence of the resource reuse possibilities on the D2D links. In particular, in the best-case a smaller number of coalitions is formed and longer D2D chains are created (they can reach the length of seven UEs), whereas in the worst-case the longest chain is of four UEs. The motivation for this behavior is related to the lower amount of radio resources available on the D2D links in the worst-case, which reduces the cooperation possibilities and gains. We notice also that three UEs (i.e., UEs 5, 8 and 12) do not receive radio resources from the MT scheduler as they experience very bad channel conditions. Moreover, in the worst-case analysis, UE 20 is not joining any coalition and will operate in traditional cellular mode, since no other UE finds it advantageous to merge with it in a coalition.



(a) Best-case



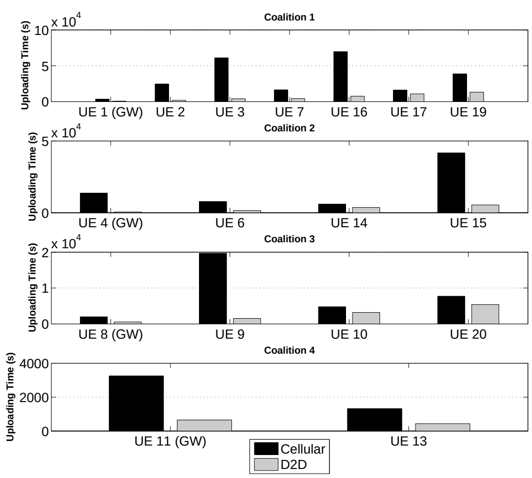
(b) Worst-case

Fig. 3. Coalitions in a sample study case with $N = 20$, based on the MT radio resource allocation policy.

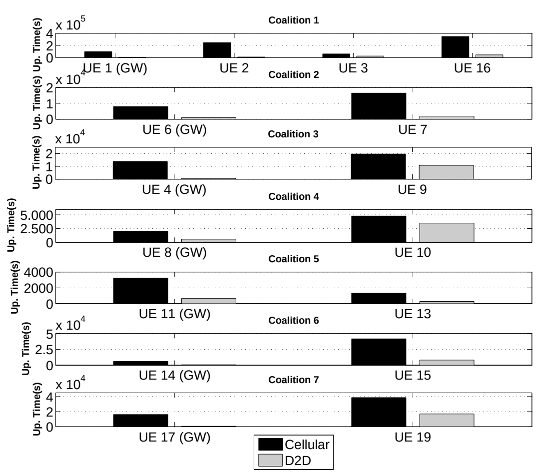
Let us now look into the details of the single coalitions being formed and the uploading time gain for the single UEs. In the plots in Fig. 4, the UE playing the gateway role in each coalition is highlighted with the (GW) notation. The first and most important observation is that all UEs in all the coalitions gain from an uploading time reduction when the cooperative technique is used. This is an expected result according to the individual preference relation set for the single UEs when joining a coalition. In particular, in all coalitions the gateway obtains the highest uploading time gain. This is also an expected result as the radio resources are pooled together and the highest transmission priority is given to the data of the gateway itself.

TABLE II
ENERGY CONSUMPTION, RBS AND DATA SIZE FOR A SAMPLE CASE WITH $N = 20$ AND MT RADIO RESOURCE ALLOCATION.

UE ID	Assigned RBs	Data size [MB]	E^c [Joule]	E^d [Joule] (Best-case)	Energy Gain [%] (Best-case)	E^d [Joule] (Worst-case)	Energy Gain [%] (Worst-case)
1	5	1003	423,94	663,91	**-36,14**	664,40	**-36,19**
2	1	1031	29414,38	0,236	+99,99	1,47	+99,99
3	6	1026	7313,37	0,0319	+99,99	0,22	+99,99
4	1	777	1641,32	663,96	**+59,54**	663,97	**+59,54**
5	X	X	X	X	X	X	X
6	3	68	939,20	0,184	+99,98	995,82	**-5,68**
7	2	873	1964,70	0,083	+99,99	0,0018	+99,99
8	7	991	237,14	597,53	**-60,31**	597,53	**-60,31**
9	2	868	2355,31	0,068	+99,99	0,044	+99,99
10	6	613	572,77	0,071	+99,98	0,020	+99,99
11	5	180	388,59	995,82	**-60,97**	995,85	**-60,97**
12	X	X	X	X	X	X	X
13	3	629	158,58	41,33	+99,99	0,013	+99,99
14	3	971	719,73	0,097	+99,98	665,01	**+7,60**
15	1	733	4995,85	0,045	+99,99	0,56	+99,98
16	1	487	41538,03	0,012	+99,99	0,083	+99,99
17	1	874	1936,45	0,014	+99,99	829,91	**+57,14**
18	X	X	X	X	X	X	X
19	1	699	4630,95	0,0012	+99,99	0,032	+99,99
20	2	1304	923,46	0,031	+99,99	X	X

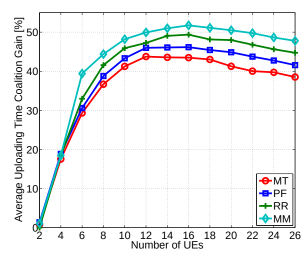


(a) Uploading time for best-case

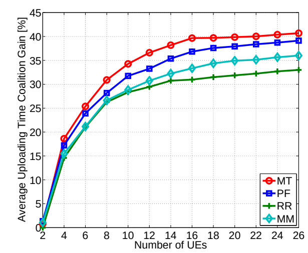


(b) Uploading time for worst-case

Fig. 4. Uploading time for the coalitions in a sample scenario with $N = 20$, based on the MT radio resource allocation policy.



(a) Best-case



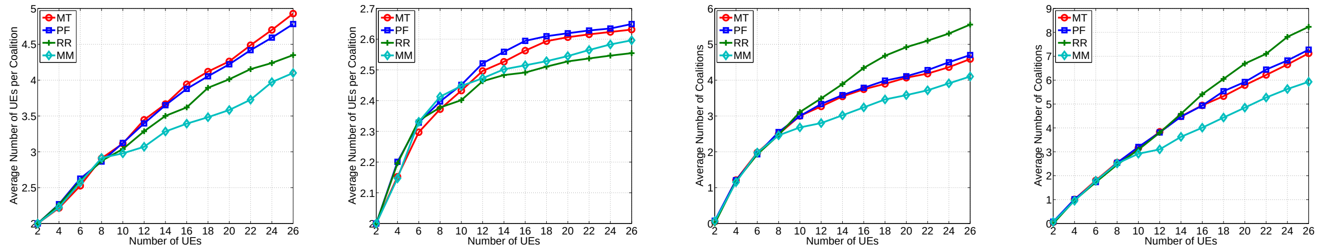
(b) Worst-case

Fig. 5. Average data uploading time gain for UEs in the D2D chain.

To complete this first analysis, in Table II further information is reported about the energy consumption gain, the allocated RBs, and the content size generated by the UEs. It is particularly interesting to observe that all UEs do not only achieve uploading time gains, but in most of the cases, they also achieve energy consumption gains. Surprisingly, also the gateways (highlighted with bold text in the Table) will save energy in some of the coalitions, e.g., UE 4 in the best-case configuration, and UEs 4, 14 and 17 in the worst-case configuration. Noteworthy, this happens for small coalitions when the total data in the chain is small and the transmission time on the cellular links is low. This result is interesting, since although the main objective of the proposed solution is to achieve gain in the data uploading time, also energy saving is obtained in small coalitions thanks to the low power consumption on the D2D links.

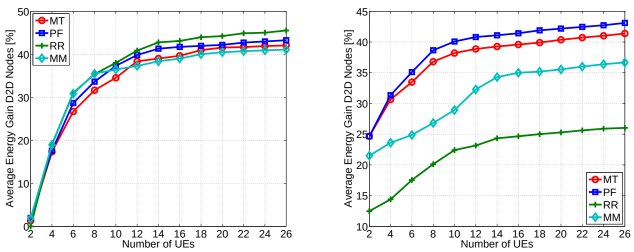
B. Analysis with a variable number of UEs

In Fig. 5 we present the average data uploading time gain in the formed coalitions for a variable number of UEs ($N = 2, \ldots, 26$) uniformly deployed in the cell. As expected, lower gain values are obtained in the worst-case analysis, since less resources can be reused on the D2D links. As it can be noticed, the gain increases with the number of UEs reaching a



(a) Best-case - D2D UEs per chain (b) Worst-case - D2D UEs per chain (c) Best-case - number of D2D chains (d) Worst-case - number of D2D chains

Fig. 6. Configuration of multihop D2D chains as a result of the coalition formation game.



(a) Best-case (b) Worst-case

Fig. 7. Average energy consumption gain for UEs in the D2D chain.

maximum value of $44-52\%$ in the best-case (in the MM, RR, PF, MT decreasing order) with 16 UEs, whereas it slightly decreases for larger numbers of UEs. The main motivation for this trend is that with small numbers of UEs a higher number of RBs can be allocated to the single UEs by the scheduler. This increases the potential gains introduced by the resource pooling at the gateway and leads to a higher average uploading time gain for the formed coalitions. To further sustain this aspect, we performed a further set of simulations with a lower number of RBs in the system, namely 25 RBs. The results showed (plots are not presented here due to length constraints) that in this case the average uploading time gain in the cooperative coalitions has a peak value at 8 UEs. On the other hand, with the UEs being uniformly distributed in the cell, the more UEs considered, the higher is the probability of having one or more UEs with high CQI. Most of the considered schedulers allocate more RBs to these nodes (the extreme case is the MT not serving "bad" users) and, as a consequence, these nodes are less interested in forming large coalitions, whereas the remaining nodes have lower potential gains (due to the lower allocated RBs).

When observing the worst case the average uploading time gain for the formed coalitions reaches a maximum value of $33-41\%$ with 26 UEs (with the MT, PF, MM, RR decreasing order). Differently from the best case, we do not observe a peak value with a decreasing trend after that peak. The reason for this is that since the D2D links are less performing due to the high interference, the average gains over the formed coalitions is lower and smaller coalitions are formed in all cases (this will be shown in the next Figures). As a consequence the obtained gains are on average lower for any value of UEs in the system.

Finally, as observed in the sample study case presented in the previous section, when considering the single UEs in the D2D chains, it can be observed that, in almost all cases, the gateway has a much higher gain w.r.t. to the last UE in the chain, whereas the other UEs will have a gain falling in-between the two previous cases (plots are not reported due to length constraints). The reason behind this is again that the first UE will have many more resources to upload its own data first. This is an important observation when also considering that, in general, the first UE will also have higher energy consumption, as commented later in this section. Noteworthy, also in these cases some of the UEs with bad channel conditions are dropped by the scheduler or are working in cellular mode in singleton coalitions and the number of singleton coalitions is larger in the worst-case analysis.

We next consider the results for the average number of UEs that is joining a multihop D2D chain and length in Fig. 6. In particular, in Fig. 6(a) and Fig. 6(b) the average number of UEs joining a multihop D2D chain is reported for the best-case and the worst-case analysis, respectively. This value increases with the total number of UEs in the cell. In particular, in the best-case the average length ranges between 2 and 5, whereas in the worst-case it ranges between 2 and 2.6. The average number of coalitions being formed, reported in Fig. 6(c) and Fig. 6(d), increases with the number of UEs with a maximum of 5.6 and of almost 8.2, in the best and worst-case respectively.

To conclude the performance evaluation, we consider the average energy consumption for the UEs in the D2D chain. We observe that all the cooperating UEs except the gateway save their energy; see Fig. 7 where the average energy consumption gain for the best and worst-case analysis is reported for all the UEs but the gateway. This positive side-effect can reach a 46% gain in the best-case and 43% in the worst-case. Noteworthy, the scheduling policy has a higher impact in the worst-case analysis. Finally, we observe that in some of the tested cases, in particular with small coalitions, the gateway also achieves energy savings. As an example, the reader can refer to the UE with ID 4 in the sample case reported in Table II. Even if this is not true in general, the strong benefits achieved by the first UE in terms of uploading time (usually much higher than for the other UEs) justify the assumption of its willingness to act as a gateway for the multihop D2D chain.

Summarizing the results, a different behavior is obtained according to the interference level on the communication links of the single coalitions. In particular, the average uploading time and the energy consumption gains in general increase with the number of UEs in the system, but are higher when the interference level is low. We also observed that the average uploading time gain in the best case is influenced by the number of RBs in the system. In particular, increasing the number of UEs smaller coalitions will be formed leading to lower gains on average. This is not observed in the worst case analysis because the coalition length is already limited by the interference level also when the number of UEs in the system is low. In fact, the average length of the coalitions is in general larger in the best case and the average number of coalitions being formed is consequently lower.

VI. Conclusions

In this paper, multihop D2D communications are studied for UEs in mutual proximity to support enhanced content uploading services in cellular environments. The main objective is to reduce the uploading time for all the UEs while allowing to upload a content of the wished quality and size. This is obtained by exploiting the channel diversity of the UEs and by suitably modeling their cooperative behavior. A constrained coalition formation game is introduced to define stable partitions with feasible coalitions under reciprocal coverage constraints for the D2D links. The cost for the game is modeled as the uploading time for the multihop D2D chain. A wide set of scenarios, with a varying number of UEs, data size, channel conditions, and target video quality for the content to upload, have been evaluated through simulations. Results testify to an average uploading time gain beyond 52% for the UEs, whereas energy savings are also obtained for the UEs. Moreover, all UEs reach the goal of uploading the video at the required quality, which would have required a non-acceptable uploading time in the traditional cellular mode.

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