Efficient Data Uploading Supported by D2D Communications in LTE-A Systems

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Abstract—The reference scenario in this paper is a single cell in a Long Term Evolution-Advanced (LTE-A) system, where multiple user equipments (UEs) aim at uploading some data to a central server or to the Cloud. The traditional uploading technique used in cellular systems, i.e., with separate links from each UE to the eNodeB, is compared to innovative relay-based schemes that exploit Device-to-Device (D2D) communications between two (or more) UEs in proximity to each other. Differences in the channel quality experienced by the UEs offer an opportunity to develop D2D-based solutions, where (i) the UE with a poor direct link to the eNodeB will forward data to a nearby UE over a high-quality D2D link; and (ii) the receiving UE then uploads its own generated data and the relayed data to the eNodeB over a good uplink channel. A straightforward gain in the data uploading time can be obtained for the first UE. To extend the benefits, also to the relaying UE, enhanced D2D-based solutions are proposed that decrease the uploading time of this UE based on the cooperative sharing of the resources allocated by the eNodeB to the cooperating devices. Finally, preliminary results are also presented for a multihop study case, where a chain of devices exploits D2D communications to upload data to the eNodeB.

Index Terms—LTE-A, Device-to-Device communications, Radio Resource Management, Data Uploading

I. INTRODUCTION

Device-to-Device (D2D) communications is gaining momentum, well justified by the promising advantages of this innovative paradigm in terms of improved spectrum utilization, higher data rate, and lower energy consumption [1]. Direct interactions between local devices enable novel applications and services [2] that can have high relevance in critical situations such as public safety and disaster scenarios, where the network resources have to be used efficiently [3]. In fact, the use of D2D links can be substantially more efficient than conventional communications through the eNodeB whenever a communication is inherently local in scope [4]: besides, it can help to either extend the cell coverage, offload cellular traffic [5], [6], or support content sharing in a neighbourhood [7], [8].

The focus of the D2D related literature has been on downlink communication in most of the cases [9], [10]. Many works have dealt with use cases and expected performance improvements related to D2D, or with specific technical issues such as peer service discovery, D2D link set-up, interference management, and so on. Even if only a few papers have considered D2D communication specifically for the uplink direction, there are several scenarios and services that can benefit from D2D interactions to improve the uplink performance of the Long Term Evolution-Advanced (LTE-A) system. This is the case of disaster scenarios, where updated information from the incident area should be timely and reliably sent to a control center, or also scenarios where several users wish to upload multimedia content to the Cloud. The interest for these scenarios is witnessed by some recent publications, e.g., in [11] D2D relaying by smartphones is used to send out emergency messages from disconnected areas and to support information sharing among people gathered in evacuation centers.

Focus of this paper is on the design and analysis of D2D-based techniques for data uploading in a single LTE-A cell coverage area. The idea is that a device with a poor link to the eNodeB may use a close device with a high-quality uplink as its own data forwarder. Given the short distance between the two devices directly connected, the quality of the D2D link is expected to be high. So, overall, the two-hop path promises benefits in terms of data uploading time reduction, energy consumption savings, and radio resources efficient use. A D2D-based scheme will be designed which proposes a cooperative use of the radio resources assigned to the directly communicating devices. A set of applications will also be identified that suit the proposed solutions. Finally, a multihop D2D scenario will be investigated to give an insight into the limit in the number of D2D hops that guarantees advantages to all communicating nodes.

The remainder of the paper is organized as follows. In Section II the reference system model and service configuration are described. In Section III the proposed D2D-based schemes are presented in details, whereas in Section IV the analysis is extended to a multihop D2D scenario. The performance evaluation results are summarized in Section V and conclusive remarks in the last section.

II. The LTE-A Reference System

In Long Term Evolution-Advanced (LTE-A) [12], Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA) are used to access the downlink and the uplink, respectively. The eNodeB manages the spectrum by assigning the adequate number of RBs to each scheduled user and by selecting the Modulation and Coding Scheme (MCS) for each RB.

1 The RB corresponds to the smallest time frequency resource that can be allocated to a user (12 sub-carriers) in LTE. For example, a channel bandwidth of 20Mhz corresponds to 100 RB.
Scheduling procedures are based on the Channel Quality Indicator (CQI) feedback, transmitted by a UE to the eNodeB over dedicated control channels. The CQI is associated to a given maximum supported MCS as specified in [12] (see Table I). The MCS parameters can be adapted at every CQI Feedback Cycle (CFC), which can last one or several Transmission Time Intervals (TTIs) (one TTI is 1 ms).

A UE in a LTE-A network can either communicate through the serving eNodeB (i.e., cellular mode) or it can bypass the eNodeB and use direct communications over D2D links (i.e., D2D mode). The eNodeB is in charge of the D2D session setup (e.g., bearer setup) [13], while power control and resource allocation procedures on the D2D links can be executed either in a distributed or in a centralized way [14]. In this paper, we assume a centralized control from the eNodeB. Accordingly, the eNodeB is aware of the current cell load and the user channel conditions and can efficiently allocate dedicated D2D resources in order to improve the session quality and the allocation flexibility.

We assume that uplink cellular resources are allocated to D2D communications, because (i) it guarantees a more efficient reuse of resources compared to downlink allocation, and (ii) downlink resources can be made available to other services within the cell.

### TABLE I
CQI-MCS MAPPING FOR D2D AND CELLULAR COMMUNICATION LINKS

| CQI index | Modulation Scheme | Efficiency D2D [bit/Hz] | Min. Rate D2D [kbps] | Efficiency Cellular [bit/Hz] | Min. Rate Cellular [kbps] |
|-----------|-------------------|------------------------|----------------------|-----------------------------|--------------------------|
| 1         | QPSK              | 0.1667                 | 28.00                | 0.1523                      | 25.59                    |
| 2         | QPSK              | 0.2222                 | 37.00                | 0.2344                      | 39.38                    |
| 3         | QPSK              | 0.3333                 | 56.00                | 0.3770                      | 63.34                    |
| 4         | QPSK              | 0.6667                 | 112.00               | 0.6016                      | 101.07                   |
| 5         | QPSK              | 1.0000                 | 168.00               | 0.8770                      | 147.34                   |
| 6         | 16-QAM            | 1.2000                 | 201.60               | 1.1758                      | 197.53                   |
| 7         | 16-QAM            | 1.3333                 | 224.00               | 1.4766                      | 248.07                   |
| 8         | 16-QAM            | 2.0000                 | 336.00               | 1.9141                      | 321.57                   |
| 9         | 16-QAM            | 2.4000                 | 403.20               | 2.4063                      | 404.26                   |
| 10        | 64-QAM            | 3.0000                 | 504.00               | 2.7305                      | 458.72                   |
| 11        | 64-QAM            | 3.0000                 | 504.00               | 3.3223                      | 558.72                   |
| 12        | 64-QAM            | 3.6000                 | 604.80               | 3.9023                      | 655.59                   |
| 13        | 64-QAM            | 4.5000                 | 756.00               | 4.5234                      | 759.93                   |
| 14        | 64-QAM            | 5.0000                 | 840.00               | 5.1152                      | 859.35                   |
| 15        | 64-QAM            | 5.5000                 | 924.00               | 5.5547                      | 933.19                   |

D2D connections can be supported on Frequency Division Duplex (FDD) and Time Division Duplex (TDD) bands. The FDD mode poses additional issues in terms of terminal design, cost and complexity [14]; for this reason, we consider TDD and refer to the frame structure type 2 configuration 0 foreseen by 3GPP [12].

As shown in Table II, 'D' denotes that the subframe is reserved for downlink transmission, 'U' denotes that the subframe is reserved for uplink transmission, and 'S' denotes a special subframe. The chosen configuration 0 guarantees the highest number of uplink slots among all the configurations of the type 2 frame. The communication range between nearby devices can reach tens of meters, indeed, the data rate on the D2D link is properly calculated based on the CQI level, the allocated resources and the UE transmitted power.

### TABLE II
UPLINK-DOWNLINK CONFIGURATIONS FOR FRAME STRUCTURE TYPE 2 (TDD)

| Subframe number | Uplink-downlink configuration | Doowndlink-to-Uplink Switch-point periodicity |
|-----------------|-------------------------------|---------------------------------------------|
| 0               | D                             | 5 ms                                        |
| 1               | S                             | 5 ms                                        |
| 2               | D                             | 10 ms                                       |
| 3               | U                             | 10 ms                                       |
| 4               | D                             | 5 ms                                        |
| 5               | S                             | 5 ms                                        |
| 6               | D                             | 10 ms                                       |
| 7               | U                             | 10 ms                                       |
| 8               | D                             | 5 ms                                        |
| 9               | S                             | 5 ms                                        |

### III. THE D2D-ENHANCED DATA UPLOADING SCHEMES

Let us refer to the case where multiple users in a single LTE-A cell are interested in uploading some multimedia content to the Cloud or to a central server on the Internet. We might think of a disaster scenario, where images and videos from several devices clustering together in a small area of interest are to be uploaded timely and reliably. In this case, the data uploading time plays a very important role. Similarly, in other scenarios of interest multiple users, for example gathered for a concert or a fair, are willing to upload some multimedia content, or even in vehicular environments where vehicles set up communications for information search and dissemination [10]. Data uploading in the classic cellular mode occurs through the activation of separate links from each UE to the eNodeB (Fig. 1(a)). In this case, the eNodeB measures the uplink channel quality from each UE and decides the MCS and the number of allocated frequency resources (RBs) in the UL slots of the transmission frame. In the reference scenarios, UEs in proximity to each other may establish D2D links, as simplified in Fig. 1(b) for the case with two users. The device with a poor uplink to the eNodeB can take advantages from a nearby device with a good channel quality by using it as a relay towards the eNodeB.
A. Cellular-mode data uploading

We use the classic data upload in a cellular mode as a term of comparison against the designed D2D-based schemes. Without loss of generality, we suppose that the eNodeB equally divides the available RBs $R$ in the uplink slots of the data frame among all the requesting users. Thus, with two users, each of the two will get $r_1 = r_2 = R/2$ RBs. The data rate for a node on a communication link is a function of the allocated resources and its CQI level \([17]\). For the sake of simplicity, in this sample study case we consider $b_c$ (where \(c = 1 \ldots 15\)) the data rate per allocated RB (see minimum rate value in Table \([1]\)) and compute the obtained data rate on a link linearly with the allocated resources. This simplification will be removed in the performance evaluation sections. Let’s say the CQI level of the two users is, e.g., $c_1 = 5$ and $c_2 = 10$, then the data rate per RB will be respectively $b_1 = 147.34kbps$ and $b_2 = 458.72kbps$, and the corresponding uplink data rate $d_1 = b_1 \cdot r_1$ and $d_2 = b_2 \cdot r_2$. In the sample case with $R = 50$, the data rate per user will be $d_1 = 3.68Mbps$ and $d_2 = 11.47Mbps$. Consequently, if the data file of each user has a size of $D = 100MB$, then the uploading time is approximately equal to $t_1 = \frac{D}{d_1} \approx 217s$ and $t_2 = \frac{D}{d_2} \approx 70s$.

B. D2D-based uploading (DBU)

With reference to the sample two-user case discussed above, $UE_1$ will transfer its data on a D2D link to $UE_2$, whereas $UE_2$ will transfer both its own data and the data received by $UE_1$ in uplink to the eNodeB. We assume that the CQI level and the radio resources available on the D2D link between the two users guarantee a data rate $d_{12}$ from $UE_1$ to $UE_2$ greater than $d_2$, the data rate in uplink for $UE_2$. In particular, under the assumption of frequency reuse and all RBs $R$ available for the communication, the data rate on the D2D link is $d_{12} = 46.2Mbps$ (based on the data rate per RB in Table \([1]\)).

In the DBU solution, $UE_2$ first uploads its own data and then takes care of the data received by the peer UE. With the same amount of resources allocated to $UE_2$ as in the cellular-mode case, i.e., $r_2 = R/2 = 25$, the time $t_c$ required to transfer its own content remains the same as $t_2 \approx 70s$. Then, it can start receiving the data from $UE_1$. Assuming that all data is first received by the relaying node, a time contribution for data transmission on the D2D link $t_{21} = \frac{D}{d_{12}} \approx 17s$ has to be added. The third time contribution to be considered is equal to 70s when $UE_2$ will upload the data for $UE_1$. With this basic configuration, $UE_1$ has a benefit in terms of time for transferring the data, i.e., $t_i < t_1$ with $t_i \approx 157s$ and $t_1 \approx 217s$. Also the network provider has benefits as it saves resources; indeed, in the DBU case 25 RBs are allocated to $UE_2$ for 140 seconds, instead of 50 RBs to $UE_1$ and $UE_2$ for the first 70 seconds and 25RBs to $UE_1$ for the remaining 147 seconds.

C. D2D-based uploading - time minimization (DBU-TM)

The promising results can be further enhanced by the DBU-TM approach. We consider that the set of resources allocated to the two users separately by the eNodeB in cellular mode, are pooled together and allocated to $UE_2$ only by the DBU-TM

In the next subsection, the proposed D2D-based approaches are discussed in details with reference to a sample study case with two-users uploading a video file to a server, see Fig. \([1]\).
scheme, i.e., in the reference sample case $r_i = 0$ and $r'_i = 50$ RBs. As a consequence, $UE_2$ will now experience a data rate in uplink equal to $d'_2 = b_{c_i} \cdot r'_2 = 22.94$ Mbps. Hence, when giving priority to its own traffic, it will be able to upload his data in half of the time $t_2 = \frac{d_2}{d'_2} \approx 35 \text{ s}$. After this, in the next $17 \text{ s}$ it will receive the data from $UE_1$ and then in $35 \text{ s}$ it will be able to upload the data of $UE_1$. Now $UE_1$ will have a reduced uploading time of $t'_1 \approx 87 \text{ s}$, which is way less than the time it would take in the cellular-mode where $t_1 \approx 217 \text{ s}$. Moreover, the network provider has still an advantage in terms of used resources compared to the cellular-mode case; the uplink radio resources used by DBU-TM are equal to 50 RBs for 70s.

IV. Extension to Multihop D2D Scenario

In this section we will give some indications on the extension of the proposed solutions to the more general case where multiple users are involved in the cooperative data uploading and form a multihop D2D chain \[11\]. An intermediate node in the chain, willing to upload its own data to the eNodeB, will have two active D2D links: one to receive some data from the previous UE and one to forward all data (its own data and the data from the incoming D2D link) to the next UE in the chain. Thus, every UE looks for a D2D peer to forward its data to, so that it can obtain some benefit in terms of data uploading time. The data a UE sends over the D2D link to the peer device may, therefore, also be forwarded again to another UE over a D2D link before being finally uploaded to the eNodeB. The UE in charge of uploading the data to the eNodeB will be the one with the best channel conditions. The resulting number of hops the data will cross before being uploaded to the eNodeB depends on the gains on the involved D2D links and the uplink.

A formulation can be derived for the time required for all data from the multihop D2D chain to be uploaded to the eNodeB, as a function of the data amount and the resources allocated to each link (noteworthy, the two-devices case discussed earlier is a particular case of this generalized formulation). Each node $i$ out of the set of $N$ nodes has $d_i \neq 0$ data to upload to the eNodeB. In particular, let $i = 1$ be the node uploading the data to the eNodeB, and $i = N$ the last node in the D2D chain. Let than $r_i$ be the allocated RBs to node $i$ in the D2D chain for the link it uses to forward its data, that is the uplink to the eNodeB for node 1 and a D2D link to the next node for all other nodes. We indicate with $f_i(r_i)$ the data rate on this link for node $i$ as a function of the allocated resources and its CQI level \[17\].

To determine the exact uploading time we will compute the number of frames required to transfer all data. Therefore, it is important to evaluate the time and the corresponding TTIs where the D2D links are still active. In fact, given the half-duplex operations for the nodes, the upload slots will be alternatively used between D2D communication and transmissions toward the BS. Considering the configuration 0 used for the data frame, as long as D2D links are active, node 1 can exploit three out of the six uplink slots per frame. When all data from the D2D chain has reached node 1, all six uplink slots can be used.

Since it is assumed that the nodes will join the D2D chain only if they have some data to upload to the eNodeB, the attention can be limited to the first two nodes of the multihop chain. The total data the multihop D2D chain has to upload is $D = \sum_{i=1}^{N} d_i$, whereas node 2 will transfer over the D2D link a data amount of $D - d_1$ to node 1. In particular, the time needed for node 1 to upload all data of the D2D chain is $t_1 = D/f_1(r_1)$ expressed in ms, and consequently, given the time duration of a TTI $t_{TTI} = 1 \text{ ms}$, the number of TTIs required is: $k_1 = t_1/t_{TTI}$. Similarly, the time for node 2 to transfer all data to node 1 is $t_2 = (D - d_1)/f_2(r_2)$, and the number of required TTIs $k_2$ is: $k_2 = t_2/t_{TTI}$. These values are important as node 1 will use data frames where 3 uplink slots are available (in the other 3 slots node 1 is receiving data over D2D link from node 2) for $k_1$ TTIs. For the remaining $k_1 - k_2$ TTIs, it can exploit all 6 uplink slots per frame. Thus, we can compute the total number of frames $F$ needed for all data to be uploaded, i.e., $F \approx k_2/3 + (k_1 - k_2)/6$, and with $t_{frame} = 10 \text{ ms}$ the corresponding total uploading time that is $t_{frame} \cdot F$.

V. Performance Evaluation

A numerical evaluation is conducted by using Matlab®, to assess the main performance of the novel D2D schemes. In particular, the main performance figures we discuss are the (i) average data uploading time, the (ii) average number of allocated RBs over time, and the (iii) data rate per allocated RB. The performance analysis is conducted by following the guidelines for the system model defined in \[17\] and for a varying number of RBs and a varying data size per user. Main simulation parameters are listed in Table III. Channel conditions for the UEs are evaluated in terms of SINR experienced over each sub-carrier when path loss and fading phenomena affect the signal reception.

| TABLE III | MAIN SIMULATION PARAMETERS |
|------------|----------------------------|
| Parameter   | Value                      |
| Cell radius | 500 m                      |
| Frame Structure | Type 2 (TDD)              |
| TTI         | 1 ms                       |
| TDD configuration | 0                      |
| eNodeB Tx power | 46 dBm                  |
| D2D node Tx power | 23 dBm                  |
| 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) |
| BLER target | 10%                        |
| # of Runs   | 500                        |

A. Two-hop scenario

The focus is first on the discussed two-user scenario. In Fig. 3 the data uploading time is shown for the different analyzed schemes. In all the tested cases, both for a varying value of data size in Fig. 3 (a) (the number of RBs is set to 100) and
for a varying number of RBs in Fig. 3 (b) (data size is set to 100 MB), the DBU-TM is performing better than the DBU technique.

Fig. 3. Mean data uploading time for the UEs.

When looking at the average number of RBs used in the system, the results in Fig. 4 reveal that the simple DBU solution is using less resources than the other solutions. This is expected, as in this case the allocated resources are not pooled together, but simply not allocated by the eNodeB and available for other services in the network. In fact, DBU has an average number of used RBs that is also lower than the cellular mode. The DBU-TM instead, is the one using the most RBs.

Looking at the data rate per allocated RB, we observe in Fig. 5 (a) that this does not change with the data amount that is uploaded. This behavior is expected, as we are assuming static channel conditions. Nonetheless, the data rate per allocated RB shows an increasing trend with the number of available RBs for all the approaches, see Fig. 5 (b). Comparing the different approaches, we can observe that from the data rate per RB point of view, the DBU-TM is the best performing solution.

B. Multihop scenario

In Fig. 6 we present results for a multihop scenario with the results being averaged on a set of random configurations of the CQI for the nodes in the cell. On the x-axis we set the maximum number of hops/users obtained for the D2D multihop scenarios. As it can be noticed the maximum value is 15 as D2D links bring benefits only if the involved nodes experience different CQI values. On the y-axis we plot the uploading time for the last node of the D2D chain, as this is the node with the lowest CQI value (all other nodes in the D2D chain will experience better performance and an uploading time gain). As we observe from the plots, the DBU-TM solution is always offering the nodes in the D2D chain a lower uploading time w.r.t. the case where no D2D solution is implemented (cellular plot in the Figure). This is because DBU-TM uses the entire pool of RBs allocated to the involved nodes. Moreover, for the DBU solution we observe that the

![Figure 3](image1.png)

![Figure 4](image2.png)

![Figure 5](image3.png)

![Figure 6](image4.png)

Table IV

| Approach    | Use Cases                  | Target Feature                |
|-------------|----------------------------|-------------------------------|
| DBU         | Social Networking          | Low data-rate                 |
|             | Machine-to-Machine         | Low data-rate                 |
|             | Communication              |                               |
|             | Multicast Communication    | High/low data-rate            |
|             | Public Safety and Disaster | Reliable transmission, low    |
|             | Scenario                   | uploading time                |
|             | Multiplayer Gaming         | High data-rate, low delay     |
|             | Streaming Services         | High data-rate, low delay     |
|             | Scenario                   |                               |
| DBU-TM      | Multicast Communication    | High/low data-rate            |
|             | Public Safety and Disaster | Reliable transmission, low    |
|             | Scenario                   | uploading time                |

Fig. 4. Mean RBs used over the time.

Fig. 5. Average RBs used over time.

Fig. 6. Average RBs used over the time.
multihop chain should be no longer than ten hops on average, to guarantee a time uploading benefit to all users in the chain.

To conclude our analysis, in Table IV we report a list of the possible applications that can benefit from the D2D-based solutions proposed in this paper to underline how the different approaches match a different set of target applications.

VI. CONCLUSION

In this paper the potential benefits introduced by D2D communication for data uploading are investigated. Different approaches have been evaluated and compared based on a set of performance figures like the average data uploading time, the average number of RBs used, and the data rate per RB obtained. We showed that in a simple two-Ue scenario the aggregation of data packets through D2D links improves the network performance with respect to the cellular mode uplink transmission. Also preliminary results on multihop cases are presented to understand what the maximum number of hops is so that uploading time benefits are guaranteed to all UEs.

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