Design Aspects of Network Assisted Device-to-Device Communications

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ABSTRACT

Device-to-device (D2D) communications underlaying a cellular infrastructure has been proposed as a means of taking advantage of the physical proximity of communicating devices, increasing resource utilization, and improving cellular coverage. Relative to the traditional cellular methods, there is a need to design new peer discovery methods, physical layer procedures, and radio resource management algorithms that help realize the potential advantages of D2D communications. In this article we use the 3GPP Long Term Evolution system as a baseline for D2D design, review some of the key design challenges, and propose solution approaches that allow cellular devices and D2D pairs to share spectrum resources and thereby increase the spectrum and energy efficiency of traditional cellular networks. Simulation results illustrate the viability of the proposed design.

INTRODUCTION

Device-to-device (D2D) communications in cellular spectrum supported by a cellular infrastructure holds the promise of three types of gains. The *proximity* of user equipments (UE) may allow for extremely high bit rates, low delays and low power consumption [1]. The *reuse gain* implies that radio resources may be simultaneously used by cellular as well as D2D links, tightening the reuse factor even of a reuse-1 system [2]. Finally, the *hop gain* refers to using a single link in the *D2D mode* rather than using both an uplink and a downlink resource when communicating via the access point in the cellular mode. Additionally, D2D communications may extend the cellular coverage and facilitate new types of wireless peer-to-peer services [2, 3].

However, D2D communications utilizing cellular spectrum poses new challenges, because relative to cellular communication scenarios, the system needs to cope with new interference situations. For example, in an orthogonal frequency division multiplexing (OFDM) system in which D2D communication links may reuse some of the OFDM time-frequency resources (physical resource blocks, PRB), intracell interference is no longer negligible [4].

In addition, in multicell systems, new types of intercell interference situations have to be dealt with due to the undesired proximity of D2D and cellular transmitters and receivers. Interestingly, these new types of interference situations are intertwined with the duplexing scheme that the cellular network and the D2D link employ, and also depend on the spectrum bands and PRBs allocated to D2D links. For example, when a D2D link utilizes some of the cellular uplink PRBs, a transmitting cellular user equipment (UE) may cause much stronger interference to a receiving UE of a D2D pair in a neighbor cell than the interference caused to a radio base station in that same neighbor cell.

Solution approaches to deal with this problem include power control [5], various interference avoiding multi-antenna transmission techniques [6] that can be combined with proper mode selection — which decides whether a D2D candidate pair should be communicating in D2D or in cellular mode [7] — and advanced (network) coding schemes [1].

The purpose of the current article is to provide a brief overview of the main technical challenges that need to be addressed to realize the potential gains of D2D communications and propose solution approaches to these challenges. Throughout we will assume OFDM as the transmission scheme and the 3GPP Long Term Evolution (LTE) system as our baseline for D2D design [10]. The key functions of D2D communications include peer discovery, physical layer procedures, such as synchronization and reference signal design, and various radio resource management functions including mode selection, scheduling, PRB allocation, power control, and intra- and intercell interference management.

We structure the article as follows. The next section presents D2D scenarios and discusses the role of a cellular infrastructure in peer discovery and radio resource management. We briefly overview the key design challenges for D2D communications. Next, we focus on peer discovery and examine the role of the network in this important procedure. We discuss radio resource management issues, including mode selection, scheduling, channel quality estimation, and power control in the mixed D2D and cellular environment. We discuss simulation results

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that indicate that D2D communications helps to improve the energy efficiency and to reduce the probability of infeasibility of a target spectrum efficiency. Finally, we draw conclusions and point at future works.

Device-to-Device Communication Scenarios and Design Questions

D2D Scenarios

As illustrated in Fig. 1, one of the key aspects of D2D communications is the set of spectrum bands in which D2D communications takes place. Various ad hoc and personal area networking technologies utilizing unlicensed spectrum bands such as the industrial, scientific, and medical bands are available for short range communications, including Bluetooth and WiFi Direct. Although such technologies can operate without any infrastructure assistance (lower left part of Fig. 1), future ad hoc local area networks operating in unlicensed bands could also benefit from a cellular infrastructure providing node synchronization and assisting security procedures (lower right).

D2D communications utilizing licensed (and in particular cellular) spectrum has only recently been proposed and studied [1, 2]. According to this concept, cellular UEs in the proximity of each other can exchange information over a direct link rather than transmitting and receiving signals through a cellular base station. In this case, in a national security and public safety situation or outside of cellular coverage, cellular devices could communicate without network support (upper left), similarly to the Terrestrial Trunked Radio (TETRA) technology, although such solutions have not yet been standardized by major cellular standards organizations. Also, ad hoc networking in licensed spectrum bands relying on cognitive radio techniques and acting as a secondary user when the primary spectrum utilization is low has been studied for long and some parts are being standardized [9].

D2D communications in cellular spectrum assisted by a network infrastructure (upper right) has recently been proposed as a means to improve the utilization of cellular spectrum resources and to reduce the energy consumption of UEs [2, 5]. The expected added value of network control, in addition to providing node synchronization and security, is to allow D2D pairs to communicate using cellular resources even at high spectrum utilization, when cognitive radio techniques would not indicate unused spectrum holes.

The potential gains of D2D communications are equally attractive in cellular networks operated in paired as well as unpaired frequency bands. In the 3GPP LTE system, for example, the Frequency Domain Duplexing (FDD) and Time Domain Duplexing (TDD) modes are specified in the same set of specifications for both the UE and the base station (eNB), and it is a natural requirement for LTE based D2D communications that D2D mode should be supported in cellular networks operated in either of the duplexing modes. Independently of the duplexing mode of the cellular network, the duplexing mode of the D2D link can be based on frequency or time division (i.e. FDD or TDD for the D2D link itself). Thus, in terms of duplexing, in principle four scenarios are possible. However, it is clear that for the UE transmitter and receiver design for D2D traffic, a half duplex TDD design base is advantageous, because it allows transmission and reception by a given UE without having to implement separate Tx/Rx hardware in the devices. Because of the expected gains of network assisted D2D communications in licensed spectrum, in the rest of the article we focus on this (upper right of Fig. 1) scenario.

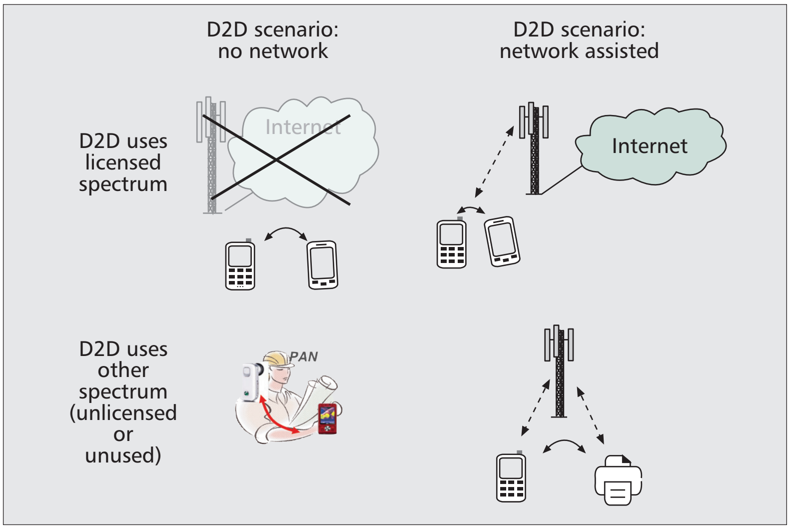

Figure 1. *D2D communications scenarios can be categorized in terms of the utilized spectrum resources and the involvement of various network entities such as a cellular base station or a core network. In this article we focus on cellular network assisted D2D communications utilizing licensed spectrum resources.*

Design Questions

For cellular network assisted D2D communications, the role of the network is a major design question. For example, in the cellular underlay concept [5–7] the network can play an active role for mode selection, power control, scheduling, and selecting transmission format (modulation and coding rates, multi-antenna transmission mode, etc.). In contrast, in the Aura-net concept, the role of the network is kept at a minimum, mainly to provide synchronization signals to devices [3].

Peer and service discovery is a major issue in D2D communications, since before two devices can directly communicate with one another, they must first know (discover) that they are near each other. Peer discovery without network support is typically time and energy consuming, employing beacon signals and sophisticated scanning and security procedures often involving higher layers and/or interactions with the end user. In network assisted mode, it is a design goal to make such peer discovery and pairing procedures faster, more efficient in terms of energy consumption and more user friendly.

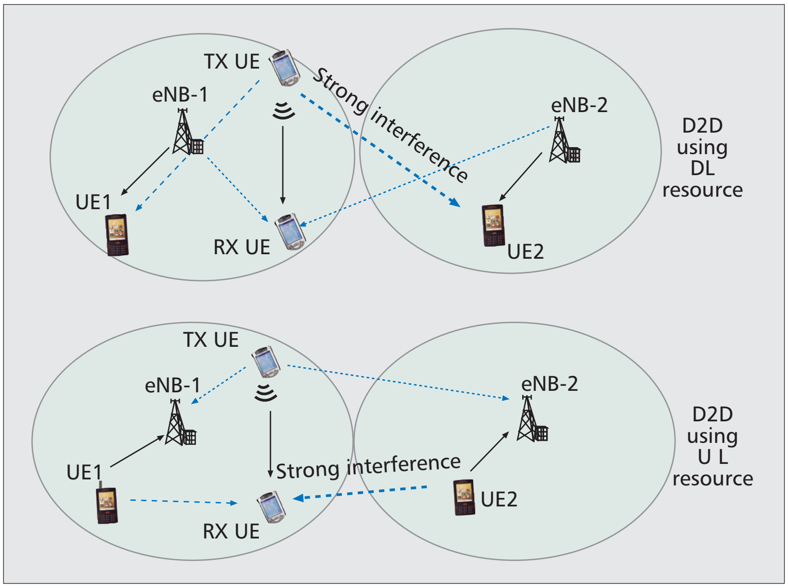

Figure 2. *D2D communications gives rise to intracell interference between the cellular and D2D layer and also new types of intercell interference situations, because D2D pairs and cellular UEs may use overlapping time and frequency resources. The interference situations are different when the D2D link uses DL or UL PRBs (upper and lower figure respectively).*

Mode selection means that the network and/or the D2D pair decide whether the D2D pair should communicate directly or via the network. Design issues around mode selection include:

- At what time scale mode selection and associated channel quality estimations and reporting should operate. Since the radio conditions within the cell and between the D2D pair may change rapidly, the time scale for mode selection cannot be too coarse. On the other hand, the measurements and control signaling required for mode selection should be kept at a minimum to avoid too much overhead.
- What measurements, reporting mechanisms, and (periodic and/or event triggered, hybrid) algorithms should be used by the devices and the eNB to select between the D2D and the cellular links.

D2D bearer establishment involves the allocation of resources to the D2D link and the protocols to establish, maintain, and terminate D2D bearers and to ensure proper quality of service (QoS) for the D2D bearer. Some control logic needs to decide whether UL or DL PRBs should be used for the D2D link and which resources should be used in each direction for the communication between the D2D pair.

The design of power control and scheduling (including retransmissions and hybrid automatic repeat request (HARQ) operation) involves deciding on:

- The functional distribution between the network and the D2D pair.
- The time scale of interaction between the network and the D2D pair.

One extreme approach is to let the network schedule on a very short time scale, whereas an alternative design is to let the network decide on the long term resource usage and allow the D2D pair to schedule their transmissions autonomously (as will be discussed later).

Intercell interference coordination becomes a major issue in cellular networks supporting D2D communications, since interference needs to be managed between multiple cells and between the cellular and the D2D layers. The intercell interference situations can be different and more severe due to the D2D layer, as illustrated in Fig. 2. When the D2D link uses DL resources, a transmitting device may cause high interference to a *cellular* UE in the neighbor cell receiving DL traffic on the same resource. Similarly, when a D2D pair uses uplink cellular resources, the receiving device of the *D2D pair* may suffer strong interference from a cellular UE in the neighbor cell transmitting uplink traffic to its serving eNB. These situations are in fact similar to the ones that can occur in unsynchronized TDD systems and problematic because they cannot be easily handled with single cell approaches that focus on managing interference between cellular UEs and D2D pairs within the same cell. From this perspective, as well as for regulatory reasons, a cellular operator may prefer to use UL resources for the D2D layer in order to better protect the cellular layer from intercell D2D interference (lower part of Fig. 2).

Service and Peer Discovery Techniques

The first step in the establishment of a network assisted D2D link is that the network and/or the UEs discover the presence of their peer and the devices are identified as D2D *candidates*. Peer discovery and device pairing are well known procedures in, for example, Bluetooth, where the so called *inquiry process* allows a potential master node to identify devices in range that wish to participate in a piconet, whereas the *page process* allows the master node to establish links toward desired slave nodes. From a cellular (LTE) network perspective, peer discovery has a similar functionality as *cell search* in LTE by which the UE determines the time and frequency parameters that are necessary to demodulate the downlink and to determine the cell identity [10] (and thereby the UE effectively "discovers," i.e. detects the cell).

In both the ad hoc and the cellular cases, the discovery is made possible by one party transmitting a known synchronization or reference signal sequence (which we will refer to as the *beacon*). Such a beacon is exemplified by the primary and secondary synchronization sequences in LTE or known frequency hopping sequences (FHS) and specific FHS packets in Bluetooth. Irrespective of the technology details, the fundamental problem of device discovery is that the two peer devices have to meet in space, time, and frequency. Without any coordination, this can be made possible via some randomized procedure and one of the peers assuming the responsibility of sending the beacon. This role arbitration and transmitting/searching for the beacon are typically time and energy consuming. In the case of network assisted D2D, however,

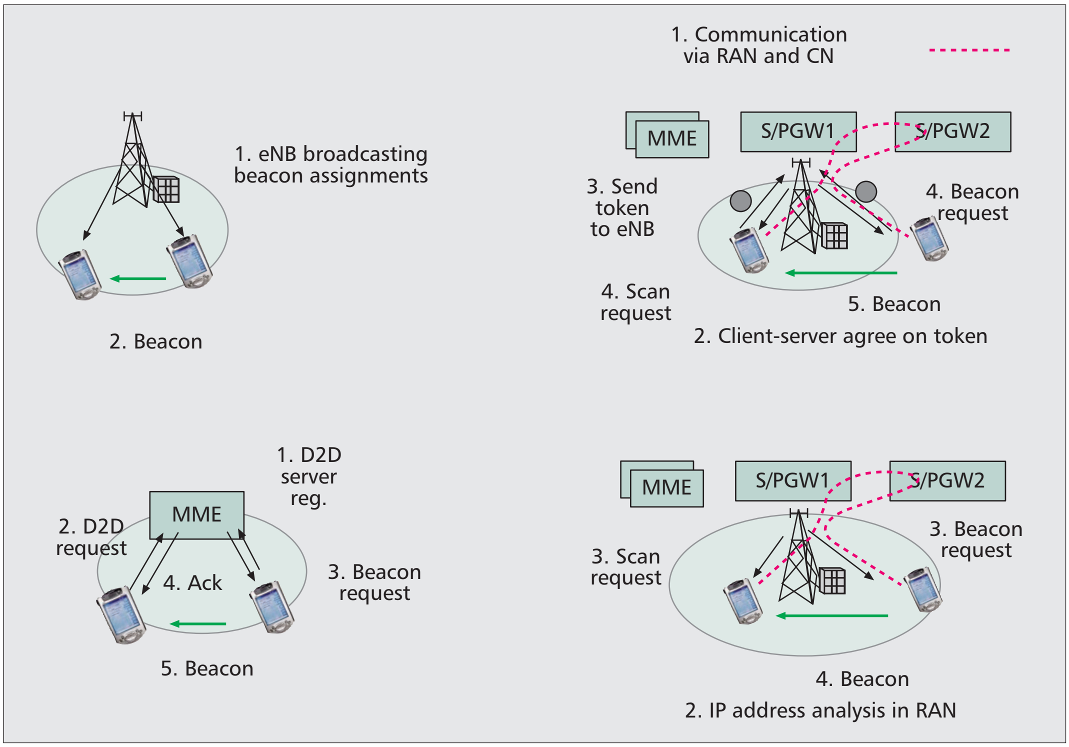

Figure 3. *Peer discovery techniques include a-priori (left) and a-posteriori (right) methods. In both cases, the involvement of the communicating user equipments and various network entities (such as a base station or a packet/serving data gateway) can be different.*

From a cellular (LTE) network perspective, peer discovery has a similar functionality as cell search in LTE by which the UE determines the time and frequency parameters that are necessary to demodulate the downlink and to determine the cell identity.

the network can mediate in the discovery process by recognizing D2D candidates, coordinating the time and frequency allocations for sending/scanning for beacons, and thereby making the pairing process more energy efficient and less time consuming.

Building on these design experiences from existing technologies, identifying D2D candidates in a network assisted scheme can be based on the alternatives depicted by Fig. 3. In a-priori schemes, the network (and/or the devices themselves) detect D2D candidates prior to commencing a communication session between the devices (left hand side schemes of Fig. 3). As an extreme approach (upper left), the network does not actively participate in the discovery process other than assigning beacon resources to the devices. Such beacon assignments are broadcast in the coverage area of the cell so that D2D *servers* (transmitting a beacon) as well as D2D *clients* (detecting beacons) can readily find one another. According to an alternative approach (lower left) the server first registers to the network, and the client willing to engage in D2D communications sends a request to the network (e.g. the serving eNB or other network entity (NWE)). Such registration and request messages may contain other information such as an own identity, a buddy list, or offered/required services. In this case the NWE takes a more active role in the discovery process mediating between the server and the client and requesting the D2D server to generate the beacon (Step 3 in the lower left scheme).

In a-posteriori device discovery, the network (e.g. an eNB) realizes that two communicating devices are in the proximity of one another and thereby they are D2D candidates when the communication session is already ongoing (in cellular mode) between the UEs (Step 1 on the right hand side of Fig. 3). In the UE assisted a-posteriori device discovery (upper right) the UEs agree on a token that is unique to the already ongoing communication session (Step 2 in upper right). Notice that the communication path typically goes through different serving and/or packet data gateways (S/PGW) (illustrated in the figure) and therefore relying on the same physical GW identifying D2D candidates is not a viable option. Once the token is established, the UEs register the token at the serving eNB that can easily recognize the two UEs as D2D candidates. Alternatively, in the radio access network based a-posteriori device discovery (lower right) the eNB analyzes the Internet protocol (IP) packets and in particular the source and destination IP addresses to detect D2D pairs communicating within the same cell/sector (Step 2 in lower right).

A-priori and a-posteriori schemes are useful to identify D2D candidates — essentially identifying that the two UEs are in the proximity of one another and/or in the same cell — but they do not by themselves reveal the actual radio conditions between the D2D candidate nodes. Therefore, the next step in the D2D link establishment procedure is to trigger a beacon signal between the D2D server and client indicated as the last step in all four schemes of Fig. 3, which the D2D client can then use to report on the D2D link quality to the eNB. Once this piece of information is available at the eNB, it serves as the basic input to the mode selection that is discussed further in the next section.

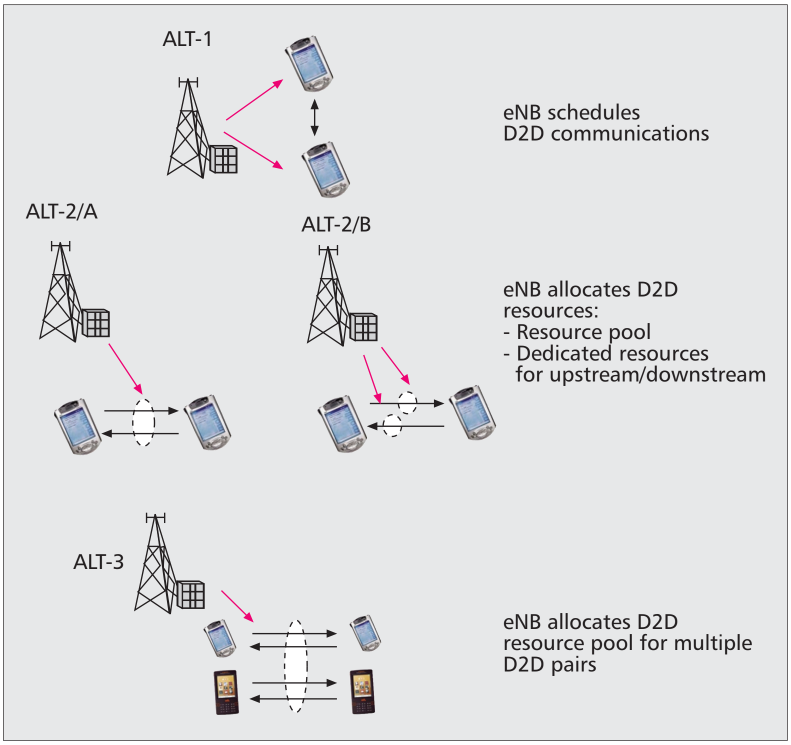

Figure 4. *The role of the network (and in particular the radio base station) can be quite different in resource allocation, scheduling and power control over the D2D link. The scope of network control and the time scale over which the network controls D2D communications is an important design aspect.*

D2D Resource Allocation and Mode Selection Alternatives and D2D Channel Quality Estimation

Mode Selection and D2D Resource Allocation Alternatives

To realize the proximity, reuse, and hop gains, it is intuitively clear (and will be illustrated later) that the instantaneous network load, channel conditions, and intercell interference situation should be taken into account when selecting the best mode (cellular or direct) and allocating resources to the cellular and D2D links in the network. Thus, at one extreme (ALT1 of Fig. 4), the eNB collects up-to-date information on channels, buffer status, and traffic load and selects the mode and allocates resources (e.g. schedules and allocates power for UL/DL) on a time scale that is similar to LTE's scheduling and transmission time interval of 1 ms [10].

However, channel measurements, reporting and handling the resources at this time scale for all D2D pairs and cellular UEs in the cell may increase the signaling and processing overhead and may not scale well as the number of D2D pairs in the cell increases. Therefore, an alternative approach in which the eNB allocates dedicated resources to each D2D pair on a time scale of hundreds of milliseconds, is motivated (ALT-2/A and ALT-2/B of Fig. 4). In alternative ALT-2/A a resource pool is allocated to the bidirectional communication between the devices, whereas in alternative ALT-2/B distinct resources are allocated to each direction of the D2D link.

A third approach is to manage resources on an even longer time scale. In this case the eNB reserves a pool of resources for a set of (maybe all) D2D pairs in that cell. In this approach (ALT3 of Fig. 4) there is a need for an access mechanism to the resources within the resource pool that can lead to, for example, WLAN or Bluetooth-like medium access schemes. This alternative is not so attractive, because it does not fully exploit the advantages of network control.

Various hybrid solutions of these three alternatives are also possible. For example, the time scale for the reallocation of resources and mode selection in ALT-2/A and 2/B could come close to the time scale of ALT-1 (e.g. once in every 10 ms) or of ALT-3 (e.g. once in every second). Our proposal is therefore that ALT-2/B of Fig. 4 be used as a resource allocation design base for D2D communications. ALT-2/B implies that dedicated resources to the two directions of a D2D pair are reserved by the eNB as part of the mode selection procedure. In this design both periodic and event triggered mode selection should be allowed. In the periodic case, the mode selection period should be configurable in the range of several hundreds of ms. In the event triggered mode selection case the event can be at the eNB and/or at the UE.

D2D Channel Quality Estimation and Power Control

For the D2D link, channel estimation for coherent detection is relevant only for the PRBs that are reserved for the D2D link at mode selection in alternative ALT-2 above and at D2D resource allocation occasions. For D2D communication, it resembles the task of the LTE UL demodulation reference signals (DMRS) that are embedded (at a predefined OFDM symbol position within the resource block) in the transmitted signal [10]. Therefore, for the D2D channel estimation, an embedded reference signal similar to DMRS can be used.

Recall from earlier that the D2D bearer is assumed to use either cellular UL or DL resources in both directions between the two UEs. Therefore, we can assume D2D channel reciprocity both in TDD and FDD based cellular networks. For the sake of channel quality indication (CQI) and estimation (similarly to CQI reporting in LTE), the eNB can assign (and reassign) client-server roles to the UEs, including the case when *both* UEs transmit and receive known DMRSs for channel quality estimation. In our design, the D2D pair is assigned a D2D pair specific physical identity (PHY ID). DMRSs are then generated by the Server UE based on D2D PHY ID and possibly other parameters, e.g. a D2D DMRS transmit power (scaling factor) or a D2D pair frequency shift. The D2D DMRS parameters are communicated to both UEs of the D2D pair. To avoid frequency domain collisions between D2D DMRSs and/or cellular DMRSs in the neighbor cells, the D2D DMRSs need to be carefully designed. D2D DMRS measurements can then be reported to the eNB to facilitate mode selection, power control, and other RRM functions controlled by the eNB [12].

As will be illustrated in the numerical section, power control is a key RRM function when D2D and cellular links use overlapping PRBs. Thus, due to the strong near-far effect, power control plays a key role in mitigating intracell interference. Since intracell channel quality information can be made available at the eNB, intracell power control can advantageously be enforced by CQI dependent SINR target setting [11], as will be explained in the next section.

PERFORMANCE ASPECTS

In this section we consider the uplink transmission of a seven-cell system with intersite distance ISD = 500 m, in which D2D (candidate) pairs and cellular UEs (i.e. UEs transmitting to an eNB) are dropped according to a surface uniform distribution in a series of Monte Carlo experiments. To gain an insight into the reuse and proximity gains, we are interested in the performance of the system in two extreme cases. When all the D2D candidates operate in cellular mode, they communicate via their respective serving eNBs. In contrast, when the D2D candidates in each cell operate in D2D mode, they use a direct D2D link using cellular uplink resources. The cellular UEs (i.e. the UEs that are not candidates for D2D communications) always transmit to their respective serving eNBs using a cellular uplink. For resource sharing, we assume that in cellular mode the resources allocated to the UEs are orthogonal either in time or in frequency, while in D2D mode PRBs are reused by cellular and D2D links.

For ease of presentation, we are primarily interested in the system performance as the function of the maximum D2D distance (i.e. the distance between the devices), but also as the function of the distance between the cellular UE and the serving eNB. The main performance measure of interest is the (uplink) power efficiency, that is the required sum transmit power in the system to realize a capacity (spectrum efficiency) target. Depending on the actual outcome of the Monte Carlo experiment, and depending on the mode selected for the D2D candidates (D2D or cellular) this capacity target may not be feasible, because the required transmit power would grow infinitely large. Indeed, the infeasibility of a capacity target is a key performance measure when minimizing the sum power consumption [8, 11]. Therefore, the second performance measure of interest is the probability of the infeasibility of the capacity target.

SETTING THE SINR TARGETS

In order to reach a predefined sum capacity (spectral efficiency) target, we study two solution approaches. In the first approach, each link is assigned a predefined SINR target that corresponds to the capacity target. This fixed SINR target approach is relatively simple, but has the drawback that it does not consider the actual geometry of the system. Therefore, a fixed SINR target can be suboptimal in terms of the required power to realize that SINR target or in terms of

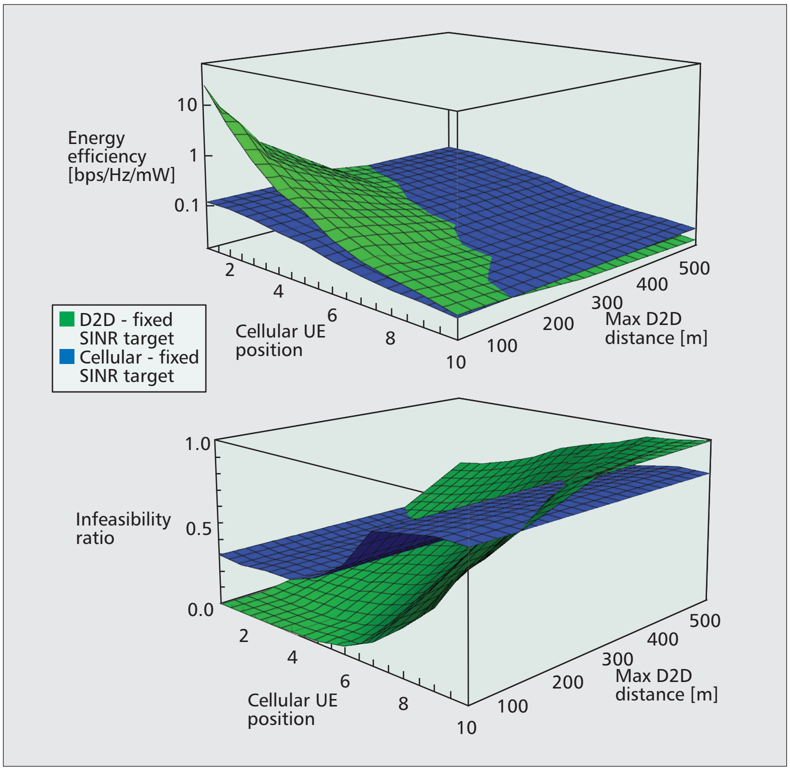

Figure 5. *Energy efficiency and infeasibility probability in a multicell system using fixed SINR targets. When D2D candidates use D2D mode, the gain of D2D communications heavily depends on the maximum D2D distance and also on the position of the cellular UE with which the D2D link shares the cellular resources (uplink PRB).*

feasibility (that is, the predefined SINR target may not be feasible for some links). In the second approach, the SINR targets are determined such that the capacity target is reached, but the individual SINR targets are set differently taking into account the geometry of the system. In short, this second approach assigns higher SINR target to links in favorable channel conditions and thereby it stimulates higher rate allocations on links with lower path loss values. The details of the SINR target setting algorithms are described in [11].

CELLULAR UE POSITIONS

To understand the impact of the cellular UE locations within the cell on the system performance, we perform Monte Carlo simulations in the following manner. In experiment series-*i*, the cellular UEs are dropped according to a surface uniform distribution within a ring such that their distance from their respective serving eNB falls in the interval of $[i \cdot r, (i + 1) \cdot r]$, where r is the granularity with which the cell radius R is divided (e.g. $r = R/10$). Thus, in experiment series 1 (UE Position 1), the cellular UE is dropped close to the cell center, whereas in series 10 (UE Position 10), the cellular UE is dropped within the outer ring area at the cell edge. The UEs of the D2D candidate pair are dropped according to a surface uniform distribution within the entire cell area such that the maximum distance between a D2D pair is bounded (specifically by the value shown on the "Max D2D distance" axes in Fig. 5 and Fig. 6).

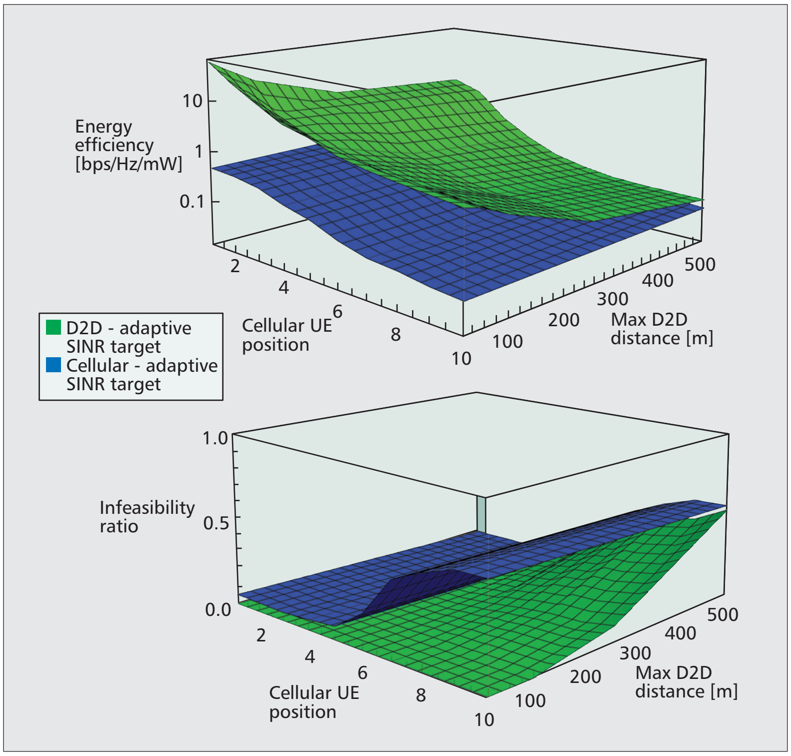

Figure 6. *Energy efficiency and infeasibility probability in a multicell system using adaptive SINR targets. When the SINR targets are properly set, D2D communications has the potential to drastically improve the energy efficiency and reduce the probability of infeasibility over a wide range of D2D distances and cellular UE positions.*

NUMERICAL RESULTS WITH FIXED SINR TARGET SETTING

The results for the case with fixed SINR targets are shown in Fig. 5. In D2D mode, the required sum power and thereby system-wise energy efficiency are sensitive not only to the D2D distance, but also to the position of the particular cellular UE with which the D2D candidate reuses the PRB. We see that the system performance for up to 100 m maximum D2D distance, (especially when the cellular UE is close to the cell center) is significantly better in D2D mode, both in terms of energy efficiency and infeasibility probability.

NUMERICAL RESULTS WITH ADAPTIVE SINR TARGET SETTING

The results for the case with adaptive SINR targets are shown in Fig. 6. As we see in the figure, adaptive SINR targets lead to a significant improvement both in cellular and D2D modes both in terms of spectrum efficiency and infeasibility probability. The reason for this improvement is that that the adaptive SINR target setting algorithm sets a higher SINR target for links with a low path loss value and thereby the algorithm encourages spending energy on links with a high rate utility. More interestingly, the D2D mode shows superior performance even when the D2D distance is high and for all cellular UE positions. The reason for this improvement is that adaptive SINR targets are the key to fully exploit the proximity gain and at the same time to control the interference between the D2D and the cellular layers.

CONCLUSIONS

Network assisted D2D communications in cellular spectrum can take advantage of the proximity of communicating devices, allow for reusing resources between D2D pairs and cellular users, and take advantage of the hop gain. These three factors can lead to power savings, increased throughput, and higher spectrum efficiency. To harvest these potential gains, there is a need to carefully design peer discovery mechanisms, physical layer procedures, and radio resource management algorithms that manage the interference between D2D pairs as well as between the D2D and the cellular layers. Our system simulations indicate that proper mode selection and power control algorithms can play a key role in realizing the proximity and reuse gains in the mixed D2D and cellular environment. To integrate D2D piconets and multihop D2D links in cellular networks, to explore the possibilities of dynamic spectrum allocations for D2D communications, and to devise solutions for interoperator D2D schemes are interesting topics for future works.

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