Device-to-Device Communication Underlaying Cellular Networks: Connection Establishment and Interference Avoidance

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Abstract

It is expected that device-to-device (D2D) communication is allowed to underlay future cellular networks such as IMT-Advanced for spectrum efficiency. This article studies the mechanisms of D2D communication and interference avoidance when the D2D subsystem reuses uplink resources and downlink spectrums with a cellular system, respectively. We firstly propose an effective scheme to establish and maintain D2D communication. Moreover, a novel method to deal with the resource allocation and interference avoidance issues by utilizing the network peculiarity of a hybrid network to share the uplink resource is proposed. Most research focuses on reusing the uplink spectrums, but how to share the downlink frequency bands is seldom addressed. To share the downlink spectrums and avoid the interference to the primary cellular devices, a labeled time slots based mechanism is proposed. Implementation details are described in a real cellular system and simulation results prove that satisfying performance can be achieved by using the proposed mechanisms.

Keywords: Device-to-device communication, hybrid system, near-far interference, long term evolution, labeled time slots

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A preliminary version of CE-OLSR appeared in the seventh IEEE Conference WiAD'2011, London, UK, June 20-22, 2011.
This paper integrates obstructing obstacles and their handling by CE-OLSR, and includes an extensive state of the art, a propagation model with obstacles and a more extensive simulation set using scenarios including obstacles.
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1. Introduction

Recently, major efforts have been spent on the development of Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) for the higher data rate and system capacity. Showing substantial performance improvements in the throughput and spectrum efficiency, LTE is foreseen to be a solid ground for the future IMT-Advanced (IMT-A) technology [1]. IMT-A will offer a high bandwidth up to 100MHz for higher data rates, global operation and economy of scales supporting a wider range of services. Many candidate radio interface technologies have been submitted to the International Telecommunications Union (ITU) to prepare new technology components for LTE to meet IMT-A requirements. Among which, device-to-device (D2D) communication has received increasing attentions as a promising component to improve spectrum efficiency [1][2][3].

Unlike the infrastructure based cellular network, D2D users (user equipments or mobile terminals) do not communicate via the central coordinator (base station, NodeB or evolved NodeB) but operate as an underlay and communicate directly with each other or more hops. Excluding the unnecessary core network involvement, D2D communication is an appealing concept which can provide several advantages such as low cost, plug-and-play convenience, and flexibility. Its usage of bandwidth and battery power is more efficient and interference can be reduced if two near terminals in different cells communicate directly [4][5][6][7][8]. Furthermore, increased network efficiency supports more services or improves current services and applications. The services which can possibly benefit from direct communication include information sharing, mobile multiplayer gaming, mobile advertising, streaming services, social or community services with D2D and extending D2D concepts to a mobile relay [9].

Indeed, such D2D communication is likely to become integral to the future beyond 3G world to form a hybrid network [8][10]. **Fig.1** illustrates the basic and extended concept of D2D communication and hybrid networks. In **Fig. 1**, a user equipment (UE) can communicate with another UE directly or by the aid of a base station. Moreover, multiple D2D subsystems can share resources in a cell.

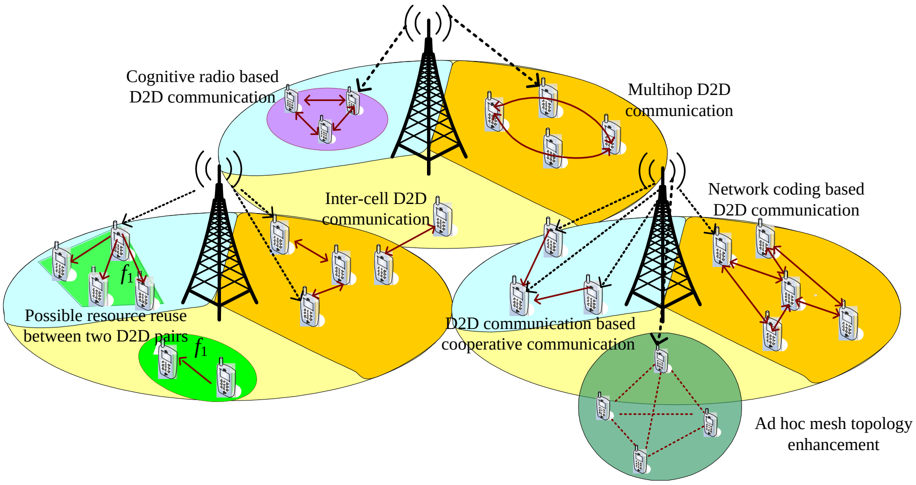


Fig.1. Illustration of D2D communication as an underlay to a cellular system.

Actually, the trait of D2D communication is not new in the cellular system and it has been identified in some specifications such as Private Radio Communication System (PRCS), Japanese Handy Phone System (HPS), Digital Enhanced Cordless Telecommunications (DECT), etc. Many companies devote actively much in this research. Qualcomm, for example, is heading and has been very active recently. A prototype of "FlashLinQ" modem has been developed since 2006 to enable direct D2D communication over a licensed spectrum. The prototype effort covers the protocol stack from the host software interface to the physical layer algorithm. "FlashLinQ" is even a new trademark registered in 2008 by Qualcomm [11].

The key motivation for utilizing D2D communication underlaying a cellular network is to keep local communication local. D2D communication shares the same resources with the cellular system whereas under the control of the evolved NodeB (eNB). In such a case, an eNB can still control the resource and power assigned for D2D transmission to limit the interference to the primary cellular networks. Although the concept of D2D communication as an underlay to a cellular network is not new in a cellular system, it is new in LTE systems. As a result, some new challenges are incurred. The first key issue to be resolved is how to facilitate D2D communication in the licensed frequency band. Different from a centralized system where an eNB fully controls the data transmission which should be sent on the pre-allocated resources and UEs must synchronize with the eNB, devices would compete with each other for the resource in a distributed way in the D2D subsystem. Secondly, interference management in a hybrid network is a critical issue in that the interference from D2D links can be expected to reduce the cellular capacity and efficiency and vice versa. In this paper, focusing on frequency division duplex (FDD) LTE networks, we concentrate on the D2D communication establishment and maintenance, and near-far interference avoidance.

There has been some research on D2D communication underlaying a cellular network. [1] proposed a mechanism for D2D communication session setup and management along with the interference coordination between two subsystems in the LTE system architecture evolution. To manage the interference between D2D and cellular networks, in [12], by assuming that an eNB completely controls over the D2D links, a power control scheme is suggested to maximize the system sum throughput. [3] also applied a power control method to mitigate the interference by using the channel statistics instead of instantaneous channel state information of the links between the cellular UEs and the D2D users. [7] formulated the power control problem as a mixed integer nonlinear programming and further proposed a greedy heuristic algorithm to realize this method. By employing a game theory based power control scheme, an interference suppression mechanism is studied in [13]. A time hopping based mechanism rather than a typical power control scheme is presented in [6]. The author suggested that interference among multiple D2D pairs is randomized by allocating different time hopping sequence offsets among them.

We make three main contributions in this work. We firstly propose a feasible and effective D2D communication mechanism named Synchronized Slotted Aloha with RTS/CTS (SSARC) to implement an autonomous handshake, competition and data transmission among D2D users. By synchronizing with the primary cellular system and following the same time structure with it, D2D users compete for transmission priority based on the Aloha with Request to Send/Clear to Send (RTS/CTS) mechanism and then the D2D communication is maintained to reuse the cellular uplink (UL) resources. To best of our knowledge, no such similar work was proposed before.

Furthermore, when UL spectrums are reused, the victim device is commonly considered to be the eNB and several algorithms are studied to coordinate this interference by reducing transmission power of D2D users [1][7][12]. However, with respect to the amount of cellular users and the short distance between two D2D UEs, it is D2D users that have higher possibility to be interfered. In our work, we address the near-far interference to the D2D devices and propose a proactive interference avoidance scheme by utilizing the helpful information from the eNB.

Due to heavier traffic and fast resource scheduling in LTE downlink (DL) transmission, most work emphasized that D2D devices make use of the cellular UL spectrum [9][13][14][15][16][17]. Different from the previous research, we propose a novel interference avoidance scheme to reuse DL resources by using labeled time slots. Extensive simulations prove the better efficacy of our method over the traditional power control scheme.

The paper will be organized as follows. In Section 2, we present the procedure of D2D transmission establishment and maintenance aiming to realize efficient resource utilization in the hybrid network. Since D2D devices work autonomously and fully share frequency resources with cellular users, sometimes there is near-far interference between cellular users and D2D pairs. In Section 3, we propose a novel scheme to realize UL resources sharing meanwhile avoiding near-far interference to D2D transmission in a hybrid network. Furthermore, Section 4 describes the mechanism and implementation details to reuse DL resources by applying labeled time slots. Finally, performance evaluation and discussions are presented in Section 5 and conclusions are given in Section 6.

2. Establishment and Maintenance of D2D Communication

2.1 Prior art overview

The establishment and maintenance of D2D communication is a preliminary problem to enable D2D sessions. Since D2D terminals will not be under the tight control of an eNB and D2D subsystems share the resource with their anchored cellular systems, consequently, several questions are thus raised. Firstly, D2D communication may exert serious interference to the cellular system or it may be interfered by the cellular users. Thus, how to coordinate the interference between the two subsystems? Furthermore, there maybe exist multiple D2D pairs which initiate their communication simultaneously such that inter-pair interference happens. Then the competition problem among them should be solved efficiently to avoid such harmful interference. Our third concern is how to synchronize those D2D partners to avoid disordering the transmission. That is a question on how to inform the D2D transmitter and receiver when and on which resource to start the transmission. To answer these questions, let us first investigate several currently proposed methods. In this article, a D2D transmitter and receiver are abbreviated as ‘Tx_D_UE’ and ‘Rx_D_UE’ separately.

Prior Art 1: eNB arbitrarily controlling D2D communication

One intuitive solution is to allow an eNB to control the D2D communication arbitrarily. **Fig. 2** depicts the procedure and signaling of this mechanism. Obviously, D2D transmission is completely controlled by the eNB.

The advantage of this approach is that the eNB is able to easily handle the procedure for all the D2D transmission, and it is unnecessary to worry about the mess caused by any uncertainties. Moreover, resource allocation can be performed completely by the eNB such that less interference exists in such networks. Inevitably, this method has several disadvantages. Since the eNB takes charge of the whole D2D communication procedure, all the D2D related signaling consumes the radio resources of the cellular network and may reduce the throughput and capacity of a cellular network. Another, if a large number of D2D

UEs transmit the data at the same time, the amount of D2D signaling would be huge. Furthermore, when the D2D partners are at the edge of different cells, it will become worse. Under such a situation, extra information (such as the pathloss between D2D users) would be required by an eNB to make radio resource management (RRM) decision for D2D data transmission. Otherwise, signaling needs to be exchanged over the X2 interface between neighboring eNBs for the resource coordination which will result in a long delay.

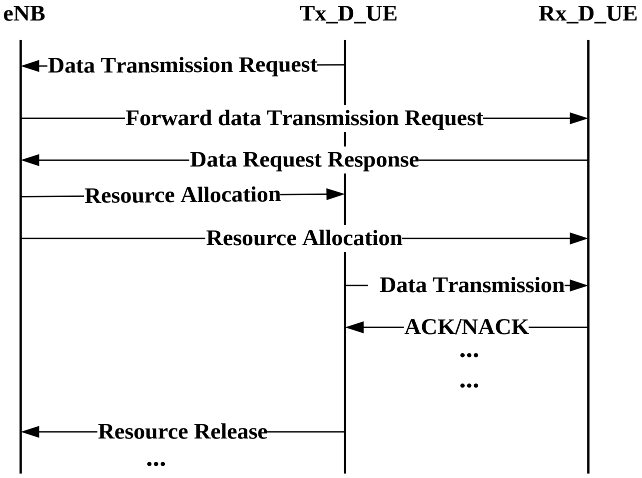


Fig. 2. An example of D2D transmission under arbitrary control of an eNB.

Prior Art 2: Resource contention based D2D communication

Another straightforward solution is a purely autonomous solution, which uses the similar schemes to those for Ad-hoc networks, Carrier Sense Multiple Access/Collision Avoid (CSMA/CA) with or without RTS/CTS, which are adopted in IEEE 802.11.

Notwithstanding this contention based framework can effectively resolve the data collision between D2D pairs in the hybrid network, it is challenged by threefold shortcomings. Firstly, the signaling such as RTS, CTS and ACKnowledgement (ACK), Negative ACKnowledgement (NACK) uses the same channel resources as the data transmission which results in the fact that data and signaling can not be transmitted simultaneously. Secondly, Distributed Interframe Space (DIFS) and Short Interframe Space (SIFS) are necessary to reduce the possibility of collisions, however, in the sensing duration data transmission is impossible thus leading to low resource utilization efficiency. Especially in the scenario where there are lots of short data to transmit, the overhead will be quite high. Finally, such a contention based mechanism can not avoid the interference from the cellular communication efficiently when sharing the licensed cellular system frequency band.

As a summary, a smart D2D RRM is necessary to control the interference and improve the performance. It requires that the solution should be able to take advantage of all the available information, including the signaling in the cellular network, to facilitate D2D RRM functions, such as frequency resource allocation, power control, interference avoidance, and so forth.

To this end, we propose an autonomous D2D communication mechanism named SSARC, which is assisted by the infrastructure system. The key point of this novel mechanism is a synchronized slotted Aloha with RTS/CTS, which achieves the handshake, competition and data transmission between D2D users effectively and efficiently.

2.2 Autonomous D2D communication assisted by the infrastructure system

In the initial stage, D2D UEs should firstly register to one cell to obtain some essential information from an eNB such as whether it is D2D capable or not, Cell-ID of the anchored cell, fractional power control parameters used by this cell and the allocated Cell Radio Network Temporary Identifier (C-RNTI). It also should be noted that before the D2D communication is established, it is necessary for two neighboring eNBs to exchange their D2D devices information to smooth the communication when two or multiple terminals are located in different cells.

To implement the successful handshake procedure, it is necessary to define several channels for D2D communication which are illustrated in **Fig. 3**.

Common Control Channel (CCCH): CCCH is used by the D2D pair to claim a set of dedicated resource for D2D communication in a contentious way using the RTS/CTS based mechanism. At the beginning of D2D transmission, the eNB broadcasts the reserved resource including time and frequency of CCCH in the broadcasting channel (BCH) such that all cellular UEs and D2D pairs know the information of D2D CCCH. To increase the spectrum efficiency, different D2D pairs share the same CCCH based on the Time Division Multiple Access (TDMA) mode.

Data Control Channel (DCCH): DCCH is used to carry data associated control information such as ACK/NACK and data control information (DataCtrl). DCCH resource corresponding to a certain CCCH would be reserved to ensure no collision with other D2D users and cellular communication. In our approach, DataCtrl signaling and ACK/NACK feedback are sent on the even TTI and odd TTI separately to improve the spectrum usage and avoid the possible collisions among multiple D2D transmission. To realize this trait, 1-bit information is needed to show the even or odd TTI by the eNB companying with the DCCH reserved resource information on the BCH.

Data Traffic Channel (DTCH): DTCH is used to carry the D2D data traffic by reusing the UL spectrum with LTE users. It is actually not a specific channel for D2D users but a part of Physical Uplink Shared Channel (PUSCH) in the LTE system. Channel qualification information (CQI) could be carried on CTS signaling to provide channel condition information for the Tx_D_UE. Consequently, adaptive modulation and coding can be applied for D2D communication based on the CQI.

To reuse the spectrum between PUSCH and DTCH, the eNB sends the C-RNTIs of all cellular users to D2D UEs to decode the uplink transmission resource allocations (UL MAP) and performs pre-detections of interference. The UL MAP information is sent on the Physical Downlink Control Channel (PDCCH) which is encrypted by the C-RNTI. After obtaining the UL MAP, D2D UEs monitor the corresponding UL transmission channel to detect the interference. This detection may continue some periods until a list of average interference can be built. From this list, D2D UEs can find which cellular UE may exert slight interference on it which implies that this D2D UE is far away from this cellular user and can share the same resource with it. Here, an optimal threshold for slight interference depends on some factors, such as the number of D2D UEs and cellular UEs in a cell, the distance between a D2D UE and a cellular UE, the transmission power of the cellular UE, etc. Commonly, the optimal threshold can be set up by the operator according to an experiential value. In the following D2D data transmission, D2D UEs will share the same resource with this cellular UE. Decoding the C-RNTIs of all users is unavailable for the cellular UEs in the current LTE systems, whereas it is expected to be a common ability for the users in the IMT-A network. To comprehend the detailed procedure and signaling of this solution, please refer to our previous work [13].

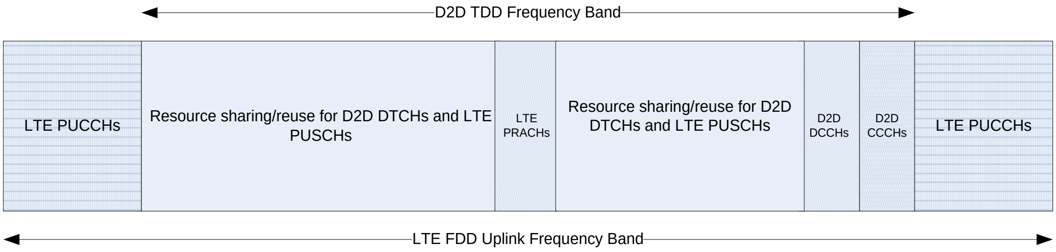


Fig. 3. Illustration of frequency resource sharing between D2D and LTE systems.

Furthermore, the following assumptions are used in our design.

1) The cellular network and D2D subsystem use FDD and Time Division Duplexing (TDD) respectively whilst D2D users will share the UL spectrum of cellular system with the cellular UEs. Comparing with other duplex modes, the benefits by using this mode include that only one transceiver is needed for D2D devices and channel reciprocity and asymmetric data transmission can be realized which are in-built traits of a TDD system. Another, since the cellular system works in the FDD mode, it is possible to dynamically switch shared spectrums between UL and DL to adapt to different UL/DL interference.

2) The following description is based on the assumption that the cellular system is LTE as an example. However, the idea can also be used in other Orthogonal Frequency Division Multiple Access (OFDMA), Single-Carrier Frequency Division Multiple Access (SC-FDMA) or FDMA systems.

3) The proposed scheme can be easily adapted to the mixed scenario where the cellular system uses TDD.

Based on the above descriptions, the complete handshake mechanism is described as follows.

Step1: The eNB broadcasts the reserved resource information on CCCH and DCCH along with the TTI characteristic on LTE BCH to all UEs in the hybrid network.

Step2: The Tx_D_UE transmits RTS to announce its data transmission request, which is also a competition announcement to the neighboring D2D pairs. The identity (ID) of the Tx_D_UE and Rx_D_UE should also be included in RTS signaling.

Step3: The Rx_D_UE will respond with CTS if RTS is received without any collision with other D2D UEs. Otherwise no CTS will be sent back to the Tx_D_UE. In CTS signaling, the ID of the Tx_D_UE and Rx_D_UE should also be included.

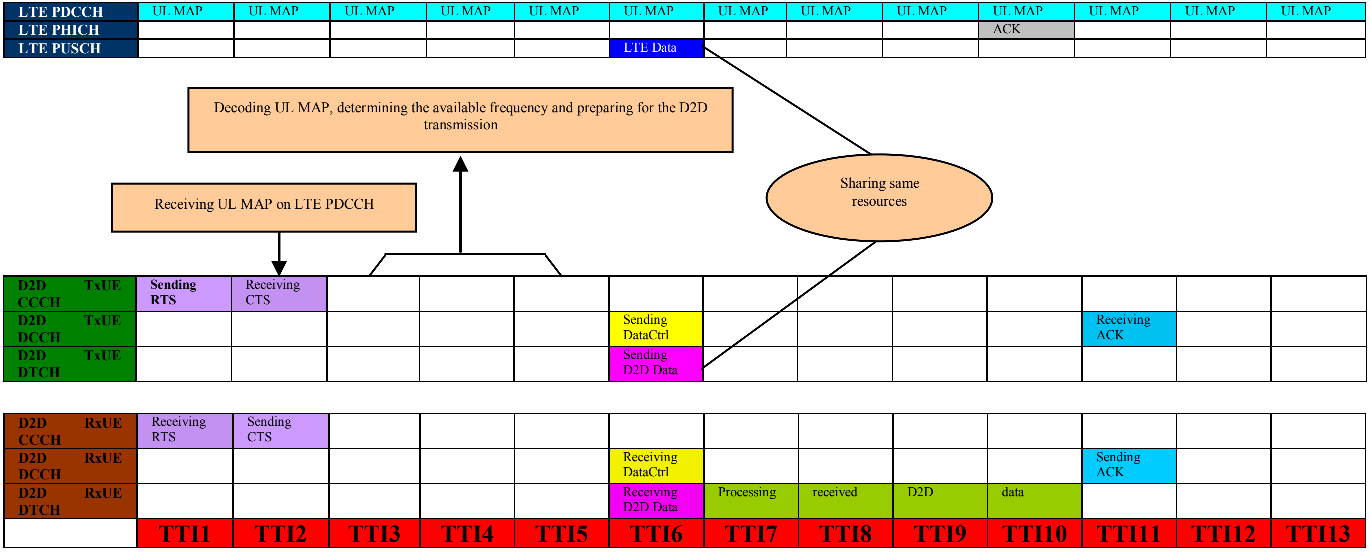
Step4: Receiving CTS from the Rx_D_UE correctly means Tx_D_UE has obtained the priority to send data in the corresponding TTI. Else if no CTS is received, Tx_D_UE will back off for some random time T_0 before a new data transmission request. When a handshake procedure stops because of no CTS response, T_0 will be augmented, otherwise it will be decreased. In this way, the intensity of the competition through RTS and CTS can be controlled even if there are a large number of D2D UEs in a small area. To keep the rigid time relationship, T_0 should be defined as $T_0 = 2T_t + NT_\Delta$, where T_t means the duration of a TTI, N denotes a random integer and T_Δ is a fixed period. In this expression, two TTIs are used to avoid the possible collisions at the CTS signaling thus leading to high spectrum efficiency.

Step5: Receiving CTS from the Rx_D_UE successfully, Tx_D_UE receives UL MAP from

PDCCH simultaneously. Using 3 TTIs to decode the UL resource and prepare for the data transmission, Tx_D_UE sends the DataCtrl signaling on DCCH on the fourth TTI and D2D data on the DTCH which is a reusing channel with the PUSCH of the LTE system. The DataCtrl signaling associates with the data transmission, such as the data format, coding and modulation modes, resource assignment and so on.

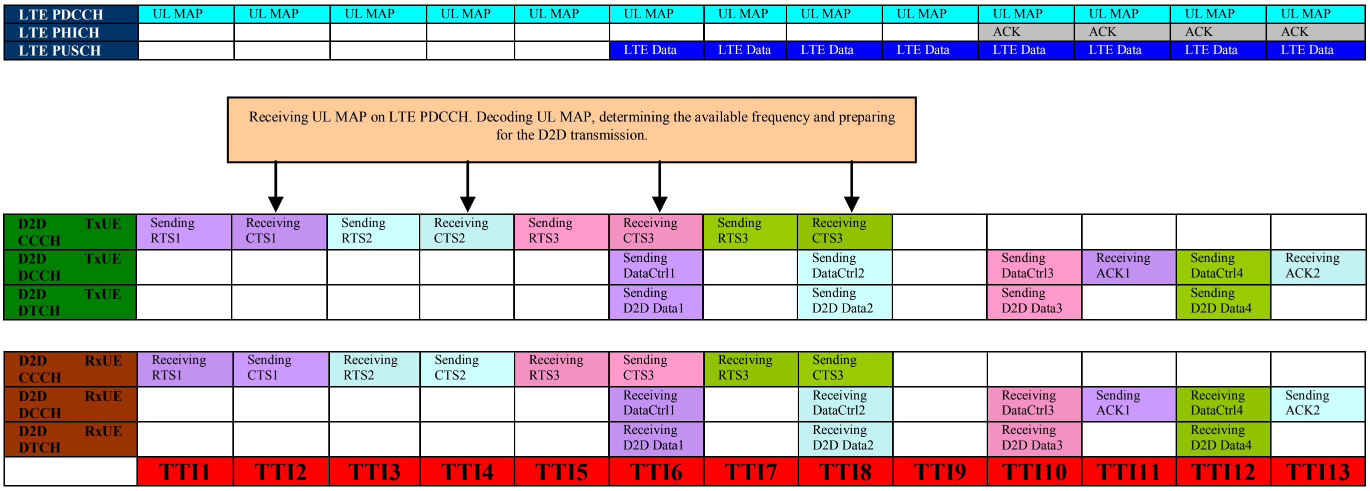
Step6: On reception of D2D data and DataCtrl signaling, the Rx_D_UE needs 4 TTIs to process them and then sends ACK/NAK back to Tx_D_UE on DCCH to feed back the status of data reception, which will be used for data retransmission by Tx_D_UE. Note that different from a regular LTE system, in this step an additional TTI is used to allow the Rx_D_UE to process the received data. By doing so, DataCtrl and ACK/NACK signaling can appear alternately on the DCCH and thus avoiding collisions.

The detailed time relationship of a single and multiple D2D communication are shown in **Fig. 4** and **5**, respectively.



LTE PDCCH	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP
LTE PHICH										ACK			
LTE PUSCH						LTE Data							
D2D TxUE CCCH	**Sending RTS**	Receiving CTS											
D2D TxUE DCCH						Sending DataCtrl					Receiving ACK		
D2D TxUE DTCH						Sending D2D Data							
D2D RxUE CCCH	Receiving RTS	Sending CTS											
D2D RxUE DCCH						Receiving DataCtrl					Sending ACK		
D2D RxUE DTCH						Receiving D2D Data	Processing	received	D2D	data			
	TTI1	**TTI2**	**TTI3**	**TTI4**	**TTI5**	**TTI6**	**TTI7**	**TTI8**	**TTI9**	**TTI10**	**TTI11**	**TTI12**	**TTI13**

Fig. 4. A complete time relationship of single D2D transmission.



LTE PDCCH	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP	UL MAP
LTE PHICH										ACK	ACK	ACK	ACK
LTE PUSCH						LTE Data	LTE Data	LTE Data	LTE Data	LTE Data	LTE Data	LTE Data	LTE Data
D2D TxUE CCCH	Sending RTS1	Receiving CTS1	Sending RTS2	Receiving CTS2	Sending RTS3	Receiving CTS3	Sending RTS3	Receiving CTS3					
D2D TxUE DCCH						Sending DataCtrl1		Sending DataCtrl2		Sending DataCtrl3	Receiving ACK1	Sending DataCtrl4	Receiving ACK2
D2D TxUE DTCH						Sending D2D Data1		Sending D2D Data2		Sending D2D Data3		Sending D2D Data4	
D2D RxUE CCCH	Receiving RTS1	Sending CTS1	Receiving RTS2	Sending CTS2	Receiving RTS3	Sending CTS3	Receiving RTS3	Sending CTS3					
D2D RxUE DCCH						Receiving DataCtrl1		Receiving DataCtrl2		Receiving DataCtrl3	Sending ACK1	Receiving DataCtrl4	Sending ACK2
D2D RxUE DTCH						Receiving D2D Data1		Receiving D2D Data2		Receiving D2D Data3		Receiving D2D Data4	
	TTI1	**TTI2**	**TTI3**	**TTI4**	**TTI5**	**TTI6**	**TTI7**	**TTI8**	**TTI9**	**TTI10**	**TTI11**	**TTI12**	**TTI13**

Fig. 5. A complete time relationship of multiple D2D transmission.

As a summary, the proposed transmission mechanism has the following traits.

1) The D2D signaling and data transmission follow the same frame and timing structure as the UL operation of the cellular network.

2) Under the proposed scheme, D2D and cellular communication share the same frequency to send data thus improving the spectrum efficiency and avoiding transmission collisions.

3. Mechanisms of Near-Far Interference Avoidance in Cellular UL Spectrums

Interference management in a hybrid network is a critical issue in that the interference from D2D links is expected to reduce the cellular capacity and efficiency. In the LTE UL, a cellular UE sends data after several TTIs on receipt of resource allocation information from the eNB. Therefore, D2D UE may finish its RRM by using the related cellular information within these several milliseconds [13]. Additionally, the UL is underutilized by the cellular operators comparing to DL [14]. Thereby, most research of D2D transmission focuses on the scenario that D2D users use the uplink spectrum of an LTE system [9][13][14][15][16][17]. However, working autonomously and fully sharing frequency resources with cellular users, D2D UEs may sustain near-far interference from cellular terminals. The addressed problems are illustrated in **Fig. 6**, where cellular UE1 may impose serious interference to D2D transmission if they are sharing the same resource. Whereas the interference from UE2 can be negligible since the long distance between the D2D pair and UE2. To arrange the dedicated resource for the cellular system and D2D users is an intuitive solution but leads to inefficient utilization of the available resources and low system throughput.

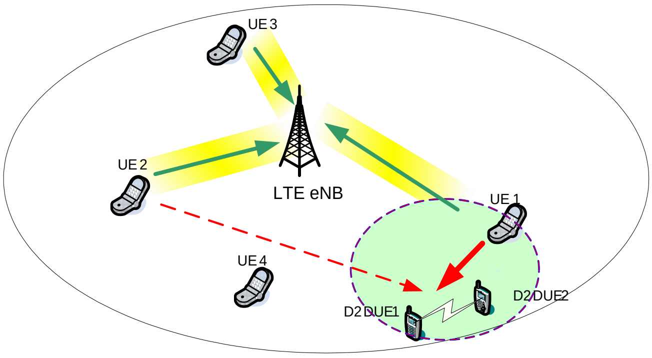


Fig. 6. An example of near-far interference in the LTE uplink spectrum.

In our work, we consider the D2D UEs reuse the whole uplink frequency bands with cellular UEs in an LTE FDD system and the proposed mechanism in Section **2** is used to establish and maintain D2D transmission. When UL spectrums are used, the victim cellular device is the eNB. Given that fractional power control in LTE can be used on D2D communication, the interference from a D2D user to the eNB can be avoided efficiently according to the existing study. Consequently, the interference from cellular users to D2D transmission will be addressed. In this section, we propose a novel scheme to realize UL resources sharing meanwhile avoiding near-far interference to D2D transmission in a hybrid network. By monitoring the D2D channels (CCCH and DCCH), an eNB will identify the ‘near-far-risk’ cellular users and broadcast the information on their allocated resources. Based on this knowledge, D2D devices can proactively perform RRM to avoid the near-far interference from cellular UEs. Different from the previous work [9][13][14][15][16][17], by utilizing the proposed scheme, the C-RNTI of D2D UEs is not always necessary and the interference from the neighboring cell can be suppressed as well.

In our work, autonomous D2D transmission is assumed which means that each D2D pair autonomously determines the resource allocation by using some useful knowledge from the eNB. Comparing with the eNB completely controlled D2D communication, it benefits from lower control signaling overhead and less modification to the existing cellular infrastructure. Since the D2D subsystem is underlying the LTE network, the eNB allocates the resources to cellular UEs in a dynamic way, which means that the cellular UL resource allocation can not be predicted accurately by the accumulated knowledge. Therefore, blind interference avoidance methods are difficult to work if there is no tight time correlation among resource allocation of cellular users.

Denote C_UE and D_UE a cellular UE and a D2D UE separately, the proposed scheme to share cellular UL resources in a hybrid system is presented in detail as follows.

Step 1: At the beginning of D2D transmission, eNB broadcasts the reserved resource including time and frequency of D2D CCCH and DCCH in the broadcasting channel such that all C_UEs and D_UEs have the idea of the information on D2D channels.

Step 2: After that, cellular UEs periodically listen to the signaling on CCCH and DCCH from D2D UEs to ensure whether D2D UEs are close to them.

Based on the explanation of the handshake process during the D2D communication, control signaling is always transmitted on the CCCH and DCCH which is a dedicated channel for D2D communication. Hence, the sensed signals from D2D channels are assumed to be reliable.

Here a signal-to-interference-plus-noise ratio (SINR) threshold and a listening period are needed to identify the adjacent D2D UEs accurately. According to the peculiarity of the cellular system, two criteria are proposed for the cellular users.

- **Criterion I**: Cellular UEs only monitor the power of D2D channels regularly without decoding the information they received.
- **Criterion II**: Cellular UEs decode the information obtained from D2D channels to find the IDs of neighboring D2D UEs and then report their IDs to the eNB in the next step.

Note that, to utilize Criterion II, the information such as Cell ID and C-RNTI should be included in the handshake procedure. C-RNTI is assigned by the eNB on the PDCCH during the *Random Access Response* to identify the UE uniquely [18].

Step 3: Once a C_UE senses an SINR beyond the predefined threshold, it will report the measurement result to the eNB in the earliest available UL time slot in a dedicated channel. According to the two different criteria in *Step 2*, two report formats will be utilized.

- **Format I**: Cellular users report their position information to the eNB. In this format, it is required that C_UEs and D_UEs can obtain their position information. Considering that mounting a Global Positioning System (GPS) device in a cell phone is so popular nowadays we think this format is feasible.
- **Format II**: Cellular users report the ID of the detected D2D UE to its eNB.

Two examples are given in **Table 1** and **2** according to Format I and Format II, respectively. From **Table 1** we can observe that C_UE1 with the position of (X1, Y1) and C_UE2 with the position of (X2, Y2) are near to the D2D pairs such that they will impose strong interference to the D2D communication if the same UL resource is reused. Different from **Table 1** where the IDs of D2D users can not be obtained, eNB is able to derive directly that C_UE1 is adjacent to D_UE1 and D_UE2 by using Format II.

Table 1. Interference Map Based on Format I

ID of C_UE	Position of C_UE
C_UE1	(X1,Y1)
C_UE2	(X2,Y2)
…	…

Table 2. Interference Map Based on Format II

ID of C_UE	ID of D_UE
C_UE1	D_UE1
	D_UE2
C_UE2	D_UE3
…	…

Note that the reported measurement results can be Time Division Multiplex (TDM), Frequency Division Multiplex (FDM) or Code Division Multiplex (CDM) on the dedicated channel and only the cellular UEs receiving higher power from D2D channels will report to the eNB thereby reducing the signaling overhead.

In a scenario of multiple cellular networks, inter-cell interference from the neighboring cell may occur especially when D2D UEs are at the edge of the given cell. To overcome such interference, a TDM scheme is proposed. When a cellular UE measures the power from the D2D channels beyond the pre-defined threshold, it should report to its anchored eNB. Then by checking the D_UE's ID, an eNB can determin if this D_UE is under its control. If it is not true, it means that inter-cell interference occurs and therefore the eNB stops scheduling these reporting cellular UEs during this D2D transmission. By using this mechanism, the inter-cell interference from the neighboring cell can be avoided effectively.

Step 4: According to the received measurement results, the eNB identifies the 'near-far-risk' cellular UEs. For a 'near-far-risk' UE, its received SINR from the D2D channels is beyond the threshold therefore having high probability to interfere with its neighboring D2D users. Thus, the eNB broadcasts the allocated resources for all the 'near-far-risk' cellular UEs in the dedicated channel. Based on the two different report formats in *Step 3*, the broadcasting information can be classified as follows.

- **Broadcasting information I**: The eNB broadcasts the position information and allocated resources of 'near-far-risk' cellular users, thus D2D users can use such information to avoid reusing those resources at the specific location. To implement this approach, D2D UEs need to know the position of their own. As a result, a D_UE can reuse the resource with a distant C_UE and avoid interference from a near cellular user. Here, no D2D RNTI is needed so security and reusing efficiency is guaranteed.
- **Broadcasting information II**: Prohibited frequency resources and IDs of D2D UEs are sent by the eNB.

Table 3 and **4** present examples to explain this step. From **Table 3** all D2D UEs know that the allocated resource for the C_UE with the position (X1, Y1) is RB3, such that after the simple calculation, the D2D UEs whose positions are near to (X1, Y1) will not use the RB3 to implement their D2D transmission. However, D2D UEs can obtain the prohibited resource directly from **Table 4**. For example, D_UE 1 can know that RB3 and RB6 are allocated to the adjacent cellular UEs so D_UE 1 will avoid reusing these two RBs to mitigate the near-far interference.

Table 3. Broadcasting information I

Position of C_UE	Allocated Resources
(X1,Y1)	RB3
(X2,Y2)	RB6
…	…

Table 4. Broadcasting information II

ID of D_UE	Prohibited Resources
D_UE 1	RB3
	RB6
D_UE 2	RB8
…	…

Step 5: On receipt of the broadcasting messages in *Step 4*, D2D UEs autonomously perform RRM to mitigate near-far interference from cellular UEs.

Note that the information in *Step 4* should be broadcasted in advance of 4 TTIs with the cellular UL grant information. By doing so, D2D signaling and data transmission can follow the same frame structure as the UL of the cellular network. Therefore the time relationship could be well defined to allow D2D UEs know that which resource will be utilized through the handshake and competition procedure at the specific time.

The complete procedure of our proposed near-far interference cancellation mechanism in an LTE FDD system is illustrated in **Fig. 7**.

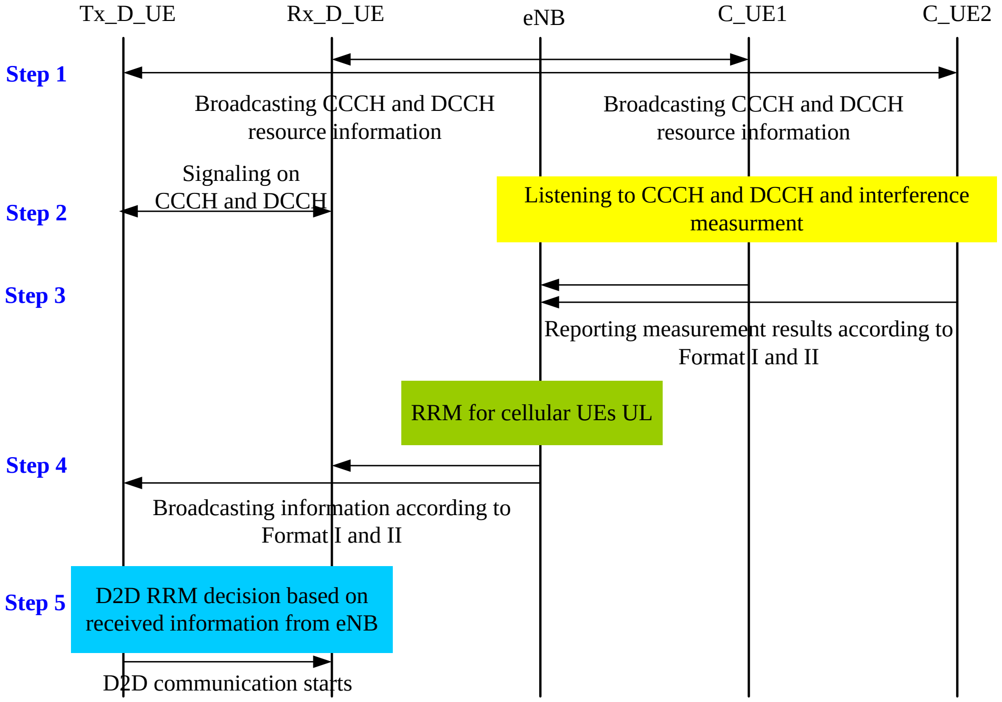


Fig. 7. Procedures of the proposed method to share LTE UL spectrums.

4. Effective Labeled Time Slots Based D2D Transmission in Cellular Downlink Spectrums

In an LTE system, different scheduling mechanisms enable unparallel opportunities for D2D users using UL and DL of a cellular network. In the LTE system, the UL resource is underutilized by the cellular operators comparing to DL [14] and several milliseconds are reserved for the UE after receiving the resource allocation information from the eNB, thus making the RRM of D2D systems feasible. On the contrary, in an LTE like cellular network, since continuous control signaling and data are transmitted and fast scheduling are used in the DL spectrum, it is very difficult for the D2D transmission to share DL spectrums with cellular users. This problem can be illustrated in **Fig. 8**. In the first TTI, by decoding the control part of cellular DL signaling, D2D UEs may know which resources are available for them to perform D2D communication. However, in the following second TTI, before D2D UEs can finish resource allocation for D2D communication, the available resources for D2D UEs changed.

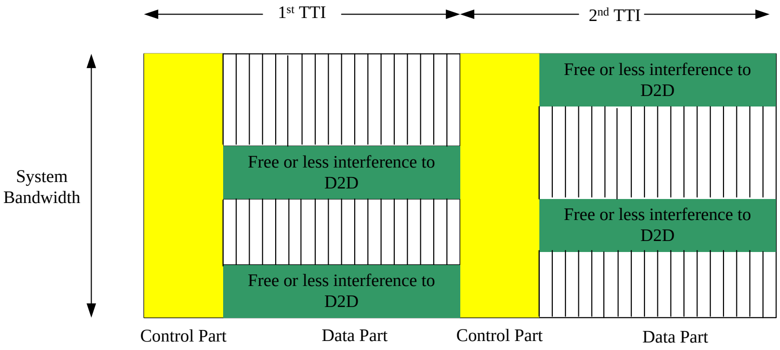


Fig. 8. An example of fast scheduling in the LTE DL transmission.

Other than the fast resource allocation, possible near-far interference is another serious problem when DL spectrums are reused and this interference is presented in **Fig. 9**. From this figure we observe that the D2D UE1 and D2D UE2 may impose significant interference to the cellular UE1 since the short distance between them. So the key problem for sharing DL spectrums of a hybrid system is to avoid interference to nearby cellular UEs.

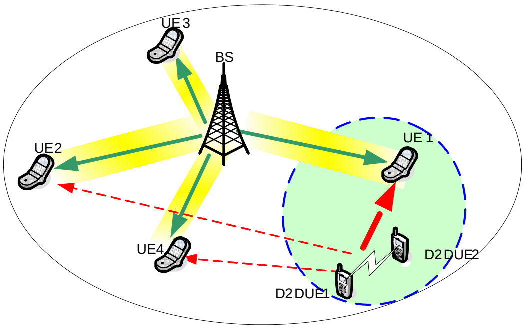


Fig. 9. Near-far interference when sharing cellular downlink spectrums.

In this section, we propose a novel scheme to realize DL resources sharing meanwhile avoiding near-far interference from D2D transmission by using labeled time slots. By classifying the cellular users as ‘non-near-far-risk’ cellular users and ‘near-far-risk’ cellular users, the eNB disparts the whole system resource as ‘shared time slots’ and ‘cellular dedicated time slots’. As a result, the eNB will schedule ‘near-far-risk’ cellular users in ‘cellular dedicated time slots’ only but the ‘non-near-far-risk’ cellular users in both kinds of time slots while D2D pairs will share ‘shared time slots’ with the ‘non-near-far-risk’ cellular users.

Similar to Section **3**, the handshake and competition mechanisms described in Section **2** are used and we assume the sensed signals from D2D channels are reliable. Moreover, D2D users operate in an underlay mode which means that the eNB controls D2D users loosely by sending limited assisting information to facilitate D2D RRM. Thus the proposed scheme to share cellular DL resource in a hybrid system is presented in detail as follows.

Step 1: At the beginning of D2D transmission, the eNB broadcasts the reserved resource of D2D CCCH and DCCH in the LTE BCH such that all cellular UEs and D2D pairs know the information of D2D channels.

Step 2: After that, cellular UEs periodically listen to the signaling on CCCH and DCCH to ensure whether D2D UEs are near to them. Here an SINR threshold and a listening period are needed to identify the adjacent D2D UEs accurately.

Step 3: Once a cellular UE whose sensed SINR from D2D channels is beyond the predefined threshold, it will report the measurement result to its eNB in the earliest available UL time slot in a dedicated channel. Here, a 1-bit result can be used to show whether there are D2D pairs nearby or multiple bits can also be used to indicate different interference levels.

Step 4: According to the received measurement results, the eNB classifies all cellular UEs into two groups, namely, ‘non-near-far-risk’ UEs and ‘near-far-risk’ UEs. A ‘non-near-far-risk’ UE sensed SINR to be below the known threshold so that D2D users do not impose interference to it despite sharing the same resource. Nevertheless, a ‘near-far-risk’ UE whose received SINR from the D2D channels is beyond the threshold has high probability to be interfered by the adjacent D2D users. Correspondingly, the eNB divides the time resources in one radio frame into two groups which are ‘cellular dedicated time slots’ and ‘shared time slots’. All cellular UEs can be scheduled in the ‘cellular dedicated time slots’ whereas no D2D UEs is allowed to send data in these time slots. Nevertheless, D2D communication may occur in the ‘shared time slots’ with ‘non-near-far-risk’ cellular UEs.

To implement our approach, all cellular UEs will be identified as ‘non-near-far-risk’ UEs in the initial communication stage and the eNB will modify its scheduling decision according to the following interference report. Additionally, the allocated time slots which may be continuous or not should depend on the traffic of cellular and D2D UEs and be updated from time to time. Furthermore, D2D UEs are allowed to require the eNB to allocate more or less ‘shared time slots’.

Step 5: The eNB will broadcast the available time slots allocation information (namely the ‘shared time slots’ information) for all D2D UEs in advance.

Step 6: Obtaining the available DL resource information, D2D transmission may occur in the 'shared time slots' along with the ‘non-near-far-risk’ UEs. In addition, the eNB will schedule 'near-far-risk' cellular users in 'cellular dedicated time slots' only. Note that multiple D2D pairs can share resources spatially by using the contention based RTS/CTS procedure aforementioned in Section 2.

The complete procedure of our proposed labeled time slots based mechanism in an LTE FDD system can be summarized in **Fig. 10**.

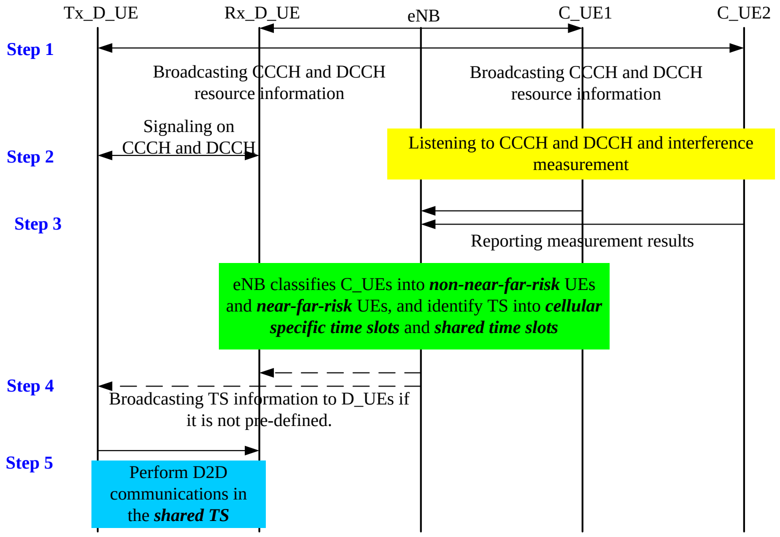


Fig. 10. Procedures of the proposed method to share cellular DL spectrum.

In that D2D communication will continue for some periods and it is unnecessary for cellular UEs to periodically monitor D2D channels during this interval, here a power saving scheme is proposed which is illustrated in **Fig. 11**. Two periods, namely, interference-avoidance period and interference-clear period are defined by the eNB and are broadcasted to cellular UEs in advance. During the interference-avoidance period, D2D UEs are active and cellular UEs close to them do not listen to D2D interference periodically. An interference-clear period is at the end of the interference-avoidance period, during which, cellular UEs sense D2D channels and send 'near-far-risk' indication if there is D2D signaling in the most recent interference-clear period. As shown in **Fig. 11**, since no D2D signaling is detected at the end of an interference-clear period, an interference-avoidance period ends and cellular UEs continue to monitor D2D channels periodically.

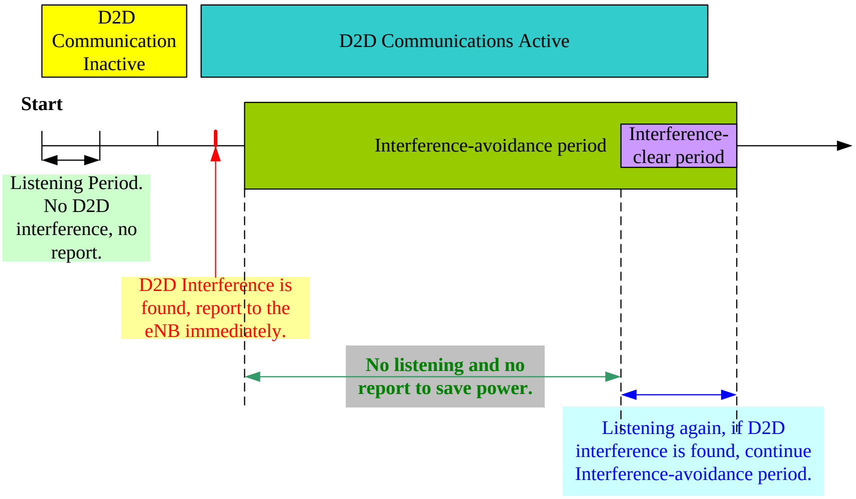


Fig. 11. Power saving scheme for cellular UEs.

5. Simulation and Performance Analysis

In this section, simulation results are shown to evaluate the performance of a hybrid system by using our ideas for both UL and DL resources sharing.

5.1 Simulation Parameters

The topology of the hybrid system will be modeled in a fashion way where D2D users are distributed in a randomly placed cluster with a radius of 10m and cellular users are also dropped uniformly through the cell with a radius of 300m. Such a topology is more realistic in modeling urban environments [17]. There are altogether 50 D2D users placed in the system with regards to the number of cellular UEs changing from 50, 100, 200 to 2000. Considering the short distance between a D2D pair and the large radius of the cellular system, a simple power control scheme is utilized by letting the transmission power of Tx_D_UE 15dB lower than that of cellular users. The used system bandwidth is 1.4MHz, i.e., 6 RBs altogether. By reserving 2 RBs for the CCCH and DCCH of a D2D subsystem, the left 4 RBs are available to transmit data for both networks. The adopted threshold by cellular UEs to determine if D2D users are adjacent to them is SINR which is received from CCCH and DCCH.

The other parameters are set up according to [19] and are presented in **Table 5**.

Table 5. Parameters for simulation

Cell radius	300 m
Distance of two D2D UEs	10 m
Noise Power Density	-174 dBm/Hz
Noise figure	5 dB
Cellular link pathloss (PL) model	PL=128.1+37.6*log10(R), R is the transmitter-receiver separation in kilometers [6]
D2D link pathloss model	PL=127+30*log10(R), R is the transmitter-receiver separation in kilometers [6]
Maximum transmission power of eNB, C_UE and D_UE	46dBm, 24dBm and 9dBm
RB bandwidth	180 kHz
Carrier frequency	2000 MHz
TTI length	1 ms
System bandwidth	1.4 MHz

5.2 Simulation Results and Discussions

Fig. 12 and **13** firstly presents the system average throughput vs. the threshold for reusing UL and DL spectrums, respectively. In order to show the effectiveness of our method, we also consider different densities of mobile users in sharing UL and DL scenarios. To evaluate our method, the curve of cellular system average throughput when no D2D users present is used as the benchmark. We also plot the cellular system average throughput when D2D users exist but no any method is employed to mitigate the interference. In order to prove the performance of our method, the cellular system average throughput and average throughput of the cellular users plus D2D UEs are compared in each figure. For sharing DL spectrums, a power control scheme is typical to suppress the interference from D2D users to the cellular UEs. We compare the performance of the proposed mechanism with the power control scheme and the results are presented in **Fig. 13**. To be fair, the transmission power of a D2D device is set up to keep the same average throughput of cellular users by exploiting our approach and the power control method.

Four observations can be made from **Fig. 12** and **Fig. 13** under different densities of mobile users. First of all, D2D transmission imposes significant interference to the cellular users when sharing DL spectrums and such interference can degrade the system performance greatly. For reusing UL resources, cellular UEs also interfere with D2D transmission remarkably. By applying the proposed mechanism, the system average throughput is increased substantially under different mobile user densities. Secondly, the throughput is highly related to the adopted threshold. We can observe that with the increase of the adopted threshold, the curves with and without interference avoidance gradually converges and this is especially remarkable when sharing UL spectrums. While the used threshold is increased, the throughput is reduced. This result is feasible and can be explained as follows. For sharing UL resources, when a higher threshold is adopted, few cellular UEs report to the eNB as ‘near-far-risk’ UEs thereby imposing much more interference on the D2D subsystem. However, a lower threshold means more cellular devices are determined to be the interferers of the D2D subsystem. As a result, the eNB and D2D UEs need to deal with more information and the system complexity is increased. Consequently, a tradeoff should be made to balance the system performance and complexity. Similarly, when DL spectrums are reused, a higher threshold means more D2D devices are able to use the ‘cellular dedicated time slots’ thereby imposing interference to the cellular terminals to degrade their performance. Thirdly, when reusing UL resources, with the reduction of the cellular users, the system throughput increases significantly due to the decrease of the interference incurred by the cellular devices. Finally, from **Fig. 13** we conclude that a gain of system sum throughput can be obtained by using the proposed scheme comparing with the traditional power control method under three different densities of mobile users. This result is straightforward that by reducing the transmission power of D2D pairs, the average throughput of the cellular users is kept invariable but the throughput of the D2D subsystem will decrease thus leading to the decrement of the sum throughput.

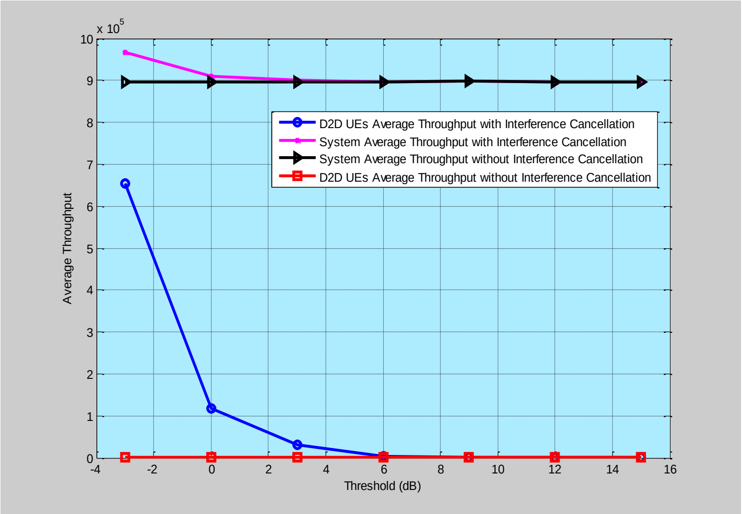


Fig. 12. (a) 200 cellular UEs vs. 50 D2D UEs

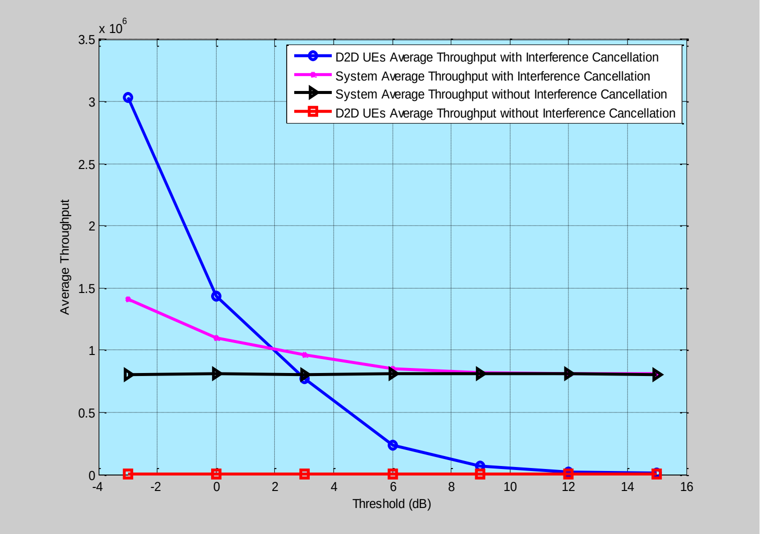


Fig.12. (b) 100 cellular UEs vs. 50 D2D UEs

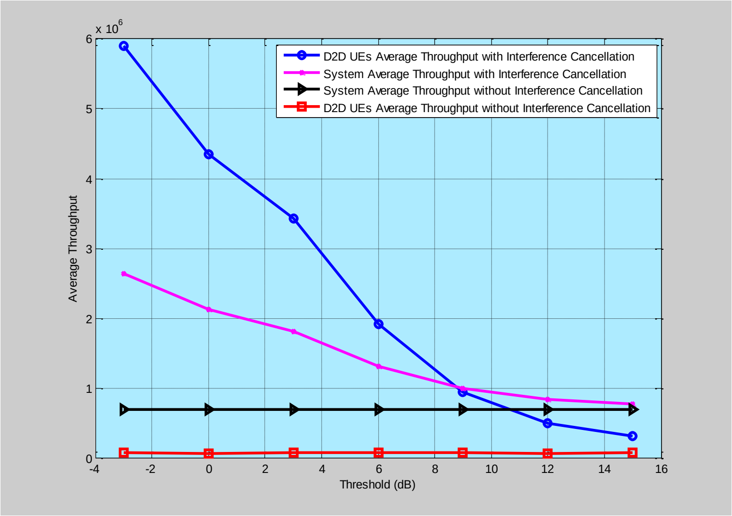


Fig.12. (c) 50 cellular UEs vs. 50 D2D UEs

Fig. 12. System average throughput vs. the threshold when reusing UL spectrums under different densities of mobile users.

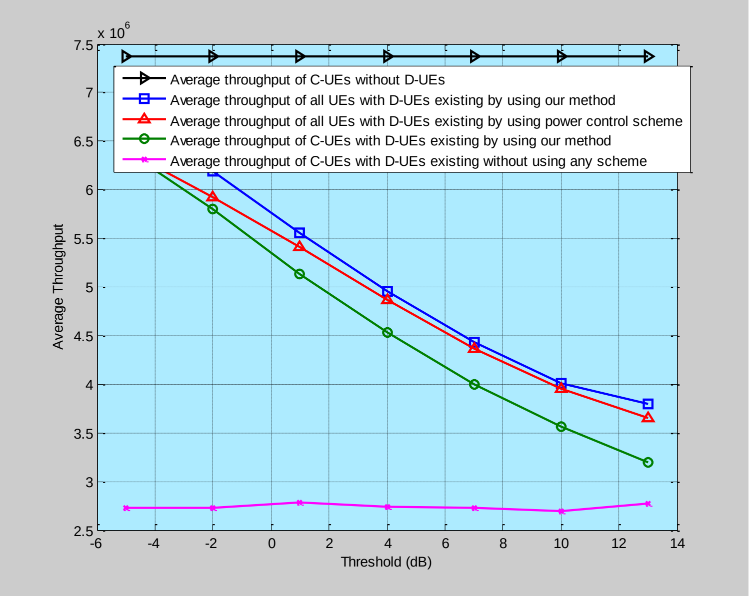


Fig. 13. (a) 2000 cellular UEs vs. 50 D2D UEs

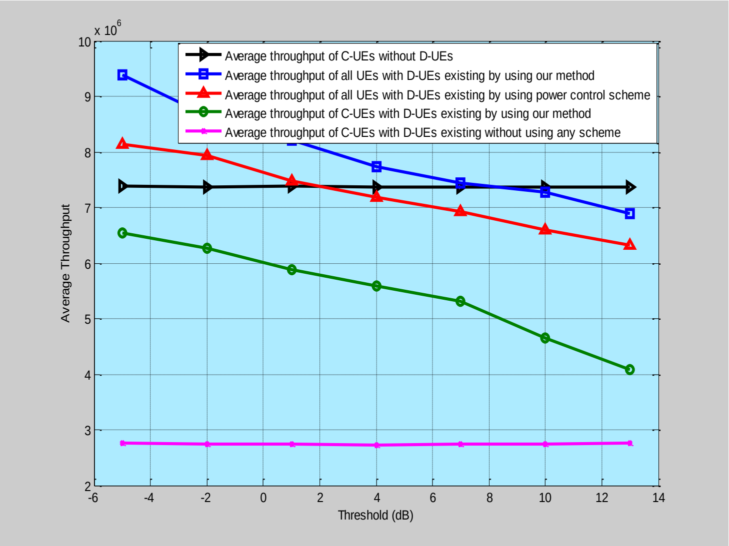


Fig. 13. (b) 200 cellular UEs vs. 50 D2D Ues

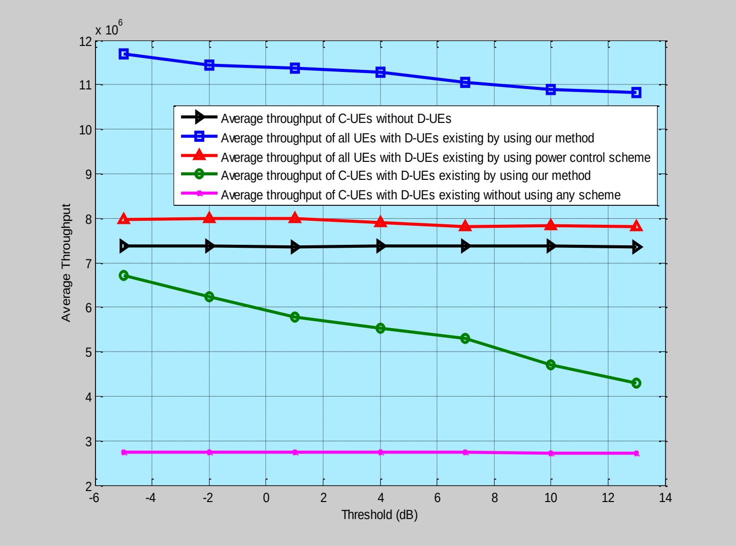


Fig. 13. (c) 50 cellular UEs vs. 50 D2D Ues

Fig. 13. System average throughput vs. the threshold when reusing DL spectrums under different densities of mobile users.

We further investigate our approaches when considering the different ratios of a transmission duration of the D2D subsystem and the cellular subsystem as 1:1, 1:2, 1:3 and 1:4 respectively. The simulation results corresponding to reusing UL and DL spectrums are seperately illustrated in **Fig. 14** and **15**. The considered system consists of 50 C_UEs plus 50 D_UEs for sharing UL spectrums whilst 200 C_UEs plus 50 D_UEs when reusing DL resources. The presented simulations prove the effctiveness of the proposed schemes in shaing UL and DL spectrums under different transmission duration ratios settings.

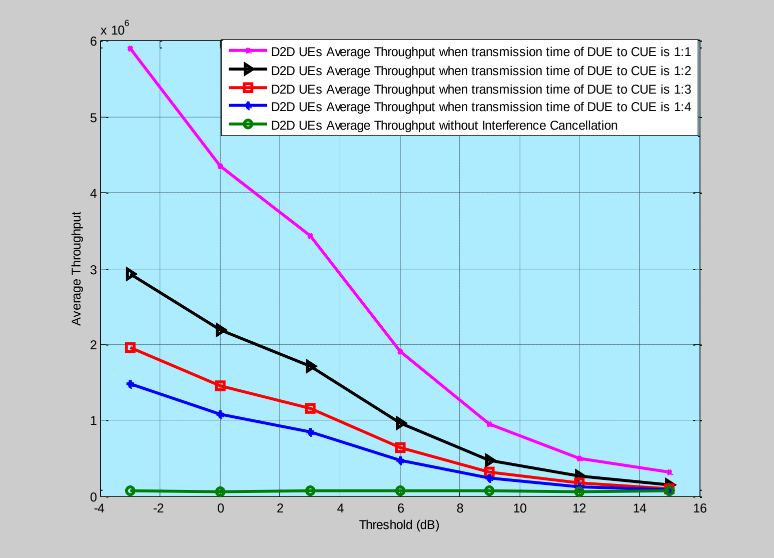


Fig. 14. System average throughput vs. the threshold when reusing UL spectrums under different transmission duration ratios.

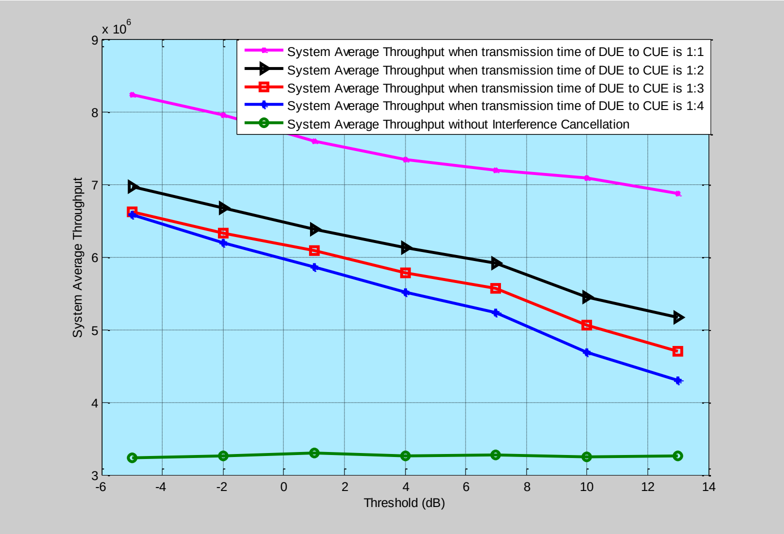


Fig. 15. System average throughput vs. the threshold when reusing DL spectrums under different transmission duration ratios.

Fig. 16 and **17** show the effects of our interference cancellation mechanisms when changing the distance of two D2D users when sharing UL and DL spectrums respectively. The considered hybrid system consists of 50 C_UEs plus 50 D_UEs for sharing UL spectrums and 200 C_UEs plus 50 D_UEs for sharing DL resources with the adopted threshold of 3dB. For sharing UL spectrums, distance between two users is vital in a D2D subsystem. When two D2D users are very close, high throughput can still be obtained in that the close D2D pair can effectively counteract the interference from the cellular system. However, distance of two D2D users is not so important to avoid the interference to the cellular UEs but improving the system sum throughput when these two subsystems reuse DL spectrums.

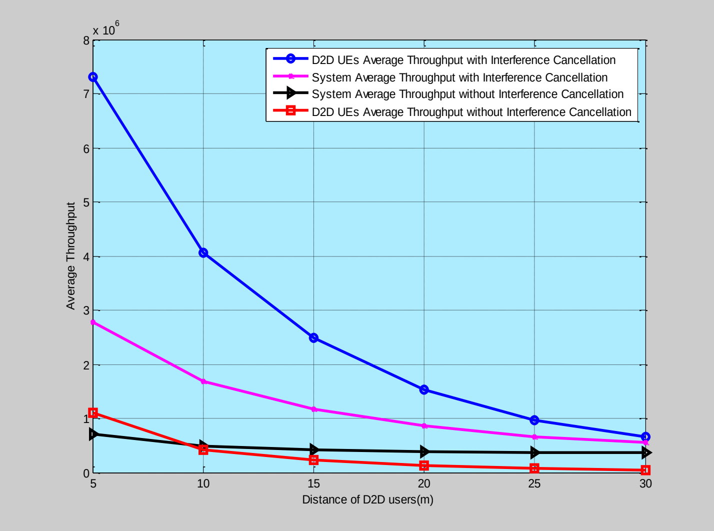


Fig. 16. System average throughput vs. distance of D2D users when reusing UL spectrums.

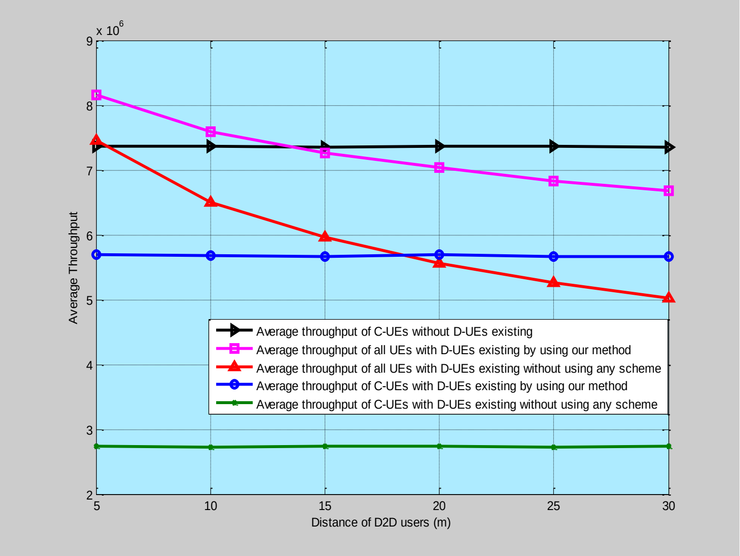


Fig. 17. System average throughput vs. distance of D2D users when reusing DL spectrums.

To evaluate our approach to cancel UL interference, the cumulative distribution function (CDF) curves of received interference from the cellular subsystem are collected and the simulation results are plotted in **Fig. 18**. Here, we use the population of 200 C_UEs plus 50 D_UEs with the adopted interference cancellation threshold of -3dB, 2dB and 7dB, respectively. From this figure we can conclude that the interference is mitigated significantly after using our mechanism comparing with no approach is implemented to avoid such interference. Furthermore, the efficacy becomes better with the decrement of the threshold. This is due to the fact that a lower threshold results in avoiding more interference to the D2D subsystem.

To get insight of the proposed mechanism to reuse DL spectrums with LTE systems, the CDF curves of received interference by cellular subsystem are presented in **Fig. 19** with 2000 C_UEs plus 50 D_UEs and the adopted threshold of 3dB and 6dB separately. To investigate the performance improvement by utilizing the proposed approach, we also compare the simulations of our method with the power control scheme. The same method is used to set up the transmission power of the D2D UEs as **Fig. 13**. From this figure we observe that the proposed mechanism outperforms the typical power control method and such near-far interference is mitigated greatly after using our approach. We also conclude that lower threshold leads to a better performance because more interfernce is detected and suppressed.

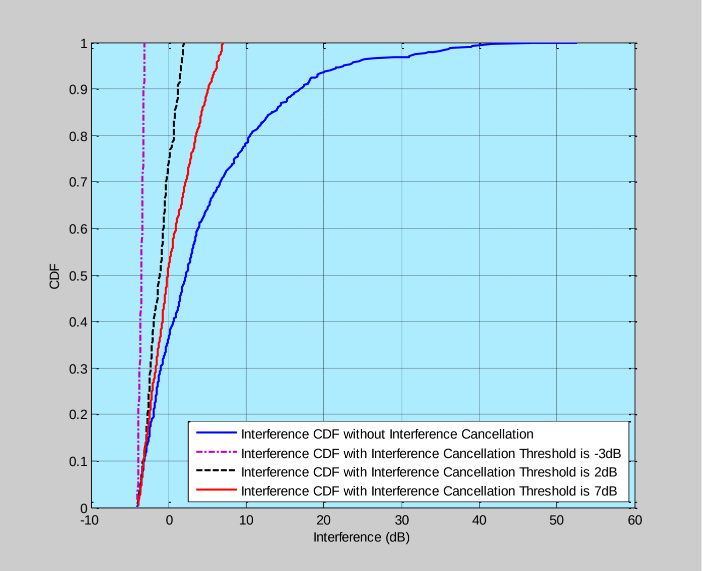


Fig. 18. CDF of near-far interference from cellular transmission when reusing UL spectrums.

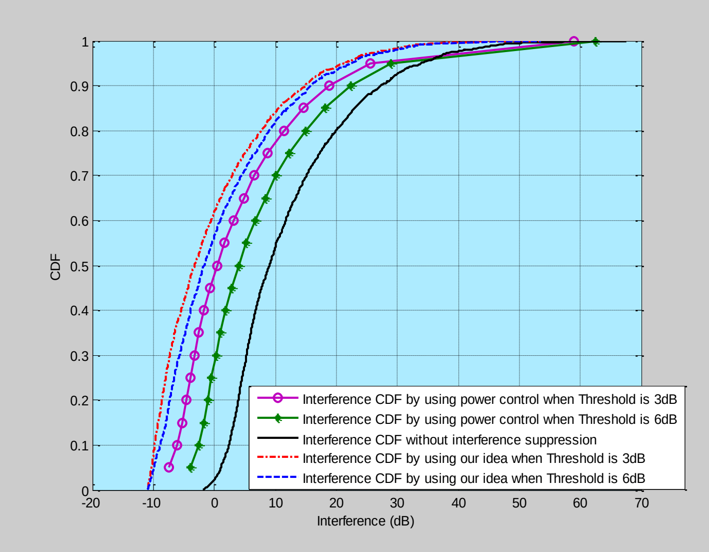


Fig. 19. CDF of near-far interference from D2D transmission when reusing DL spectrums.

Conclusions

In this article, we firstly propose the effective mechanism to establish and maintain D2D communication in a hybrid network by using the SSARC scheme. Based on this proposed handshake procedure, the approaches to share UL and DL spectrums with an LTE FDD network in a hybrid system are addressed respectively in this paper. By tracking the near-far interference and identify the interfering cellular users, the UL frequency bands can be used efficiently meanwhile avoiding the harmful interference from cellular networks to D2D transmission. To efficiently share the DL spectrums, the time slots are labeled and the cellular users are identified so that the harmful interference from D2D transmission to cellular networks can be avoided as well. The proposed schemes are evaluated in a local area cellular network. The extensive simulations prove that better performance can be obtained by comparing with the conventional power control mechanism.

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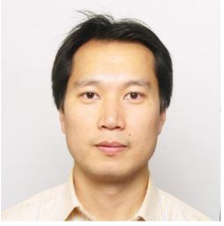

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