Device-to-Device communications; functional prospects for LTE-Advanced networks

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***Abstract*— In this paper the possibility of device-to-device (D2D) communications as an underlay of an LTE-A network is introduced. The D2D communication enables new service opportunities and reduces the eNB load for short range data intensive peer-to-peer communication. The cellular network may establish a new type of radio bearer dedicated for D2D communications and stay in control of the session setup and the radio resources without routing the user plane traffic. The paper addresses critical issues and functional blocks to enable D2D communication as an add-on functionality to the LTE SAE architecture. Unlike 3G spread spectrum cellular and OFDM WLAN techniques, LTE-A resource management is fast and operates in high time-frequency resolution. This could allow the use of non-allocated time-frequency resources, or even partial reuse of the allocated resources for D2D with eNB controlled power constraints. The feasibility and the range of D2D communication, and its impact to the power margins of cellular communications are studied by simulations in two example scenarios. The results demonstrate that by tolerating a modest increase in interference, D2D communication with practical range becomes feasible. By tolerating higher interference power the D2D range will increase.**

Keywords: device-to-device, D2D, Evolved UTRA, LTE, LTE-Advanced, IMT-Advanced.

I. Introduction

3GPP Long Term Evolution (LTE) technology [1] has been shown to have high performance in the measures of spectral efficiency and throughput as the mean, cell edge and peak values in a cellular, frequency reuse one network. Hence, it can be foreseen that LTE technology forms a solid ground to become a technology proposal for the IMT-Advanced (IMT-A).

IMT-A systems [2] are mobile broadband communication systems that include new capabilities that go significantly beyond those of the IMT-2000 family of systems such as WCDMA or WiMAX. International Telecommunications Union (ITU) has issued a request to submit candidate Radio Interface Technologies [3] for IMT-A. These candidate technologies will be evaluated and an ITU-R recommendation containing the IMT-A radio interface specification is scheduled for February 2011 [3].

Further currently of LTE are currently studied and labeled as LTE-Advanced (LTE-A) technology. LTE-A technology components will be studied among the Release'9 study items. Some of these study items, e.g. relaying, advanced MIMO techniques, have already been identified and their research is progressing well.

This paper introduces a technology component that has not been taken sufficient notice so far, namely the device-to-device (D2D) communications opportunity. The motivation for D2D does not come directly from IMT-A or LTE-A requirements. However, D2D communications could be a promising add-on component that serves specific future needs. These needs arise e.g. from local ad hoc networking, new types of short range services and data intensive short range applications. It is recognized that several incompatible techniques have been studied and used for this purpose earlier like Bluetooth, Ultra-wideband (UWB) and wireless local area networks (WLAN, WiFi) based on IEEE 802.11 standards. However, the benefits of using LTE standard technology (on licensed bands) and the benefits of giving the control of session initiation and control of radio resources to the operator network have not been sufficiently taken into account yet. In this paper, the potential of LTE technology as a platform for D2D communications is addressed and the key issues are raised. The time schedule of these studies would rather be aligned to LTE-A than LTE, thus LTE-A technology is referred here.

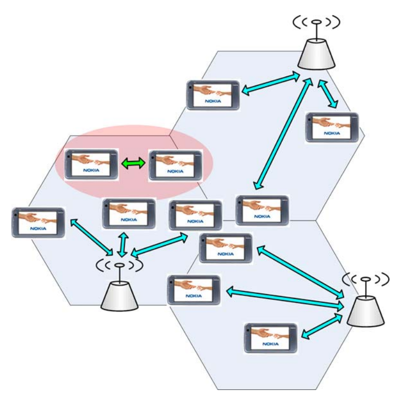

Fig. 1. Illustration of D2D communications as an underlay to a cellular network. Cellular and D2D communications share the same resources with potential interference between them (marked as shaded area).

In [4] we have proposed to enable local services by a

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device-to-device (D2D) radio that operates as an underlay to a cellular network (see Fig. 1). In this paper we present selected services that are enabled by the D2D radio and the motivation to integrate the D2D radio in an LTE-A network. We review the coordination mechanisms required to enable the co-existence of D2D radio with the cellular radio and show how to apply them in an LTE-A network. Further, we introduce functional blocks which are required for the D2D and present co-existence results illustrating the tradeoffs that need to be considered when operating D2D.

The remainder of this paper is organized as follows. In Section II we present service opportunities of D2D. Section III outlines the functional blocks in the System Architecture Evolution (SAE) architecture that enable D2D communications. A special emphasize is on the coordination mechanisms that enable the underlay operation. In Section IV we present some results on the co-existence study of the D2D radio with the cellular network.

II. Service opportunities

Currently, cellular communication systems such as 3GPP LTE operate on spectrum that is licensed to operators. The networks are optimized for wide area and metropolitan area operation resulting in rather complex and expensive network equipment. In contrast, WLANs allow access to the internet and to local services using license exempt bands. In recent years WLANs have become increasingly popular because of the low cost access points and cheap and fast access to wireless spectrum. However, only a licensed band can guarantee a controlled interference environment and local service providers might prefer to pay a small amount of money to offer guaranteed services avoiding the uncertainties of the license exempt bands. The proposed Device-to-Device (D2D) communications operate as an underlay of the cellular network and enable the cellular network operator to offer cheap and fast access to its spectrum with controlled interference margins.

Device-to-device communications has been studied earlier in 3GPP [5] as an ad-hoc multi-hop relaying protocol based on [6]. It requires the UEs to probe the neighborhood in regular intervals for potential relays. In other words, it causes overhead even if there is no relaying in the cell. The example in [5] teaches an important lesson for the design of the D2D radio. First, it should not be limited to only one service and second, no overhead should be caused to the system when D2D communications is not used.

D2D communications will allow new types of local services. As an example, consider the case where a media server is installed at a rock concert tour from which visitors can download promotional material using the D2D radio. The organizers of the rock concert simply put up the media server which registers to the cellular network and it is immediately operational. Alternatively, the cellular network could handle the traffic from the media server. However, by using the D2D radio the cellular network can handle phone calls and internet data traffic without the additional network load from the promotional material.

As the second alternative, WLAN or Bluetooth could be used. However, because they operate in the license exempt bands, organizers cannot be sure if the media server will work at every place they visit as there is always the possibility of presence of severely interfering systems and other sources of non-coordinated interference.

The D2D operation itself can be fully transparent to the user. Once the user enters a URL, the cellular network detects traffic to the media server and may hand it over to a D2D connection. Since both D2D devices already have a secure connection to the cellular network, it is easy to setup a secure D2D connection. Thus, compared to WLAN or Bluetooth, no manual pairing or access point definition is required.

The D2D communications also allows to share for example photos or videos taken by a mobile device between users. The videos can be shared without pairing Bluetooth devices or setting up an ad-hoc connection. Again the cellular network will hide the complexity of setting up the D2D connection from the user.

III. Functional blocks to enable D2D communications

LTE operates fully in the packet-switched domain. Hence it is natural to propose D2D connectivity that is based on Internet connectivity, mainly Session Initiation Protocol (SIP) and Internet Protocol (IP). D2D connectivity based on SIP and IP has the benefit of providing the control over the D2D connectivity to the operator, and fitting readily to the operators' infrastructure with some updated software functionality.

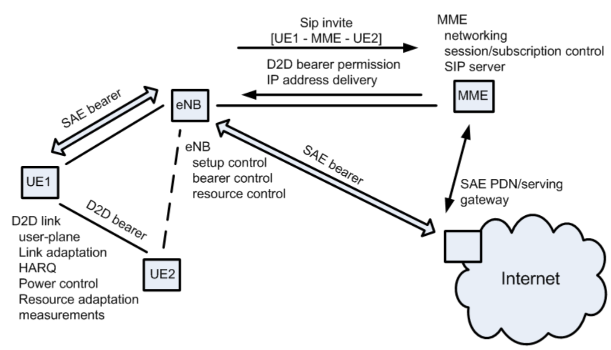


Fig. 2. D2D communications in the SAE architecture. Added functionality regarding D2D communications is indicated for UE, eNB and MME. SAE bearers are shown for reference.

Fig. 2 depicts the additional functionalities which are required for D2D communications in the current LTE architecture. For this purpose, SIP and IP connectivity is provided by the Mobility Management Entity (MME), which negotiates with the Serving/PDN gateways to get IP addresses to the user equipment (UE). The MME thus acts as a binder between the IP addresses, subscription information, SIP presence and SAE network identification. All this justifies that a D2D session initiation request (like SIP invite) should be delivered to the MME. The MME then could initiate the setup of a D2D radio bearer and initiate an IP address delivery for the D2D terminating devices. IP addresses for D2D communications could be created with a local subnet scope, similar to a local breakout solution. The IP-like connectivity over the D2D link offers seamless operation to the higher layer protocol stack (TCP/IP and UDP/IP) in the UE and it eases the mobility procedures between cellular and D2D networking.

In the following we describe some of the functions required to enable the D2D operation.

A. Radio identification and bearer setup

After finding the D2D terminating UE by their radio network identities (s-TMSI) or IP addresses, the MME should delegate the local control of radio resources to the base station (eNB), which is also serving the cellular radio connections of the D2D devices. Thereby the additional complexity to the MME can be limited. The D2D link itself could operate according to the principles of an LTE-Advanced radio.

The eNB could keep the UE control by defined procedures using the cell radio network temporary identifier (C-RNTI) as a unique identification in the cell.

The cellular bearer identification mapped by one-to-one relationship to a logical channel in LTE could likewise be replaced by a new extension of having a D2D bearer identification on a logical channel, where the logical channel identification acts as the signalling unit similar to LTE-A cellular, but could now be assigned to serve either a cellular logical channel or a D2D logical channel instead.

B. User plane

The unit of information exchange over the D2D connection in this paper is proposed to be the IP packet, even though it is understood that any alternative form of packet communications could be motivated too, because D2D packets are not routed through the network. Re-using IP datagrams for this purpose offers IP level compatibility to the higher layer protocol stack like TCP/IP or UDP/IP socket that can transparently be used for cellular or D2D communications.

We propose that an application software that is capable of handling different ports, port types and port numbers should choose to open TCP/IP sockets for cellular communications and UDP/IP socket for D2D communications. Using UDP ports is expected to avoid major problems caused by the varying radio capacity of D2D links to TCP due to slow start and congestion control algorithms. TCP probing of capacity over unknown (interconnected) network paths is not necessary in D2D links, where the link capacity may be directly available at the peer entities. TCP retransmissions are not necessary either, because reliable transmission can be provided by the radio (layer 2) protocols, which in D2D case have complete retransmission information available at the peer entities.

UDP provides the most important properties of segmentation and in-sequence delivery windows. The UDP segment size could be made radio dependent to avoid segmentation by the radio protocols. This is easy to handle for example by negotiating the Maximum Segment Size for a D2D connection (e.g. as a D2D bearer parameter) and by supporting the concatenation of multiple UDP segments in a single transport block. The UDP segment receive window is used to cope with fast retransmissions by the radio protocols and to offer in-sequence delivery to the application. If the UDP segment length variation is not sufficient to adjust to the varying radio capacity of D2D, a radio layer segmentation of UDP segments could be considered. This would add some radio protocol overhead and increase the complexity of segmentation

C. Interference management

Interference management in a cellular environment with D2D links is a critical issue as the interference from D2D links can be expected to reduce the cellular capacity and efficiency. However, LTE technology offers unparalleled opportunities for this, unlike any earlier spread spectrum (WCDMA, WLAN) or OFDM WLAN system. The LTE scheduling operates on short time intervals of 1ms subframes and on flexible frequency allocations in physical resource blocks (PRB) of 180kHz.

Therefore, D2D links may find short time intervals and frequency proportions, where communications is feasible without causing harmful interference to the cellular network. Similar problems are observed in the context of cognitive radios (see for example [7] and [8]) where the cellular usage is the primary service. However, in the case of a dense LTE network with high network load and fast scheduling variations, a cognitive radio would not be able to detect "white spaces".

On the other hand, our proposed D2D radio will still be able to operate because it uses a compatible technology and it is controlled by the cellular network. The easiest way to coordinate interference between the cellular and D2D communications is to assign dedicated PRBs for D2D, where these resources are dynamically adjusted based on temporal needs.

Dedicated resources for D2D communications could lead to inefficient use of the available resources and efficiency can be increased when D2D links would reuse the same PRBs as allocated for the cellular links. In order to control the interference from D2D to the cellular network when reusing the same resources, we proposed in [4] that the eNB is able to control the maximum transmit power of D2D transmitters. Furthermore, the eNB assigns resources to D2D connections reusing either the uplink or downlink resources or both, in the cellular network.

There is no fundamental difference in the interference coordination mechanisms when D2D works as an underlay to an LTE network operating in frequency division duplex (FDD) or time division duplex (TDD) mode. However, different interference coordination mechanisms are needed when D2D reuses cellular uplink and downlink resources. Please note that in D2D links, there is no clear differentiation between the uplink and downlink as such.

1) Interference coordination for D2D sharing uplink resources with the cellular network: During the cellular uplink transmission, the eNB is the victim receiver of interference from all the D2D transmitters. Since the UEs in D2D connection are still controlled by the serving eNB, it can limit the maximum transmit power of the D2D transmitters. In particular, it can utilize the cellular power control information also for the devices using D2D communications. The transmit power of the D2D transmitter is reduced by a back-off value compared to the transmit power determined by the cellular power control. The eNB can additionally apply power boosting for the uplink transmission of a cellular user to ensure that the signal to interference plus noise ratio (SINR) of the cellular uplink meets the target SINR. The boosting is dependent on the back-off value, as detailed in [4].

2) Interference coordination for D2D sharing downlink resources with the cellular network: The actual location of the cellular receiver in the downlink phase of the cellular network depends on the short-term scheduling decisions of the eNB. Hence, the victim receiver at a time can be any of the served cellular UEs. After setting up a D2D connection, the eNB can set the D2D transmit power to limit the interference to the cellular network. A suitable D2D transmit power level can be found by long term observations of the impact for different D2D power levels on the quality of the cellular links. In addition, the eNB can ensure that the cellular users scheduled on the same resources with the D2D connections are well isolated in propagation conditions [9]. For example, the eNB might schedule indoor D2D connections together with outdoor cellular users.

D. Link adaptation

Link adaptation provides self-adaptation of the operation points to varying signal to interference plus noise ratios (SINR) and block error rates (BLER) and aims to maximize the efficiency. Link adaptation can be achieved by means of modulation and code rate selection and automated repeat requests (ARQ) retransmissions. The instantaneous selection of modulation and coding could be based partly on channel sounding measurements and partly on the buffer status information indicating the amount of bytes in the buffer.

In link adaptation, Hybrid ARQ is a necessary feature, because the BLER on the D2D resources could vary largely depending on whether a D2D link operates on dedicated resources or reuses cellular resources. Compared to cellular links the BLER operation point could be higher and higher variations should be tolerated. The details of how Hybrid ARQ should operate and what kind of Hybrid ARQ should serve D2D are open research questions. Further studies on transport format adaptation could be carried out for multi-antenna configuration, whether precoding or beamforming type of solutions provide gains.

E. Channel measurements

The channel measurements in LTE (LTE-A) have the nice properties of being time and frequency configurable with low overhead and a resolution of multiple subframes and multiple resource blocks, respectively. Only a single symbol position is reserved for the sounding reference symbol per repetition interval. Thus, the measuring receiver obtains full band channel information by integrating the sounding sequences over time and frequency.

In addition to sounding, the demodulation reference symbols transmitted along the PRBs of the payload can be used for channel measurements, even if their main importance is in channel estimation, equalization, demodulation and decoding. It is assumed that LTE-like structures for demodulation reference symbols and sounding reference symbols are feasible for D2D links as well.

F. Timing

The burst timing of D2D links is an issue for D2D communications underlaying both FDD and TDD cellular operation. In both cases D2D transmissions will most likely be operating in TDD mode with flexible switching points.

Fortunately, block transmissions with long symbol duration (LTE symbol length is 67 μs) and cyclic signal extensions (LTE has 5 μs and 17 μs defined) does not make the time alignment very critical. For D2D links, the normal cyclic extension length of LTE is well sufficient for all environments. It could even be seen as over-dimensioned, but keeping the LTE symbol compatibility is such a big advantage that it should not be sacrificed here. Secondly, a possible multi-hop solution for D2D communications could benefit a lot of this large time tolerance. The burst timing could be derived from the eNB timing, if any one of the D2D terminating devices can communicate to the eNB, as assumed in this paper.

G. Mobility

The range of D2D is expected to be limited. It should be a subject for further study, how large D2D ranges are feasible in different scenarios when operating D2D with a tolerable impact to the cellular network. Due to the limited range, D2D radio should be designed for rather stationary links. Nevertheless, it should also offer limited mobility support. The default mobility case is to handover IP connections from D2D links to the cellular links and vice versa, if feasible. In a radio sense, this could be enabled by a common c-RNTIs managed by the eNB. In IP sense, this could work based on having multiple IP addresses valid, which allows ”routing” the user plane either to a direct D2D link or to the IP tunnel of the cellular network. The distinction of traffic flows by the IP addresses would be unique and easy to manage by the UE.

IV. Numerical evaluation of underlay operation

In this section we evaluate the co-existence of D2D communications in the local area scenario depicted in Fig. 3. The indoor environment has small rooms, representing stores or offices, a larger open area and longer rooms representing also corridors. In here, nine eNBs serve a whole floor of 100m times 100m. Scenario 1 represents an indoor cellular network deployment which is a very challenging environment for the underlay operation because the eNB density is high and the scenario is clearly interference limited. Scenario 2 represents a metropolitan area outdoor eNB deployment, modeled by the well known Manhattan grid. Here we assume that all the cellular users are moving in the streets. The D2D communication takes place indoors using the same room layout as scenario 1 but without indoor eNBs present. It is a very optimistic scenario for indoor D2D communications, because the building walls provide good isolation from the outdoor eNB.

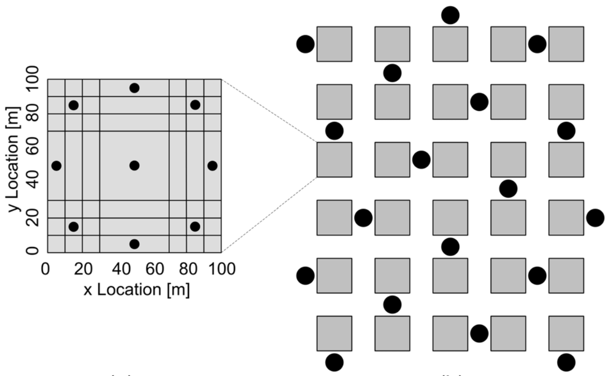
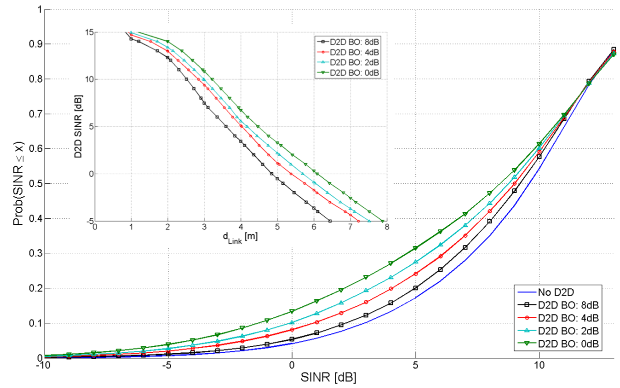


Fig. 3. Evaluation Scenario. (a) the indoor deployment of scenario 1 (b) the Manhattan grid of scenario 2. The outdoor eNBs are active only in scenario 2 and indoor eNBs only in scenario 1. (eNB locations are marked as black dots)

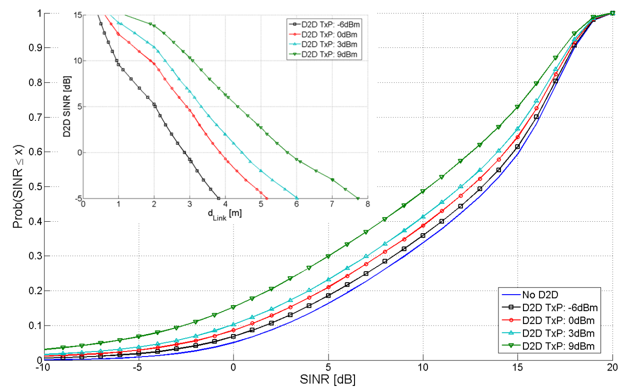
We assume a synchronized LTE-A cellular network operating on a 100 MHz TDD band. The band is split into five sub-bands of 20 MHz to keep backwards compatibility with LTE. One cellular UE and one D2D communications pair are assigned to each sub-band and transmit and receive on the whole sub-band. The interference coordination mechanisms in Section III are utilized to control the interference of D2D to the cellular communications. The D2D pairs are generated into the same room to reflect a local area scenario. Allowing only one D2D pair in each sub-band within a single cell is a simple admission control method to keep the interference from D2D communications to the cellular network low and to limit the need to coordinate the transmissions of different D2D pairs.

We use the channel and propagation models defined in WINNER [10]. The WINNER scenario A1 (indoor/office) is assumed for the indoor links with a distance dependent probability for line of sight (LOS) for nodes in the same room. The WINNER scenario B1 is used for outdoor links with LOS between nodes in the same street and non LOS for nodes in different streets. Further, the B4 outdoor-to-indoor scenario is assumed for the links between outdoor nodes and indoor nodes. The transmit power of the outdoor eNB, indoor eNB and UE are set to 37dBm, 24dBm and 24dBm respectively. Further, their antenna gains are 14dBi, 7dBi and 0dBi respectively.

Table I and Fig. 4 present a tradeoff between Signal to Interference plus Noise Ratio (SINR) degradation of the cellular communications and the achieved range of the D2D communications. The SINR degradation is measured at the 10 percentile of the Cumulative Distribution Function (CDF). The D2D range is defined as the range up to which 75% of the D2D connections have SINR of at least 5dB.



(a)



(b)

Fig. 4. Cellular SINR (cdf) in Scenario 1 (a) with different Backoff margins, when D2D reuses cellular uplink resources and (b) with the maximum D2D Tx power constraint, when D2D reuses cellular downlink resources. The embedded subfigure shows the D2D SINR that was achieved by 75% of the links as a function of D2D range.

TABLE I
TRADEOFF BETWEEN CELLULAR SINR DEGRADATION AND D2D RANGE WHEN REUSING CELLULAR UPLINK (UL) OR DOWNLINK (DL) RESOURCES, RESPECTIVELY.

Scenario 1

SINR degradation [dB]	1	2	3	5
D2D range UL [m]	3.6	4.1	4.2	4.5
D2D range DL [m]	2.1	2.9	3.5	4.3

Scenario 2

SINR degradation [dB]	1	2	3	5
D2D range UL [m]	15	20	20	20
D2D range DL [m]	4	7	8	8

The results demonstrate that underlay D2D communications by reusing cellular resources is possible for both scenarios. The D2D pairs in the downlink of scenario 2 can operate at full power without causing more than 3dB SINR degradation to the outdoor cellular network and the resulting D2D range is about 8m. The D2D transmitters do not cause harmful interference to the cellular UEs, because the eNB uses 13dB higher transmit power and has 14dBi higher antenna gain. Further, the building walls provide additional isolation. However, the

D2D range is limited because the outdoor eNB will generate high interference to D2D receivers close to the walls. Since we require that the SINR of 75% of the D2D connections is higher than 5dB, the resulting range is quite pessimistic. The D2D range would be much higher in the center of the buildings (away from walls).

In UL the D2D transmitters use the power control procedure with backoff as described in Section III which reduces the transmit power margin. The transmit power used by the cellular UEs and the D2D UEs is limited by the same maximum transmit power and the isolation from the walls is not sufficient to allow full power for D2D transmitters. Nevertheless, the achievable D2D range is between 15 and 20m, because the interference from the cellular UEs is much lower than the interference from the eNB when the D2D connections reuse cellular downlink resources. Scenario 1 allows local services with a range of 2m up to 5m depending on the allowed interference to the cellular network. Even though this range seems low, it is still reasonable compared to the average eNB-UE link distance of 10m for UEs served by the indoor eNBs in this scenario.

These results demonstrate that reusing downlink resources is more challenging than reusing uplink resources. Please note that this study assumes the worst case of a fully loaded cellular network. The range of D2D will be higher in a partially loaded cellular network where unused resources could be dedicated to D2D communications. Further, the D2D range can be increased if the cellular network tolerates higher interference.

V. Summary

In this paper we discussed relevant issues regarding the feasibility of D2D communications as an underlay to the LTE-Advanced network. It is seen that LTE-Advanced, if any system, offers opportunities for D2D communications due to its time-frequency flexibility in allocations. D2D communications could offer new service opportunities and potentially new revenues for the cellular operators.

In this paper, we have sketched solutions, how the interference of D2D communications to the cellular network can be controlled. The co-existence studies demonstrate that it is feasible for D2D communications to reuse the same resources as the LTE-Advanced network is using. Yet, many open questions remain in, how the interference margins are controlled by the eNB and what kind of protocol solutions should be designed for the D2D communications itself.

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