Enable Device-to-Device Communications Underlaying Cellular Networks: Challenges and Research Aspects

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ABSTRACT

Device-to-device communication underlaying a cellular network is a promising technology in future wireless networks to improve network capacity and user experience. While D2D communication has great potential to improve wireless system spectral and energy efficiency due to the proximity of communication parties and higher spectrum reuse gain, tremendous work is still ongoing to turn the promising technology into a reality. This article discusses D2D technical challenges as well as standards progress and important research aspects that enable D2D communications underlaying cellular networks. The key research areas addressed include interference management, multihop D2D communications, and D2D communications in heterogeneous networks. When enabling D2D communications underlaying cellular networks, D2D communications can use either cellular downlink or cellular uplink resources. The two resource sharing modes will create different interference scenarios. The performance evaluation on D2D communications underlaying cellular networks under these two different scenarios is provided.

INTRODUCTION

In the past two decades, there have been tremendous technology development and commercial success in wireless cellular networks. Cellular users are increasing exponentially, spread out all over the world, benefitting from various services including voice, data, and video. Recently, device-to-device (D2D) communications underlaying a cellular network infrastructure has been proposed and has attracted much attention [1–3]. D2D underlaying a licensed cellular network, which can provide more service guarantees in a controlled environment, enables user equipment (UE) to communicate with other nearby UE directly over a D2D link under the cellular network channel resources without extra hops through the central base station. In general, D2D communication allows fast access to the radio spectrum with a controlled interference level and holds the promise of four types of gain: proximity gain, reuse gain, hop gain, and paring gain [3]. Typical D2D communication applications are peer-to-peer (P2P) file sharing, local voice service, video streaming, and content-aware applications.

There are paramount challenges and active research activities regarding D2D communications underlaying cellular networks. First, interference management is critical since cellular networks need to manage new interference scenarios by supporting D2D communications. In cellular networks, traditional cellular UEs (CUEs) can be considered as primary UEs, and additional D2D UEs (DUEs) should not degrade the performance of CUEs. On the other hand, the interference from current cellular networks may also hurt the quality of service (QoS) requirements of DUEs. Many research aspects are related to interference management, including mode selection, resource allocation, power control, and so on. Second, multihop D2D communication, which allows a UE to be a relay to help other UEs, has not been fully investigated yet. Network coding can be attempted in such scenarios and help improve the throughput of multihop D2D communications underlaying cellular networks. Third, since heterogeneous cellular architecture with a mixed deployment of macro and micro base stations is a key technology in future wireless systems, coexistence of D2D communications in such heterogenous networks is also worth discussing.

This article is organized as follows. First, we give a summary of D2D technology's merits, challenges, and progress in standards. Then we focus on critical challenges and research aspects in D2D communications underlaying cellular networks: interference management, multihop D2D communications with network coding, and D2D communications in heterogeneous networks. Specifically, mechanisms such as mode selection, resource allocation, D2D communications with multi-antenna transmission techniques, and power control are considered. Finally, performance evaluation in D2D communications underlaying cellular networks is provided.

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D2D TECHNOLOGY MERITS, CHALLENGES, AND STANDARDS SUMMARY

The explosive demand for future applications on high data rates and spectral efficiency triggered the launch of the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) standard. LTE mobile communication systems are developed as a natural evolution of second and third generation (2G and 3G) systems, including Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), and code-division multiple access 2000 (CDMA2000). With orthogonal frequency-division multiplexing (OFDM), multiple-input multiple-output (MIMO), capacity-approaching codes, a pure packet-switched core network, and other technologies, LTE aims to achieve a peak data rate of 300 Mb/s in the downlink and 75 Mb/s in the uplink, respectively, as in 3GPP Release 8 [4]. LTE-Advanced, as in 3GPP Release 10, is an enhancement of the LTE standard, and further improves capacity and coverage. New technologies have been studied for LTE-Advanced to meet International Mobile Telecommunications (IMT)-Advanced requirements, one category being local area optimization.

As a response to local area services, D2D communications underlaying a cellular network infrastructure becomes a promising technology in future wireless networks to improve network capacity and the user experience. In 3GPP Release 12, it has been agreed that D2D technology is of high interest for further investigation. The initial use cases of 3GPP D2D study are focused on social networking, cellular network offloading, public safety networks, and media sharing. As shown in Table 1, with more check-marks representing more design and optimization concerns, different D2D applications may have significantly different requirements on D2D discovery and data communication.

	Range	Data rate	Battery life	Privacy	Scalability
Social networking	✓✓✓	✓	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓
Network offloading	✓	✓✓✓	✓✓	✓✓	✓✓
Public safety	✓✓✓✓✓	✓✓	✓	✓✓	✓✓✓
Media sharing	✓	✓✓✓✓✓	✓✓✓	✓✓	✓

Table 1. Design and optimization requirements for different D2D applications.

Previously, D2D communication has been widely used in consumer Bluetooth and the WiFi unlicensed band for individual pairing and connectivity. The connection is activated only when needed through user manual pairing, and there is little concern about privacy, security, and power. In addition, since the density of these individual D2D applications is relatively low, interference is usually not a major issue in these cases.

When we develop D2D communications underlaying licensed cellular networks, better service guarantee can be provided in a controlled environment. By facilitating the physical proximity of communicating UEs and reuse of spectrum resources, D2D communications has the advantages of high local data rate, offloading the traffic load from the central base station, and increasing cellular capacity. In addition, as D2D communications is short-range transmission, the UE power consumption can be set very low; hence, the battery lifetime of UEs with D2D communications can be extended. In the meantime, these devices for D2D communications need to discover each other constantly and determine service compatibility before communicating with each other. Interference often becomes the limiting factor in building a large-scale D2D network cluster.

Standardization of D2D is therefore essential, ranging from air interface design, device discovery mechanism, communication protocol, services and applications, to security and privacy. The introduction of D2D communications underlaying cellular networks represents a significant step toward future 5G heterogeneous networks. We are still at an early stage in D2D technology development. There are many challenges to be addressed, including device power consumption for D2D user/device/service discovery, interference management and power control among D2D devices and coexistence with overlay networks, radio link design to compensate for the link budget reduction due to no base station, cluster-level vs. global-scale synchronization, device/user identifiers, open vs. restricted device discovery, security and privacy protection, user mobility and cluster group management, group communication for public safety, multihop D2D and D2D in heterogenous networks, seamless service or session transfer with overlay network, and network densification in terms of both number of D2D devices and data communication intensity.

INTERFERENCE MANAGEMENT IN D2D COMMUNICATIONS

As D2D communications are considered underlaying cellular networks and may not have dedicated channel resources, chances are that D2D pairs will share resources with some existing CUEs. In this framework, we allow multiple D2D pairs in the same cell to share the same resources in order to maximize spectrum efficiency. In such a co-channel sharing mode, Fig. 1 shows different interference scenarios when D2D communications are using cellular downlink or uplink channel resources, respectively. The central base station is denoted as the evolved NodeB (eNB) in the 3GPP LTE architecture.

When DUEs share downlink cellular resources, for the DUEs of interest (D2D pair 1), the interference sources consist of interference from the eNB in the same cell, interference from other co-channel DUEs in the same cell, and interference from eNBs and co-channel DUEs

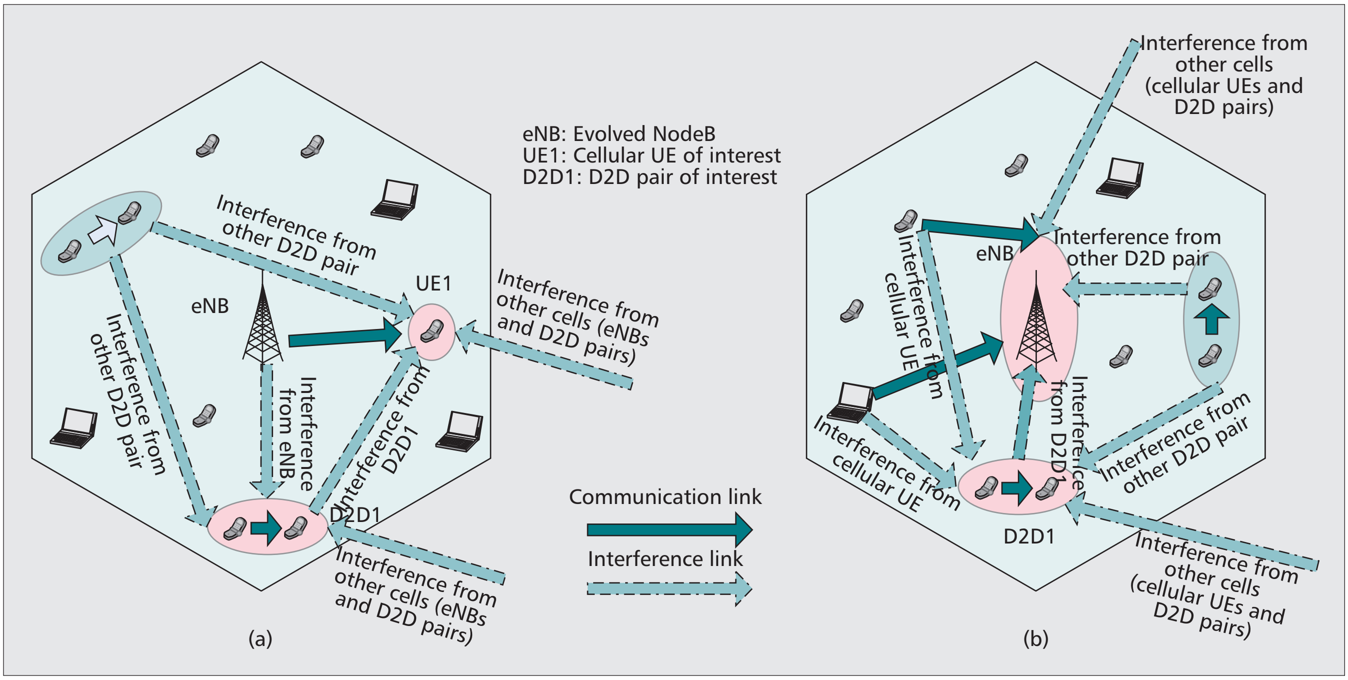

Figure 1. Interference in D2D communications: a) downlink; b) uplink.

from other cells. Since a D2D pair is normally formed between two UEs with physical proximity, the power needed for D2D communications is hence much lower than that for traditional cellular communications. As a result, if DUEs share the downlink cellular resources, they have to stay far away from the high-power eNB transmissions; otherwise, the interference from the eNB could be overwhelming. For the traditional CUE of interest (UE1), when the DUEs are sharing downlink resources, the interference will come from all the co-channel DUEs (at the same cell and at other cells) and co-channel CUEs at other cells. As a result, a D2D communication may have to keep a distance from the primary CUEs to avoid harmful interference to the CUEs.

When the DUEs share the uplink cellular resources, for the DUEs of interest (D2D pair 1), the interference sources consist of interference from all co-channel CUEs at the same cell and other cells, and interference from all co-channel DUEs at the same cell and other cells. Hence, DUEs should stay away from their co-channel CUEs in order to avoid the harmful interference from them. For CUEs on the uplink, the eNB is the receiving end. The interference comes from all co-channel DUEs (at the same cell and at other cells) and co-channel CUEs from other cells.

As D2D communications underlaying cellular networks bring forth many new interference scenarios, effectively managing these interference scenarios is essential to realize efficient D2D communications underlaying cellular networks. In the following sections, research aspects regarding interference management are addressed.

MODE SELECTION

In traditional cellular networks, all UEs communicate with other UEs through eNBs on both downlink and uplink. When D2D communications underlaying cellular network are made possible, if two UEs in the same cell want to communicate with each other, it can have multiple mode choices for communications, which we refer to as mode selection and which are categorized as follows [5].

Silent Mode: In this mode, the network cannot accommodate the D2D communication request due to the lack of resources or too strong interference to the nearby primary CUEs, etc. Then the DUEs may have to stay silent.

Non-Orthogonal Sharing Mode: This is also called reuse mode, in which the D2D communication will share the same resources with existing CUEs and hence may cause interference to CUEs. There could be more than one D2D pair sharing the same resources, which can greatly complicate the interference management task.

Orthogonal Sharing Mode: This is also called dedicated mode. In this mode, the cellular network has abundant channel resources so that the DUEs can use dedicated resources that are orthogonal to CUEs. Apparently there is no interference between DUEs and CUEs. However, it is still possible that multiple DUEs share the same resources, so interference between different D2D pairs can still exist.

Cellular Mode: The two UEs will communicate as traditional CUEs, that is, communicate with each other through the eNB.

RESOURCE ALLOCATION

In 3GPP LTE specifications, UEs are allocated with a specific number of subcarriers for a predetermined amount of time duration, which are referred to as physical resource blocks (PRBs) [6]. Each PRB is equal-sized and defined as consisting of 180kHz in the frequency domain with 12 consecutive subcarriers (subcarrier spacing of 15 kHz) and one slot (0.5 msec) in the time domain. A PRB is the smallest element of resource allocation by the eNB. When a D2D pair needs to communicate underlaying a cellular network, how to allocate cellular resources to the D2D transmission is critical since the interference to other primary CUEs should be kept below a certain level while the D2D communication also needs to be fulfilled with quality. Resource allocation should be jointly considered with mode selection, that is, whether the network can allow some channel resources to the D2D pair, and if so, whether some dedicated PRBs or some shared PRBs the D2D pair will obtain; if it is a shared case, which cellular UEs' resource blocks should be shared with this D2D pair; if it is a dedicated case, how many PRBs should be permitted for this D2D communication.

On the other hand, instead of centralized resource allocation, in which the eNBs take full responsibility in controlling/allocating the resources of D2D communications, resource allocation may also proceed in a distributed manner. If D2D communication is favorable between two UEs, the UEs need to sense the network environment, access the cellular resources without causing harmful interference to the CUEs, and inform the eNBs of D2D resource occupations.

POWER CONTROL

Power control is vital in achieving efficient energy usage and interference coordination in wireless networks. In D2D enabled cellular networks, we consider CUEs as the primary users and their quality-of-service (QoS) requirements are delivered with priority. Hence, the power control in such a network will first intend to control the transmission power of DUEs such that the interference from DUEs to CUEs can be throttled [7]. Power control can be centrally optimized such that the overall network throughput is maximized. which means in some cases, we may need to lower the power of eNBs in the downlink given that the CUE performance will not be degraded, such that the transmission rates of DUEs will improve and the overall sum-rate of all network UEs increases accordingly. In addition, power control mechanism can be considered jointly with mode selection and resource allocation to optimize the network performance. Power efficiency or energy efficiency for D2D communications underlaying cellular spectrum is also worthy of discussion.

D2D COMMUNICATIONS WITH MULTI-ANTENNA TRANSMISSION TECHNIQUES

Multi-antenna transmission techniques [8] can be incorporated into D2D communications underlaying cellular networks to further avoid interference among different UEs. When DUEs and CUEs are sharing the same LTE resources, with multiple antennas, we get an additional space dimension, besides time and frequency dimensions, to cope with interference. The difference of design beamforming vectors for D2D communications underlaying cellular networks and the traditional cellular networks lies in that, in D2D communication environment, CUEs and DUEs may be considered as two groups of users with CUEs as primary users. The design criterion may aim to lessen interference among CUEs or from DUEs to CUEs, etc.

In [9] we discussed the scenario that multiple CUEs and multiple DUEs co-exist in the cellular network. The eNB is equipped with multiple antennas, hence it can formulate precoding vectors in the downlink transmission to CUEs with different criteria. For the conventional beamforming method, the precoding vector of a CUE will lie in the direction of its own channel vector. For the zero-forcing (ZF) beamforming method, to cancel out inter-UE interference, the information data of a CUE is designed to be transmitted in the null space of the channels of all other CUEs. If we consider ZF beamforming to cancel out the interference caused by the eNB transmission to DUEs, we can design a CUE's precoding vector so that its data is transmitted in the null space of DUE channels. Based on the different multi-antenna transmission techniques, D2D pair associations and precoding vectors can be jointly optimized to maximize the overall system throughput. The D2D pair associations should also keep the interference from DUEs to CUEs below a certain level so that the signal-to-noise-plus-interference ratio (SINR) of CUEs will meet the requirements. Further studies can be extended with robust beamforming design for D2D communications underlying cellular networks.

MULTI-HOP D2D COMMUNICATIONS WITH NETWORK CODING

In general, we think of D2D communications as two UEs communicating directly without going through eNBs. In fact, D2D communications can be further broadened to the multi-hop D2D communications in which a UE may help other UEs communicate with each other, or assist other UEs to communicate with eNBs.

For example, as one scenario of multi-hop D2D communications, if multiple UEs are requesting the same contents from the eNB, they can first form cooperative clusters according to the geometry to achieve a higher energy efficiency and spectrum efficiency during content distribution. In the first step, the eNB will first transmit the contents to the cluster heads. In the second step, each cluster head will in turn multicast the contents to other UEs within the cluster through D2D links. The eNB can stay silent during the second step and hence keep the network energy efficient. The application of this multi-hop D2D communication scenario includes video streaming of most popular programs, for instance during the FIFA World Cup, when multiple UEs are watching the same football match.

In such multi-hop D2D communications, network coding [10], which is a promising mechanism in cooperative networks to improve throughput, can be applied. Originally designed for wired networks, network coding is a generalized approach that breaks the traditional assumption of simply forwarding data, and allows intermediate nodes to send out functions of their received packets, by which the multicast capacity

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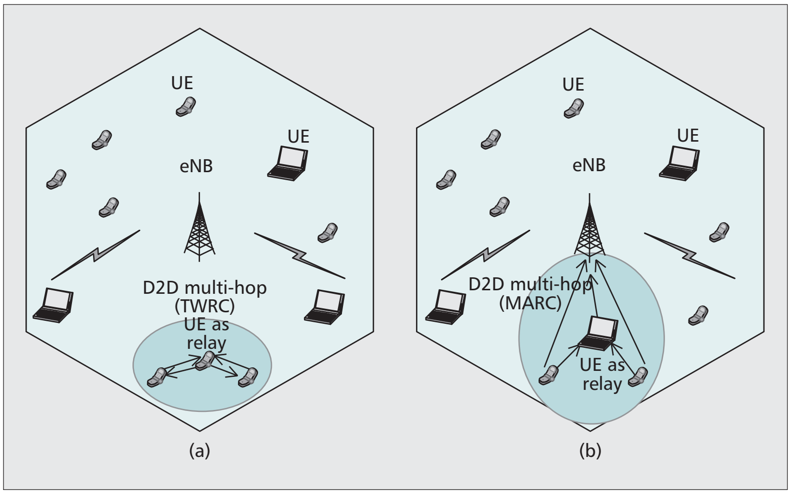

Figure 2. Multi-hop D2D communications with network coding.

given by the max-flow min-cut theorem can be achieved. For multicasting, intermediate nodes can simply send out a linear combination of their received packets. In order to address the broadcast nature of wireless transmission, physical layer network coding [11], in which intermediate nodes attempt to decode the modulo-two sum (XOR) of the transmitted messages, has been proposed.

Multi-hop D2D communications with network coding techniques will be beneficial from the merits of both D2D communications and network coding. There are two typical network coding scenarios that have been widely investigated, namely, two-way relay channel (TWRC) and multiple-access relay channel (MARC). In TWRC two sources exchange information through a relay, while in MARC multiple sources are communicating with a destination through a relay with direct links. We can apply those two scenarios to multi-hop D2D communications as shown in Fig. 2. In Fig. 2a, when two UEs in a cellular network desire to exchange information with each other, another UE that is close to both of them can help and serve as a relay. In Fig. 2b, two UEs desire to transmit to the eNB with existing direct links, another UE that has access to both of them and has a good channel to the eNB can help and serve as a relay. Practical two time slot physical layer network coding [12] can be utilized for the relay UE, while in the first time slot, the relay UE receives mixed messages from two UEs, and amplifies and forwards in the second time slot. The challenges of applying network coding techniques in multi-hop D2D include the following issues: when to switch from CUE or direct D2D pair to multi-hop D2D; how to find and decide which UE to serve as relay UE; and the central scheduling of multi-hop D2D with network coding, and so on.

D2D COMMUNICATIONS IN HETEROGENEOUS NETWORKS

Unlike homogeneous deployment, in heterogeneous networks [13, 14] there are a diverse set of eNBs, such as traditional macro eNBs (MeNBs), and low power and low cost micro eNBs (meNBs) such as picos, femtos, and relays to enhance network capacity, coverage, and energy efficiency. Those low power and low cost nodes can be scattered in wireless networks on coverage holes or capacity-demanding hotspots to supplement conventional single-tier cellular networks. CUEs and channel resources can be distributed to MeNBs and meNBs accordingly. Heterogeneity is expected to be a key feature in LTE-Advanced networks. Efficient resource management and interference coordination among network nodes in heterogeneous networks are essential to optimize the usage of network resources and supporting satisfactory user experience.

When D2D communications coexist in heterogeneous networks, which are very likely in the future LTE-Advanced networks, there are many research and design aspects that need to be addressed. Mode selection for D2D communications will be more complicated than in a traditional homogeneous cellular network. For example, in a heterogeneous relay network, when a UE desires to communicate with another UE, there will be silent mode; non-orthogonal sharing with eNB mode (D2D pair communication shares the same channel resources from eNB); non-orthogonal sharing with relay mode (D2D pair communication shares the same channel resources with a relay); orthogonal sharing mode, cellular mode (UEs communicate with each other through eNB); and relay mode (UEs communicate with each other through relay). How to choose an optimal mode for the D2D pair to optimize the network performance will be an interesting research direction. Similarly, when D2D communications occur in heterogeneous networks, resource allocation and power control mechanisms are also more complicated than in the traditional homogeneous cellular networks.

PERFORMANCE EVALUATION

In this section we provide the performance evaluation on D2D communications underlaying cellular networks. The spatial distributions of both CUEs and DUEs follow independent homogeneous Poisson Point Process (PPP) [15], which is often used to model random UE positions in a wireless network. We consider a normalized circular cell with unity radius R and set the eNB transmit power P_b to ensure that the signal-to-noise ratio (SNR) at cell edge is at least 1dB. All other simulation parameters are given with respect to these two values. DUEs are dropped as D2D pairs. Each D2D pair's location from the PPP distribution is considered as the center of a circle, within which the two DUEs forming the pair can be randomly located. The radius of the circle where the D2D pair is constrained is R_d and set as $R_d = 0.025 * R$. Some main simulation parameters are listed as follow.

R	The normalized unity radius of the cellular cell.
R_d	The radius of the circle where the D2D pair is constrained, set as $R_d = 0.025 * R$.
P_b	The transmission power of eNB.
P_d	The transmission power of a UE (CUE or DUE).

N The mean of active D2D pairs in the cellular cell, set as $N = 5$.
α The pass loss exponent, set as $\alpha = 4$.
R_{gu} The guard uplink distance between any D2D pair and the eNB, set as $R_{gu} = 0.2 * R$.
R_{gd} The guard downlink distance between any D2D pair and the eNB, set as $R_{gd} = 0.5 * R$.

We consider the non-orthogonal sharing mode of D2D communications, where a physical radio resource can be allocated to one CUE and multiple D2D pairs in the same cell. For D2D pairs with homogeneous PPP, the number of active D2D pairs in the cellular cell is Poisson with mean N, set as $N = 5$. In other words, within one cellular cell, there are one CUE and on average five D2D pairs sharing the same resource. The D2D communication can either use the cellular downlink resources or uplink resources. All the point-to-point channels are modeled with Rayleigh fading, exponential pass loss (the path loss exponent is set as $\alpha = 4$), and additive Gaussian noise. Under this simulation setup, we evaluate the performance of average throughput for CUEs and DUEs. We also include the case that only CUEs exist in the cellular network (no D2D communications), and the cases of D2D communications without and with distance control, which is a simple interference management mechanism.

When D2D communications use cellular uplink resources, we present in Fig. 3 the average throughput of a CUE and a DUE with regard to the power ratio P_d/P_b. There are different scenarios relating to the CUE:

- "CUE: No DUEs" is the scenario that no D2D pairs exist in the cellular network and only CUEs are using the radio resources.
- "CUE: With DUEs, No Distance Control" gives the scenario that CUEs and DUEs spread out in the cell under PPP distribution, without specific distance control.
- "CUE: With DUEs, With Distance Control" is that with CUEs and DUEs presented, we set up a distance control mechanism that the guard uplink distance between any D2D pair and the eNB cannot be less than R_{gu} (in the simulation, R_{gu} is set to be $0.2 * R$), such that the interference from DUEs to the CUE uplink transmission can be lowered.

As shown in the figure, when the transmission power of a D2D pair increases, the throughput of the CUEs will decrease with respect to the no DUEs case due to the interference from DUEs. With distance control, we can alleviate the CUE throughput loss with less D2D interference. In the meantime, there is a prominent DUE throughput increase as D2D pairs are close to each other and can have high transmission rates.

Similar results are shown in Fig. 4 when D2D communications operate on the downlink resource sharing mode. The throughput of the CUEs will also decrease when the transmission power of D2D pairs increases. In the downlink case, since the transmission power of the eNB is overwhelming, we set up the distance control mechanism that the guard downlink distance between any D2D pair and the eNB cannot be less than R_{gd} ($R_{gd} = 0.5 * R$ in this simulation), such that the interference from eNB to DUEs will be reduced. We can see that "DUE — With Distance Control" has a significant improvement over the "DUE — No Distance Control" case. Although we constrain the same distance (the distance from DUEs to eNB) in the uplink and downlink, CUE transmission is the principal beneficiary in the uplink, while in the downlink DUE throughout has the major improvement with distance control.

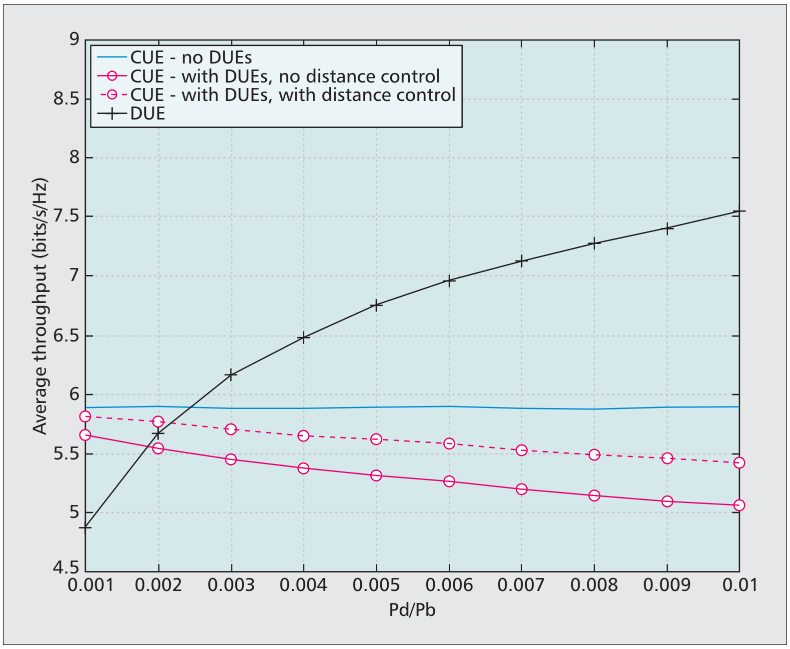

Figure 3. Average UE throughput for uplink.

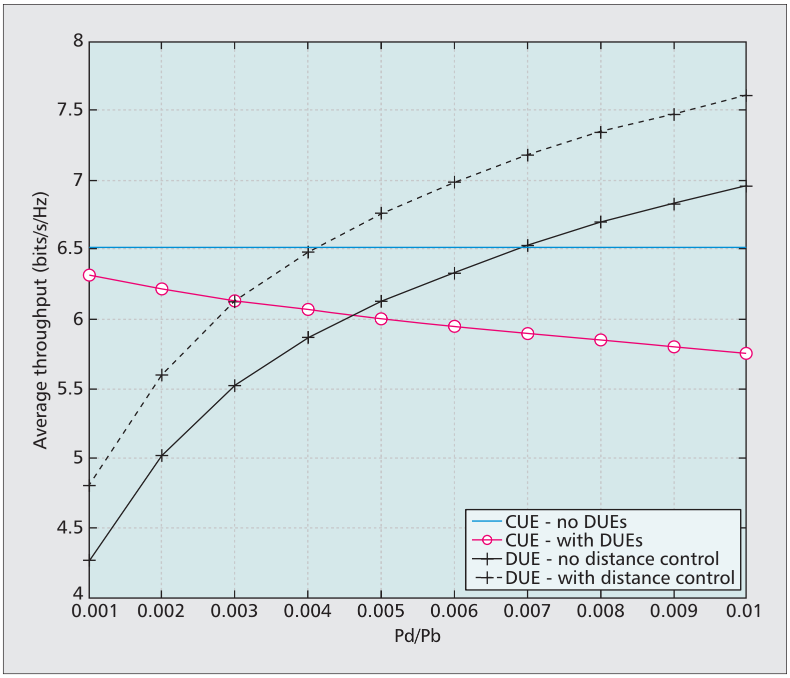

Figure 4. Average UE throughput for downlink.

With distance control, we can alleviate the CUE throughput loss with less D2D interference. In the meantime, there is a prominent DUE throughput increase as D2D pairs are close to each other and can have high transmission rates.

CONCLUSIONS

In this article critical D2D communication challenges and important research aspects that enable device-to-device communications underlaying cellular networks are discussed. The topics addressed include interference management, multi-hop D2D communications with network coding, and D2D communications in heterogeneous networks. Mechanisms such as mode selection, resource allocation, D2D communications with multi-antenna transmission techniques, and power control are illustrated in detail. Performance evaluation based on PPP distributions of CUEs and DUEs is provided. Effective D2D communications can be enabled in a cellular network through proper radio resource sharing, interference management and power control mechanisms.

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BIOGRAPHIES

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