Centralized and Decentralized Multi-cell D2D Resource Allocation using Flexible UL/DL TDD

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Abstract— **Device to device (D2D) communication is expected to be an important aspect in future 5G communication systems. To this end, D2D has been identified as an important topic in the EU flagship project METIS, wherein commercial D2D use cases are also considered. In principle, direct D2D communication offers the double benefit of low latency and high data rate at the same time. Interference mitigation and performance optimization alongside cellular users are however some of the key challenges to D2D communication. In this paper, we present a flexible D2D concept which is based on integration of D2D communication in flexible UL/DL TDD scheduling. We then compare multi-cell decentralized and centralized approaches for joint resource allocation for direct D2D and cellular links. Simulation based results are shown in a challenging indoor scenario where direct D2D users are placed among a high density of indoor cellular small cells and users. We find that centralized multi-cell resource allocation can improve overall system performance by 24 % for supporting D2D communications. Our results also show that substantial system level gains above 30% are achieved by enabling resource reuse between direct D2D and cellular users in both uplink and downlink cellular time slots. Furthermore, we see that flexible TDD provides overall better system performance as compared to fixed TDD even with a decentralized scheduler.**

Index Terms—**5G, RRM, dynamic TDD, D2D centralized resource allocation**

I. INTRODUCTION AND STATE OF THE ART

METIS (*Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society*) is the EU flagship project aiming towards 5G enablers. The project has identified D2D as an important communication method which can be used for future 5G services which are classified in three following broad categories: *Extreme/advanced/flexible Mobile Broad* Band (xMBB), *Massive MTC* (M-MTC) and *Ultra reliable MTC* (U-MTC) [2]. Especially in the context of xMBB, it is envisioned that the evolution of dense urban society scenarios will experience significant growth in locally routed traffic. It is thus proposed that traffic offloading by direct D2D will be one of few key methods to provide high data rates, low E2E latency and improved quality of experience (QoE) for various commercial use cases such as: virtual reality office (TC1), dense urban (TC2), shopping mall (TC3), stadium(TC4) & open air festival(TC9) [1].

D2D communication in cellular frequency bands has been addressed in various literary works recently. One common approach used to limit the interference from D2D links is to apply power control mechanisms [3-5], which can be controlled by the base station. On the other hand, resource allocation based approaches are also possible for D2D interference coordination [11-14]. For example, the algorithms in [11] and [14] exploit the knowledge of slow-scale parameters, such as path loss for interference-aware resource allocation of D2D users during uplink and downlink phases of cellular communication. The interference coordination mechanisms proposed in [11] and [14], however, assume a fixed split of downlink and uplink cellular TDD frames. In [13], interference avoidance mechanisms are considered between cellular and D2D which are limited to only the uplink part of the spectrum. Moreover, the aforementioned works do not consider multi cell resource allocation, and only optimize resource allocation per cell.

Literary work [12] presents a multi-cell joint mode selection, resource allocation and power control mechanism which can be used for the uplink band of cellular spectrum. In contrast to all the above mentioned works, in this paper we consider joint multi-cell D2D and cellular resource allocation in the context of flexible (dynamic) UL/DL TDD scheduling [9], [10]. The flexible UL/DL TDD concept allows fast switching on a data frame basis between uplink and downlink direction per cell based on short term traffic requirements, without imposing clustered TDD, for example as in [6]. This flexibility in per cell TDD switching leads to various cross-link interference situations between neighbouring cells. As a consequence, D2D resource allocation has to be adapted to the TDD switching decisions over multiple cells.

Our main contribution in this paper is to provide a performance upper bound for joint D2D and cellular resource allocation using flexible TDD. Performance results are demonstrated in an ultra-dense multi-cell indoor scenario, where D2D links may extend over neighboring cells because of short cell radii. We then compare centralized and decentralized approaches to multi-cell scheduling. Our results show that around 24% packet delay reduction can be achieved through multi-cell coordinated (e.g. centralized) resource allocation, with performance benefits realized for both D2D and cellular users. Our results further illustrate flexible TDD and D2D resource reuse to be efficient mechanisms which vastly improve the system performance. Through this paper, we thus extend our previous work [15] to D2D use cases and present further findings on centralized and decentralized multi-cell resource allocation. The paper is arranged as follows. Section II introduces the D2D concept and related working assumptions. Section III describes the multi-cell resource allocation problem and schemes. Finally, sections IV and V provide numerical results and conclusions respectively.

II. D2D CONCEPT

One of the key goals of the 5G METIS project is to incorporate novel technology components such as D2D communication into the overall system concept using system level enablers. To this end, we consider a D2D concept by natively integrating D2D communication to flexible UL/DL air-interface. This seamless integration is supported by means of a flexible multi-cell link scheduler, which considers both cellular and D2D key performance indicators for the link scheduling decisions. The main principle of flexible UL/DL is that each cell could flexibly switch the data frames to uplink or downlink directions on a scheduling slot which is called as flexible TDD which is then further optimized through proper resource allocation mechanisms. We thus consider only network-controlled D2D such that the resource allocation decisions for D2D are made by the network, even though the data transmission is done directly between the D2D devices.
A scenario for flexible link scheduling is shown in Figure 1.

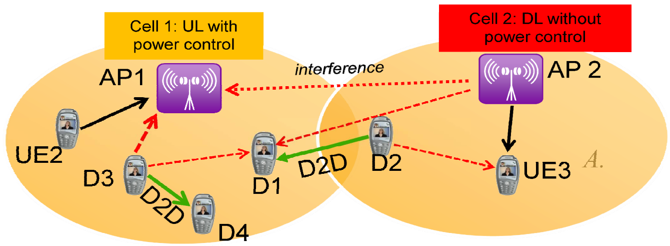

Figure 1. Multi-cell D2D in Flexible UL/DL air interface. Dominant interferers are shown in red dotted lines.

In the example of multi-cell D2D as in Figure 1, D2D transmitting device and receiving device can be located in neighboring cells as shown (D2D links shown in green). It can be observed that one of the main challenges in the flexible link concept will be to mitigate interference arising from a variety of cross-coupled interference situations such as: a) uplink-downlink interference and vice versa between cellular users, b) uplink and downlink cellular links of different cells generating interference towards D2D, c) interference generated by D2D users towards uplink and downlink cellular users in different cells and d) interference between different D2D links.

Still, the main motivation for using D2D communication in challenging scenarios such as in Figure 1 is to leverage the following gain mechanisms: a) off-loading gain wherein locally routed traffic can now be handled directly between devices by avoiding a hop, thus reducing latency, b) proximity gain wherein devices in close range can transmit with better communication efficiency and c) spectrum re-use gain, wherein the spectrum is reused for both cellular and D2D users, through non-orthogonal resource allocation.

Finally, we make the following assumptions while integrating D2D links into the flexible UL/DL air interface: a) half duplex constraint, i.e. a D2D device can either only transmit or receive in a scheduling slot, b) multi-link D2D, by which a D2D device could transmit to multiple D2D devices in a scheduling slot on different resource blocks, and c) slow power control, wherein power control is applied on D2D links based on path loss between the devices.

III. MULTI-CELL D2D RESOURCE ALLOCATION

We now present two network controlled D2D resource allocation schemes for flexible D2D and cellular link scheduling. In a wider sense, flexible scheduling can be realized by using centralized or decentralized approaches, thus leading to two different architecture alternatives. In the decentralized case, each cell (which could be a small cell) performs its own resource scheduling decisions. Thus in this case, the D2D users and cellular users send channel quality information only to their own associated small cell. In the centralized case, the channel quality information from the users is further forwarded by their respective small cells to a centralized entity in the network which oversees the small cells, e.g a macro cell. Clearly there are pros and cons in either approach; in the centralized case, joint resource allocation decisions are made in a coordination group at the expense of additional signaling cost, while in the decentralized case, no signaling is made for coordinated resource allocation but a possible performance loss can be expected because of sub-optimal scheduling decisions.

DECENTRALIZED

In the decentralized scheme, each small cell makes its own independent decisions regarding resource allocation for cellular and D2D users associated to it. We consider weighted sum rate maximization for each resource block in a cell k and the problem is to determine the optimal binary decision variables x_i and y_i to maximize

$$\sum_{i\in C_k} w_i\, x_i\, R_i + \sum_{i\in D_k} w_i\, y_i\, R_i\,,$$

$$s.t\ x_i \in [0,1], y_i \in [0,1] \quad (1)$$

In Eq (1), x_i and y_i represent the resource allocation decisions for cellular and D2D links respectively, where i represents the index of a link. The sets C_k and D_k represent the set of all cellular and D2D links originating from that small cell k respectively. Further in Eq (1), we impose the constraint that $\sum_{i\in C_k} \mathrm{x_i} = 1$, while $\sum_{i\in D_k} \mathrm{y_i} > 1$. Thus a resource block can be reused by multiple D2D links along with a cellular link, which is a non-orthogonal resource allocation. $\mathrm{w_i}$ is set equal to the maximum delay among all packets waiting to be transmitted on link i. Thus Eq(1) performs delay weighted sum rate maximization, such that links with longer delays get higher weightage for providing user fairness in terms of delay.

It can be noted that in Eq (1), resource allocation can potentially allow reuse of resource blocks for D2D, i.e a the extent of reuse of that resource block between cellular and D2D users is also made. In Eq(1) R_i represents the data rate of that link on that resource block, which is calculated using signal to interference noise ratio (SINR) estimation using a mapping given by R_i =min(0.88 * log2(1 + $SINR_i$ / 1.333), maxSpectralEff) * bandwidth, where maxSpectralEff relates to the maximum modulation and coding scheme utilized.

In this decentralized case, SINR estimation for a link is made using the interference received on the previous scheduling slot. Thus, this scheme is interference-aware w.r.t. the interference measured in the last scheduling slot. In principle, this interference awareness can also prevent multi-cell D2D conflicts such as scheduling a D2D device to simultaneously transmit and receive on the same slot. However, in instances of conflict e.g., when a new link is scheduled, we assume that a randomized conflict resolution is done by the device itself or by the network without any optimization. This means in such cases the decision whether to transmit or receive is made randomly. The decentralized scheme is suboptimal because scheduling decisions are made selfishly without accounting for the interference generated towards neighbouring cells.

Other assumptions such as duplex constraint, multi-link D2D and slow power control are applied as in Section II.

CENTRALIZED

In the case of centralized scheduling, all resource allocation decisions are made jointly. For each resource block, we determine the optimal resource allocation solution x_{ik}, y_{ik} jointly for coordinating cells to maximize the metric

$$\sum_{k\in G}\left(\sum_{i\in C_k} w_{ik}\, x_{ik}\, R_{ik} + \sum_{i\in D_k} w_{ik}\, y_{ik}\, R_{ik}\right)$$

$$s.t\; x_i \in [0,1], y_i \in [0,1] \quad (2)$$

It can be noted that the above formulation benefits from multi-cell coordination through a joint resource allocation for cellular and D2D users across multiple cells in a coordination group. This is indicated by the set G and using cell index k in variables of Eq (2). R_{ik} is calculated similar to R_i in decentralized case. A joint optimization as in Eq (2) has two main benefits for D2D: a) the interference between cellular and D2D is captured for making optimal resource allocation decisions for multi-cell D2D, and b) the link flow direction decision, whether a D2D device is a transmitter or a receiver can be made optimally. This is because a centralized scheduler makes optimal decisions while also satisfying the half duplex constraint, thus translating to optimal link direction decisions in the case of multi-cell D2D. The following remarks are in order. First, in Eqs (1) and (2) of the above-mentioned schemes, MIMO processing is done as in [15], by calculating the SINR on a per stream basis after performing singular value decomposition. Second, we have not considered opportunistic mode selection mechanisms, e.g. as in [12], through which the decision to opportunistically route the D2D packets through cellular access points can also be made instead of only a direct D2D transmission. A joint mode selection and resource allocation will be a part of our future work.

IV. SIMULATION SETUP

The following schemes are simulated and compared: a) fixed UL/DL frame split of 1:4, and with an assumption that D2D traffic is served only during UL frames, b) flexible UL/DL frame with decentralized and centralized resource allocation as in section II allowing reuse of resources between cellular and D2D users, c) flexible UL/DL frame with decentralized and centralized scheduling as in section III but without allowing reuse of resources between cellular and D2D users, called as ‘no-reuse’ in the figures. We consider a MIMO-OFDMA air interface based on flexible (dynamic) TDD. LTE-like power control is assumed in the uplink, while the downlink has a flat power spectral density and no power control. The novel OFDMA-based flexible uplink and downlink PHY is similar to the proposal in [10]. A scheduling slot of 2 ms comprises of many time slots, where each time slot is only 0.25ms and there is no multiplexing between uplink and downlink directions within a scheduling slot. We further assume that 200 MHz bandwidth is split into 100 resource blocks, and for simplicity, simulations are conducted only on a sub-group of 10 resource blocks corresponding to 20 MHz bandwidth. The traffic payload for the 20 MHz sub-band is one-tenth of the whole payload for 200 MHz

Parameter	**Default value**
Carrier frequency	2600 MHz
Path loss model	3GPP small cell path loss model [8], Indoor fast fading model [16]
Wall Penetration loss, UE noise figure, Max spectral efficieny	3 dB, 9 dB, max spectral efficiency=8 , corresponding to 256QAM
Total SC power	-3 dBm in downlink over 20 MHz bandwidth. Uplink SNR target of 42 dB after slow power control.
D2D tx power	SNR target of 42 dB. Slow power control using distance between devices
UE speed	3 kmph
Antenna configuration	4X4 MIMO. Isotropic
Receiver type	Interference Rejection Combining
Traffic	Poisson with 1 sec inter-arrival time at each device and with fixed file sizes.
Number of cellular and D2D users	12 indoor users per small cell. D2D users with a range of maximum 4 m, resulting in 26 D2D links across 7 coordinating small cells. 14 users out of 84 users in coordinating cells are a priori classified as D2D users.

Table 1. Table of simulation parameters

Multi-cell D2D simulation setup

To conduct a system level study, we assume an indoor scenario with 25 rooms, each of size 10m x 10m, and a small cell access point is placed ideally in the center of each room. In each simulation drop, users are randomly deployed, and a fixed percentage of those users within the coordinating cells are then classified as D2D users without any cellular traffic. A D2D transmitter may communicate to any D2D users within a 4 m range based on traffic arrival. The rest of the users are cellular users who communicate to the access points. Simulations are performed on a sub-band of 20 MHz bandwidth which consists of 10 resource bocks. The file sizes over 20 MHz are 960 Kbytes, 240 Kbytes and 240 Kbytes for downlink, uplink and D2D respectively (one-tenth the file sizes for 200 MHz). The rest of the simulation parameters are shown in Table 1.

Simulations are conducted for 20000 scheduling intervals, with each scheduling interval being 2ms. Thus, the total simulated interval is 40s, and approximately 560 files generated for all D2D users, while 2800 files each for uplink and downlink cellular users. A file is transmitted as multiple packet segments during the course of a simulation. The packet segment sizes correspond to the link data rate in a scheduling interval. Further analysis has shown the number of packet segments to be around 7900 for all D2D traffic. In our results we show the cumulative distribution function of packet segment serving delay, which is defined as difference between the arrival time and serving time of a packet segment. We make all our observations on the delay measured at the 99th percentile of the cumulative distribution for users in the coordination group, so that the worst case performance is measured. This could mean that there is a performance trade-off between reducing worst case packet delay and average packet delay.

Illustrative example of a simulation drop:

We now consider one illustrative drop as in Figure 2 below, and show D2D, uplink and downlink delay results for the illustrative example.

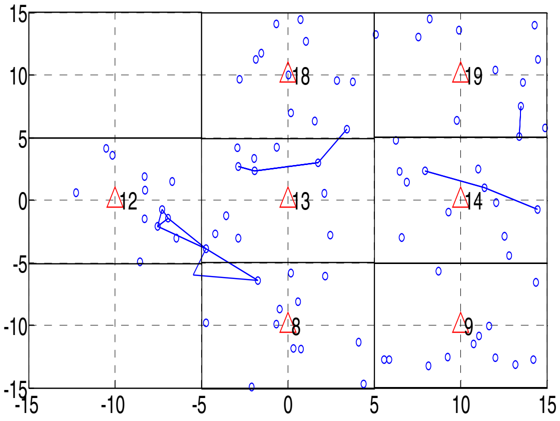

Figure 2. Example D2D scenario with cellular users. Circles - user equipments. Triangles are small cell access points. D2D links are shown in blue. Cellular links are not shown. D2D users are deployed only in coordinating cells.

It can be observed from Figure 2 that there are 14 bidirectional D2D links (28 D2D links in total). Out of those D2D links, 7 links are intra-cell D2D while the other 7 links are D2D links which extend over adjacent cells. Figures 3-5 show the results for the illustrative scenario.

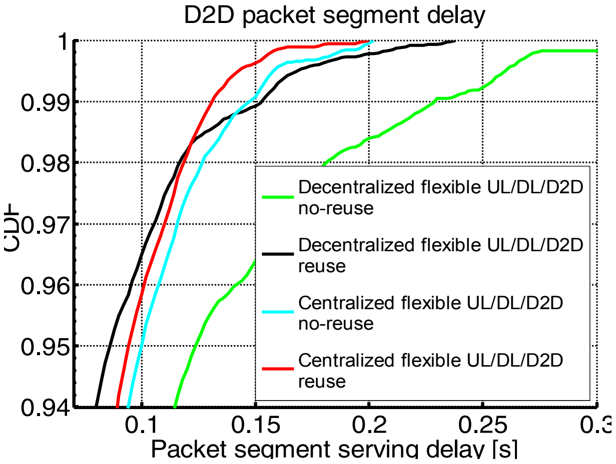

Figure 3. D2D delay distribution

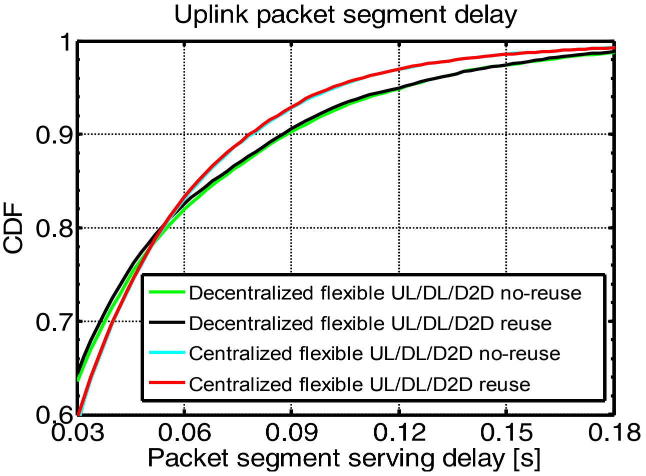

Figure 4. Uplink delay distribution

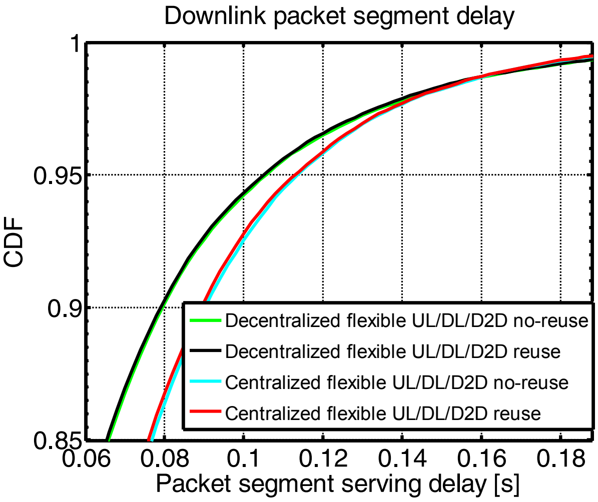

Figure 5. Downlink delay distribution

Centralized vs Decentralized multi-cell scheduling.

Figure 3 shows the D2D delay distribution results, while Figure 4 and 5 show the results for cellular traffic. Figure 3 shows that D2D delay reduces from 150 ms to 130 ms using centralized flexible UL/DL/D2D scheduling, which is a 13 % gain. At the same time, from Figure 4 we observe that the uplink delay reduces from 175 ms to 155 ms with centralized resource allocation for flexible UL/DL/D2D, which is a 11 % gain. The downlink performance in Figure 5 however does not show any substantial change. Thus we observe a sum of 23 % gain with centralized resource allocation for flexible UL/DL/D2D. It can be noted that in flexible UL/DL/D2D , the gains of D2D and cellular may be complementary, which means that the 13% D2D delay reduction could have resulted in better cellular performance by 11% and vice versa.

D2D re-use benefit:

In Figures 3-5, we demonstrate the benefit of scheduling D2D and cellular links on same resources, termed as D2D reuse. In principle, non-orthogonal resource allocation between D2D and cellular is performed in 'D2D re-use', whereas with no-reuse, the resource allocation between D2D and cellular are strictly orthogonal. For decentralized flexible UL/DL/D2D, we see that D2D reuse provides substantial gains as compared to no re-use. D2D delay reduces from 230 ms to 152 ms which is a 34 % gain when reuse is utilized. Results show that re-use is also beneficial in the case of centralized scheduling and provides around 10 % delay reduction (from 145 ms to 130 ms). Importantly, results in Figures 4-5 show that cellular performance does not undergo any performance degradation with D2D re-use. This seems to be the case for both decentralized and centralized schedulers. This result can be explained by the fact that both the decentralized and centralized schedulers allow D2D re-use only when it benefits the metric in (1) and (2) respectively. One could thus directly infer from the results in Figure 3- Figure 5 that re-use is indeed found to be beneficial by the schedulers from a system perspective.

Results with multiple simulation drops :

We now present delay results by simulating three independent user drops (i.e three independent drops as in Figure 2). The statistics of the three drops are then concatenated to obtain the delay distributions, which are shown in Figure 6- Figure 7 below. Thus the statistics in this case are three time the size of the illustrative example. In Figure 7, we show the overall segment delay which is obtained by further concatenating the statistics of downlink, uplink and D2D links.

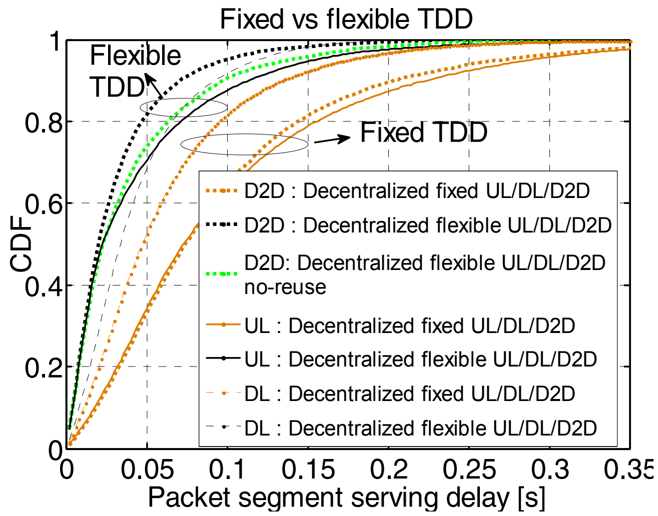

Figure 6. Gain of flexible TDD for uplink, downlink and D2D traffic. D2D reuse is assumed unless stated otherwise.

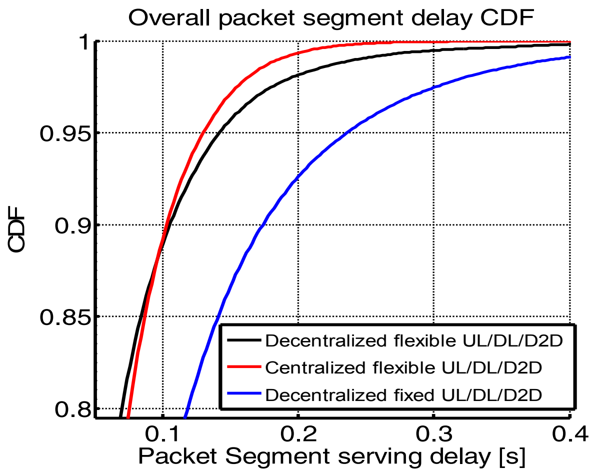

Figure 7. Overall segment delay

Figure 6 compares the cellular and D2D performances of decentralized flexible UL/DL/D2D TDD to that of fixed TDD. In the fixed TDD scheme, the first four out of five time slots are assigned to downlink, while one slot is used for both uplink and D2D. Thus in the fixed TDD scheme there is no D2D interference in downlink slots, while this is allowed in case of flexible TDD. In flexible TDD, the downlink can also avail 20% more system resources in certain instances as required by short term traffic demand. Results in Figure 6 show that downlink performance actually improves with flexible TDD. This suggests that for the downlink, the benefit of using up to 20 % more system resources outweighs any degradation arising from D2D interference. The uplink and D2D performances also clearly improve with flexible TDD because in this case clearly much more system resources can be utilised whenever required by those links. Figure 6 shows substantial delay reduction with flexible UL/DL/D2D for D2D, uplink and downlink users, with 55%, 35% and 35% gains at 99 percentile. Multi-drop simulation results in Figure 6 show the D2D re-use gain to be around 22 % (225 ms to 175 ms) for decentralized resource allocation thus supporting our findings in Figure 3-5. For clarity, Figure 7 shows the system performance improvement in terms of overall packet segment delay, where 99 percentile of overall packet segment delay would capture the worst performance among D2D and cellular links. The overall delay reduces from 245 ms to 185 ms with centralized resource allocation, a 24 % gain. Figure 7 also shows that the gain with decentralized flexible TDD is 36 % as compared to fixed TDD, thus supporting our results in Figure 6.

V. CONCLUSIONS AND FUTURE WORK

This paper presented a novel D2D communication concept which incorporates D2D in flexible UL/DL TDD frames. The paper also presented centralized and decentralized multi-cell resource allocation schemes for joint D2D and cellular scheduling. Performance benefits in terms of delay reduction were illustrated in an indoor multi-cell scenario with a high density of small cell access points and users. Results show that approximately 24 % system performance gain can be achieved in terms of reduced packet delay with multi-cell centralized resource allocation for D2D communication. Results also show that centralized resource allocation can be realized for both D2D and cellular users, with one multi-cell scenario showing 13 % delay reduction for D2D users and 11 % for uplink users. We also compared the performances of flexible UL/DL/D2D to that of fixed TDD in which D2D is scheduled only on uplink frames. With this comparison, we find that flexible TDD offers excellent gains for downlink, uplink and D2D users, providing an overall 36 % delay reduction. Our results also showed that reuse using non-orthogonal resource allocation between D2D and cellular can provide over 20% system level gains. While we have provided an upper bound of multi-cell coordination gains through centralized resource allocation and compared to a completely decentralized resource allocation assuming multi-cell D2D conflict resolution is in place, performance comparison to distributed multi-cell D2D resource allocation is an open issue. Multi-cell scheduling along with mode selection, when longer range D2D links are opportunistically routed through small cells is part of ongoing research.

ACKNOWLEDGMENT

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