Reports of the Department of Mathematical Information Technology
Series D. Telecommunication
No. D 1/2014

Device-to-Device Communication for LTE-Advanced Network System

Tao Chen Esa Kunnari
Tapani Ristaniemi

University of Jyväskylä
Department of Mathematical Information Technology
P.O. Box 35 (Agora)
FI-40014 University of Jyväskylä
FINLAND
fax +358 14 260 2771
http://www.mit.jyu.fi

Copyright © 2014
Tao Chen and Esa Kunnari and Tapani Ristaniemi
and University of Jyväskylä

ISBN 978-951-39-5919-7
ISSN 1456-4386

Device-to-Device Communication for LTE-Advanced Network System

Tao Chen [†] Esa Kunnari[‡] Tapani Ristaniemi[§]

Abstract

Device-to-device (D2D) communication has been proposed as a mean for local connections in future cellular networks in order to provide improved throughput, spectrum savings, and longer battery lives. Here we widen the investigations of D2D communication to a 3GPP Long Term Evolution (LTE) system simulated in the interference limited macro-cellular environment, in which D2D communication is applied with D2D specific power control and resource allocation schemes and with a wide range of deployment ratios. Furthermore, we introduce channel model parameters applicable for a fair performance comparison between conventional cellular and D2D enhanced systems. The simulation results demonstrate that both the D2D and cellular users can gain significant throughput improvements when appropriate power control and resource allocation methods are used. This is further emphasized when the share of D2D users increases.

1 Introduction

It has been envisioned that new innovative local services will make up a significant part of traffic in future cellular systems. In these services, a client and a service provider would often be in the immediate vicinity of each other and much further away from a base station. Therefore, they could potentially have much better radio channel between themselves than towards a base station. However, the conventional cellular operation cannot handle their mutual traffic any differently but will transfer it via a base station and further route it through the core network. Similar suboptimal relaying of traffic through a base station and the core network occurs in a file share, voice call or other communication between two close-by

---

[†] Department of Mathematical Information Technology, University of Jyväskylä, P.O. Box 35 (Agora), FI-40014 University of Jyväskylä, Finland, shinechen@gmail.com
[‡] Centre for Wireless Communications, University of Oulu, P.O.Box 4500, FI-90014 University of Oulu, Finland, esa.kunnari@ee.oulu.fi
[§] Department of Mathematical Information Technology, University of Jyväskylä, P.O. Box 35 (Agora), FI-40014 University of Jyväskylä, Finland, tapani.e.ristaniemi@jyu.fi

users of conventional cellular systems. This twofold transmission of the same data, which takes place first in the uplink and then in the downlink, will result in a waste of scarce radio frequency spectrum and a higher end-to-end packet delay in comparison with a direct transmission between the two communicating devices. Meanwhile, it increases the burden of the core network for delivering and processing the duplicated data. Moreover, the possibly longer distances and, therefore, greater path losses of cellular links in comparison with that of a direct link will require much higher transmit powers, which in turn results in increased power consumption and intra-system interference.

In the literature, the direct communication between two terminals of an infrastructure-based network has been called with various names, out of which we use the device-to-device (D2D) term. Among the first propositions of using D2D communication in conjunction with cellular communication was the one in [1], where this hybrid scheme was considered to be especially suitable for applications such as communication between operational mobile robots and inter-vehicle communication. The latter usage of D2D communication has been an integral part of a number of multi-hop peer-to-peer network extensions proposed for the conventional cellular network topology. This network model was reviewed and its performance for Internet access was investigated in [2]. A survey on D2D communications in various infrastructure-based networks has been carried out in [3]. Network controlled D2D communication without the ad-hoc relaying functionality has also been proposed as an underlay to an IMT/LTE-Advanced cellular network and its performance has been simulated in a single-cell scenario and Manhattan grid model with indoor D2D communication [4] and in an indoor environment [5]. The optimal selection between the D2D and cellular modes within a WCDMA cellular system has been analyzed in [6]. Time hopping based radio resource allocation schemes for mitigating interference arising from the spatial reuse of cellular resources for D2D communication were proposed in [7]. In most of the prior studies, D2D concept is aiming for a generic solution without specific consideration on the practical constraints of LTE system. Furthermore, the D2D link distance has been either fixed or artificially limited, and the effect of the D2D user penetration ratio has not been considered. In addition, the channel and system models used have been fairly limited and highly simplified.

Recently, D2D is getting to be a hot topic with more and more interest from the academy and industry. In [8, 9, 10], the general concepts and survey on the latest research outcomes have been presented. Service driven D2D communication are discussed in [11] and [12] considering the initial service setup procedure and content downloading service. More specifically, the various RRM schemes for D2D communications have been also presented and evaluated. For resource allocation, interference coordination based schemes are extensively studied in [13, 14, 15, 16, 17]. In addition, game theory is also considered for resource allocation as indicated in [18]. For power control schemes, [19] and [20] proposed dynamic power control schemes for interference coordination. In [21], it provides some QoS-aware mode selection and resource allocation schemes. Random access protocol for collision avoidance in cellular device-to-device communication is presented in [22].

In this report, we present a D2D enhanced system concept with some essential radio resource management (RRM) schemes aiming for the long term evolution of 3GPP LTE system. Moreover, we extend the performance study of D2D communication within cellular networks to an LTE system under the interference limited micro-cell environment and the coverage limited macro-cell environment. To address the above mentioned shortcomings of the prior studies, we have evaluated the performance of this system with a 3GPP compliant multi-cell LTE network simulator that is complemented with D2D functionality based on our concept and an appropriate channel model. D2D communication system concept with its power control and resource scheduling alternatives in addition to D2D mode selection is presented in Section 2 and the adopted channel model in Section 3. Simulation results are presented in Section 4 and, finally, conclusions are drawn in Section 5.

2 Device-to-Device Communication System

In general, the D2D communication can be deployed either under LTE frequency division duplexing (FDD) cellular system by using the uplink cellular band for D2D communication or under LTE time division duplexing (TDD) cellular system by utilizing the uplink subframes of TDD cellular resources. Thanks to the high commonality between LTE FDD and LTE TDD system in the 3GPP system design, it provides the feasibility for such integrated FDD/TDD implementation at UE in terms of the cost and the complexity.

In this report, the considered D2D communication is assumed to use TDD and it takes place in the uplink band of an LTE FDD cellular system. With this setup a dual mode FDD/TDD user equipment (UE) can use the FDD mode for conventional cellular operation and an enhanced TDD mode for D2D communication. The uplink was chosen in order to ease out the control of the effects that the D2D communication has on the cellular operation. On the other hand, the interference situation is getting more complicated compared to the conventional cellular system due to the mix of the centralized cellular system and the distributed D2D communication system, which has to be addressed for the success of D2D communication under cellular system. Essentially, there are four types of interference:

1. d2c interference: Interference from D2D transmission to the cellular link reception at eNB.
2. d2d interference: Cross-link interference between D2D communications.
3. c2c interference: Inter-cell interference between cellular transmissions.
4. c2d interference: Interference from cellular links to D2D Rx UE.

In addition, the interference can be further categorized as intra-cell and inter-cell interference. There is only c2c inter-cell interference assuming the orthogonal resource allocation for cellular communications in LTE system. However, intra-cell interference can be occurred for d2c, d2d, and c2d cases in addition to the inter-cell interference, which depends on resource allocation schemes among D2D and cellular communications. For example, in case of frequency resource reusing, there will be additional intra-cell d2d, d2c and c2d interference, especially for the case with imperfect spatial multiplexing.

The setup and the related interference couplings are further illustrated in Figure 1, where it is assumed the D2D users are allocated dedicated resources within a cell while the frequency reuse factor of the cellular network equals one, i.e., there is no intra-cell D2D or cellular interference similarly to the conventional LTE system. Besides, the shared resource allocation for spatial reuse is also allowed to further improve the spectrum usage as long as there is sufficient decoupling among D2D users or between D2D user and cellular users, in which the occurred intra-cell interference from D2D users has to be well controlled for achieving the performance gain.

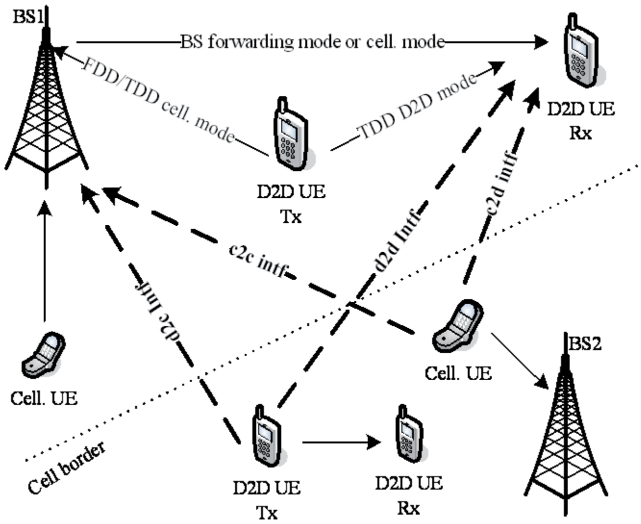

Figure 1: D2D and cellular links (solid line) and interference couplings (dashed line) when D2D operation uses the uplink band of a cellular system with the frequency reuse factor of one and dedicated D2D resources within a cell.

The Signal-to-Interference-Noise-Ratio (SINR) at a D2D Rx UE per subcarrier for D2D communication can be expressed as

$$\gamma_{d_{rx}} = \frac{P_{s,d_{rx}} \cdot c_{s,d_{rx}}}{\underbrace{\sum_{j=1,j\neq s}^{N_{tx}} P_{j,d_{rx}} \cdot c_{j,d_{rx}}}_{d2d\ Intf} + \underbrace{\sum_{k=1}^{N_c} P_{k,d_{rx}} \cdot c_{k,d_{rx}}}_{c2d\ Intf} + \sigma_{d_{rx}}{}^2}, \qquad (1)$$

and the perceived SINR at eNB for cellular uplink reception is

$$\gamma_b = \frac{P_{s,b} \cdot c_{s,b}}{\underbrace{\sum_{j=1}^{N_{tx}} P_{j,b} \cdot c_{j,b}}_{d2c\ Intf} + \underbrace{\sum_{k=1}^{N_c} P_{k,b} \cdot c_{k,b}}_{c2c\ Intf} + \sigma_b{}^2}, \qquad (2)$$

where $P_{i,j}$ and $c_{i,j}$ denote the transmit power and the channel gain for the link between device i and j respectively; s, d_{rx} and b stand for the Tx UE, D2D Rx UE and base station; N_{tx} is the number of D2D Tx UEs and N_c is the number of cellular UEs; ${\sigma_{d_{rx}}}^2$ and ${\sigma_b}^2$ represent additive white Gaussian noise at D2D Rx UE receiver and base station receiver separately.

According to SINR expression given in equations (1) and (2), it can be noted that the overall system performance in a mixed system with both D2D and cellular communications can be affected by several factors:

- D2D pathloss with the impact on D2D mode selection criteria,
- D2D transmit power control scheme,

- Frequency resource allocation strategy,
- Proportion of D2D communication.

These factors are also tightly coupled between each other, which makes a big challenge for system operation and optimization.

In detail, the key components of the concept: the selection between the D2D and cellular operation modes, the power control of D2D links, and the allocation of D2D radio resources, are discussed in Sections 2.1, 2.2, and 2.3, respectively.

2.1 Mode Selection

A pair of close-by cellular users supporting D2D operation can communicate by using the conventional cellular mode, the simplified cellular mode or D2D mode of operation. The simplified cellular mode is an optimization of the conventional cellular mode based on packet direct forwarding or routing via eNB rather than the gateway, which can significantly reduce the end-to-end packet delivery latency. In short, the latency can be expressed below for the conventional cellular mode (T_{cc}), the simplified cellular mode (T_{sc}) and the direct D2D cellular mode (T_{d2d}):

$$T_{cc} = t_{ul} + t_{cn} + t_{dl}, \quad (3)$$

$$T_{sc} = t_{ul} + t_{dl}, \quad (4)$$

$$T_{d2d} \approx t_{ul}, \quad (5)$$

where t_{ul} and t_{dl} denote the delay for the successful packet delivery in uplink and downlink air interface separately including the Hybrid automatic repeat request (HARQ) (re)transmission delay and UE/eNB processing delay; t_{cn} stands for the routing delay for the packet in the core network. It is clear that the simplified cellular mode based on packet routing or direct forwarding via layer 2 function can avoid the huge latency in the core network caused by the conventional cellular mode using layer 3 routing (up to 200ms delay reduction) whereas the direct D2D transmission mode can further reduce the half latency thanks to one-hop instead of two-hop transmission in the simplified cellular mode. Considering the fact the devices with the potential for D2D communication are typically close to each other and under the same eNB, the simplified cellular mode can be exploited as one mode to offer the D2D service.

To maximize the system throughput, the optimal criterion for selecting between these two modes would be the sum-rate criterion. That is, the mode which would result in the highest system sum-rate would get selected. For optimality, the mode selection should also be done jointly with power control and resource allocation based on instantaneous channel and interference conditions. This, however, would largely increase complexity and control signaling. Depending on the phase of D2D operation, Initial D2D link setup phase or D2D operation maintenance phase, the mode selection criteria can be different considering the tradeoff between the performance and link management complexity.

In the initial D2D link setup phase, the mode selection can be based on a long-term measurement, e.g., pathloss or the received power. The purpose is to establish a stable communication link for initial D2D setup. During this phase, eNB is lacking of the full knowledge of link quality due to limitation on channel information reporting. In this case, we resort to a suboptimal but much simpler and more practical approach where the mode selection is done based on the received power level.

The D2D mode is selected if the smaller of the powers received at the two directions of a D2D link between two users would be higher than the smaller of the two powers that a base station would receive from these two users. Otherwise the users operate in the cellular mode. The above criterion can be also expressed as

$$min(P_{1,2,d_{rx}} \cdot c_{1,2}, P_{2,1} \cdot c_{1,2}) > min(P_{1,b} \cdot c_{1,b}, P_{2,b} \cdot c_{2,b}), \tag{6}$$

where $P_{i,j} \cdot c_{i,j}$ is the power from unit j that is received at unit i and unit index b belongs to the base station and indices one and two to the D2D users. With this criterion we assume that the bidirectional cellular link between the users is limited by the uplink and that the users may have different transmit powers also in D2D operation. Note that if the transmit powers of the links considered in (6) are the same, this criterion reduces to selecting the mode with the lowest path loss.

Although the above simple suboptimal mode selection criterion ensures that the mode and link with the highest signal level is chosen, it does not take into account the interference level at the receiver. In particular, the presence of strong inter-cell interference variation during the operation at the cell edge may eventually lead to degraded performance in the D2D mode. However, during D2D operation phase with the established D2D link and the simplified cellular link, eNB can make a fast or dynamic mode selection based on the frequent channel quality indication (CQI) report which can capture the effect of varying interference. In this case, the criteria can be established based on the short-term D2D SINRs ($\gamma_{2,1}$ and $\gamma_{1,2}$) derived from the reported D2D CQIs, and cellular uplink SINRs ($\gamma_{1,b}$ and $\gamma_{2,b}$) estimated from the uplink sounding reference signal (SRS). Similarly to (6), the SINR based criteria can be expressed as

$$min(\gamma_{2,1}, \gamma_{1,2}) > min(\gamma_{1,b}, \gamma_{2,b}). \tag{7}$$

In practical operation, the dynamic mode switching would require the unique sequence number for the packet by D2D Tx UE so that the D2D Rx UE can re-order the packets received from either eNB forwarding or D2D direct transmission, as indicated in Figure 1. The dynamic mode switching can be transparent to the D2D UEs due to the characteristics of broadcasting transmission. Whether to dynamically switch is fully controlled by eNB via the resource allocation grant.

One use case for dynamic mode switching is illustrated in Figure 2. In this case, based on the established D2D communication eNB can derive the SINRs for two modes based on D2D CQI reports and SRS estimation. D2D Tx UE will transmit the data to Rx UE using the resources indicated by the D2D resource grant from eNB. Meanwhile, the packets can also be received by eNB, given the suitable transmit power setting. In retransmission phase triggered by D2D negative-acknowledge (NACK), eNB can choose whether to retransmit the data by eNB forwarding mode or D2D direct mode supposing the packet has been received by eNB successfully in the initial transmission. In case of eNB forwarding mode, eNB will suspend the resource allocation to D2D Tx UE for retransmission. Instead, eNB would retransmit the data directly to D2D Rx UE. For each retransmission, eNB can dynamically determine the mode of communication based on the estimated SINRs. eNB can resume the D2D transmission via a D2D resource grant for either new transmission or retransmission. The dynamic mode switching can secure the robust and flexible communication between two devices, especially in case of varying channel and interference conditions. In addition, it can also reduce the retransmission delay since there is no need of D2D grant with UE processing (up to 3ms delay) compared to eNB direct forwarding mode.

Besides, it should be kept in mind that there is another benefit of downlink resource saving with direct D2D communication only using the uplink resources, compared to the simplified or conventional cellular transmission mode where BS has to transmit the same data to the peer user using the downlink resources. Essentially, this also provides the potential for D2D communication triggered by offloading the traffic in cellular downlink for the scarce downlink resources.

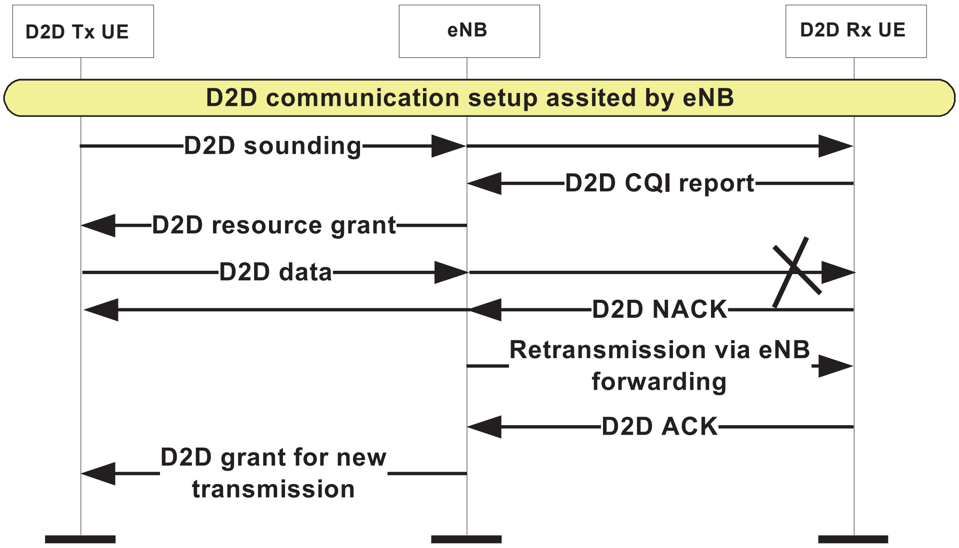

Figure 2: Illustration of sequence diagram for dynamic mode switching.

Thus, there can be different criteria for the mode selection depending on the target of network optimization. The key for However, the interference caused to and received from the other users in the D2D mode can be affected to some extent by power control and resource allocation scheme, which would be further discussed in the following sections. For simplicity, the term "cellular mode" would be used to represent the simplified cellular mode below.

2.2 Power Control

Both the cellular and D2D links use the fractional power control according to the LTE specifications [25]. For the D2D links, we consider two schemes which differ in what path loss is to be fractionally compensated. The first scheme targets the path loss in the D2D link, whereas the second scheme uses the loss of the cellular link towards the serving base station. In principle, the transmit power for D2D communication in subframe i can be determined by

$$P_{d2d}(i) = min(P_c(i), P_0 + \alpha \cdot PL + 10 \cdot log_{10}(M(i)), \quad (8)$$

where PL is the pathloss for either cellular link or D2D link depending on the PC scheme to be discussed later, $P_c(i)$ is the transmit power assuming the cellular mode operation in subframe i, which is derived based on the cellular link pathloss for PL in (2), and P_0 is the power per PRB, $M(i)$ is the allocated bandwidth in subframe i for data transmission measured in number of physical resource blocks (PRBs) specified in [25], α is for partial pathloss compensation with a value in between 0 and 1. Specifically, supposing $\alpha = 1$, P_0 can be interpreted as the target received power per PRB to achieve a certain SNR.

Essentially, the D2D link based power control of D2D users operates in the same principle as the power control of cellular users, but due to the shorter average link distances of D2D users with the proper mode selection, their transmit power levels are much lower. This saves D2D users' battery resources and decreases their interference towards other users in comparison with their operation in the cellular mode. On the other hand, the low D2D link power without consideration of the interference may be overshadowed by nearby cellular users, especially in the cell edge where the transmit powers of the neighbor cellular users are at the highest. This disadvantage can be countered by the cellular link based power control that allows the user to transmit in the D2D link with the same power as it would if it was transmitting to the base station. This power also serves as the upper limit for the D2D link based power control, which implies that D2D transmission won't cause more interference to the incumbent cellular users than the conventional cellular mode. With the cellular link based power control option, however, the D2D transmission does generate more interference to the system, but not more as it would in the cellular mode. Thus, a sensible D2D PC scheme can effectively reduce the power consumption and/or enhance the overall system performance.

2.3 Resource Allocation

The primary radio resource allocation scheme we consider for D2D links in this study is similar to that of conventional cellular users. That is, D2D pairs are scheduled dedicated resources by their serving base station in the same way as the base station schedules its cellular users. Moreover, the D2D links have access to all the same time and frequency resources as the cellular links. Both link types are scheduled by using the proportional fair scheduling algorithm and are assigned the same number of PRBs. The number of users and the number of PRBs per user were set with the view to having a fully loaded system while having an activity factor of one for all users.

While the above centralized resource allocation scheme with dedicated resources avoids intra-cell interference, it is not able to utilize the spatial reuse gain potential of D2D communication. To explore this potential, we considered also a decentralized resource allocation scheme where the D2D pairs employ autonomous scheduling. In that case, the D2D pairs use the resources providing the highest scheduling metric for their link. This may result in a blind reuse of resources scheduled to cellular or other D2D users in the cell. The spatial reuse of the resources within a cell can increase the spectral efficiency if the resulting intra-cell interference can be either tolerated, avoided, or suppressed. If not, the intra-cell interference may eventually degrade the spectral efficiency. In addition, the available radio resources are increased for both the cellular and D2D users in comparison with our primary resource allocation scheme ensuring dedicated resources. This provides a higher frequency diversity gain, which becomes beneficial especially in light system loads where there are less collision between the resources allocated to the cellular and D2D users. One more benefit for the autonomous reuse is the low signaling overhead in the practical operation. However, in case of the high load, the gain of spatial reuse may rely on more precise interference control for decoupling of the shared users. Then, the network controlled reuse scheme for resource allocation associated with mode selection and power control may be more favored. So, selection of the suitable resource allocation scheme can further improve the spectrum usage.

3 D2D Channel Model

Since the interest in D2D communications within a cellular system has raised relatively recently, there are no widely accepted channel models for D2D links with cellular radio frequencies. Furthermore, models that would encompass comparable modeling of both the D2D links (MS–MS) and the conventional cellular links (MS–BS) are even scarcer. One existing study that includes channel models for both the MS–BS and MS–MS links, as well as for links involving relays was presented in [23]. From those results, we extracted parameters for the path loss and LOS probability discussed in Sections 3.1 and 3.2, respectively.

3.1 Path Loss Model

The mean path loss of a link can be expressed by the well-known log-distance model:

$$L[dB] = L_0 + 10nlog10(d/d_0) + 20log10(f/MHz), \tag{9}$$

where L_0 is the path loss at the reference distance d_0, n is the path loss exponent, d is the link distance, and f is the carrier frequency. The adopted values for n and L_0 with one meter reference distance d_0 and 2 GHz carrier frequency f that were given for both the line-of-sight (LOS) and non-LOS (NLOS) type MS–BS and MS–MS links in [23] are represented in Table 1. With $n = 2$, the LOS path loss for both the MS–BS and MS–MS links is simply the free-space path loss. This, together with the relatively high path loss exponents for NLOS links ensures that both the strong desired and interfering links with longer distances as well as the relatively heavily attenuated links with shorter distances will be well represented.

Table 1: Path Loss Parameters

Link type	L_0	n
LOS MS-BS/MS	-27.6	2
NLOS MS-BS	-57.37	4.88
NLOS MS-MS	-62.01	5.86

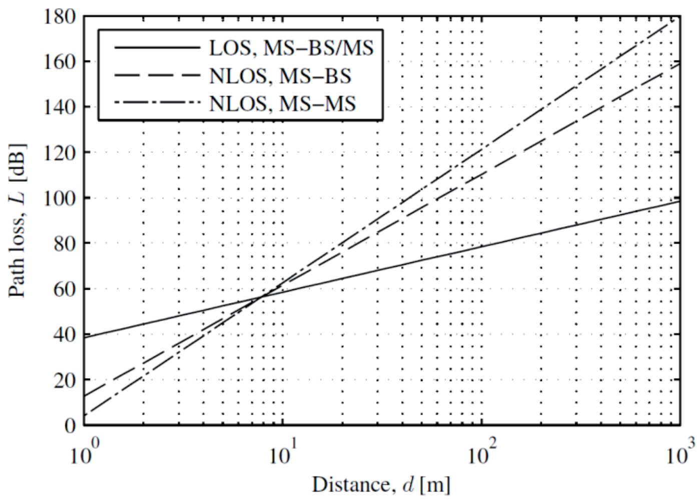

Figure 3: Path loss as a function of link distance for LOS and NLOS links between a base station and a mobile or between two mobiles.

The path losses obtained with the above parameters are illustrated in Figure 3. It can be seen that for very short link distances, which are below the shortest distances at which the models have been fitted to experimental data, the proportions between the path losses of different link types become illogical. This behavior is typical for log-distance path loss models and was avoided here by lower bounding the path loss to the free-space path loss that is now equal to the LOS path loss. In any case, these shortest links are very likely to be LOS links, as will appear in the following.

3.2 Line-of-Sight Probability

The link distance dependent LOS probabilities were derived by fitting a LOS probability equation similar to the equation given for mobile station to relay station (MS–RS) links in [24] to the LOS probability illustrations in [23] based on visual fit. The considered LOS probability equation includes two exponential terms, one of which defines the divergence of the probability from unity at short link distances, and the other of which determines the convergence of the probability towards zero at long link distances. We elaborated this equation further by parameterizing it as:

$$P_{LOS} = 1 - P_j - \min[1 - P_j, k_1 \exp\left(-\frac{d_1}{d}\right)] + \min[1 - P_j, k_0 \exp\left(-\frac{d}{d_0}\right)] \ , \qquad (10)$$

where P_j is interpreted as the joint point of the exponential terms, d_1 and d_{01} determine the distances at which the terms diverge from unity and converge towards zero, and k_1 and k_0 contribute to the slopes of the terms, respectively. The above parameters obtained for MS–BS and MS–MS links are given in Table 2, and the resulting LOS probabilities are illustrated in Figure 4.

Table 2: Loss Probability Parameters

Link	P_j	k_1	d_1	k_0	d_0
MS-BS	0.85	6	130	1.6	56
MS-MS	0.80	7	130	2.0	40

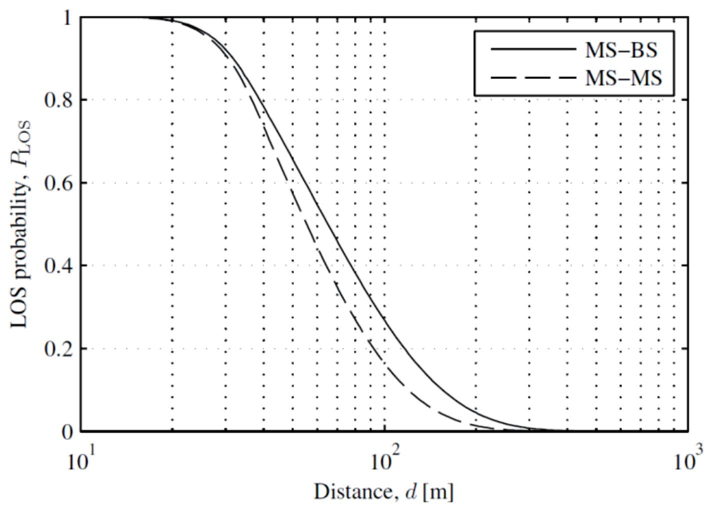

Figure 4: LOS probability as a function of link distance between a base station and a mobile or between two mobiles.

4 SIMULATION SETUP AND RESULTS

The main simulation and LTE system parameters, which are either alternative or differ from those defined in LTE specifications, are given in Table 3. If the location of a D2D Rx user dropped into the network layout did not led up to the D2D operation mode, the user was relocated until the D2D mode got chosen. This procedure is similar to the widely used load balancing approach that was also used here for the cellular and D2D Rx users. These procedures enable to study the effects of D2D communication with a fixed number and proportion of cellular and D2D users per cell. Without loss of generality, we assume the traffic in D2D links to be unidirectional within a simulation drop.

The cellular layout is a wrapped-around hexagonal grid with 19 base station sites and 3 sectors per site. Both the interference limited scenario (3GPP Case 1) and the cover limited scenario (3GPP Case 3) as defined in [24] are adopted for an extensive performance evaluation, in which the inter-site distance (ISD) between eNBs is 500m corresponding to an interference limited macro-cell scenario and 1700m for a coverage limited macro-cell scenario. There is a balanced load of N_c cellular users and N_{tx} D2D Tx users per sector, that is, altogether $N_c + N_{tx}$ Tx users per sector. The total number of Tx users is fixed with 8 users in the study with a varying number of N_{tx}. The cellular users and D2D Rx users have random locations uniformly distributed over the whole network under the load balancing condition. Each of the D2D Tx users is given a random uniformly distributed location over a disc with a given maximum radius r_{max} around its pairing D2D Rx user. The value of r_{max} was set to be 400 m, which is well above the maximum MS–BS distance of 500/√3≈289m in Case 1 scenario, in order not to artificially limit the D2D link distances. There is no lower limit for the distance between mobiles, whereas for the MS–BS distance the limit is 35 m.

The mean physical-layer user throughput with overhead for different number of D2D Tx users out of the total number of eight links per cell is illustrated with different cases in Figures 5 and 7 for the interference limited and the coverage limited scenarios separately. “Case 1” and “Case 3” are the baselines without any D2D operation. In both figures, the D2D pairs use dedicated resources in the without intra-cell interference from the other D2D and cellular users unless “Bld” is presented in the name of the case, while they use the D2D link based power control for “Dpc” cases and use the cellular link based counterpart for “Cpc” cases. In “Bld” cases, the D2D pairs use now the autonomous scheduling scheme, whereas their power control method is again the D2D link based one in order to limit the interference towards cellular users whose resources can be reused. These cases are based on the decentralized scheduling with independent resource allocation by D2D pairs and eNB separately, which is used to check the potential of D2D autonomous communication performance in case of lacking the network assistance.

Table 3: System Parameters

Parameter	Value
User deployment	Total 8 D2D/cellular Tx users per cell
N_{tx}	0, 2, 4, 6, 8 D2D Tx users
Macro cell deployment	3GPP Case 1 with 500m ISD;
	3GPP Case 3 with 1732m ISD
Minimum MS-BS distance	35 m
Carrier frequency	2 GHz
Bandwidth	10 MHz
Power control	$P_0 = -56\ dBm, \alpha = 0.6$
Modulation scheme	BPSK, QPSK, 16-QAM, 64-QAM
Coding rate	1/3, 1/2, 2/3, 3/4
BLER target	20% after 1st transmission
Max. retransmissions	3
Channel estimation	Non-ideal
Traffic model	Full buffer
Scheduler	Proportional fair
Resource allocation	6 PRBs per Tx user
UE transmit power	24 dBm

4.1 Performance for the interference limited scenario

It can be seen from Figure 5 for the interference limited scenario that when the system operation shifts from cellular to D2D connections for “Dpc” cases, the mean throughput of the all users gradually increases with D2D share of the total system load as the inter-cell interference level decreases due to D2D lower transmit powers. For the same reason, the cell edge performance at 5% -tile also benefits as the load shifts from cellular to D2D links with less inter-cell interference. For “Cpc” cases, both the mean throughput and cell edge throughput over all users gradually increases with D2D share of the total system load. However, the cell edge performance is significantly improved for “Dpc” cases than “Cpc” cases thanks to the low transmit power. On the other hand, the relatively low transmit power in “Dpc” case may result in the slightly lower mean throughput than the “Cpc” cases as the power setting based on the D2D pathloss doesn’t take into account any inter-cell co-channel interference. In this interference limited scenario, the performance is more sensitive to the setting of the transmit power which may increase the interference while enhancing the signal strength. Essentially, the gain mechanism is quite different for "Dpc" cases and "Cpc" cases although both of them can improve the overall system performance. In practical operation, the selection of power control scheme may also depend on the goal of network optimization.

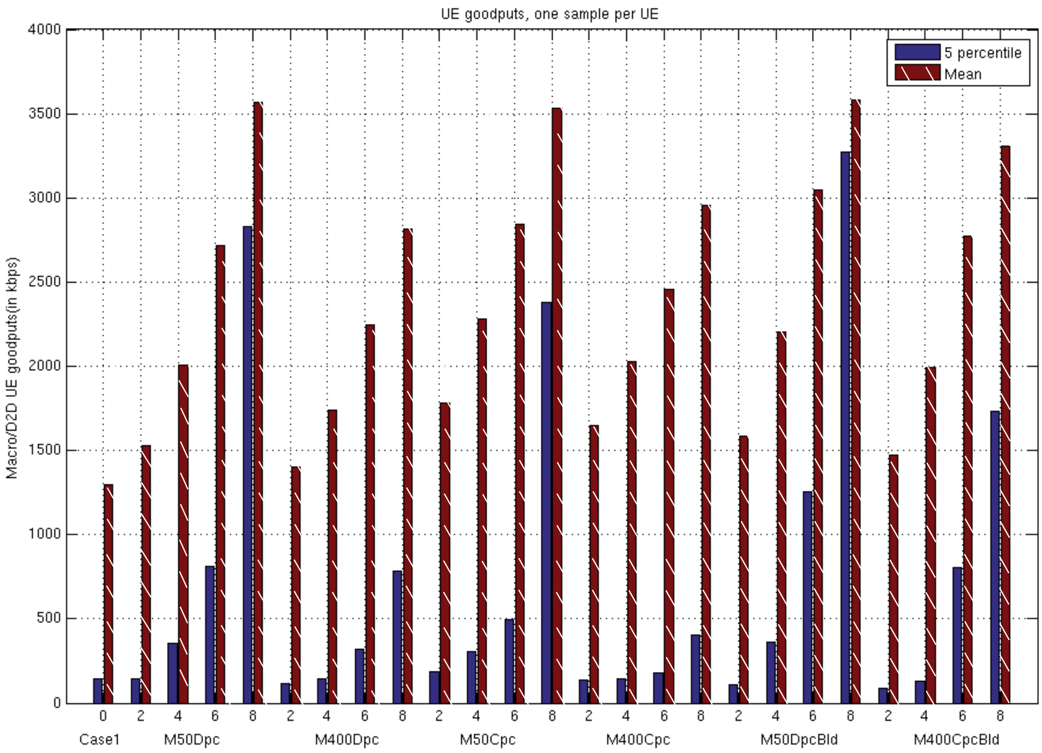

Figure 5: Performance results for deployment under Case 1 macro-cell scenario.

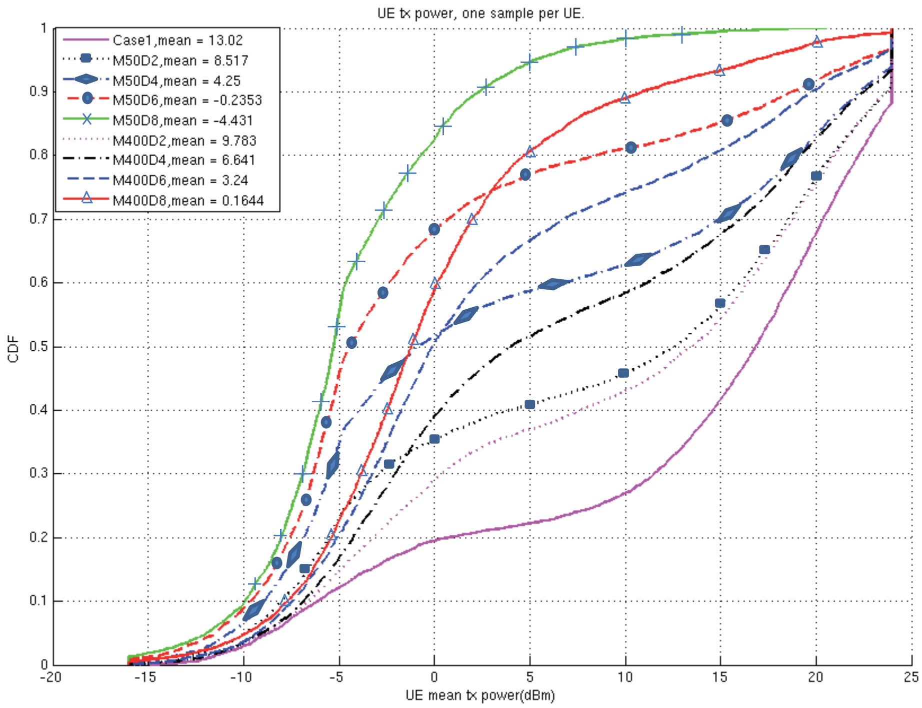

Figure 6. UE transmit power for deployment under Case 1 macro-cell scenario.

For the "Bld" cases with D2D autonomous scheduling, they show quite promising gains in terms of both the mean throughput and the cell edge throughput. Even though the resource allocation between D2D and cellular links is not fully orthogonal compared to the cases with centralized scheduling, it would not cause a big problem in case of the fractional load, especially considering the potential gain from spatial multiplexing between D2D and cellular links. Furthermore, the frequency diversity gain can be achieved thanks to frequency domain scheduling over the whole bandwidth for D2D users and cellular users separately, which can avoid the performance loss due to the shared frequency resources in the centralized scheduling.

In terms of UE Tx power consumption as shown in Figure 6, it is obvious that "Dpc" cases can significant save UE power whereas "Cpc" cases may drain the UE batter more quickly. With the shorter D2D distance and more D2D pairs, the mean power is getting much lower.

4.2 Performance for the coverage limited scenario

Similarly to the performance in the interference limited scenario, both the mean throughput and the cell edge throughput over all UEs are significantly improved compared to the baseline without any D2D operation thanks to the contribution of D2D operation, as indicated by Figure 7. In addition, it seems no clear performance difference for the cases with the maximum D2D distance of 50m. And for the case with maximum 400m D2D distance, the overall performance is much lower than the case of D2D operation with maximum 50m distance. The larger allowed D2D operation range would require much higher transmit power as proved in Figure 8. In other words, in this coverage limited scenario with the larger D2D operation range, the overall performance is more limited by the affordable transmit power to improve the signal strength rather than the co-channel interference.

In 3GPP case 3, the inter-site distance is 1732m, which is much larger than Case 1. It will implicitly lower the UE density given the same number of UEs. Accordingly, the main source of the interference for D2D communication, c2d interference, can be reduced, which will potentially improve the overall performance. The mode selection coupling with the max D2D distance of 50m would make the D2D performance quite good so that the 5% UE throughput in the combined performance figure with mixed UEs is actually not from the D2D UEs but mainly from the cellular UEs. That's why the mean UE throughput in the combined figure is improved much more than 5% UE throughput.

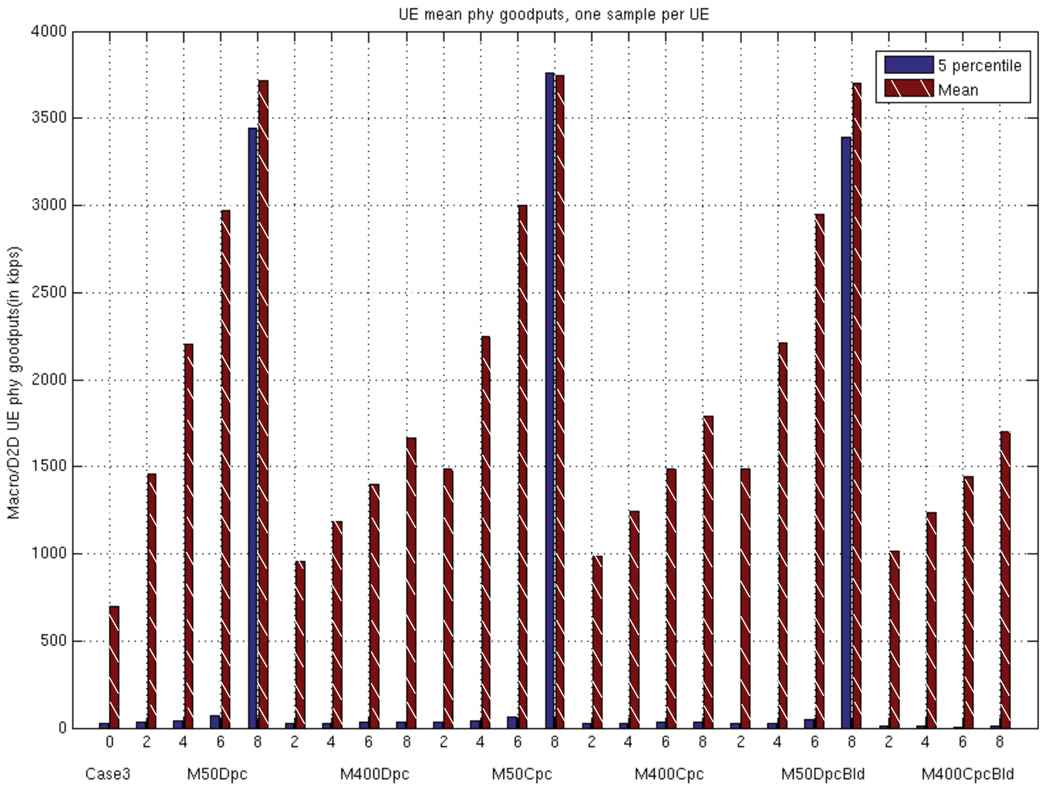

Figure 7: Performance results for deployment under Case 3 macro-cell scenario.

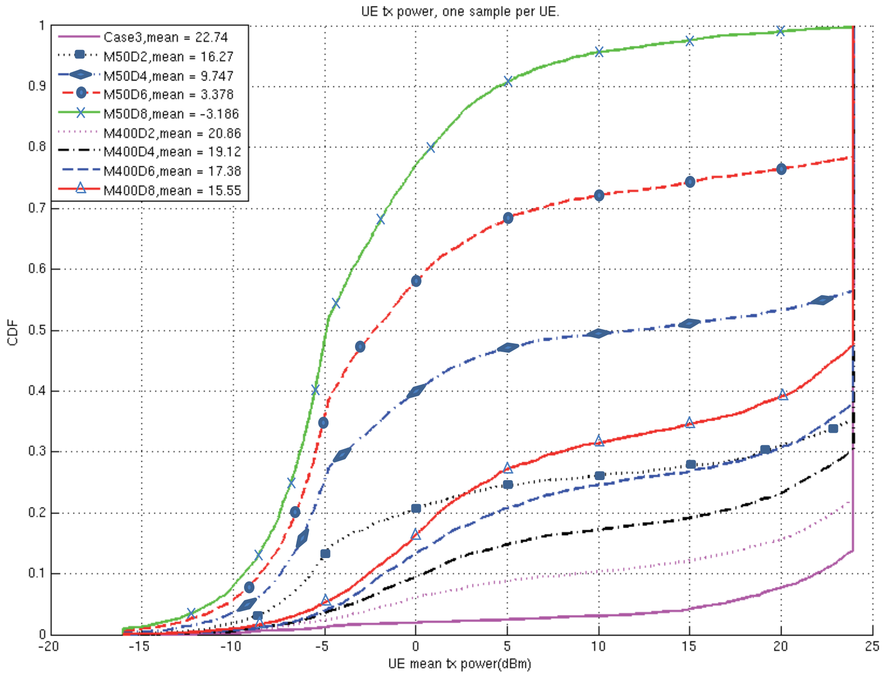

Figure 8: UE transmit power for deployment under Case 3 macro-cell scenario.

And with D2D links only, there is no notable difference between the two PC schemes. This is because the inter-cell interference is more contributed by D2D transmission rather than the cellular transmission. Then the high transmit power with cellular link based PC would likely lead to more interference, thus slightly or even no improvement on the performance compared to D2D link based PC. For the throughput of cellular links, it should be kept the same thanks to the same interference level caused by the unchanged transmit power for D2D mode and cellular mode with cellular link based PC. Eventually, the overall performance is improved significantly.

As can be seen from the results for the autonomous D2D scheduling with D2D link based PC and maximum 50m D2D distance, the throughput performance is similar to those obtained with the same power control scheme but dedicated resources. However, in case of maximum 400m D2D distance, the autonomous scheduling may provide a slightly worse performance due to more severe cross-link interference caused by the larger D2D operation range with non-orthogonal resource allocation. In addition, compared to the performance with cellular link based PC, there is a slightly performance loss due to the same reason that there is no power control margin for D2D link based PC to overcome the unexpected inter-cell interference. Even though the autonomous D2D scheduling results in a blind reuse of resources, the benefits of the spectral reuse surpass the increased intra-cell interference. D2D pairs benefit from the full freedom of scheduling themselves on the best frequency resources, while the increased share of D2D users decreases the competition for schedulable resources among the remaining cellular mode users. Supposing there is no limitation of 6PRBs for resource allocation in this study, it is expected to further improve the overall performance with more frequency resources for reuse by each user.

Similarly to Case 1 in terms of power consumption, there is also a significant power saving with D2D link based power control. However, it can be noted that the maximum power is more reached in this case due to the larger communication range.

5 Conclusion

In this paper, we presented a system concept of D2D communication for the long term evolution of 3GPP LTE-Advanced network system to address the fast increasing local traffic. The performance of direct D2D communication in an LTE system over an interference limited micro-cellular environment and a coverage limited macro-cellular environment was evaluated. The D2D operation deployed the uplink band of the LTE FDD mode and took place between two same-cell users that had higher received power in their mutual link than in those towards the base station. The simulation results showed that besides removing the duplicated traffic from the downlink with additional downlink resource saving, D2D transmission can improve the overall system throughput also in the uplink. Since receiving D2D users are susceptible to interference from nearby high-power users that are scheduled on the same resources, their throughput can be greatly improved by allowing them to use higher cellular link based transmit power instead of D2D link based power when the majority of other users in the network are conventional cellular users. The lower D2D transmit powers, on the other hand, reduce the interference level and, therefore, improved the throughput of cellular users as the system load shifts from cellular to D2D links. Finally, the reuse of cellular resources for D2D communication, even when done so blindly, was demonstrated to provide further improvement in the system throughput.

References

[1] T. Adachi and M. Nakagawa, “A study on channel usage in a cellular–adhoc united communication system for operational robots,” IEICE Trans. Commun., E81-B(7):1500–1507, 1998.

[2] H.-Y. Hsieh and R. Sivakumar, “On using peer-to-peer communication in cellular wireless data networks,” IEEE Trans. Mobile Comput., 3(1): 57–72, 2004.

[3] J. Lehtomäki, I. Suliman, J. Vartiainen, M. Bennis, A. Taparugssanagorn, and K. Umebayashi, “Direct communication between terminals in infrastructure based networks,” in Proc. ICT Mobile and Wireless Commun. Summit, Stockholm, Sweden, Jun. 2008.

[4] P. Jänis, C.-H. Yu, K. Doppler, C. Ribeiro, C. Wijting, K. Hugl, O. Tirkkonen, and V. Koivunen, “Device-to-device communication underlaying cellular communications systems,” Int. J. Commun. Netw. Syst. Sci., 2(3):169–178, 2009.

[5] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, “Device-to-device communication as an underlay to LTE-advanced networks,” IEEE Commun. Mag., 47(12):42–49, 2009.

[6] S. Hakola, T. Chen, J. Lehtomäki, and T. Koskela, “Device-to-device (D2D) communication in cellular network — Performance analysis of optimum and practical communication mode selection,” in Proc. IEEE Wireless Commun. and Networking Conf., Sydney, Australia, Apr. 2010.

[7] T. Chen, G. Charbit, and S. Hakola, “Time hopping for device-to-device communication in LTE cellular system,” in Proc. IEEE Wireless Commun. and Networking Conf., Sydney, Australia, Apr. 2010.

[8] S. Vasudevan, K. Sivanesan, S. Kanugovi, and J. Zou, “Enabling data offload and proximity services using device to device communication over licensed cellular spectrum with infrastructure control”, IEEE 78th Vehicular Technology Conference (VTC Fall), 2013

[9] A. Asadi, Q. Wang, and V. Mancuso, “A survey on device-to-device communication in cellular networks”, IEEE Communications Surveys & Tutorials, 2014, to appear

[10] M. Alam, D. Yang, J. Rodriguez, and R. Abd-Alhameed, “Secure device-to-device communication in LTE-A”, IEEE Communications Magazine, 52(4):66—73, 2014

[11] J. Lee, J. Gu, S. J. Bae, and M. Chung, “A session setup mechanism based on selective scanning for device-to-device communication in cellular networks”, 17th Asia-Pacific Conference on Communications (APCC), 2011.

[12] Y. Li, Z. Wang, D. Jin, and S. Chen, “Optimal mobile content downloading in device-to-device communication underlaying cellular networks”, IEEE Transactions on Wireless Communications, 13(7):3596—3608, 2014

[13] W. Zhou, X. Sun, C. Ma, J. Yue, H. Yu, and H.-W. Luo, "An interference coordination mechanism based on resource allocation for network controlled Device-to-Device communication", IEEE/CIC International Conference on Communications, China, 2013

[14] Y. Xu, R. Yin, T. Han, and G. Yu, "Interference-aware channel allocation for device-to-device communication underlaying cellular networks", 1st IEEE International Conference on Communications in China (ICCC), 2012

[15] S. Wen, X. Zhu, Z. Lin, X. Zhang, and D. Yang, "Optimization of interference coordination schemes in device-to-device (D2D) communication", 7th International ICST Conference on Communications and Networking in China (CHINACOM), 2012

[16] T. Han, R. Yin, Y. Xu, and G. Yu, "Uplink channel reusing selection optimization for device-to-device communication underlaying cellular networks", IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), 2012

[17] B. Wang, L. Chen, X. Chen, X. Zhang, and D. Yang, "Resource allocation optimization for device-to-device communication underlaying cellular networks", IEEE 73rd Vehicular Technology Conference (VTC Spring), 2011.

[18] L. Song, D. Niyato, Z. Han, and E. Hossain, "Game-theoretic resource allocation methods for device-to-device communication", IEEE Wireless Communications, 21(3):136—144, 2014

[19] J. Gu, S. J. Bae, B.-G. Choi, and M. Y. Chung, "Dynamic power control mechanism for interference coordination of device-to-device communication in cellular networks", 3rd International Conference on Ubiquitous and Future Networks (ICUFN), pp. 71—75, IEEE, 2011

[20] S. J. Bae, D. H. Kim, B.-G. Choi, and M. Y. Chung, "Transmission power control for FlashLinQ device-to-device communication system", IEEE 77th Vehicular Technology Conference (VTC Spring), 2013

[21] S. Wen, X. Zhu, X. Zhang, and D. Yang, "QoS-aware mode selection and resource allocation scheme for device-to-device (D2D) communication in cellular networks", IEEE International Conference on Communications Workshops (ICC), 2013

[22] E. Zihan and K. W. Choi, "Random access protocol for collision avoidance in cellular device-to-device communication", IEEE International Conference on Communications (ICC), 2014

[23] Z. Wang, E. K. Tameh, and A. R. Nix, “Statistical peer-to-peer channel models for outdoor urban environments at 2 GHz and 5 GHz,” in Proc. IEEE Veh. Technol. Conf., vol. 7, Los Angeles, USA, Sep. 2004, pp. 5101–5105.

[24] Further Advancements for E-UTRA. Physical Layer Aspects, 3rd Generation Partnership Project 3GPP TR 36.814 V1.5.0, Nov. 2009, Release 9.

[25] Evolved Universal Radio Access (E-UTRA); Physical layer procedures, 3rd Generation Partnership Project 3GPP TS 36.213 V9.3.0, Sep. 2010, Release 9.