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When D2D communication improves group oriented services in beyond 4G networks

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Abstract The design of effective radio resource management policies for group-oriented services in beyond-4G networks is attracting the interest of the research community. Along this line, this paper analyzes some novel approaches that take advantages of the Device to Device (D2D) communication paradigm with the aim of improving the session quality experienced by mobile users in terms of delay and energy consumption. The basic idea is to enable receivers with a bad cellular link from the evolved Node B (eNodeB) to receive the multicast service through another mobile device located in proximity over a direct link. Two schemes are proposed that exploit different radio technologies to enable nearby multicast subscribers to establish direct local links, either Long Term Evolution-Advanced (LTE-A) or Wi-Fi Direct. The effectiveness of the proposed solutions is demonstrated through a comprehensive simulative analysis and compared with traditional techniques that only exploit point-to-multipoint communication from the eNodeB to all the group members not taking advantages of the multi-user diversity or alternative network technologies to serve the multicast users.

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1 Introduction

The support of group-oriented services, based on transmissions to selected groups of users, is among the key requirements that are driving the development of wireless systems beyond the fourth generation (4G). For instance, video conferencing, mobile TV, traffic and weather reports, local news, location-based advertisements, and other multimedia services, challenge the next-generation network asking for the deployment of efficient multicast technology. With the aim to support group-oriented services in cellular systems, the 3rd Generation Partnership Project (3GPP) defined the Multimedia Broadcast/Multicast Service (MBMS) [1] standard, which introduced point-to-multipoint data delivery through a single transmission over the radio interface toward multiple destinations that require the same content. Multicasting allows the formation of groups that share allocated resources with clear advantages compared to unicasting in terms of spectral efficiency, transmission power consumption at the base station, and utilization of radio resources.

One of the main issues in the management of multicast communications over cellular systems is that the link adaptation must be performed by the transmitter (i.e., the base station) according to the channel conditions of *all* the users in the multicast group. This aspect may be the cause of several inefficiencies in terms of radio channel utilization and multicast session quality, especially when the receivers experience heterogeneous channel conditions [2].

Long Term Evolution-Advanced (LTE-A) [3] is currently considered as the best candidate to efficiently support group-oriented services in cellular systems, since it promises high data rate, low latency, low cost per bit, high spectrum efficiency, and high system capacity. LTE-A systems also feature Device to Device (D2D) communication [4], whereby two or more mobile devices in mutual proximity are allowed to establish direct local links and bypass the LTE base station (i.e., evolved Node B (eNodeB)).

D2D communication has recently gained momentum in the research community as a means to extend coverage and overcome the limitations of conventional cellular systems [5]. However, direct communications among mobile devices is not only a peculiarity of LTE-A, but whenever communication is inherently local in scope, direct links can be established that use alternative radio technologies like Wi-Fi [6]. The two approaches are also known in the literature respectively as: (i) *inband* D2D (i.e., D2D communication exploiting cellular spectrum), and (ii) *outband* D2D (i.e., D2D communication exploiting unlicensed spectrum) [7]. A comprehensive investigation is still missing about the feasibility of the two solutions and the analysis of their pros/cons, when focused on the support of group-based services.

In this paper we propose radio resource management (RRM) strategies that leverage D2D communications to enhance the state of the art of multicast service delivery in 4G networks and beyond. The idea at the basis of our analysis is to effectively exploit multi-user diversity by not necessarily serving all devices in the group with a point-to-multipoint transmission from the eNodeB, but by reaching those ones experiencing a poor channel quality through a forwarding device (FD) over D2D links. The reference scenario is illustrated in Fig. 1. The FDs are chosen among the multicast members interested to receive the content. After the reception of the content by the eNodeB, these selected devices will also re-transmit the received data in order to reach, through direct short-range communications, the terminals with poor links. Activating direct links between multicast subscribers has the twofold beneficial effect of adopting high-performing modulation and coding schemes (MCS) both (i) in downlink from the eNodeB to the subset of multicast subscribers able to decode the transmitted data, and (ii) on D2D links (exploiting either LTE-A or Wi-Fi resources) between the subset of subscribers acting as FDs and the other interested devices in proximity which were not able to receive the data from the eNodeB. In the proposed solutions the objective is to improve the system performance and the user quality in terms of *time interval required to receive the data* compared to conventional approaches for multicast content delivery. Moreover, it will be shown that the proposed schemes will also play in favour of the *energy consumption reduction* for all the multicast users w.r.t. other approaches available from the literature.

The remainder of this paper is structured as follows. Section 2 focuses on the research background for the proposal and the related work on multicast service delivery solutions. The introduced strategies are illustrated in Sect. 3; a performance evaluation can be found in Sect. 4; finally, conclusive remarks are given in Sect. 5.

2 Background and related work

2.1 LTE-advanced and D2D communication

LTE-A [3] represents the most promising wireless system able to support the growing demand of high quality multicast services. Transmissions in downlink direction adopt

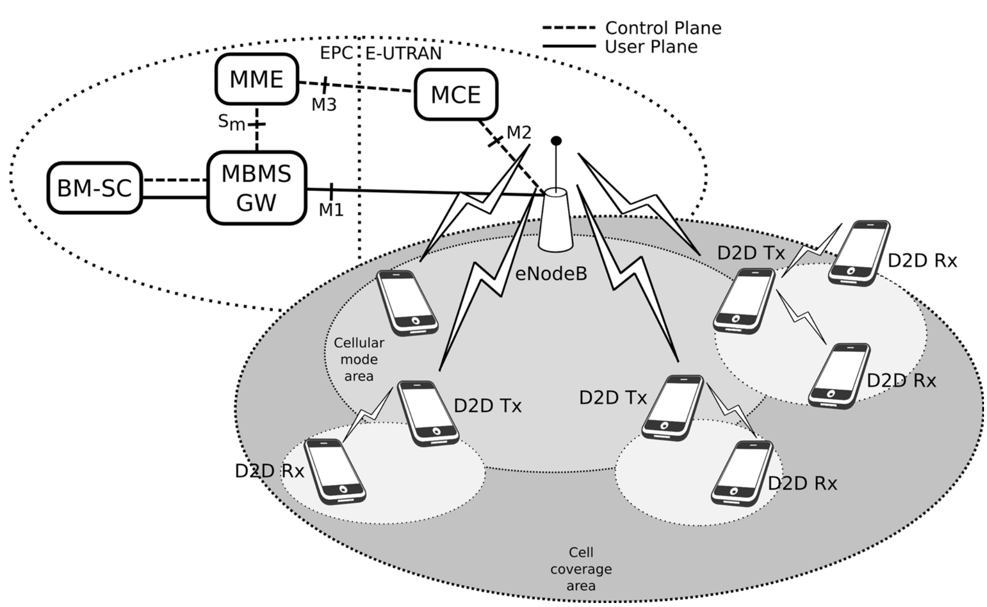


Fig. 1 Cellular multicast transmission enhanced by D2D communications

orthogonal frequency division multiple access (OFDMA). The spectrum is managed in terms of resource blocks (RBs), the smallest radio resource which can be assigned to a user equipment (UE). The overall portion of available RBs is managed by the eNodeB, which efficiently handles the resource allocation in the time and frequency domains. The LTE/MBMS architecture [1] is shown in Fig. 1. The access network is composed of the eNodeB and the MultiCell/Multicast Coordination Entity (MCE), responsible for transmission parameters configuration in single- and multi-cell mode, respectively. The core network includes: Mobility Management Entity (MME) that is responsible for authentication, security, and mobility management procedures; MBMS Gateway (MBMS-GW), a logical entity whose principal function is data packets forwarding to eNodeBs; Broadcast Multicast-Service Center (BM-SC) that is the MBMS traffic source which also accomplishes service announcement and group membership functions.

The frequency domain packet scheduler (FDPS), which performs the link adaptation every transmission time interval (TTI, equal to 1 ms), is of particular interest for the research in this paper. The FDPS assigns the RBs and adapts the MCS according to the channel conditions experienced by the scheduled users. These procedures are performed based on the channel quality indicator (CQI) feedback, an indication of the maximum supported MCS, transmitted by the UE to the base station. Table 1 shows the CQI values defined in the LTE-A standard.

3GPP has recently introduced the support of D2D communications over LTE-A to enable direct connections among mobile devices in mutual proximity [4]. Two solutions are currently investigated. According to the *reuse mode*, D2D nodes reuse some radio resources of the cellular air interface to improve the spectrum utilization. On the contrary, in the *dedicated mode*, D2D links exploit a dedicated portion of spectrum so to avoid interference with cellular UEs. D2D connections can be supported over both frequency division duplex (FDD) and time division duplex (TDD) bands. The TDD mode is more suitable to our research compared to FDD, which poses additional issues in terms of terminal design, cost and complexity [9]. We use as reference the frame structure *type 2* foreseen by 3GPP [3] and *configuration 1* which guarantees an equal number of downlink and uplink slots over the frame, see Fig. 2. The whole radio frame lasts 10 ms and consists of ten subframes of 1 ms each. A special subframe is defined for switching between downlink and uplink transmissions; it is composed of three special fields: Downlink Pilot Time Slot (DwPTS), Guard Period (GP) and Uplink Pilot Time Slot (UpPTS). The length of such fields is configured by the eNodeB under the constraint that the sum must be equal to 1 ms [3].

Table 1 CQI-MCS mapping [8]

CQI index	Modulation scheme	Code rate × 1,024	Efficiency [bit/s/Hz]	Minimum rate [kbps]
1	QPSK	78	0.1523	25.59
2	QPSK	120	0.2344	39.38
3	QPSK	193	0.3770	63.34
4	QPSK	308	0.6016	101.07
5	QPSK	449	0.8770	147.34
6	QPSK	602	1.1758	197.53
7	16-QAM	378	1.4766	248.07
8	16-QAM	490	1.9141	321.57
9	16-QAM	616	2.4063	404.26
10	64-QAM	466	2.7305	458.72
11	64-QAM	567	3.3223	558.72
12	64-QAM	677	3.9023	655.59
13	64-QAM	772	4.5234	759.93
14	64-QAM	873	5.1152	859.35
15	64-QAM	948	5.5547	933.19

D2D communications enable mobile terminals to forward data received from the eNodeB, thus extending the network coverage or supporting content sharing among users [4]. The eNodeB is in charge of link adaptation and resource allocation for D2D links as well as selection of the most efficient transmission mode.

2.2 Wi-Fi direct

Wi-Fi Direct [6] allows mobile devices (e.g., smartphones, tablets) to connect directly over unlicensed bands and transfer content or share applications anytime and anywhere.

Although the idea of supporting direct links was already found in the original IEEE 802.11 standard through the *ad-hoc* mode, the lack of efficient power saving and enhanced QoS support has limited the market penetration of this functional mode [10]. Wi-Fi Alliance recently certified Wi-Fi Direct to support peer-to-peer (P2P) communications between 802.11 devices by jointly exploiting the potentialities of ad-hoc and infrastructure modes. Wi-Fi Direct allows devices to implement the role of either a client or an access point (AP), and hence to take advantage of all the enhanced QoS, power saving, and security mechanisms typical of the infrastructure mode.

Wi-Fi Direct devices can connect for a single exchange, or they can retain the memory of the connection and link together each time they are in proximity. Data communication is accomplished by creating a *P2P group*. When two P2P devices discover each other, they negotiate their roles, i.e., P2P client and P2P group owner (P2P GO). The P2P GO is in charge for service announcement through beacon transmission and supports power saving functionalities for the associated clients. Other P2P Clients can join the group

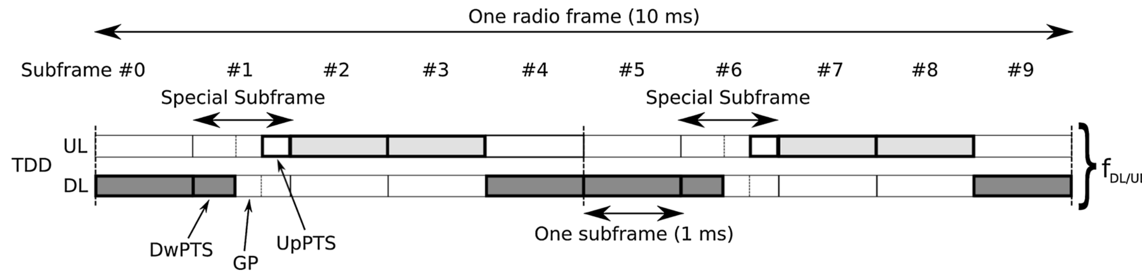


Fig. 2 Frame structure type 2 (configuration 1) [3]

as in a traditional Wi-Fi network. Finally, the P2P GO is in charge for the cross-connection of the devices belonging to its own P2P group to an external network (e.g., an LTE-A network).

2.3 Related work

The focus of this paper is on a group of mobile subscribers in close proximity interested in accessing contents of common interest from the Internet through the cellular network. For instance, groups of students in an aggregation place downloading and exchanging lecture notes and other contents, visitors of tourist attractions willing to receive additional related information, and so on. These scenarios pose several issues related to scheduling and resource allocation, mainly challenged by the heterogeneous channel conditions experienced by users in the group. Indeed, procedures such as resource allocation, MCS selection, and QoS management are typically performed on a *per-group* basis, i.e., by taking into account the status of all members.

A very common approach, which we call here the *conventional multicast scheme (CMS)*, adopts a conservative and spectrally inefficient choice by serving all multicast destinations with a group transmission rate that suits the user with the worst (minimum) channel quality (usually located at the cell-edge). As a consequence, users with good channel conditions (e.g., close to the base station) suffer from a performance degradation, because they cannot exploit their good channel gain. Furthermore, the capacity benefits of the multicast transmission diminish when the number of users in the group increases because the group data capacity becomes limited by the worst user [2].

In order to overcome the capacity limitations of the traditional approach, an alternative philosophy follows what we call an opportunistic multicast scheduling (OMS). OMS exploits the idea of serving, during any given time slot, only the "best" subset of multicast members, i.e., those which maximize the system throughput. Authors in [11] propose different solutions to improve the group data rate by exploiting multi-user diversity. In [12] the selection of the users to serve is based on a signal to interference plus noise ratio (SINR) threshold, where the terminals that experience a SINR value below the threshold are not served at all. Differently, the policy proposed in [13] is designed to guarantee a predefined target spectral efficiency, and to select the users that match this constraint. Although this approach effectively exploits the multi-user diversity, the price to pay is a multicast gain reduction, i.e., the reduction of the number of users served in each time slot. Moreover, OMS-based solutions need to be coupled with rateless coding schemes because the portion of users served by the scheduler dynamically changes over the time. This additional coding introduces additional issues of computational burden, buffer size, decoding delay, and short-term fairness [14].

Direct device communications over links of a technology other than the cellular one has been largely debated in the literature. However, few works addressed multicast service delivery over D2D links. For example, in [15] some mobile devices are selected as anchor points in a cell to forward multicast data received from the base station to other devices in proximity through multi-hop ad-hoc Wi-Fi links. In [16] a multi-radio cooperative retransmission scheme is presented, where users carry out retransmissions over a short-range network to reduce both the traffic load over the cellular link and the energy consumption in error recovery. On the contrary, in our proposal D2D links are not just used for retransmissions, but they are considered as an integral part of the decisions taken by the eNodeB to serve the multicast group in the most efficient and effective way. Similar to [17], the underlying idea is to suitably select a portion of the group members served through point-to-multipoint transmission from the eNodeB, that will serve the remainder of receivers through D2D links, which may use either LTE-A or Wi-Fi technology. Group members not served by the eNodeB will attach to the FD that offers the highest throughput and create a cluster around the FD.

The concept of D2D-based clustering finds different definitions in the literature. For instance, in [18] a group of nearby devices create a cluster to share, e.g., a file with other cluster members; on the contrary in our proposal D2D clusters are used to enhance the quality of multicast service delivery. Close to the approach in this paper are solutions for wireless cooperative networking scenarios, where users cluster together to cooperatively access a web content. However, in sharing complementary portions of a content of common interest, these solutions are typically limited to the use of outband short-range communications, such as Bluetooth [19, 20] or WLAN [21]. In [5], similarly to our contribution, users are grouped into clusters wherein cluster heads send data to one or more interested devices through D2D communications. However, the focus in [5] is on data retransmissions, when some of the interested nodes did not correctly receive the data. The same aspect is addressed also in [22]. On the contrary, our solution uses D2D clustering with the aim to efficiently exploiting multi-user diversity in resource allocation to improve the LTE-A spectrum utilization, as also proposed in [23]. Indeed, our approach improves the session quality of all group members: Users served via cellular link from the eNodeB will experience better performance compared to a conventional scheme, since the destinations with worse channel conditions are excluded; for these group members far from the eNodeB, reached through D2D communication, the shorter transmitter-receiver distance improves channel quality and supports higher data rates compared to traditional cellular transmissions.

3 The proposed D2D-enhanced multicast schemes

Two D2D-based resource allocation schemes are proposed in this paper. They are designed to enhance the performance of conventional multicast delivery in cellular systems and differ in the way D2D communications are managed:

Multicast scheme with cellular D2D (MS-CD2D): It uses uplink cellular resources for D2D communications from the selected FDs to the attached subscribers. Allocating uplink resources is a common choice in the literature [24], because it makes frequency reuse less challenging as the introduced interference is significantly lower w.r.t the use of downlink resources. Once a cluster is created between a FD and its attached clients, data will be delivered with a point-to-multipoint transmission [5]. It is assumed that the FD uses a decode-and-forward (DF) relaying protocol. This means that the FD decodes the message received from the eNodeB, and then it transmits the decoded message over the D2D link. We assume that the FD transmitter is operating in the half-duplex mode in which it cannot transmit and receive at the same time. Therefore, a FD receives the multicast content from the eNodeB in the downlink slots, and this is then forwarded over D2D links in the uplink slots.

Multicast scheme with Wi-Fi D2D (MS-WD2D): It considers Wi-Fi Direct for D2D communications from the selected FDs (also acting as group owners) toward the group of associated clients. In this case, downlink cellular resources are allocated from eNodeB to the downlink, while P2P (unicast) connections are activated from each GO to the devices in its group. Obviously, with this approach, D2D communication does not interfere with cellular transmissions since they use different frequency bands.

Either of the two proposed solutions requires the eNodeB to implement the following RRM steps for the multicast service:

- *Channel quality information collection*: The eNodeB collects the CQI feedbacks relevant to downlink direction from all interested UEs as well as the quality parameters for the D2D links that can be activated among the multicast group members.
- *FDs selection*: Based on the collected information and according to the solution to be used for the data forwarding, the eNodeB selects the best subset of the multicast devices to be used as FDs.[1]
- *Radio resource allocation*: The available cellular resources are exploited by the eNodeB to send data in the downlink direction to nodes to be served via a cellular link. In case of cellular D2D communication, during this step radio resources are allocated also to the activated D2D links, so that selected FDs can forward all data received in downlink to the remainder of the multicast users.
- *Network configuration selection and service activation*: the eNodeB chooses the solution to activate based on a given performance figure. In particular, in this paper we focus on the mean data delivery time, i.e., the average time for all the UEs to receive the data of interest. After this final choice is performed, the multicast service can be finally activated by the eNodeB.

3.1 System model

The reference scenario is a single LTE-A cell where a set of subscribers, denoted with $\mathcal{K}$, is interested in downloading the same file of B Megabytes from the eNodeB. We assume that the available LTE-A spectrum is composed of N RBs, i.e., the eNodeB manages N resources in the downlink slots and the

[1] We assume that all devices are willing to act as FD. This assumption is well justified by the downloading time improvement obtained by every device in the multicast group, as shown in the performance evaluation section. Noteworthy, also for the energy consumption the D2D forwarding nodes will experience a reduction w.r.t. the standard CMS solution.

same number of RBs for the D2D links which exploit uplink slots.

Let $\mathcal{M} = \{0, 1, 2, \ldots, M\}$ be the set of indexes of available MCSs in LTE-A (value 0 considers the "out of coverage" case). For a given MCS value m, the attainable data rate (Mbps) depends on the number of assigned RBs and on the spectral efficiency for the given MCS, b_m expressed in bit/s/Hz as reported in Table 1. We represent with $f(m, n_m)$ the data rate for the MCS level m as a function of m and the assigned RBs.[2]

In every scheduling frame, the eNodeB collects the CQI feedback from all multicast users before implementing the resource allocation algorithm. The collected information will be also used by the eNodeB to decide on the potential direct links that can be formed between UEs. As discussed in [25] and [5], if UEs are continuously connected to LTE-A, the eNodeB can quickly and without significant overhead determine if they are potentially within D2D range and inform them when this is the case.

Let $c_k \in \mathcal{M}$, with $k \in \mathcal{K}$, be the maximum MCS supported by user k for the transmissions from the eNodeB, based on the collected CQI feedback from the user. If D2D links use LTE-A resources, let $e_{k,j}$ with $k, j \in \mathcal{K} | k \neq j$, be the maximum MCS supported on the direct LTE-A link between user k and user j [5]. On the contrary, when considering Wi-Fi Direct for D2D communication, let $t_{k,j}$ be the achievable throughput over the link between user k and user j. This throughput depends on the inter-node distance [25] that is supposed to be known to the eNodeB. In particular, the throughput on the Wi-Fi Direct link will comply with the measurements in [25] where also interference is considered. The measurements showed that in a realistic, non-regular network, where the topology is random, the performance can actually vary greatly, even for the same link length. As this is the scenario of interest for our problem, we refer to the average throughput results in [25]. The average throughput reaches the highest value (about 20 Mbps) at less than 1 m inter-node distances, and decreases reaching zero at about 41 m of inter-node distance.

If $e_{k,j} > 0$ (or $t_{k,j} > 0$ when considering Wi-Fi Direct), then a D2D link can be potentially established. Instead, the case where $e_{k,j} = 0$ (or $t_{k,j} = 0$ when considering Wi-Fi Direct) indicates that users k and j are out of coverage for a D2D communication.

3.2 Implementing the proposed schemes

A flow chart for the implementation of the proposed MS-CD2D and MS-WD2D schemes is presented in Fig. 3. For both schemes only the network configurations that guarantee all group members to be served through any technology are considered as eligible. Among all candidate configurations, the eNodeB will choose the one minimizing the *delivery time* (i.e., the time interval between the content download start and the instant when all devices received the data).

Going into details, based on the CQI feedback from the multicast group members, the MCS levels supported by the UEs are sorted in descending order from the most robust to the less robust. Then, an iterative analysis is carried out on the ordered list of MCS levels to find the solution that serves all the UEs and minimizes the delivery time.

In the first iteration, the configuration with the most robust MCS is considered for the multicast cellular transmission from eNodeB, i.e., $m = 1$. We denote with $\mathcal{D}_1$ the set of destinations potentially served directly by the eNodeB in this iteration. In particular, for the most robust MCS, $\mathcal{D}_1$ is equal to the whole multicast user set, i.e., $\mathcal{K}$. The delivery time for the first iteration is equal to $\Omega_1 = B/f(1, N)$, as all users are simultaneously served through the point-to-multipoint transmission from the eNodeB and require the same data delivery time.

In the second iteration, the eNodeB considers the next MCS level (i.e., $m = 2$) and identifies the set of UEs supporting the specific MCS, i.e., $\mathcal{D}_2 = \{k \in \mathcal{K} | c_k \geq 2\}$. This set of UEs served directly by the eNodeB in downlink are also the set of potential FDs. In particular, we have that $\mathcal{D}_2 \subseteq \mathcal{D}_1$. If $\mathcal{D}_2 \neq \mathcal{K}$, then this means that some nodes in the multicast group do not support the selected MCS on the cellular link and need to be served via a D2D link (either LTE-A or Wi-Fi direct link). In this case, the eNodeB performs a coverage check to evaluate if each of the users not served through the eNodeB can possibly be served by at least one FD. If this is the case, then the eNodeB will select the subset of nodes acting as FDs and compute the cost of the solution in terms of delivery time.

The procedure continues by examining the successive MCS levels, and storing the value of the delivery time for each potential resource assignment. Not necessarily all MCS for the group are examined as the iteration can stop when for a tested MCS no eligible solution can be found. The reason behind this choice can be explained as follows. Consider a generic iteration m and the corresponding MCS value, for which no cluster configuration exists allowing to serve all nodes not able to receive the data in downlink. Following an increasing order in the MCS values for the downlink from the eNodeB, in iteration $m + 1$ we will have that $\mathcal{D}_{m+1} \subseteq \mathcal{D}_m$, while for the nodes not served in downlink we have: $\{\mathcal{K} \setminus \mathcal{D}_{\Updownarrow+\infty}\} \supseteq \{\mathcal{K} \setminus \mathcal{D}_{\Updownarrow}\}$. Therefore, we can be sure that no eligible solution will be found and the iterations can be interrupted. At the end of the cycle, the eNodeB chooses the most convenient solution among the eligible ones and assign the radio resources to FDs.

[2] The admissible throughput values per MCS level are set according to Table 7.1.7.2.1-1 in [8].

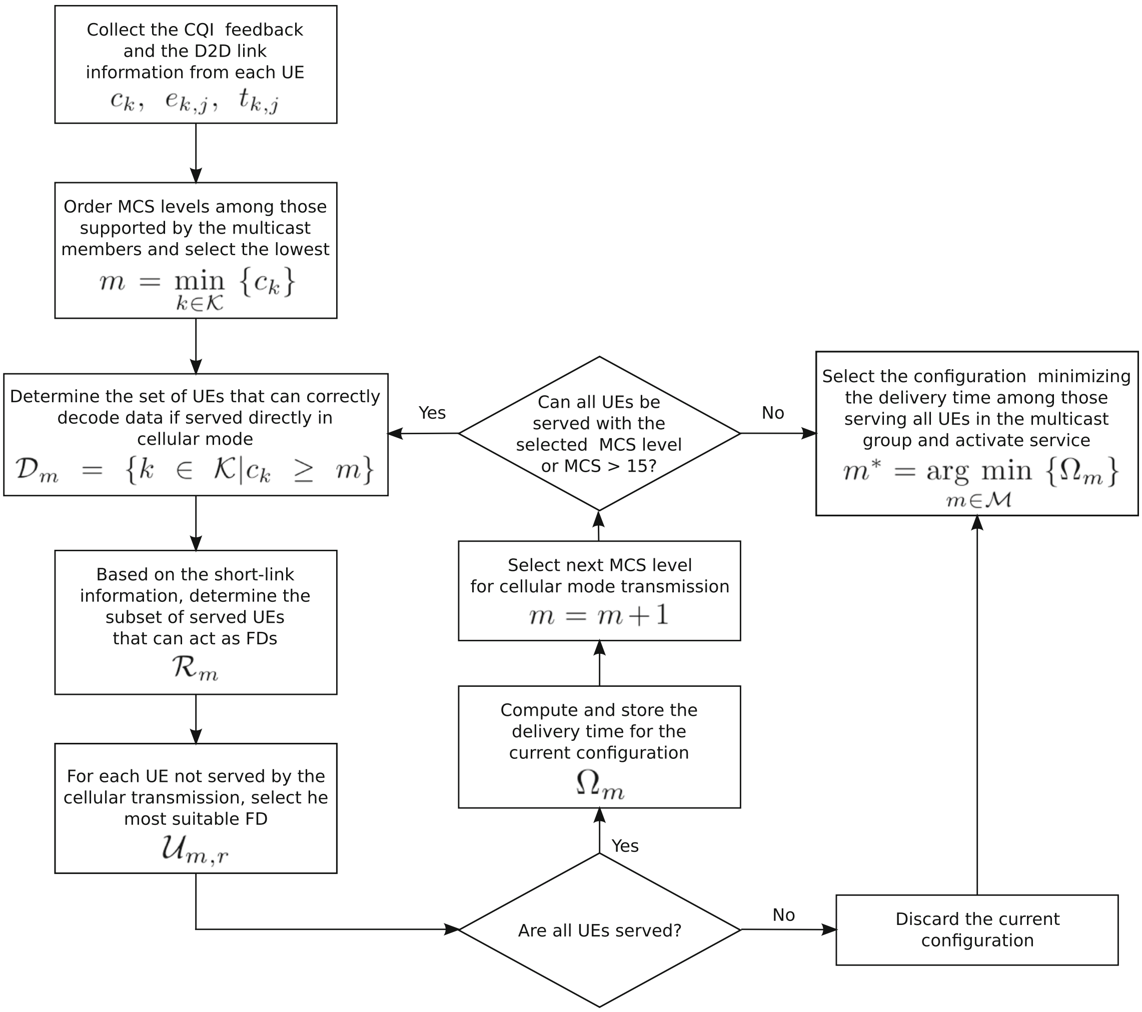


Fig. 3 Flow chart for MS-CD2D and MS-WD2D schemes

3.2.1 Forwarding devices selection

The two proposed schemes differ in the policy followed for the selection of the FDs. A detailed description of the two schemes is reported in Table 2.

3.2.1.1 MS-CD2D scheme For the MS-CD2D scheme (lines 1–12 in Table 2), in the generic mth iteration, the eNodeB computes for all $j \in \mathcal{K} \setminus \mathcal{D}_m$ the value of $e_j^{MAX} = \max_{k \in \mathcal{D}_m} \{e_{j,k}\}$. This value represents the maximum MCS for the D2D links between the jth user and all its potential FDs. If $e_j^{MAX} = 0$ for some of the $j \in \mathcal{K} \setminus \mathcal{D}_m$ nodes, then not all the nodes in the multicast group can be served with the current configuration which will be discarded from the set of eligible solutions. As discussed earlier in this section, when this happens, also the iterative algorithm for the MS-CD2D scheme will stop at the current iteration. Differently, full network coverage is achieved when $e_j^{MAX} > 0 \ \forall j \in \mathcal{K} \setminus \mathcal{D}_m$. For every configuration considered as eligible, each D2D receiver will be associated to the "best" serving FD. This means for the MS-CD2D scheme that each user $j \in \mathcal{K} \setminus \mathcal{D}_m$ will be associated to the FD that guarantees the highest MCS on the D2D link.

3.2.1.2 MS-WD2D scheme According to the FD selection for the MS-WD2D (lines 13–24 in Table 2), the eNodeB will compute for all $j \in \mathcal{K} \setminus \mathcal{D}_m$ the maximum achievable throughput over the potential Wi-Fi Direct links, i.e., $t_j^{MAX} = \max_{k \in \mathcal{D}_m} \{t_{j,k}\}$. If $t_j^{MAX} = 0$ for some node $j \in \mathcal{K} \setminus \mathcal{D}_m$, then not all the nodes in the multicast group will be served with the current configuration. Consequently, this configuration is not considered in the set of eligible solutions. Also in this case the iterative algorithm for the MS-WD2D scheme will stop at the current iteration. Differently, the current configuration is considered as eligible when $t_j^{MAX} > 0 \ \forall j \in \mathcal{K} \setminus \mathcal{D}_m$. Finally, each user $j \in$

Table 2 FD selection for MS-CD2D and MS-WD2D schemes

1: ***Case MS-CD2D***
2: **for all** $j \in \mathcal{K} \setminus \mathcal{D}_m$ **do** ▷ *FD selection*
3: $\quad e_j^{MAX} = \max_{k \in \mathcal{D}_m} \{e_{j,k}\}$
4: $\quad$ **if** $e_j^{MAX} = 0$ **then** ▷ *No full network coverage*
5: $\quad\quad$ Discard the current configuration
6: $\quad\quad$ Stop iterations
7: $\quad$ **else** ▷ *FD selection*
8: $\quad\quad$ Select $r = \arg\max_{k \in \mathcal{D}_m} \{e_{j,k}\}$
9: $\quad\quad$ Update $\mathcal{R}_m$ with r
10: $\quad\quad$ Update $\mathcal{U}_{m,r} = \mathcal{U}_{m,r} \cup \{j\}$ ▷ *Associate j to FD r*
11: $\quad$ **end if**
12: **end for**
13: ***Case MS-WD2D***
14: **for all** $j \in \mathcal{K} \setminus \mathcal{D}_m$ **do** ▷ *FD selection*
15: $\quad t_j^{MAX} = \max_{k \in \mathcal{D}_m} \{t_{j,k}\}$
16: $\quad$ **if** $t_j^{MAX} = 0$ **then** ▷ *No full network coverage*
17: $\quad\quad$ Discard the current configuration
18: $\quad\quad$ Stop iterations
19: $\quad$ **else** ▷ *FD selection*
20: $\quad\quad$ Select $r = \arg\max_{k \in \mathcal{D}_m} \{t_{j,k}\}$
21: $\quad\quad$ Update $\mathcal{R}_m$ with r
22: $\quad\quad$ Update $\mathcal{U}_{m,r} = \mathcal{U}_{m,r} \cup \{j\}$ ▷ *Associate j to FD r*
23: $\quad$ **end if**
24: **end for**

$\mathcal{K} \setminus \mathcal{D}_m$ will be served by the FD that offers the highest throughput on the Wi-Fi Direct link.

3.2.2 Resource allocation

Once the eNodeB becomes aware of the nodes acting as FDs in the generic iteration m, i.e., $\mathcal{R}_m$, and of the receivers associated to each of the FDs $\mathcal{U}_{m,r}$, with $r \in \mathcal{R}_m$, then it can simulate the resource allocation and compute the delivery time of the current solution, as listed in Table 3.

3.2.2.1 MS-CD2D scheme For the MS-CD2D scheme, given the cellular resources N available in downlink, the eNodeB determines for each of the D2D links, the needed resources such that all data received in downlink can be forwarded over the D2D links. In all cases, the eNodeB checks if the requested resources are available before allocating them and stops the allocation procedure if this check fails.

We consider that each FD serves all the involved UEs in its D2D group through a multicast transmission, by adopting the lowest MCS among those supported by the associated devices (see definition for $c_{m,r}^{D2D}$ in line 3 in Table 3). To implement this behaviour, for each RB allocated in downlink, the eNodeB verifies whether each FD belonging to $\mathcal{R}_m$ needs additional resources to forward the received data.[3]

MS-WD2D scheme

When considering the MS-WD2D scheme (line 21), all N downlink RBs are used for serving the subset $\mathcal{D}_m$ of multicast users. Then each FD will forward the received data to the connected devices through consecutive one-to-one unicast transmissions over Wi-Fi Direct links.[4]

3.2.3 Network configuration selection

For both the proposed schemes, the eNodeB will evaluate the tested configurations based on the mean delivery time Ω_m.

When the iterations are completed (i.e., when either no user can be served by the MCS under examination or all MCSs have been examined), the configuration m^* minimizing the delivery time will be selected $m^* = \arg\min_{m \in \mathcal{M}} \{\Omega_m\}$.

[3] In general, a D2D link is expected to need a fewer resources compared to those needed in the cellular communication, due to shorter distances among involved devices.

[4] We assume a FD has the possibility to buffer the data if the throughput over the D2D link is not high enough to forward all data downloaded over the cellular link to all the associated nodes. This is a reasonable assumption as also the FD itself is interested in the received multicast content.

Table 3 Resource allocation for MS-CD2D and MS-WD2D schemes

Case MS-CD2D
for all $r \in \mathcal{R}_m$ **do**
  $c_{m,r}^{D2D} = \arg\min_{u \in \mathcal{U}_{m,r}} \{c_u\}$
end for
$N_m^{cell} = 0$
$N_{m,r}^{D2D} = 0, \forall r \in \mathcal{R}_m$
while $N_m^{cell} < N$ **do**
  $N_m^{cell} = N_m^{cell} + 1$ ▷ *Assign an RB to cellular link*
  for all $r \in \mathcal{R}_m$ **do**
    $l = c_{m,r}^{D2D}$
    if $(f(l, N_{m,r}^{D2D}) < f(m, N_m^{cell}))$ **then**
      if $(\sum_{r \in \mathcal{R}_m} N_{m,r}^{D2D} + \lceil \frac{b_m}{b_l} \rceil < N)$ **then**
        $N_{m,r}^{D2D} = N_{m,r}^{D2D} + \lceil \frac{b_m}{b_l} \rceil$ ▷ *RBs to D2D link*
      else
        Stop Resource Allocation
      end if
    end if
  end for
end while
Case MS-WD2D
$N_m^{cell} = N$ ▷ *Assign RBs to cellular link*

Noteworthy, in the worst case when none of the tested MCS levels satisfies the requirement, our proposals converge to the conservative CMS solution (i.e., the most robust MCS is chosen to serve all UEs from eNodeB without activating any D2D link).

The complexity of the proposed schemes is related to the maximum number of iterations that is equal to M. At each iteration, the eNodeB will select the most suitable FD for each user not served through multicast cellular transmission. Consequently, the complexity of the proposed algorithms is equal to $\mathcal{O}(MK^2)$.

4 Performance evaluation

A simulative analysis has been conducted, by using the MATLAB tool, to compare the proposed MS-CD2D and MS-WD2D schemes with some benchmarking solutions in the literature. To this aim, we have selected the conventional CMS and the opportunistic OMS schemes, described in Sect. 2.3.

Focusing on the LTE modelling, the channel conditions for each UE are evaluated in terms of SINR when path-loss, shadowing, and multipath fading affect the signal reception [26, 27]. The effective SINR, calculated through the exponential effective SIR mapping (EESM), is eventually mapped onto the CQI level ensuring a block error rate (BLER) smaller than 10 % [26]. As already mentioned, we follow the suggestion in [4] and assume that D2D cellular links exploit the uplink frequencies. The maximum range for a D2D cellular link connection is set to 50 m [22].

The Wi-Fi Direct system is modelled based on the results in [10] and [6], while the distance-throughput mapping follows the results in [25]. In particular, in a realistic, non-regular network, where the topology is random, the performance can actually vary greatly and the average throughput results are used. Namely, the highest value is about 20 Mbps and is reached at less than one meter inter-node distances, and a decreasing throughput is observed reaching zero at about 41 m. The power consumption values for LTE and Wi-Fi systems are set like in [28]. In particular, the power consumption of user j in the cellular network is:

$$P_{c_j} = \beta_{LTE} + \alpha_d R_{c_j} \quad (1)$$

where β_{LTE} is the baseline power, i.e. 1,288.04 mW, α_d is the downlink power consumption, i.e. 51.97 mw/Mbps, and R_{c_j} is the downlink data rate (in Mbps) for user j over the LTE interface, which depends on the allocated RBs and the channel quality experienced by the user. Similarly, for the Wi-Fi links the power consumption when receiving data is:

$$P_{rx}^{wifi} = \beta_{wifi} + \alpha_d R_{wifi} \quad (2)$$

with $\beta_{wifi} = 132.86\text{mw/Mbps}$, $\alpha_d = 137.01$ mw/Mbps and R_{wifi} follows the values reported in [25] as a function of the inter-device distance. In transmission the power consumption P_{tx}^{wifi} follows a similar equation, but α_d is replaced by $\alpha_u = 283.17\text{mw/Mbps}$. Main simulation parameters and channel information are listed in Table 4. Outputs are achieved by averaging a sufficient number of simulation results to obtain 95 % confidence intervals.

We consider a typical file download, where the file dimension is 100 MB. UEs are randomly deployed in a 50 × 50 m area located at the cell edge, as in these cases a greater need for enhancing solutions [2] is felt and D2D communications show the best potentialities. We focus on time and energy gains introduced by MS-CD2D, MS-WD2D and OMS w.r.t. the conservative CMS scheme. Three scenarios are considered:

Scenario A: the number of RBs used N is set to 100 and the number of UEs in the multicast group K is in the range [20–200];

Scenario B: the multicast group size K is set to 100 while a variable number of RBs N is considered in the range [10–100];

Table 4 Main simulation parameters

	Parameter	Value
LTE	Cell layout	3GPP macro-cell case #1 [29]
	Carrier frequency	2 GHz
	Frame structure	Type 2 (TDD)
	UL/DL configuration	1
	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 std.	10 dB (cell mode); 12 dB (D2D mode)
	Fast fading	ITU-R PedB (extended for OFDM)
	RB size	12 sub-carriers, 0.5 ms
	Sub-carrier spacing	15 kHz
	CQI scheme	Wideband
	BLER target	10 %
	TTI	1 ms
	CQI feedback cycle	10 ms
	eNodeB Tx power	46 dBm
	Maximum UE Tx power	29 dBm (D2D mode: 20 dBm)
	Antenna gains	eNodeB: 14 dBi; UE: 0 dBi
	Thermal noise	−174 dBm/Hz
Wi-Fi	Medium access	CSMA/CA, −76 dBm yielding threshold
	Power and rate control	Open-loop SINR target at 25 dB
	Frequency resources	20 MHz TDMA
	Signaling mode	Green-field, control rate 18 Mbps, RTS/CTS
	RF equipment	Noise figure 7 dB, noise floor −95 dBm

Scenario C: a variable area is considered for the UEs distribution in the range [100 × 100–1,000 × 1,000] m, and the number of UEs K is in the range [100–500]; in this case we present a sample channel bandwidth with 100 RBs (however, similar results have been obtained for different values of RBs).

The results relevant to Scenario A are plotted in Fig. 4. Both D2D-enhanced schemes outperform both CMS and OMS. OMS guarantees a time saving from 20 % up to 25 % w.r.t. CMS. MS-CD2D achieves the highest gain, with up to three times higher performance compared to MS-WD2D and a maximum time gain w.r.t. CMS of about 72 %. When observing the variations with the number of UEs, the MS-CD2D time savings are more or less constant, while the MS-WD2D gains reduce with the number of UEs, coming close to OMS when the number of UEs is equal to 200 (i.e., a time saving equal to 25 %). The reason for this latter gain reduction is that having more UEs, increases the number of nodes to be served per cluster. Since consecutive unicast transmissions are performed by the FDs to all the nodes in the clusters, the time needed to

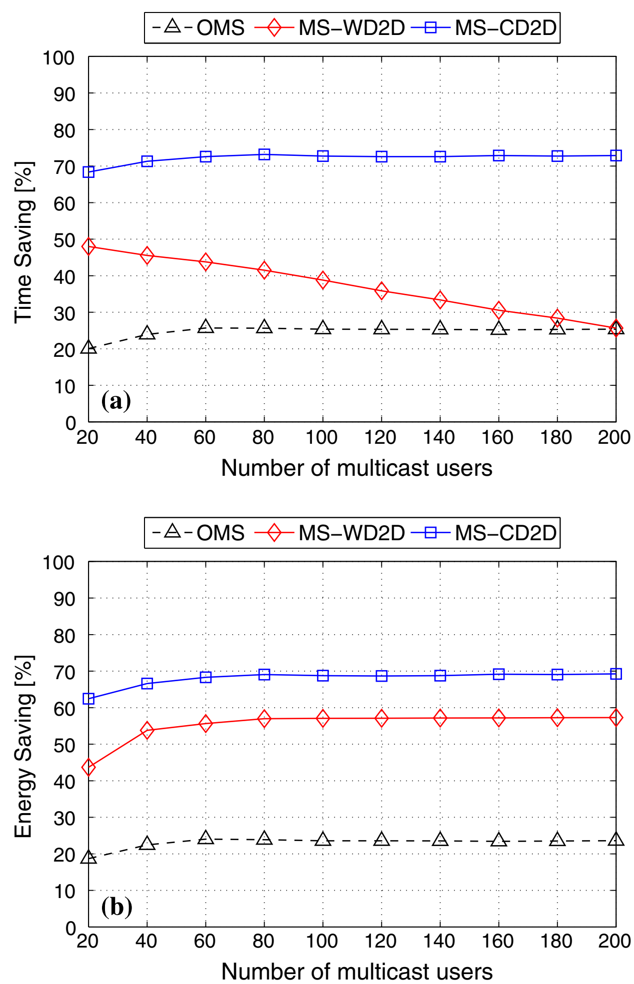


Fig. 4 Time and energy savings w.r.t. CMS in Scenario A

forward the data increases having the commented negative impact on the performances.

As for the gain in energy consumption plotted in Fig. 4(b), one notices that MS-CD2D outperforms again the other solutions; in particular, energy saving varies in the range between 61 and 70 %. Moreover, we observe that differently than for the time saving results, the energy gain for the MS-WD2D does not decrease with the number of UEs. This is an expected behaviour, because even if the total delivery time increases, the overall energy consumption, which is the sum of the energy consumptions of each single node, depends on the time each single UE is active in the data transmission. In particular, the energy saving for MS-WD2D goes from 42 % (with 20 UEs) to 58 % (with 200 UEs).

Results in Scenario B, presented in Fig. 5, show again that the proposed MS-CD2D scheme is performing the best in almost all cases, both in terms of energy and time savings introduced w.r.t. CMS. Savings are constant with the number of RBs both for the OMS and the MS-CD2D. Differently, for the MS-WD2D the time and energy savings decrease with the number of RBs. In particular, for 10 RBs time and energy savings are equal to 52 and 88 %, respectively, and these values become equal to 40 and 58 % in case of 100 RBs. The motivation for this is that with larger channel bandwidth the data rate in downlink increases, with consequent higher energy and time required on the Wi-Fi Direct interface and an overall reduction in the introduced gains. Moreover, it is interesting to observe that the MS-WD2D scheme offers the highest energy savings when the channel bandwidth is set to 10–30 RBs.

The analysis for Scenario C assesses the benefits of the D2D-based solutions in a wide set of UEs distributions within the cell considering a sample case of 100 RBs available (a similar trend has been obtained for other values of the number of RBs, highlighting that the trend is not really influenced by the number of RBs). The number of UEs varies between 100 and 500 while the area where the UEs are uniformly distributed, is progressively extended

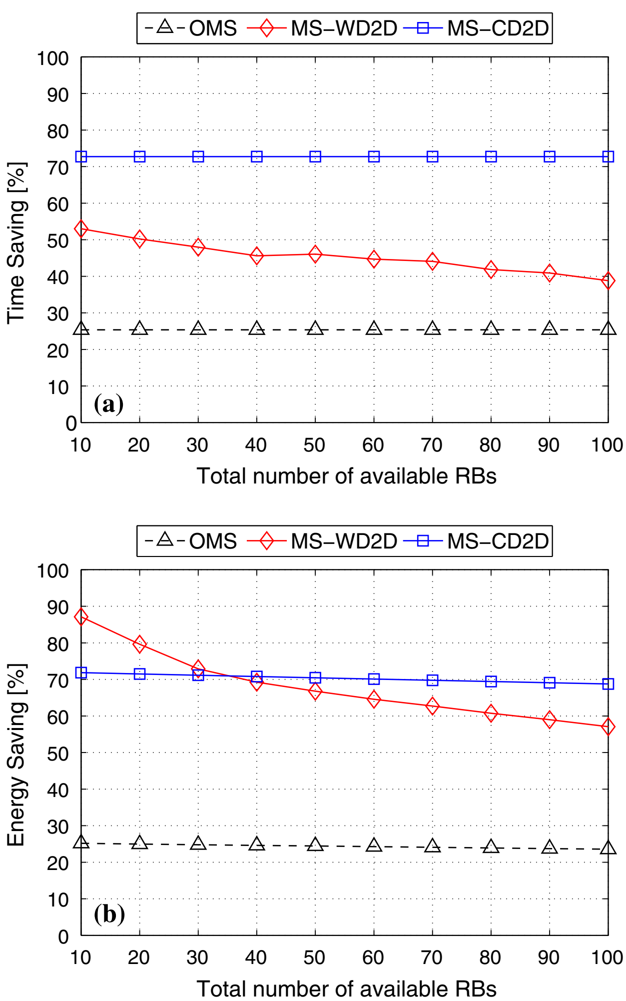
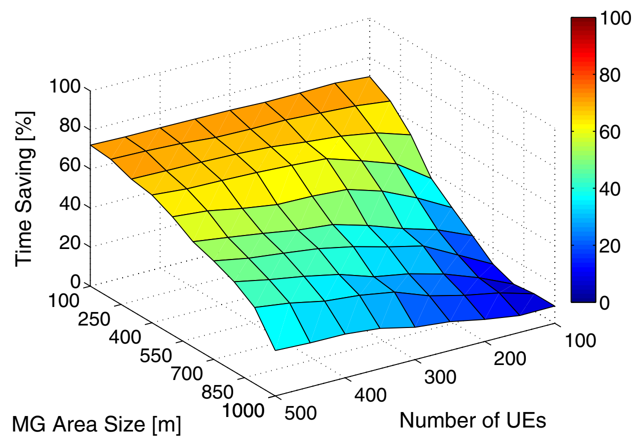
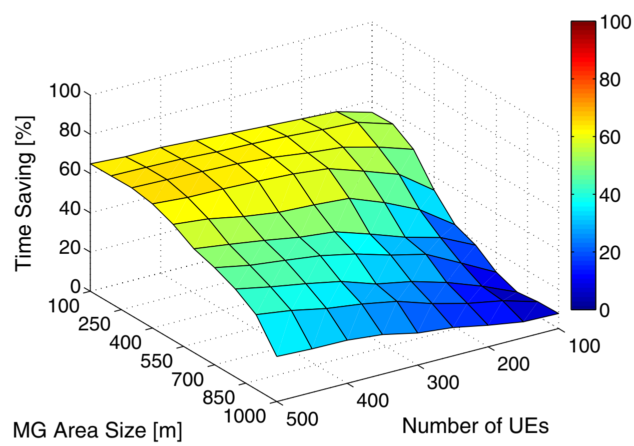


Fig. 5 Time and energy savings w.r.t. CMS in Scenario B

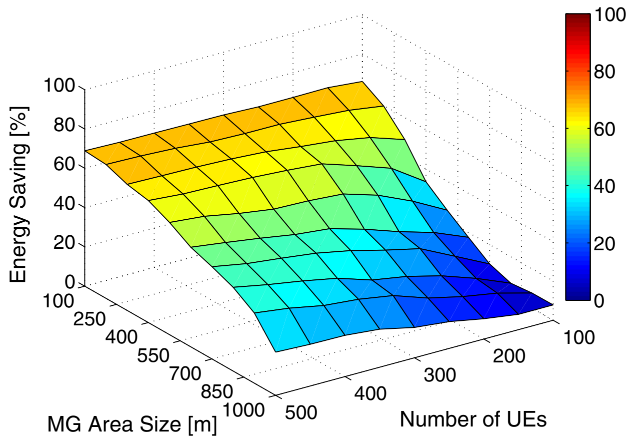


(a) MS-CD2D

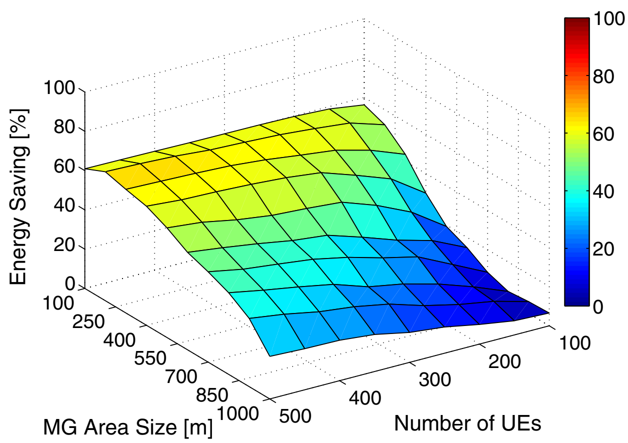


(b) MS-WD2D

Fig. 6 Time saving for MS-CD2D and MS-WD2D versus CMS in Scenario C

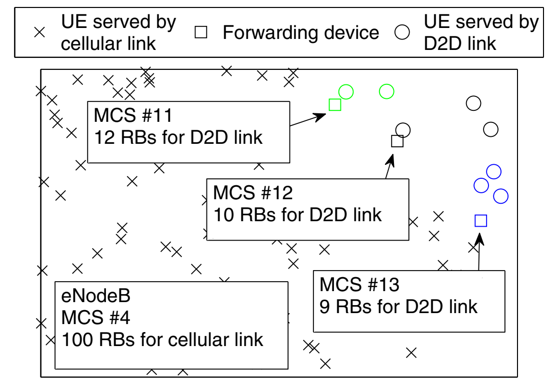


(a) MS-CD2D

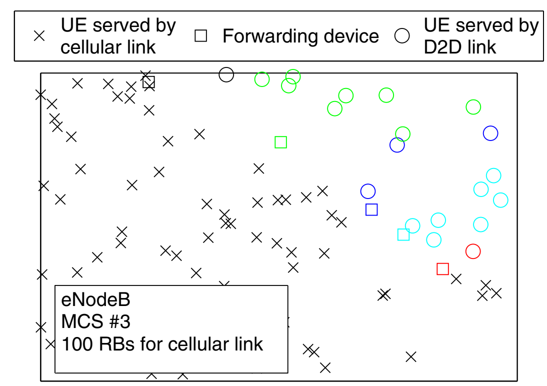


(b) MS-WD2D

Fig. 7 Energy saving for MS-CD2D and MS-WD2D versus CMS in Scenario C



(a) MS-CD2D



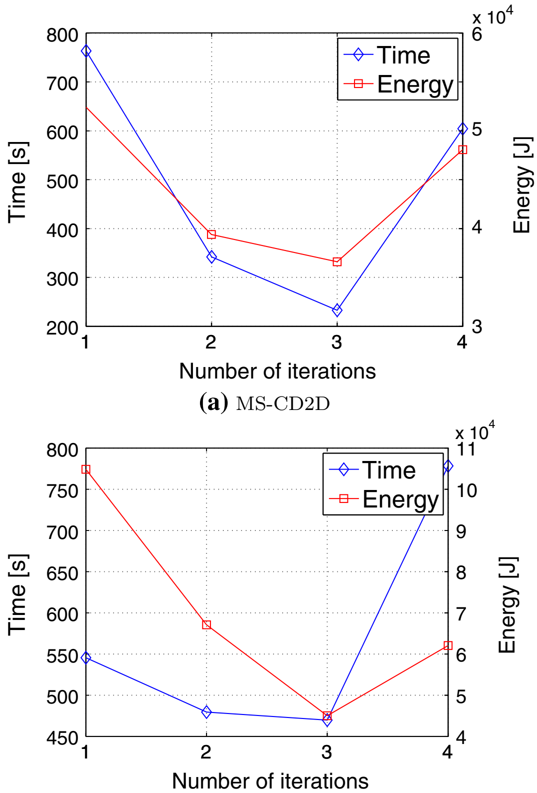
(b) MS-WD2D

Fig. 8 Sample service configurations for the proposed schemes (100 UEs, 100 RBs)

from the cell-edge scenario until the whole cell of 1,000 × 1,000 m is covered. The average gains in time and energy, w.r.t. the CMS, introduced by the MS-CD2D and MS-WD2D schemes are plotted in Figs. 6 and 7, respectively. Focusing on the time savings, the gain obtained with the MS-CD2D scheme is always higher than the MS-WD2D case with a 72 and 65 % gain in the best case for the solutions respectively. The same behaviour can be observed focusing on the energy savings, where the highest gain w.r.t. CMS for MS-CD2D and MS-WD2D is equal to 69 and 66 %, respectively. When considering the number of UEs in the multicast group (MG) (x-axis in the plots) and the MG area, that is the covered within the cell (the y-axis in the plots reports the side length of the considered square area), in general for all tested cases both the time and energy gains increase with the number of users and decreases with the area size for both D2D-based schemes.

A further comparison of the proposed schemes can be found in Fig. 8, which plots a nice example of service configuration for MS-CD2D and MS-WD2D. In particular, the role of each UE in the group is highlighted in the reference cell-edge scenario for a sample study case. It clearly emerges that different configurations are obtained in the two cases due to the different channel conditions over the two LTE-A and Wi-Fi Direct interfaces adopted for the D2D link. Noteworthy, in both cases the MCS used in downlink is not the lowest one and D2D links are required to serve all UEs. Moreover, for the MS-CD2D it can be observed how the MCS used on the D2D links is very high and a lower number of uplink RBs is required to serve all UEs when compared to the downlink from the eNodeB.

The presented results demonstrated the improvements in terms of delivery time and energy consumption for the proposed schemes when compared to the classic CMS and OMS solutions. The last result we want to show is that, even if the proposed schemes are designed to select the solution that minimizes the delivery time, the selected configuration is also the one with the lowest energy consumption. In Fig. 9 we report the behaviour of time and energy metrics during the iterations of MS-CD2D and MS-WD2D schemes for a sample case with 100 UEs and 100



(a) MS-CD2D

(b) MS-WD2D

Fig. 9 Time and energy performance during the iterations of proposed schemes

RBs (similar results are obtained for other tested cases). In this particular case, the number of iterations for the algorithms is four. As it clearly emerges, the delivery time and the energy consumption are both minimized in the third iteration for both the proposed schemes.

5 Conclusions

In this paper we propose solutions to enhance conventional schemes for multicast content delivery in beyond-4G systems, where cellular and D2D communications are jointly exploited to reduce the delivery time and the energy consumption for the multicast group. Two different schemes are proposed where either LTE-A or Wi-Fi Direct technology are adopted for activating D2D links among the UEs in the multicast group. The service design foresees a dynamic selection of the "best" portion of UEs to serve through cellular transmissions from the eNodeB and, among those, the election of the best FDs to maximize the session quality experienced over both cellular and D2D links. The proposed schemes are compared to well-known (CMS and OMS) solutions through a simulative analysis in a wide set of scenarios.

From the obtained results, the proposed MS-CD2D scheme where LTE-A resources are used for the D2D links by the FDs, shows the highest time and energy savings. However, in all tested scenarios also the MS-WD2D solution where Wi-Fi Direct is used as a D2D link, shows important improvements w.r.t. to standard multicast approaches.

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