Device-to-Device Communication as an Underlay to LTE-Advanced Networks

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ABSTRACT

In this article device-to-device (D2D) communication underlaying a 3GPP LTE-Advanced cellular network is studied as an enabler of local services with limited interference impact on the primary cellular network. The approach of the study is a tight integration of D2D communication into an LTE-Advanced network. In particular, we propose mechanisms for D2D communication session setup and management involving procedures in the LTE System Architecture Evolution. Moreover, we present numerical results based on system simulations in an interference limited local area scenario. Our results show that D2D communication can increase the total throughput observed in the cell area.

INTRODUCTION

Major effort has been put in recent years on the development of Third Generation Partnership Project (3GPP) Long Term Evolution (LTE), which provides Evolved Universal Mobile Telecommunications System (UMTS) terrestrial radio access (EUTRA) and EUTRA network (EUTRAN) technology for higher data rates and system capacity, and the System Architecture Evolution (SAE) for efficient networking and cost saving operation.

3GPP has recently defined a further study item for LTE-Advanced, which shall prepare new technology components for LTE to meet the IMT-Advanced requirements, also in the local area scenario. IMT-Advanced will offer high bandwidths up to 100 MHz for higher data rates, global operation, and economy of scale to support a wide range of services. Such future radio access systems will be scalable in terms of carrier bandwidth and carrier frequencies on various spectrum bands [1]. This article introduces a technology component for LTE-Advanced that has so far not been considered sufficiently: device-to-device (D2D) communication as an underlay to cellular networks.

In recent years wireless local area networks (WLANs) have become increasingly popular, as they enable access to the Internet and local services with low-cost infrastructure, and cheap and fast access to the spectrum in the license exempt bands. However, operation on a licensed band has benefits, as it can guarantee a planned (interference) environment instead of an uncoordinated one. Hence, it could be more convenient for local service providers to make investment decisions based on access to the licensed spectrum compared to the unlicensed spectrum. However, the access should be granted with small enough expenses, not comparable to the license fees of cellular operators.

A cellular operator may offer such a cost efficient access to the licensed spectrum enabled by D2D communication as a controlled or constrained underlay to an IMT-Advanced cellular network, as we earlier proposed in [2]. In this article we present the necessary additions to an LTE-Advanced network to enable D2D session setup and management. We outline a solution for a D2D session setup using dedicated signaling and automatic handover of network routed traffic to D2D links between nearby (proximity) devices. Furthermore, we present the interference coordination mechanisms that enable underlay D2D communication and present results on the achievable D2D throughput in a worst case interference limited local area scenario.

The concept of D2D communication as an underlay to a cellular network, operating on the same resources, is illustrated in Fig. 1. Besides cellular operation, where user equipment (UE) is served by the network via the base stations, called evolved NodeBs (eNBs) in the LTE architecture, UE units may communicate directly with each other over the D2D links. The UE in D2D connections remains controlled by the eNBs and continue cellular operation.

The eNBs can control the resources used for cellular communications and by the D2D link. The eNBs can also set constraints on the transmit power of D2D transmitters to limit the interference experienced at the cellular receivers. Resources can also be assigned to D2D links in the case of a dense LTE network with high network load, where a cognitive radio with a cellular network as the primary service would not be able to detect locally unused spectrum (i.e., "white spaces").

In addition, 3GPP has introduced a femto base station solution. For femto, small isolated cells can be set up by the consumers themselves, when allowed by the operator, to increase spatial reuse of the operators' spectrum. Femtocells require access to the cellular core network (by fixed Internet connectivity), and the radio resources assigned to the femtocell have to remain stable and controlled.

Applications and services based on D2D communications can be manifold. As a motivating example, consider a use case where a local media server is set up at a rock concert to offer a huge amount of promotional material for visitors to download. At the same time, there is a need to handle phone calls reliably and provide Internet access without congestion that would be caused by the additional load due to the media server. While the cellular network is serving phone calls and Internet connectivity, D2D communications can provide an efficient solution for the local media service. D2D communication can be utilized to download promotional material to UE as well as to distribute it among UE. BitTorrent can be used for this, as an example.

D2D operation can be fairly transparent to the user, who simply enters a request for a uniform resource locator (URL) at the UE. The network is able to detect that the request is sent to the local media server, and it therefore hands the communication over to a D2D connection. Existing technologies such as Bluetooth or WLAN do not provide a satisfactory solution. For example, Bluetooth requires manual device pairing, and WLAN may require user-defined settings for the access points. Additionally, unlicensed spectrum operation of Bluetooth and WLAN causes uncertainty as to whether the spectrum and services are truly available. This results in a trial-and-error process users do not appreciate.

This article is organized as follows. We illustrate how D2D communication can be established in an LTE-Advanced network having an SAE architecture. The main contribution of the article is to draft the functionality and messaging required to set up a D2D connection inside the SAE architecture, and also if the session setup takes place as an application layer signaling to the Internet beyond the cellular network. We outline how the interference of D2D connections to the cellular network can be limited. Both the uplink and downlink period of time-division duplex operation of the cellular network is addressed because of their different natures in multiple access interference and power control.

Finally, we present performance assessment results showing that D2D can operate efficiently with minor and controlled degradation of cellular operation. Here, we have chosen the challenges of full load and an interference limited local area scenario. It is evident that the benefits from D2D operation during times of underutilized cellular resources and low load are even more prominent.

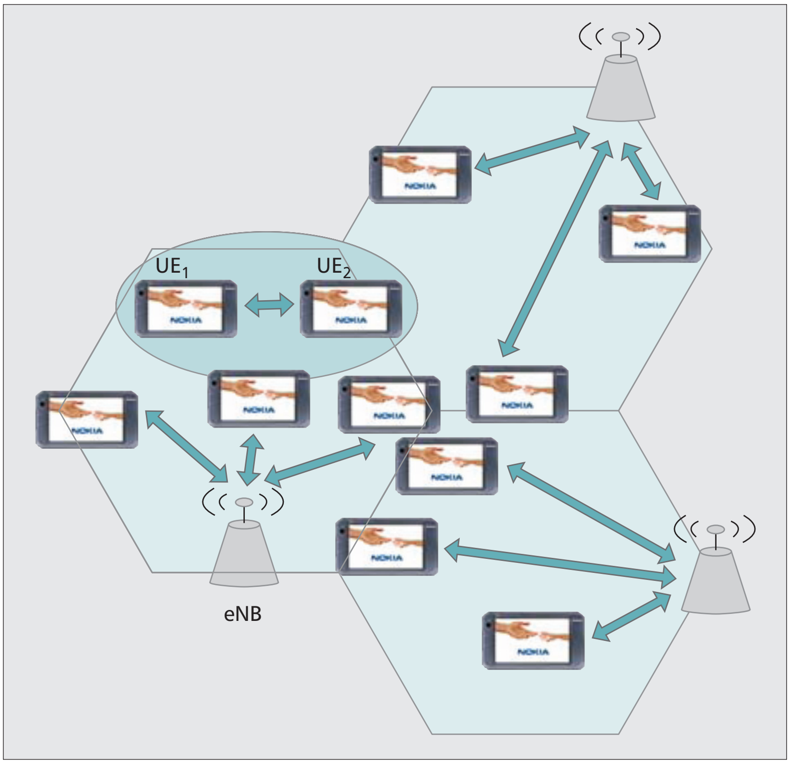

Figure 1. *Device-to-device communication between UE1 and UE2 as an underlay to a cellular network. The red shaded area indicates potential interference from D2D communication.*

D2D Session Management in System Architecture Evolution

LTE systems with the SAE architecture [3] operate fully in the packet-switched domain using Internet protocols. SAE replaces a conventional circuit-switched connection to the mobile switching center (MSC) and extends the General Packet Radio Service (GPRS) to the SAE server architecture. Session setup happens in the user plane using the Session Initiation Protocol (SIP). SAE provides connectivity to the Internet, where a SIP application server (AS) is found by a discovery procedure or operator assignment. The SAE architecture includes the mobility management entity (MME) and the packet data network (PDN) gateway, which together take care of the UE context, setting up the SAE bearers, IP tunnels, and IP connectivity between the UE and the serving PDN gateway. Figure 2 shows session setup by SIP (SIP invite) in the SAE architecture.

After successful session setup, any two or more devices (UE, or UE and servers) may communicate over the Internet. However, in peer-to-peer communication between devices in close proximity, the operator network need not be involved in the actual data transport except for signaling of the session setup, charging, and policy enforcement. Therefore, we propose to introduce a D2D communication mode to LTE-Advanced, and describe two options for session setup and management. In order to enable the D2D communication as an underlay operation to the LTE network, interference coordination is a prerequisite for D2D session setup to take place. Interference coordination is studied with a feasibility analysis.

D2D Session Setup by Detecting D2D Traffic

In the SAE architecture, the node in the network that is aware of wide-area (global) IP addresses is the gateway (serving PDN gateway).

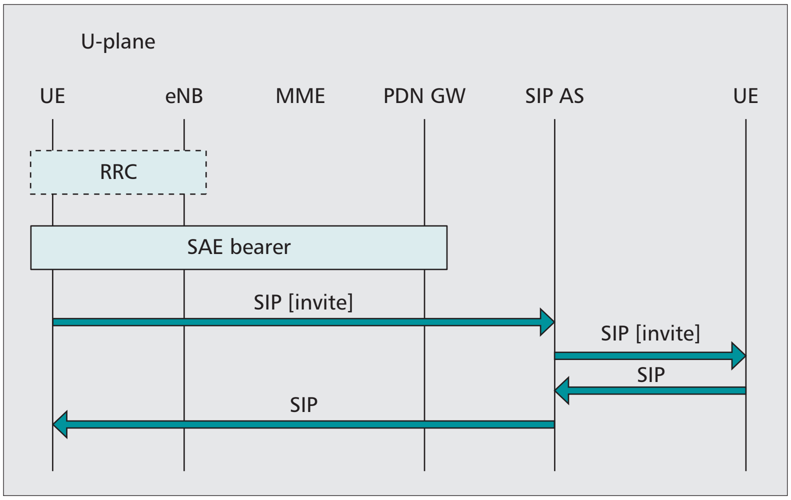

Figure 2. *SIP session initiation in LTE-Advanced with SAE architecture.*

The gateway keeps a routing table that enables IP routing from/to the Internet. The gateway is able to route IP packets to the proper eNBs serving the active destination UE. Similarly, the gateway receives IP packets from the source UE via the serving eNB and routes them to the Internet. The IP transport from/to the eNBs happens in IP tunnels set-up by the MME in the Initial Attach of the UE to the gateway.

The gateway is able to detect potential D2D traffic since it actually processes the IP headers of the data packets and tunnel headers, so it knows by which eNB the UE is served. Potential D2D traffic is any flow whose tunnel endpoint identifiers match for both UE units (i.e., the source and destination IP addresses of the forward tunnel, and the destination and source addresses of the reverse tunnel are assigned to the same eNB), or when the tunnel endpoints are assigned to neighboring eNBs. The gateway may earmark packets of a potential D2D traffic flow as depicted in Fig. 3.

As a next step, the eNB requests the UE to make measurements to check if the D2D devices are in communication range and if D2D communication actually offers higher throughput than cellular communication (discussed in more detail later). If the transport conditions for D2D communication are favorable, the eNB sets up a D2D radio bearer directly between the two UE units so that they communicate over D2D communication resources. Thus, those IP packets with an IP source address and an IP destination address of the peer UE having an active D2D connection need not be transmitted to the eNB and SAE gateway at all.

D2D communication could also be established for UE served by different eNBs since the gateway is aware of the potential cell neighborhood. This is beneficial to avoid an excessive amount of traffic routed in the network, which could actually be classified as D2D traffic instead. In cases where the UE is in neighboring cells, the eNBs serving the UE have to coordinate D2D measurements and the D2D bearer setup over the X2 interface [3].

The session setup requires the following steps:

1)A session is initiated by one of the UE units.
2)The gateway detects IP traffic originating from and destined to UE in the same subnet and to be tunneled within the same serving eNB or between eNBs serving neighboring cells.
3)If the traffic fulfills certain criteria (e.g., data rate), the gateway earmarks the traffic as potential D2D traffic.
4)The eNB(s) request measurements from the UE to check if D2D communication offers higher throughput.
5)If both UE units are D2D capable and D2D communication offers higher throughput, the eNB(s) may set up a D2D bearer.
6)Even if the D2D connection setup is successful, the eNB(s) still maintain the SAE bearer between the UE and the gateway for cellular communications. Furthermore, the eNB maintains the radio resource control for both cellular and D2D communication.
7)The UE will send/receive packets to/from the IP address of the peer UE using the D2D connection without the eNB or SAE being involved in routing.

After the D2D bearer has been established between the peer devices, it is still necessary for the eNB to control the radio resources also used by the D2D communication. The UE may of course continue communication to the Internet, because the SAE bearer is maintained and the connectivity to the gateway remains. For this activity, the UE stays in the LTE_Active state and RRC_Connected state, respectively.

In addition to checking if D2D offers benefits, the decision to establish a D2D connection can be based on a defined policy such as limiting the number of D2D connections to keep the interference to the cellular network below a tolerable level.

A handover from a D2D connection to a cellular connection is initiated when the cellular connection achieves higher throughput than the D2D or if one of the policies for D2D connections is violated.

One important property of setting up a D2D connection by a trigger of detecting IP traffic between nearby devices is that it works for any peer-to-peer IP traffic without service differentiation. Thus, it is blind to the actual service. Second, it is transparent to the user (i.e., the user does not have to select a special option for the D2D session). The D2D UE units are passive participants in the session setup, which is mainly handled at the MME and higher layers. However, the automatic switching between cellular and D2D connection should be reliable and seamless to guarantee user satisfaction.

D2D Session Setup Using Dedicated SAE Signaling

A session setup using dedicated SAE signaling avoids the overhead from detecting D2D traffic on the fly from IP packets. For this alternative, we propose to provide a specific address format to separate a D2D SIP session request from a generic SIP session request. Furthermore, we propose to enhance the MME with a light SIP handler to facilitate session setup.

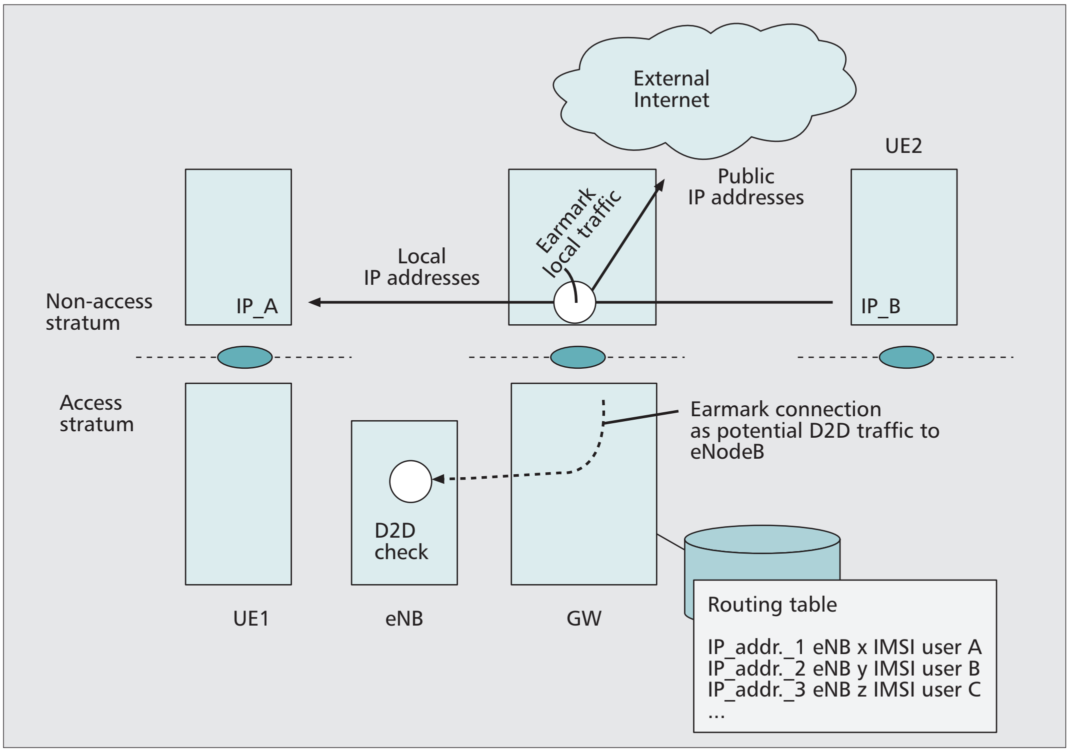

Figure 3. *The gateway earmarks local traffic to indicate potential D2D traffic to the eNB. The eNB can then check if the devices corresponding to these packets can set up a D2D connection.*

A session setup using dedicated SAE signaling avoids the overhead from detecting D2D traffic on the fly from IP packets. For this alternative, we propose to provide a specific address format to separate a D2D SIP session request from a generic SIP session request.

The new address format of D2D SIP could simply be username@realm.D2D_keyword, where the former part (username@realm) is a well-known SIP uniform resource indicator (URI), and the latter part (D2D_keyword) is a novel extension to let the SAE handle the local D2D session in a special way. The local extension is easily distinguishable as a D2D address by a special D2D_keyword such as .direct, .local, .peer, or .short.

In this approach, the application (or the user) at the requesting UE needs to decide whether to prefer initiation of a D2D session or a regular session. We foresee the following options to aid this decision:

- The user explicitly selects a D2D session by selecting the SIP URI format with a local extension.
- The UE software detects the local extension and encapsulates the SIP invite message into a control plane message to the MME instead of delivering it to a user plane TCP/IP or UDP/IP port.

The D2D session setup is illustrated in Fig. 4, which presents the peer entities UE1 and UE2 with the application layer and IP layer protocols for session initiation and connectivity. Furthermore, the radio resource control (RRC) protocol is shown.

In this case UE1 calls UE2 by SIP invite message using the .D2D_keyword extension with the URI of UE2. This lets the SAE network detect the preference for a local session, which leads to the setup of a D2D bearer instead of (or in addition to) SAE bearers. This setup procedure is local to the radio access network and does not involve a SIP server far away in the Internet, which leads to faster session setup.

We propose to encapsulate the SIP invite message in an NAS control plane message. In the SAE architecture, the MME receives all NAS messages from the served UE. The MME is in charge of the control plane functions like mobility management, and when needed it also communicates to the home subscriber server (HSS) to get subscriber records and take care of user authentication. We propose to enhance the MME functionality by a light SIP handler to keep track of the SIP addresses of the UE inside the tracking area. This can be done at the initial access, when the UE registers to the network and the MME assigns the temporary mobile subscriber identity (TMSI) to the UE that is used for all control of the UE in the wide area network. In the registration phase the HSS needs to be involved, but afterward the MME can handle the UE (mobility) context by itself.

When receiving an NAS message type for a D2D session, the MME simply passes the SIP message contents to the light SIP handler, whereas other NAS messages are treated as usual. The NAS message delivery is defined in the SAE specifications, and the proposal in this article requires no changes to the transport of NAS messages as such.

After handling the SIP message and detecting that the D2D UEs are in the same or neighboring cells, the MME will request a setup of a D2D radio bearer from the serving eNB (or serving eNBs for D2D communication happening in an area of multiple cells). The eNB(s) will then request measurements from the D2D UE to check if a D2D connection is actually possible and beneficial (discussed in more detail later). If a D2D connection is found to be beneficial, a

D2D bearer is set up and the eNB confirms the successful radio bearer setup to the MME.

This procedure takes place instead of (or in addition to) the MME setting up SAE bearers and IP tunnels between the eNB(s) and the gateway. Furthermore, a novel MME function could assign dedicated IP addresses for D2D communication and hence provide local IP connectivity. These IP addresses are preferably assigned by the MME from its local subnet domain. The MME may deliver the assigned D2D IP addresses (source addresses and destination addresses of UE1 and UE2, respectively) along with the D2D bearer request message to the eNB(s) and further from the eNB(s) with the bearer setup messages to the UEs. These IP addresses provide IP connectivity and let the UE open regular TCP/IP or UDP/IP ports for D2D communications. Nevertheless, the eNB(s) remain in control of the D2D radio bearer.

Interference Coordination with the Cellular Network

In the past, several wireless standards have addressed the need for D2D operation in the same band as the base station, access point, or central controller. Examples of such standards are Hiperlan2, TETRA, and WLAN based on IEEE 802.11 standards. In these examples D2D communication is assumed to occur on separate resources. For example, in Hiperlan2 a terminal involved in D2D communications transmits and receives in reserved time slots that are different from the time slots used by terminals communicating with the infrastructure. This is also the case in TETRA, designed for authorities, where dedicated frequency channels are specifically reserved country-wide for D2D communication.

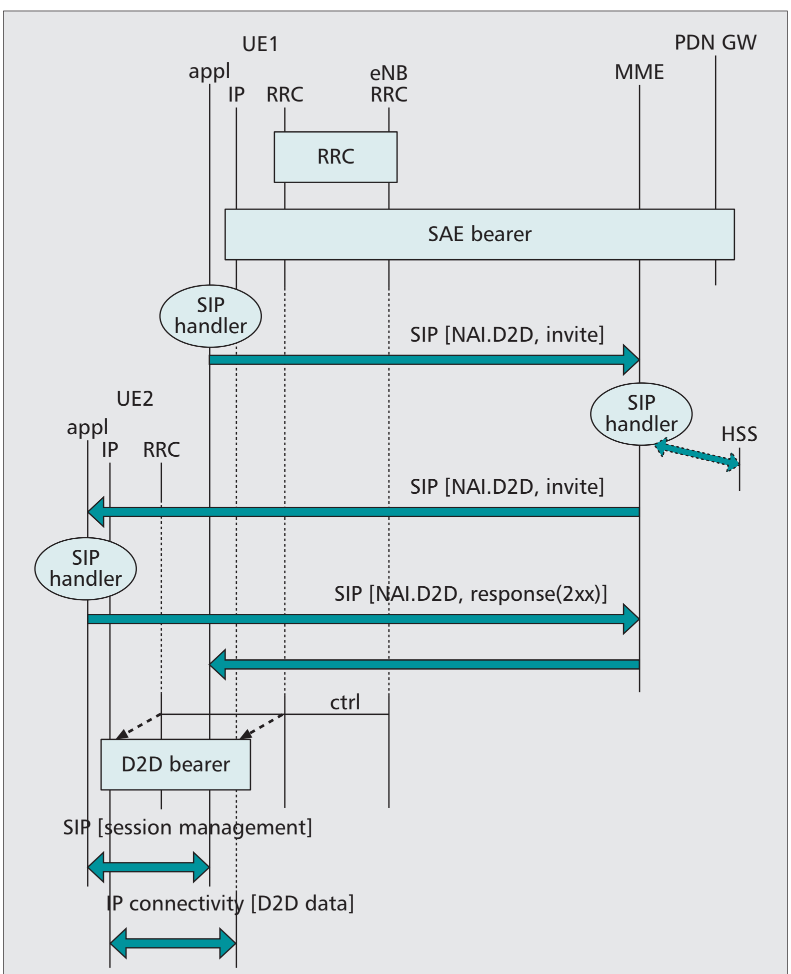

Figure 4. *Signaling graph of a D2D session setup with a dedicated D2D extension in the URI format. The MME is enhanced to facilitate session setup for the D2D communications by a light SIP handler.*

These restrictions limit the interference of D2D transmissions, particularly in an orthogonal system, such as classical time-division multiple access (TDMA). However, it leads to inefficient utilization of resources, which is especially true for the large system bandwidths deployed by LTE-Advanced networks.

WLAN allows UE to sense the radio medium and transmit only if the channel is free. A drawback of WLAN is that the access point does not have the possibility to control the resources used by the ad hoc D2D links, which could be beneficial for coordination to protect the communication with the infrastructure [4].

In this article we propose to facilitate local peer-to-peer communications by a D2D radio that operates as an underlay to an LTE-Advanced network. Although an LTE network could serve technically as well, this proposition will be timely during the era of LTE-Advanced.

In order to limit the interference of D2D connections to the cellular network, we proposed in [2] that the eNB be able to control the maximum transmit power of D2D transmitters. Furthermore, the eNB assigns orthogonal frequency-division multiple access (OFDMA) resources to the D2D connections sharing the uplink, downlink, or both uplink and downlink resources of the cellular network.

One way to coordinate interference between cellular and D2D communications is to assign dedicated OFDMA resource blocks for D2D connections, where the amount of resources may be dynamically adjusted based on temporary communication needs. This option should not compromise the experienced quality of service for cellular users with a low signal-to-interference-plus-noise ratio (SINR). It is even more challenging to protect the cellular user from interference when the cellular and D2D transmissions are allowed to reuse the same resources.

Interference Coordination in the Uplink Period

During cellular uplink transmission, the eNB is the victim receiver of interference from D2D transmitters. Since the UE in D2D connection is still controlled by the serving eNB, it can limit the maximum transmit power of the D2D transmitters. In particular, it can also utilize the cellular power control information for the devices involved in D2D communications.

The transmit power of the D2D transmitter is reduced by a backoff value from the transmit power determined by the cellular power control when the D2D transmitter reuses cellular uplink

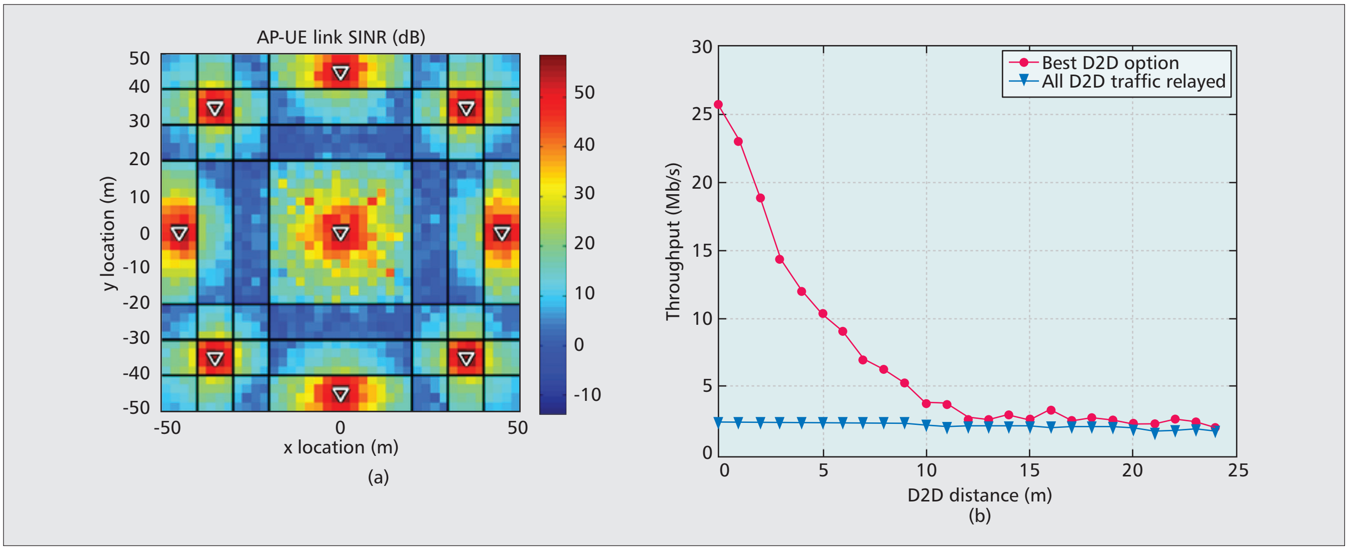

Figure 5. *Evaluation scenario and D2D throughput: a) map of downlink SINR without D2D communication (interference limited); triangles mark access point locations, lines represent walls; b) D2D throughput as a function of the D2D link distance when choosing the best sharing option and when relaying all D2D traffic through the network.*

resources. No backoff is required when the D2D transmitter uses dedicated (otherwise free) resources. The eNB can additionally apply power boosting for the uplink transmission of a cellular user to ensure that the SINR of the cellular uplink meets the target SINR. The boosting is dependent on the backoff value, as detailed in [2].

Interference Coordination in the Downlink Period

The actual location of cellular receivers in the downlink period depends on the short-term scheduling decisions of the eNB. Hence, the victim receiver at a time can be any of the served UE. After setting up a D2D connection, the eNB can set the maximum D2D transmit power to a predetermined value. The maximum D2D transmit power will be higher when a D2D connection gets dedicated (free) resources than when it reuses (reserved) cellular resources.

A suitable D2D transmit power limit can be found by long-term observations of the impact of different D2D power levels on the quality of cellular links. In addition, the eNB can ensure that cellular users scheduled on the same resources with D2D connections are well isolated in propagation conditions [5]. For example, the eNB might schedule indoor D2D connections together with outdoor cellular users.

In addition, the eNB can observe the link quality feedback from its served UE. If it observes a degradation in UE link quality, it can reduce the transmit power of D2D transmitters [6].

Feasibility Analysis

The feasibility of D2D communications as an underlay of a cellular network is evaluated by means of system simulations. A local area scenario was selected and is depicted in Fig. 5a. The scenario is fully loaded and interference limited. The layout captures characteristics of an indoor environment with small rooms, representing stores or offices, a larger open area, and longer rooms representing corridors or halls, for example. Nine eNBs serve a single floor of dimension 100 m × 100 m.

In our studies we use the channel and propagation models defined in WINNER scenario A1 (indoor/office) [7]. Links in the same room have a distance-dependent probability for line of sight (LOS) propagation with the path loss exponent 1.87, whereas for non-LOS propagation the path loss exponent is 3.68. The shadow fading has standard deviation 4 dB, and each wall introduces an additional attenuation of 5 dB.

We consider a synchronized LTE-Advanced cellular network operating on a 100 MHz band using time-division duplex. The 100 MHz band is split into five 20 MHz subbands. Both cellular UE and D2D UE are assigned to a single subband at a time. In order to guarantee a fully loaded scenario, the number of cellular users is set to 180 (on average 20 per cell), and exactly 10 D2D pairs (5 sharing the uplink period and 5 sharing the downlink period) are generated in every cell. The cellular users are uniformly distributed in the scenario, whereas the distance between D2D pairs is limited to reflect local communication.

We assume a traffic scenario where D2D users exchange rich content, such as videos and large files. The rich media content may originate, for example, from media servers or direct file exchanges between users. Hence, a full buffer traffic model holds for both cellular and D2D connections.

In order to limit the impact on the cellular communications, interference coordination mechanisms described earlier (see also [2]) are used. If the uplink period is reused, a power backoff value of 10 dB is applied for D2D transmissions, in addition to the most recent cellular power control setting. In the downlink period, the D2D transmitters have a constant transmit power of –5 dBm when they are reusing

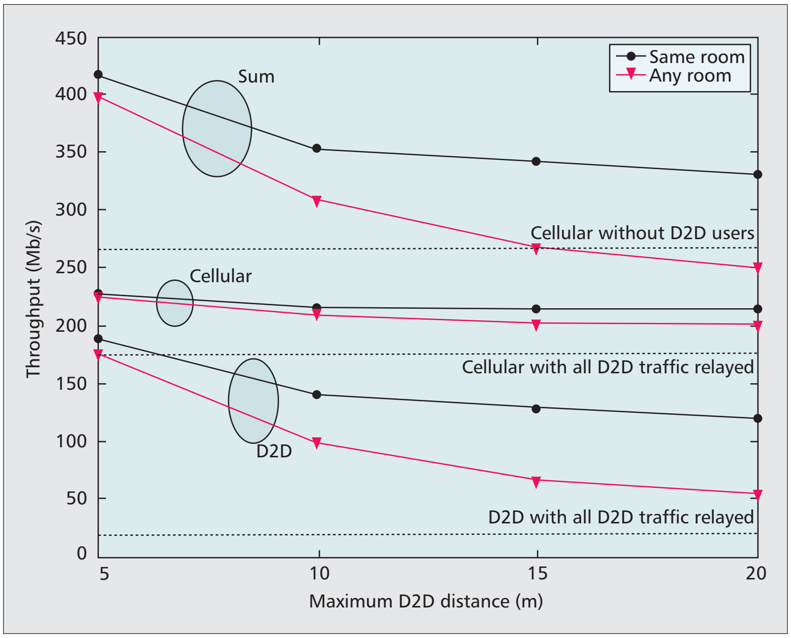

Figure 6. *Throughput of cellular users and D2D users in a cell for D2D pairs with and without restriction to be in the same room. The D2D link distance has been limited to maximum D2D distance.*

(reserved) cellular downlink resources and 3 dBm when they get dedicated (free) resources. These values have been chosen such that the SINR reduction for cellular communications is limited to 3dB. The maximum transmit power of an indoor femto type of eNB (downlink) and UE (uplink) is equal to 24 dBm.

The D2D pairs are randomly assigned to share uplink or downlink resources with the cellular network. The D2D terminals probe the D2D and cellular link quality with and without cellular transmissions in the same cell and report the results to the eNB. In this study the eNB assigns the D2D mode for UE peers offering the highest throughput taking into account the amount of resources each mode will get. The D2D modes are:

- D2D links reuse the resources allocated (reserved) for cellular use.
- D2D links use dedicated (free) resources not allocated for cellular use at that time.
- D2D traffic is relayed through the network avoiding D2D links.

In the case of dedicated resources and for traffic relayed through the network, D2D pairs are assigned a similar share of resources as cellular users; for example, a D2D pair gets one fourth of the resources when sharing the subband with three cellular users.

We assume an ideal link adaptation for all links, with a limited set of modulation and coding schemes (MCSs) [8], and an exponential effective SINR mapping (EESM) link to system mapping is used [9].

Figure 5b illustrates the D2D throughput as a function of the D2D link distance with D2D pairs located in the same room. Especially for short distances, the throughput of the direct D2D option greatly exceeds the throughput when solely relaying D2D traffic through the eNB. For 3 m link distance, the average D2D throughput in this example is 15 Mb/s compared to 2.5 Mb/s when all D2D traffic is relayed by the eNB.

The eNB relaying option was actually chosen for more than 50 percent of the D2D pairs for a D2D link distance larger than 9 m when sharing the cellular downlink period and 38 m when sharing the cellular uplink period. The large difference can be explained by the limited transmission power when sharing resources during the downlink period. The D2D link distance for resources allocated in the downlink period could be increased, for example, by utilizing multiple antennas to suppress interference from the eNB, as we have shown in [10, 11]. Dedicated resources were chosen for less than 10 percent of the D2D pairs because the share of D2D resources was rather limited in the presence of 20 cellular users per cell.

In Fig. 6 we evaluate separately the combined throughput of all cellular users, all D2D users, and their sum within a cell. Our results show that D2D throughput reduces drastically if the D2D peers are not located in the same room. Thus, D2D communication underlaying a cellular network will be limited to local (proximity) traffic (in the same room), and applications utilizing D2D communication should be designed accordingly. Nevertheless, the sum throughput (cellular plus D2D) may increase greatly (up to 65 percent compared to the sum traffic when all D2D traffic is relayed by the network) when limiting D2D communication to devices in the same room. On the other hand, the throughput of the cellular users decreases significantly (by 35 percent compared to a scenario without D2D users) if all D2D traffic has to be relayed since the D2D pairs require both UL and DL resources.

The presented simulation results focus on an indoor scenario served by a rather tight network of indoor femto type eNBs. D2D utilization increases when underlaying an outdoor wide area cellular network, as has been shown in [2].

Conclusions

In this article we propose device-to-device communication as an underlay to an LTE-Advanced cellular network. We illustrate the required small changes (additions) to the SAE procedures and functions to facilitate D2D session setup. Furthermore, we illustrate mechanisms that control and limit the interference of D2D communications to the cellular network.

In the feasibility analysis we studied D2D communication in a local area cellular network. Even though the cellular network may be interference limited already by the cellular communication alone, the D2D peers are still able to use the D2D communication opportunity, if they are close and located in the same room. By allowing D2D communication to underlay the cellular network, the overall throughput in the network may increase up to 65 percent compared to a case where all D2D traffic is relayed by the cellular network. In this manner D2D communication may also serve cellular traffic, offloading for the eNBs in addition to its other benefits of fast and light session setup, low transport delay, and high instantaneous data rate.

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Biographies

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KLAUS HUGL (klaus.hugl@nokia.com) received his Dipl.-Ing. (M.Sc.) and Dr.Techn. (Ph.D.) degrees in electrical engineering with highest honors from the Technische Universität Wien (TU-Wien), Austria, in 1998 and 2002, respectively. Since 2002 he has been with Nokia Research Center, where he is currently research manager of the optimized local access team. His main areas of research include wireless system design, multi-antenna techniques (MIMO), as well as 3GPP cellular radio technologies. He has (co-)authored about 25 conference and journal papers in wireless communications.

In the feasibility analysis we studied D2D communication in a local area cellular network. Even though the cellular network may be interference limited already by the cellular communication alone, the D2D peers are still able to use the D2D communication opportunity if they are close and located in the same room.