

Device-To-Device (D2D) Communications

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Annotation:

Direct Device-to-Device (D2D) communication, which refers to direct communication between devices (i.e. users) without data traffic going through any infrastructure node, has been widely foreseen to be an important cornerstone to improve system performance and support new services beyond 2020 in the future fifth generation (5G) system. In general, the benefits resulting from D2D operation include, among others, highly increased spectral efficiency, improved typical user data rate and capacity per area, extended coverage, reduced latency, and enhanced cost and power efficiency. These benefits are resulting from the proximity of the users employing D2D communication (proximity gain), an increased spatial reuse of time and frequency resources (reuse gain) and from using a single link in the D2D mode rather than using both an uplink and a downlink resource when communicating via the base station in the cellular mode (hop gain). The chapter starts with an overview of the fourth generation (4G) D2D development.

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1. D2D: from 4G to 5G

In the future 5G system, it is predicted that network-controlled direct D2D communication offers the opportunity for local management of short-distance communication links and allows separating local traffic from the global network (i.e. local traffic offloading). By doing this, it will not only remove the load burden on the backhaul and core network caused by data transfer and related signaling, but also reduce the necessary effort for managing traffic at central network nodes. Direct D2D communication therefore extends the idea of distributed network management by incorporating the end devices into the network management concept. In this way, the wireless user device with D2D capability can have a dual role: either acting as an infrastructure node and/or as an end-user device in a similar way as a traditional device.

Further, direct D2D facilitates low-latency communication due to the local communication link between users in proximity. In fact, direct D2D has been seen as one of the necessary features to support real-time

services in the future 5G system [1][2]. Another important aspect is reliability, where an additional D2D link can be employed to increase reliability through a larger extent of diversity. Moreover, due to the short distance transmission, the device power consumption can be reduced significantly. Figure1 illustrates typical use cases of D2D communication. A more detailed discussion on different 5G use cases can be found in Part 2. Four D2D scenarios are shown. The first one is about local data sharing where data caching in one device can be shared with other devices in proximity. In the second scenario, called relaying, D2D communication can play a key role to improve network availability (i.e. to extend the coverage area) via a D2D based relay.

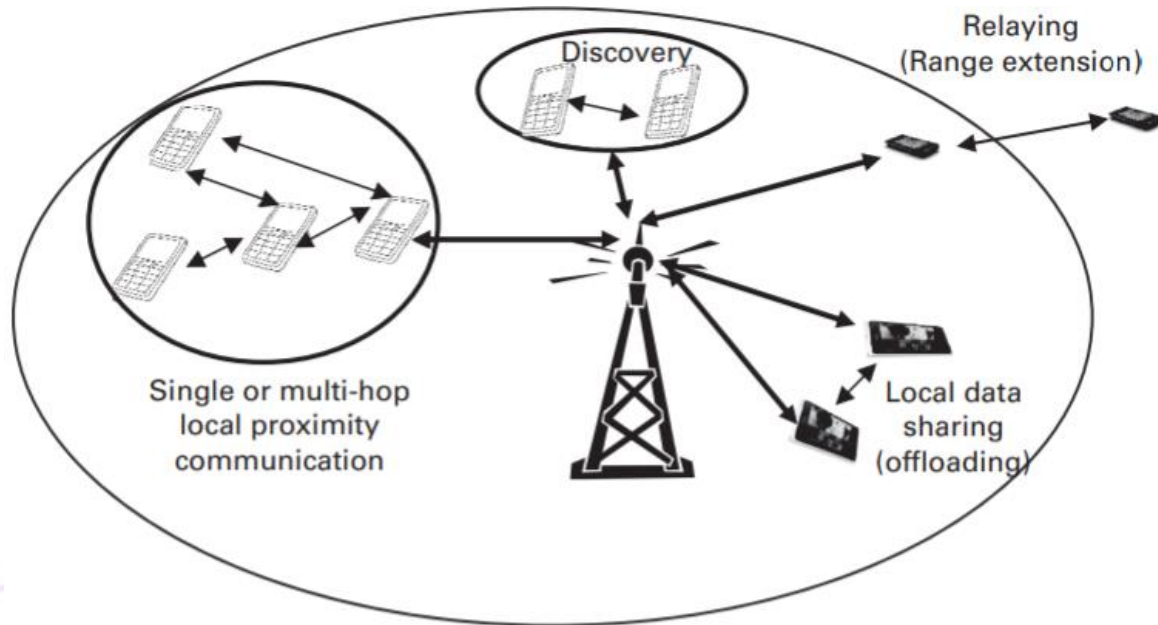


Figure 1. Typical use cases of D2D communication in cellular networks

This is especially important for the use cases related to public safety and those including both indoor and outdoor users. The third scenario, called single or multi-hop local proximity communication, is the one considered in the 3rd Generation Partnership Project (3GPP) Release 12. In this scenario, the devices within proximity can set up a peer-to-peer link or multicast link that does not use the cellular network infrastructure. One of the particular applications is the public safety service. The last scenario is D2D discovery (considered in 3GPP Release 12 as well), which refers to a process that identifies whether a UE is in proximity of another UE.

Considering D2D air interface design, it is usually assumed that the air interface for D2D communication is derived from the cellular air interface in order to simplify the design and implementation. For example, in 3GPP Release 12, Single-Carrier Frequency Division Multiple Access (SC-FDMA) based D2D signaling is employed for all data-carrying physical channels, and the structure of the Physical Uplink Shared Channel (PUSCH), as defined in 3GPP, is re-used (with limited changes) for the D2D communication channel as well. Regarding spectrum usage, D2D can operate, depending on the scenario, in licensed spectrum and/or unlicensed spectrum.

When talking about cellular network-controlled D2D, it is necessary to mention the standardization progress especially in 3GPP on Long Term Evolution (LTE) D2D (also known as Pro-Se: Proximity Services). It is worthwhile to note that Wi-Fi Direct and Wi-Fi Aware are relevant as well, although they are not addressed here since the focus of this chapter is on cellular technology-based D2D.

In the following, the current D2D development in 4G LTE is examined. Thereafter, the 5G D2D concept is introduced in order to have a full picture on D2D concept development.

Table 1. D2D scope in LTE Releases 12 and 13.

	Within LTE network coverage	Outside LTE network coverage
Discovery	Non-public safety & public safety requirements	Public safety
Direct Communication	At least public safety requirements	Public safety

1.1 D2D standardization: 4G LTE D2D

Although, in principle, D2D can offer various promising benefits as discussed previously, in 3GPP LTE D2D work, the main driver is public safety in Releases 12 and 13 [3]. In addition, commercial discovery is supported as well, as can be seen from Table 1.

LTE D2D can be seen as an add-on feature in a 4G LTE system, hence allowing legacy cellular User Equipment (UE) to operate on the same carrier. In LTE, D2D is operated in a synchronous way, where the synchronization source can be an eNode-B1 (in case of UEs being under network coverage) or a UE (in case at least one of the UEs is not under network coverage or in case of inter-cell operation). Either uplink (UL) spectrum (in case of Frequency Division Duplexing (FDD)) or UL subframes (in case of Time Division Duplexing (TDD)) can be used for D2D transmission. One interesting feature is the interference management among D2D links and cellular links. This feature has not been discussed in 3GPP, since in practice it is assumed that D2D is running within a dedicated resource pool (i.e. certain physical resource blocks in specific subframes), where the D2D-enabled UEs will get the resource pool configuration information from the eNode-B. In addition, the transmission signals are based on the UL signal design to avoid introducing a new transmitter at the UE side. Further compared to OFDM signaling, SC-FDMA can provide better coverage due to the lower Peak to Average Power Ratio (PAPR). The major features of the 4G LTE D2D concept are listed in the following, where it should be pointed out that the D2D link is referred to as sidelink in the 3GPP Radio Access Network (RAN) Working Groups (WGs).

1.1.1 D2D synchronization

The sidelink synchronization signal (i.e. D2D synchronization signal), which is transmitted by the D2D synchronization source (either eNode-B or UE), is used for time and frequency synchronization to facilitate synchronous D2D operation. In order to achieve synchronization, at least the following issues need to be solved: synchronization signal design, entities acting as synchronization source, and criteria to select/re-select the synchronization source.

The sidelink synchronization signal is composed of the primary sidelink synchronization signal and the secondary sidelink synchronization signal. Assuming the UEs have network coverage, then the eNode-B transmits primary and secondary synchronization signals (specified in LTE Release 8) that are reused for D2D synchronization. New sidelink synchronization sequences, which are transmitted by a UE acting as synchronization source (such UE can be in or out of network coverage), have been specified in 3GPP as well.

Both eNode-B and UEs can act as synchronization sources. It is easy to understand that the eNode-B can act as a synchronization source. However, in order to facilitate inter-cell D2D operation, under certain conditions, for example at the cell edge, UEs with network coverage can transmit synchronization signals as well. In case of partial coverage where some D2D UEs are with network coverage and the rest are without network coverage, synchronization signals transmitted by UEs within network coverage can also help the out-of-coverage synchronization by aligning the out-of-coverage transmission to cellular network timing. In this way, the possible interference from D2D transmission to cellular links can be reduced.

In order to solve the potential issue of synchronization source selection and reselection, different types of synchronization sources are specified with different priority levels. The eNode-B has the highest priority

order followed by in-coverage UEs, and then out-of-coverage UEs that are synchronized to in-coverage UEs. The out-of-coverage UEs not synchronized to any in-coverage UEs have the lowest priority.

1.1.2 D2D communication

In LTE Release 12, D2D communication is based on physical layer broadcast communication, i.e. a physical layer broadcast solution is used to support broadcast, multicast and unicast services at application layer. In order to support multicast or unicast, the targeted group ID (for multicast) or user ID (for unicast) is indicated in the higher layer message. Since by construction it is a broadcasted information, no physical layer closed control loop exists, i.e., no physical layer feedback, no link adaption, and no HARQ is supported for D2D links.

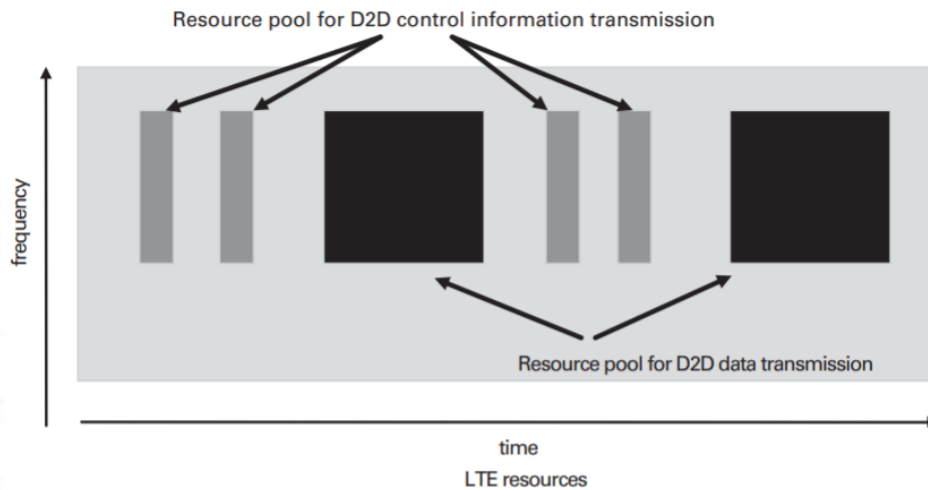


Figure 2. D2D resource pool.

The air interface is based on the Uu interface and the UL channel structure is extended to D2D communication. In particular, for D2D data communication related physical channels, the PUSCH structure (as defined in [4]) is reused whenever possible. Considering resource usage, D2D communication is based on a resource pool concept as illustrated in Figure 2, where certain time/frequency resources (called resource pool) are configured for D2D usage. The D2D resource pool is configurable within one cell and there are separate resources for D2D control information transmission and D2D data transmission. The resource pool information is carried over broadcast messages, i.e. SystemInformationBlockType18.

Before the D2D data transmission, every transmitter sends out a control signal with information on the data transmission format and the occupied resource. This applies to the scenario where the network is assigning resources to the D2D transmitter and the scenario where the transmitter selects the resource by itself.

At the receiving side, it is not necessary to listen to the cellular control channels in order to find out where the D2D data is located. Just based on the content of the D2D control channel, the receiving devices can find out the right location of the relevant resources. As to the resource usage for D2D communication, two different modes were specified:

- Mode 1: An eNode-B or relay node schedules the exact resources used by a UE to transmit D2D data and D2D control information. Obviously, Mode 1 can be only applied to the scenarios where the transmitting UEs are within network coverage.
- Mode 2: A UE by itself selects resources from the configured resource pools to transmit D2D data and D2D control information. Mode 2 can be applied no matter whether the transmitting UE has network coverage or not.

1.1.3 D2D discovery

In LTE Release 12, discovery is applicable only to the UEs with network coverage. The concerned UEs can be in either RRC_IDLE state or RRC_CONNECTED state. Similar to the resources for D2D communication, the D2D discovery resources are arranged as resource pools as well, which are indicated by the eNode-B via SystemInformationBlockType19. The resource pools are defined with the parameters including discovery Period, discovery Off set Indicator and sub frame Bitmap. The frequency resources within a D2D sub frame are given by the parameters startPRB, endPRB and numPRB. There are two ways specified for a transmitting UE to get the resources for discovery message transmission:

- Type 1: The UE selects autonomously the resource for transmission from the discovery pools (independent of the UE RRC state).
- Type 2B: The UE transmits on resources allocated for it by the network (only applicable to RRC_CONNECTED UEs).

The 3GPP RAN WGs specified further D2D enhancements in Release 13 as described in [5]. These enhancements, for the public safety use cases, aimed to solve out-of-coverage discovery, layer 3 based UE-to-network relays, enhancement of D2D communication to support group priorities and group call functionality. However, these are different from the challenges of 5G D2D that aims to address a wider range of use cases.

1.2 D2D in 5G: research challenges

Since in 4G LTE D2D communication the focus is on public safety, the potential improvements that can be provided by D2D operation are not fully exploited. In the 5G system, such restriction does not exist anymore, and it is predicted that D2D operation will be natively integrated as part of the future 5G system. Main potential gains that can be achieved include:

- **Capacity/throughput gain:** Because the involved devices are in close proximity with potentially better propagation conditions comparing to the propagation conditions toward the Base Station (BS), link throughput can be improved due to e.g. better Modulation and Coding Scheme (MCS) level. In addition, there is the possibility of sharing the same radio resources among cellular users and D2D users, which can improve the overall spectrum usage. System capacity can be improved due to offloading and local content sharing gain from D2D communication.
- **Latency gain:** The End-to-End (E2E) latency may be reduced due to a short distance with less propagation delay, and no involvement of infrastructure network entities resulting in reduced transport delay and processing delay.
- **Availability and reliability gain:** D2D can be used to extend network coverage with one hop or multi-hop. Network coding and cooperative diversity via D2D can be used to enhance link quality as well. Furthermore, a D2D ad-hoc network can provide a fallback solution in case of a failure of the infrastructure or in case the infrastructure cannot be easily established.
- **Enabling new services:** Full-blown D2D has great potential to enable new services and applications not only in the telecommunication area, but also in vertical industries, as for example Vehicle-to-X (V2X) communication as discussed in Chapters 2 and 4. The extension of D2D solutions for Vehicle-to-Vehicle (V2V) communication is part of LTE Release 14.

However, as discussed in [6][7], fully utilizing potential D2D gains poses new challenges in terms of device discovery, communication mode selection, co-existence, interference management, efficient multi-hop communication support and multi-operator support among others.

- **Device discovery:** Efficient network-assisted D2D discovery, which is used to determine the proximity between devices and the potential to establish a direct D2D link, is a key element in order to enable D2D communication and possible new applications.
- **Communication mode selection:** Mode selection is another core function that controls whether two devices will communicate to each other in direct D2D mode or in regular cellular mode (i.e. via a BS). In direct D2D mode, the devices can take advantage of their proximity and may reuse cellular resources for the direct communication link. In cellular mode, the devices communicate through a common or separate serving BS by means of regular cellular links in orthogonal resources with cellular users.
- **Co-existence and interference management:** Considering co-existence and related interference issues, at least two different aspects should be taken into account: (1) co-existence among a large number of D2D links, and (2) co-existence among D2D links and regular cellular links. Efficient schemes to handle the interference are of importance in order to achieve the potential D2D benefits.
- **Multi-operator or inter-operator D2D operation:** Inter-operator D2D is a clear requirement resulting from e.g. V2X communication, and supporting inter-operator D2D operation is essential for the 5G D2D concept. Without multi-operator D2D support, the applicability of the future D2D solution to e.g. Cooperative Intelligent Traffic Systems will be quite limited. Considering inter-operator D2D operation, issues to be solved include, for example, spectrum usage and how to control and coordinate UEs in D2D communication across multiple operators' networks.

Clearly, the above bullets are only a subset of the challenges related to D2D operation. In this chapter, the focus is on the challenges related to radio resource management with the proposal of one example of a 5G RRM concept in Section 5.2 followed by multi-hop D2D operation in Section 3. Finally, in Section 4, multi-operator D2D is addressed, including discovery support, distributed mode selection and spectrum for multi-operator D2D.

2. Radio resource management for mobile broadband D2D

In this section, the key aspects related to D2D RRM both from a state of the art and future research perspective are covered. The focus is on mobile broadband D2D scenarios, i.e. scenarios with typically low mobility where offloading of the cellular network, enhancement of system capacity and improvement of user experience in terms of reduced latency and increased data rates play a dominant role [8]. The focus will be on in-band underlay D2D, in which D2D communication uses the same spectrum and resources as cellular communication.

The section is structured as follows. Firstly, a brief overview of RRM techniques for mobile broadband D2D is presented. It is followed by some of the most significant RRM and system design challenges to be solved in order to make D2D a native and efficient technology in 5G systems. Finally, an example of a 5G RRM concept based on flexible TDD is described and performance numbers illustrating the user experience are provided.

2.1 RRM techniques for mobile broadband D2D

The addition of the D2D layer as an underlay to cellular networks poses new challenges in terms of interference management in comparison with traditional cellular communication. These challenges come from the reuse of resources between cellular and D2D users, which creates intra-cell interference [9][10]. Therefore, in order to exploit the benefits of D2D communication and achieve an improved system performance over baseline cellular-only systems, careful resource management that takes into account both cellular and D2D users is essential.

RRM algorithms and techniques for D2D underlay communications can be classified depending on the optimization metric and the tools used to achieve that optimized or improved performance. The most

common objectives or optimization metrics of RRM algorithms and techniques are spectral efficiency, power minimization and performance with Quality of Service (QoS) constraints [11]. The basic toolbox of available RRM techniques commonly agreed in the literature, such as mode selection, resource allocation and power control [12][13], is described in the following.

- **Mode Selection (MoS):** Several factors influence the MoS decision such as distance between devices, path loss and shadowing, interference conditions, network load, etc. and the time scale on which MoS should be operated. A MoS decision can be made before or after D2D link establishment, while operating on a slow time scale, e.g. based on distance or large-scale channel parameters [14]. Further, a MoS can be done on a faster time scale [15][16], based on changing interference conditions coupled with the resource allocation phase.
- **Resource Allocation (ReA):** ReA determines which particular time and frequency resources should be assigned to each D2D pair and cellular link [9][17]. ReA algorithms can be broadly classified according to the degree of network control, e.g. centralized versus distributed, and the degree of coordination between cells, e.g. single-cell (uncoordinated) versus multi-cell (coordinated).
- **Power Control (PC):** In addition to MoS and ReA, PC is another key technique to deal with the interference, both intra- and inter-cell, that results from underlay D2D operation [18][19]. The focus is mostly on limiting the interference from D2D to cellular transmission, in order to improve the overall system performance while ensuring that the cellular user experience is not degraded. The applicability of LTE power control mechanisms to efficiently support D2D, and optimizations that rely on a practical distributed scheme, have been extensively studied in [20].

It is worth mentioning that the different algorithms do not rely on just one RRM component or isolated technique, but normally combine several of them to achieve better performance [19].

2.2 RRM and system design for D2D

Complementing evolved legacy standards with non-backward compatible radio interfaces in 5G will allow designing a radio technology that natively and efficiently supports D2D from the onset. In Section 1.2, some of the general challenges to support D2D in 5G systems, with its broad scope of use cases and scenarios, were highlighted. The focus here is to specifically address some of the fundamental RRM and system design questions to be answered for an efficient support of mobile broadband D2D, for instance:

- How valuable is the usage of D2D across multiple cells, and does this justify the additional coordination and signaling burden introduced? Enabling inter-cell D2D requires some kind of basic conflict prevention of RRM decisions between the serving BSs of the devices involved in D2D communication, even if not targeting optimally coordinated resource allocation. It could be the case that, in a half-duplex system (e.g. a 5G system with flexible TDD optimized for dense scenarios), one BS schedules one of its assigned D2D users for UL transmission (cellular mode selection) while another BS schedules a direct D2D transmission toward the same user, violating the half-duplex constraint. Solutions to prevent this issue may include: exchange of scheduling information between BSs (or via a centralized coordination entity); protocol-level solutions that orchestrate the order of the transmissions; or simply disabling inter-cell D2D, i.e. only allowing intra-cell D2D and routing the inter-cell D2D traffic through the infrastructure to avoid the coordination burden.
- Does sophisticated D2D (e.g. fast joint MoS and ReA with flexible TDD) require centralized radio resource management, or can this be done in a decentralized or distributed manner? Apart from the multi-cell D2D aspect, it is possible to question whether centralized RRM can bring substantial benefits to the challenging interference conditions of D2D scenarios at a reasonable signaling and computational complexity cost.

- How should MoS between D2D communication and device-infrastructure-device (DID) be performed, and on which time scale should this be conducted? The possibility to make use of fast, instantaneous SINR-based MoS against a simpler path-loss based slow MoS will have a major impact on the protocol stack design. It is needed to carefully evaluate the trade-off between achievable gains, complexity and signaling overhead.
- Is instantaneous Channel State Information (CSI) of all potentially interfering cellular and D2D links needed for scheduling purposes, or is the statistical CSI knowledge enough? In general, D2D communication requires information on the channel gain of D2D pairs (i.e. the quality of the direct links), the channel gain among D2D pairs (i.e. generated/received interference to/from other D2D pairs), the channel gain between D2D transmitters and cellular UEs, and the channel gain between cellular transmitters and D2D receivers, in addition to the CSI information of cellular-only systems. The exchange of such extra channel information can become an intolerable overhead to the system if instantaneous CSI feedback is needed.

2.3 5G D2D RRM concept: an example

In this section, an example of a 5G D2D RRM concept in the context of a flexible TDD air interface is described. The seamless integration of D2D in the flexible UL/DL TDD frame structure is presented and the joint multi-cell D2D and cellular resource allocation is explained for the case of centralized and decentralized schedulers. Afterward, adequate mode selection schemes for D2D are analyzed. Finally, some performance numbers showing the gains of D2D with flexible TDD over fixed TDD and centralized over decentralized scheduling are provided. The performance and the implementation implications of two MoS algorithms that operate on different time scales are also compared.

2.3.1 Flexible uplink and downlink TDD concept for D2D

The UL and DL dynamic TDD concept for D2D is based on a MIMO-OFDMA air interface, similar to the proposal in [21]. The TDD optimized radio has a flexible frame structure that enables fast TDD access and fully flexible UL/DL switching, in addition to support for non-conventional type of communications such as D2D and self-backhauling. Each cell can flexibly switch the data frames to UL or DL within a scheduling slot based on short-term traffic requirements, without requiring clustered TDD.

D2D communication is natively integrated into the flexible TDD frame by considering the D2D users in addition to the cellular users. The scheduler decides among UL, DL and D2D (with simultaneous reuse of resources between cellular and D2D users allowed) for that cell, taking into account both favorable transmission conditions and user fairness [23].

Figure3 illustrates the challenges and opportunities presented by multi-cell D2D communication in scenarios with flexible TDD. The focus is on a specific scheduling slot and resource block, assuming that resource reuse between D2D and cellular users is allowed. Further, D2D communication (from UE2 to UE3 and from UE4 to UE5) may take place at the same time as a UL transmission in Cell1 (from UE1 to BS1) and DL transmission in Cell2 (from BS2 to UE6). A variety of challenging cross-interference situations arise such as:

- DL-to-UL interference from BS2 to BS1
- DL-to-D2D interference from BS2 to UE5
- D2D-to-UL interference generated by D2D transmitters like UE2 and UE4 toward BS1
- D2D-to-D2D interference from D2D transmitters like UE4 to D2D receivers like UE3

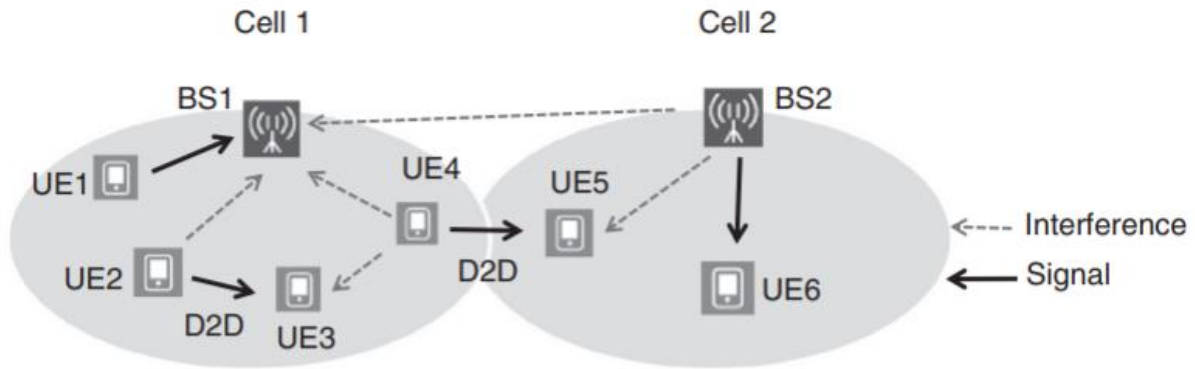


Figure 3. Multi-cell D2D in the context of a flexible UL/DL/D2D air interface.

The management of the rapidly changing interference conditions created by flexible TDD and multi-cell D2D is challenging from the scheduler perspective, but it also creates the opportunity for joint fast mode selection and resource allocation based on instantaneous channel conditions, i.e. the scheduling of direct D2D or DID communication depending on the current signal and interference conditions and network load.

2.3.2 Decentralized and centralized schedulers

Centralized (coordinated) or decentralized (uncoordinated) resource allocation approaches are considered, leading to two different architecture alternatives. In the decentralized case, each cell (which could be a small cell) performs its own resource scheduling decisions. In the centralized case, the channel quality information from the users is further forwarded by their respective small cells to a centralized entity in the network, e.g. a macro cell, which performs coordinated scheduling decisions. The optimization metric is delay-weighted sum rate maximization for each resource block in a cell (in the decentralized case) or group of cells (in the centralized case), considering all cellular (UL and DL) and D2D links in that cell or group of cells, respectively. The scheduling potential of each link, either cellular or D2D, depends on the achievable data rate on that link (based on SINR estimation from interference conditions in the previous scheduling slot) and the packet buffer delay (to provide user fairness in terms of delay) [23].

The scheduler decides for each available resource block which link should make use of it, either an UL, DL or D2D link(s) (possibly with resource reuse between cellular and D2D communications), based on a brute force search of the configuration that provides the highest delay-weighted sum rate out of all the possible combinations. In the decentralized case, the scheduling decisions are made for each cell independently, whereas in the centralized case, they are made jointly for a group of cells including all the possible schedulable links in the cluster. It should be noted that inter-cell D2D is also supported in the decentralized case by means of a simple scheduling conflict resolution mechanism that ensures the fulfillment of the half-duplex constraint in the system [22].

It is worth mentioning that the performance of the brute force scheme is to be seen as an upper bound on the performance of any practical scheduling algorithm, and that the scheduler assumes instantaneous knowledge of all channel gains between cellular and D2D users.

2.3.3 Mode selection

Mode selection is especially relevant when the separation distance between users (with traffic to be exchanged) increases. In that case, the routing of the D2D traffic through the infrastructure may be more efficient than making use of a direct link between the devices. Hence, it is important to investigate the adequate time scale to perform MoS between D2D and DID communication. Here the choice is between fast (i.e. based on instantaneous SINR information) and slow time scale (i.e. based on large-scale channel conditions). Clearly, conducting fast MoS would imply that the decision is executed at the MAC layer,

whereas in the slow MoS case the decision would be performed at the PDCP or RRC layer. In fact, the following forms of mode selection are considered:

- Direct D2D only: All D2D traffic is served through direct links between devices. Reuse of resource blocks is allowed between cellular and D2D users.
- Indirect D2D only (Device-Infrastructure-Device, DID): All D2D traffic is routed through the infrastructure. A D2D communication involves two hops, i.e. a UL transmission and a subsequent DL transmission. No direct D2D is allowed.
- Path loss-based, slow mode selection: D2D traffic is routed through the infrastructure when the path loss toward the serving base station and a bias is lower than the path loss of the corresponding direct D2D link. The bias favors direct D2D communication over DID due to the inherent advantages of direct D2D. MoSis done before resource allocation.
- Fast mode selection: D2D traffic is routed through the infrastructure or through the corresponding direct D2D link depending on the comparison of estimated SINR conditions between the link that connects the D2D UE to the infrastructure and the direct D2D link. This calculation is done per scheduling slot based on the interference conditions in the previous slot. The SINR of direct links is increased by a certain bias in dBs to favor direct D2D decisions. MoSis made jointly with resource allocation. More details can be found in [24], which is an extension and more rigorous implementation of the scheme introduced in [7].

2.3.4 Performance analysis

Results are shown for an ultra-dense multi-cell indoor scenario (25 cells, 10 m × 10 m cells, cell-center BSs), with D2D link range up to 4 m. A scheduling slot, e.g. 2 ms, consists of several time slots, with each time slot being 0.25 ms long. The system bandwidth is 200 MHz composed of 100 resource blocks. A bursty traffic model is assumed, with file size ratios of 4:1:1 for DL/UL/D2D traffic, respectively. A file is transmitted as multiple packet segments during the course of a simulation, with packet segment sizes related to the link data rate in a scheduling slot [23].

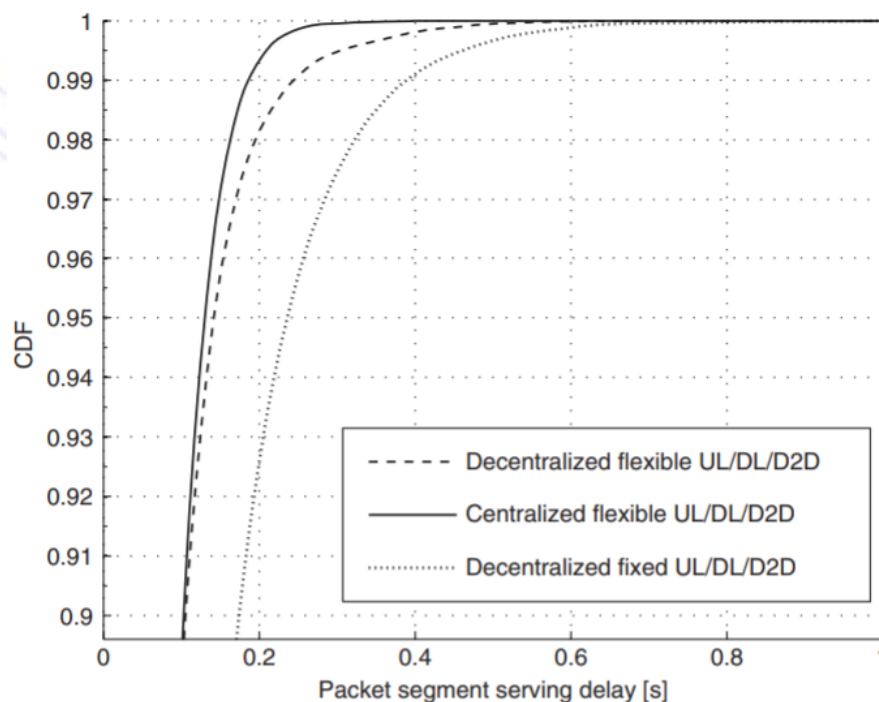


Figure 4. Overall (including UL, DL and D2D traffic) packet delays for decentralized fixed and flexible TDD and centralized flexible TDD.

The cumulative distribution function (CDF) of packet segment serving delay, defined as the difference between the arrival time and the serving time of a packet segment, is depicted in Figure 4. The packet segment delay shall not be confused with the MAC latency. The figure shows the system performance improvement from flexible TDD and centralized scheduling in terms of overall packet segment delay, focusing on the worst-case performance between D2D and cellular links, which is captured by the 99th percentile delay value. No mode selection is carried out in this case, forcing all D2D traffic to be served through direct D2D links. In the decentralized fixed TDD scheme, the first four out of the five scheduling slots are assigned to DL, whereas one slot is used for both UL and D2D. In the flexible TDD case, there is full flexibility to schedule UL, DL or D2D (with or without resource reuse) in every scheduling slot depending on short-term traffic requirements.

Decentralized flexible TDD reduces the worst-case delay by 36% in comparison with decentralized fixed TDD. With centralized flexible TDD, the overall delay is further reduced by 24% from 245 ms to 185 ms. In fact, the centralized scheduler allows to balance the delays of the different users and traffic types by means of its global knowledge and coordinated decisions, improving fairness and worst-case user experience.

The maximum allowed range of D2D links is now extended from 4 m to 8 m (with 10 m × 10 m cells) and mode selection is enabled. The results are shown in Figure 5, that presents an overview of the compromise reached between cellular and D2D delay performance for the different MoS variants described in Section 2.3.3. The vertical axis averages the values of UL and DL packet segment serving delay at both 95th and 50th percentile. Proximity to the origin of coordinates means overall improved latency experience, with the possibility to balance out cellular and D2D delays or to give priority to one specific kind of traffic by applying different biases.

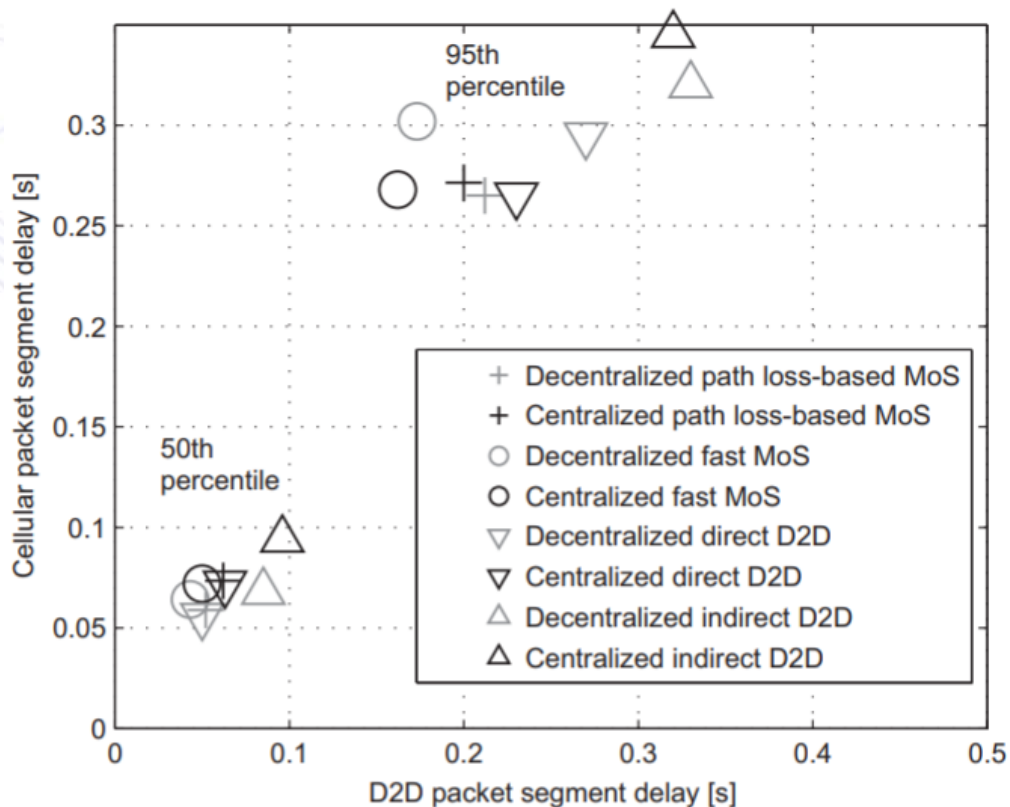


Figure 5. Cellular vs. D2D packet segment delay for different MoS variants.

The decentralized variants (in grey) perform better for median delay values whereas the centralized ones (in black) improve the delay experience at the 95th percentile. In general, fast MoS is able to reduce the D2D

delay (by around 20%), while keeping similar cellular delay values as for the path loss-based MoS. The results in Figure 5 and in [24] show that fast MoS can indeed bring gains in the form of a reduced 95th percentile packet delay for D2D transmissions, without sacrificing cellular performance, but it should ideally be done in conjunction with coordinated RRM across cells. Furthermore, the aforementioned gains are on an order that requires careful consideration whether performing D2D MoS on MAC layer is justified, with the associated likely larger burden in terms of signaling overhead and complexity.

3. Multi-hop D2D communications for proximity and emergency services

While cellular-network-assisted D2D communications can capitalize on proximity, reuse and hop gains [13], so far the main driver for standardizing D2D protocols was initially the requirement to support Public Protection and Disaster Relief (PPDR) and National Security and Public Safety (NSPS) services [25]. More precisely, from a PPDR and NSPS perspective, it is important that, as long as a cellular infrastructure is operable, communicating devices should have access to broadband services and local communication should be maintained when cellular coverage becomes unavailable due to a disaster or emergency situation [26]. Along a related line of technology development, the use of fixed and mobile relays provides a cost-efficient way of extending the coverage of cellular networks and can help maintain access to cellular services when some of the infrastructure nodes become dysfunctional, for example, in a PDPR or NSPS scenario. In the remainder of this section, some of the key requirements for NSPS services are highlighted. Afterward, two technology components that play a key role in meeting these requirements are discussed. Both D2D discovery and radio resource management for multi-hop connections should benefit from network assistance when the cellular infrastructure is intact and should remain operational, through a graceful degradation, when parts of the network become dysfunctional.

3.1 National security and public safety requirements in 3GPP and METIS

NSPS and PPDR scenarios pose a number of specific requirements that are not typically found in traditional cellular communications. One of the key requirements is robustness and ability to communicate irrespective of the presence or absence of a fixed infrastructure. In many cases, there is at least partial cellular coverage in a geographical area affected by a disaster or emergency situation, which can be exploited for communication. Although some of these scenarios can be addressed by temporary truck-mounted BSs moved into the disaster area, support for proximal or direct D2D communication – to maintain connectivity among rescue personnel or between officers and people in need – remains a critical requirement for NSPS systems [25][26]. Broadband group communication is an example of a requirement typically not supported or deployed in practice in traditional cellular systems; for example, when a dispatcher needs to address multiple officers working in an emergency situation, possibly outside network coverage. Figure 1 illustrates some of the use cases that must be supported by the combination and integration of cellular and D2D technologies. As illustrated in Figure 6, in NSPS and PPDR situations, the rescue personnel, including officers with public safety UEs, must be able to communicate in situations in which the cellular BS may provide only partial network coverage. According to the 3GPP requirements [25], such scenarios include proximity services discovery, proximity services traffic initiation, UE with multiple traffic sessions, and proximity services relay. Proximity service discovery is the scenario where a given UE discovers one or more other UEs and the given UE can be with or without network coverage. Proximity services traffic initiation refers to the use case where a public safety UE initiates one-to-one direct user traffic with another UE. UE with multiple traffic sessions means that a given public safety UE can concurrently maintain one-to-one user traffic sessions with several other UEs. With proximity services relay, it is meant that a given UE can act as proximity communication relay for one or more UEs.

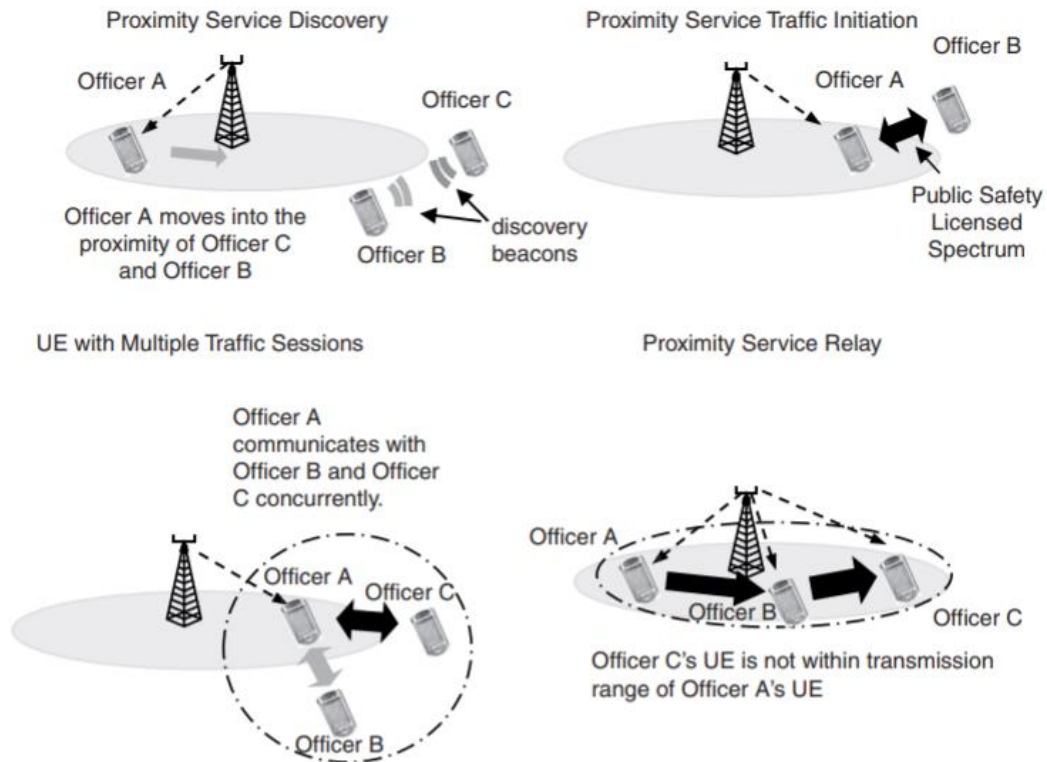


Figure 6. Examples of NSPS and PPDR scenarios.

An important aspect of these scenarios and requirements is the inherent support for in-coverage, out-of-coverage and partially in-coverage services and specifically the requirement that local (proximal) communication services must be maintained in the absence or partial availability of the cellular infrastructure.

3.2 Device discovery without and with network assistance

Peer and service discovery is a key design issue, both in mobile ad-hoc networks operating in unlicensed spectra and in cellular network-assisted D2D communications. The issue stems from the fact that, before the two devices can directly communicate with one another, the devices or a network entity (such as a cellular BS or a core network node) must recognize (discover) that they are near each other. In NSPS and PPDR scenarios, peer discovery is an important service in itself, even without a subsequent communication session. In fact, discovering devices may help rescue personnel take appropriate measures without launching further cellular or D2D communication sessions.

Peer discovery without network support is typically time- and energy-consuming, as it involves beacon signals and sophisticated scanning and security procedures that often include higher layers and/or end users. Therefore, when a cellular network is available, it should assist peer discovery to reduce the discovery time and to increase the energy efficiency of the discovery process. As shown in [12][27][28], peer discovery resources in network-assisted mode can be made available and managed efficiently by the network, which can make such peer discovery and pairing procedures faster, more efficient in terms of energy consumption and more user-friendly. For a deeper analysis of the achievable gains due to various levels of network assistance, see [26].

3.3 Network-assisted multi-hop D2D communications

Although multi-hop D2D communication requirements have been primarily defined with NSPS scenarios in mind, it is clear that commercial and traditional broadband Internet services can also benefit from range extension or multi-hop proximity communications. As shown in the figure, for a UE positioned outside the

coverage area, it needs another UE that is willing to provide relaying assistance hence extending the range of a cellular BS. The example in the figure has two single-hop and two two-hop routes (Route 1, Route 2 and Route 3, Route 4, respectively). Resources R-1 and R-3 are reused, while R-2 and R-4 are dedicated.

Between each Source-Destination (S-D) pair, a route must be defined and resources need to be allocated to each link along the route. In Figure 7, different line types indicate different time and frequency resources (Resource Blocks, RBs), while the same line type for different links indicates resource block reuse.

Further it is assumed that in the multi-hop case, the incoming and outgoing links of a relay node must use orthogonal resources. A given S-D pair may have the possibility to communicate in cellular mode through the BS or using single- or Multi-Hop (MH) D2D communications.

Recall that for D2D communications in cellular spectrum, MoS and resource allocation (scheduling) and power control are essential. However, extending these key RRM algorithms to MH D2D communication is non-trivial, since:

1. Existing single-hop MoS algorithms must be extended to select between the singlehop D2D link, MH D2D paths and cellular communications.
2. Existing single-hop resource allocation algorithms must be further developed in order to not only manage spectrum resources between cellular and D2D layers, but also to comply with resource constraints along MH paths.
3. Available D2D PC algorithms must be made capable of taking into account the rate constraints of MH paths. Specifically, it must be taken into account that, along the multiple links of a given path, only a single rate can be sustained without requiring large buffers or facing buffer underflow situations at intermediate nodes.

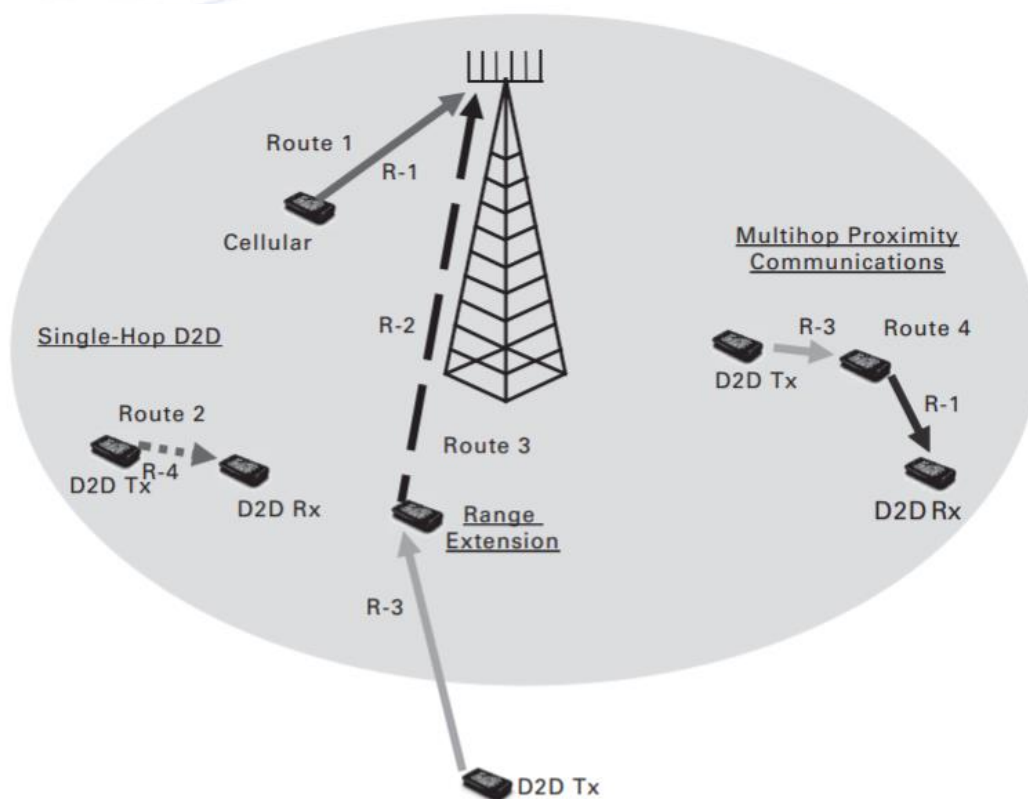


Figure 7. Single and multi-hop routes partially under network coverage [29], reproduced with permission (Lic. no. 3664040827123).

3.4 Radio resource management for multi-hop D2D

A system model that is appropriate for modeling RRM algorithms in MH D2D networks consists of two parts. The first one is a routing matrix that describes the network topology and associates links with resources. The second one is a utility function associated with a S-D pair that characterizes the utility of supporting some communication rate between the end nodes of the S-D pair.

In the proximity communication scenario, a D2D relay node helps a D2D pair to communicate. In the coverage or range extension scenario, a D2D relay node assists a coverage-limited D2D Tx node to boost its link budget to a BS, or in NSPS scenarios to a so-called Cluster Head (CH) node that is capable of taking over the core functionalities of a cellular base station [26][28].

3.4.1 Mode selection for proximity communications

For the proximity communication scenario, the notion of the equivalent channel from a D2D transmit (Tx) device to a D2D receive (Rx) device through a D2D relay based on the harmonic mean of the composite channels from D2D Tx to D2D relay (GTxRe) and from D2D relay to D2D Rx (GReRx) has been proposed [29]:

$$1/Geq = 1/GTxRe + 1/GReRx \quad (1)$$

The intuition of defining the equivalent channel according to the above is that the equivalent channel gain tends to be high only when both composite channels are high; this makes it an appropriate single measure for mode selection purposes. A pseudo-code of a heuristic mode selection algorithm based on the equivalent channel is given by Algorithm 1 below, where the channels are needed from the D2D Tx to the BS (GTxBS) and to the D2D Rx (GTxRx):

Algorithm 1: Harmonic Mode Selection (HMS) for Proximity Communication

1. **if** $Geq \geq \max\{GTxRx, GTxBS\}$ **then**
2. Choose D2D two-hop communications
3. **else if** $GTxRX \geq GTxBS$ **then**
4. Choose D2D single-hop communications
5. **else**
6. Choose cellular mode, that is D2D Tx and Rx communication through the BS.
7. **end if**

3.4.2 Mode selection for range extension

In the range extension scenario, there are only two possible communication modes (direct or relay-assisted) between the D2D Tx device and the BS or CH device. Therefore, in this scenario, the definition of the equivalent channel must be modified such that it includes the path gain between the relay device and the BS (GTxBS):

$$1/Geq = 1/GTxRe + 1/GReBS \quad (2)$$

This makes it possible to use the following modified version of the Harmonic Mode Selection (HMS) algorithm:

Algorithm 2: Harmonic Mode Selection (HMS) for Range Extension

1. **if** $Geq \geq GTxBS$ **then**
2. Choose D2D relay-assisted communication

3. else
4. Choose cellular mode that is D2D Tx transmits directly to the BS.
5. end if

3.5 Performance of D2D communications in the proximity communications scenario

An effective way to control the fundamental trade-off between power consumption and system throughput is to employ D2D power control that is not necessarily based on fixed transmit power levels or the well-known LTE path loss compensating Open Loop (OL) method. To this end, several power control algorithms have been proposed, the objective of which is not only to ensure high throughput and energy efficient operation, but also to protect the cellular layer from harmful interference caused by D2D traffic. Specifically, the algorithm proposed in [20] and [29] can tune the power consumption and the throughput of the cellular and D2D layers in single-hop D2D scenarios by setting a parameter that can be seen as the cost of a unit power investment (i.e. a higher cost of unit power implies a higher cost of increasing the system throughput by investing higher transmit power levels). This basic idea has been extended for multi-hop D2D communication scenarios, including the range extension and proximity communication scenarios of Figure 7.

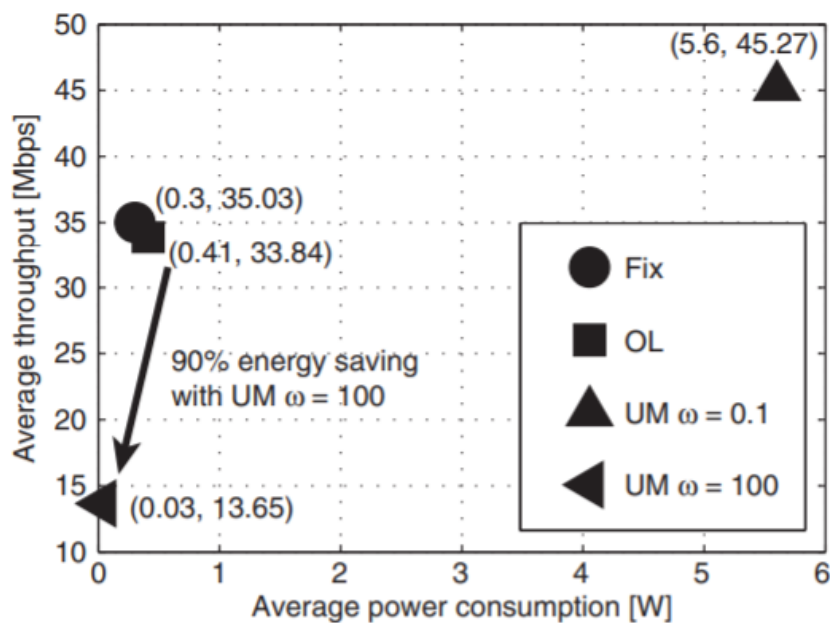


Figure 8. The impact of power control on the power consumption–throughput trade-off in the range extension scenario.

The following figures compare the performance achieved by transmitting with some fixed power level (“Fix”) or the legacy open loop (“OL”) power control algorithm (employed by both the cellular and the D2D layers, using 12 dB of SNR target) with the Utility Maximizing (UM) scheme with some parameter ω (“UM $\omega = 0.1$ ” and “UM $\omega = 100$ ”). The parameter ω represents a trade-off between power consumption and utility maximization [10][20][29]. Specifically, Figures 3 and 4 show the invested power and achieved throughput trade-off in the range extension and proximity communication scenarios, respectively. These results were obtained in a seven-cell system of a cell radius of 500 m. The D2D users are randomly dropped in the coverage area of a cell such that their distance is between 75 m and 125 m. There are 18 uplink physical RBs in each cell. The other parameters of this system are given in [29]. Further, in this system,

D2D communications are supported in UL physical resource blocks using the Harmonic Mode Selection algorithm detailed in Section 3.4.

Figure 8 is a scatter plot for the range extension scenario. The fixed power level of the “Fix” power control scheme is set such that its performance becomes similar to that of the “OL” scheme. Note that (x, y) near each symbol shows the x-axis (power consumption in W) and y-axis (throughput in Mbps) values. Compared with the traditional OL power control, utility maximizing power control (UM with $\omega = 100$) reduces overall power consumption at the expense of reducing system throughput. For UM $\omega = 0.1$, the utility maximization power control algorithm reaches the highest average throughput, with a gain of approximately 34% over LTE OL power control.

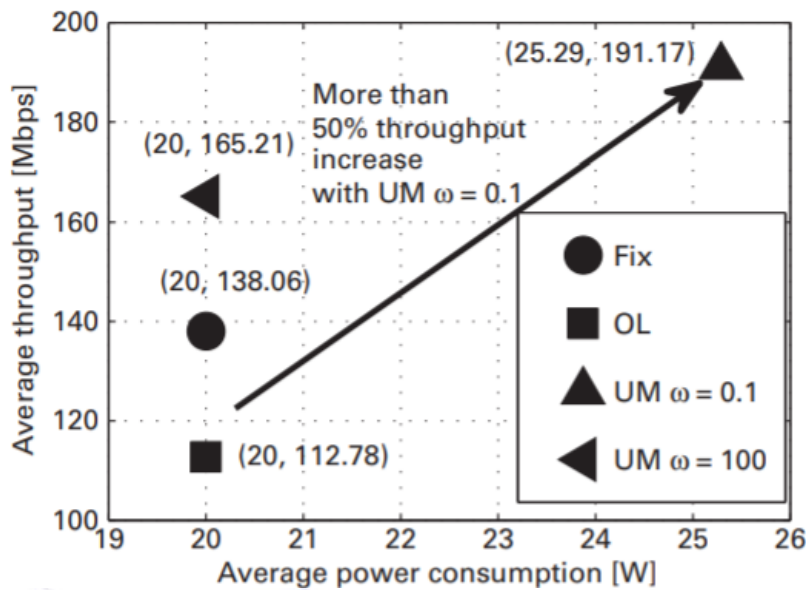


Figure 9. The impact of utility maximizing power control on the fundamental trade-off between power consumption and throughput in the Proximity Communications scenario.

However, this gain comes at the expense of transmitting at much higher power levels. In contrast, with $\omega = 100$, utility maximizing power control minimizes power consumption at the expense of reducing the achieved throughput. Clearly, utility maximizing PC can reach high throughput when using low values of ω and can transmit at low power levels with high values of ω .

Figure 9 is a scatter plot for the proximity communication scenario. Similarly to Figure 8, with UM $\omega = 0.1$ the average throughput gain is large (approximately 69%) over the LTE OL scheme, at the cost of using approximately 26% more power. Notice that in Figure 9 the average power consumption includes the power consumption of the BS. However, with UM $\omega = 100$ the average throughput gain is approximately 20% using similar transmit power levels as LTE OL. UM $\omega = 100$ boosts the average throughput at the expense of a small increase in the transmit power level. If the power consumption must be kept at low values with reasonable throughput values, utility maximization with higher ω values or using the LTE OL power control technique is a good design choice.

4. Multi-operator D2D communication

The business potential of commercial D2D would be rather limited if direct communication between devices subscribed to different cellular operators is not supported. Inter-operator D2D support is also needed to meet the requirements resulting from D2D relevant scenarios, e.g. vehicle-to-vehicle communications [7]. In general, D2D support in inter-operator scenarios becomes more complex as compared to single-operator D2D. For instance, operators may not be willing to share operator-specific information, e.g. network loads,

utility functions, between each other or with external parties to identify how much spectrum to allocate for inter-operator D2D communication. In this section, inter-operator D2D discovery, mode selection, and spectrum allocation schemes are discussed. Further, single-hop unicast D2D is considered.

4.1 Multi-operator D2D discovery

In a multi-operator setting, the D2D discovery cannot be based, for instance, on the time synchronization and distribution of common peer discovery resources unless the operators agree to do so. Further, the D2D discovery should rely on both ends of the D2D pair and on the networks of both operators. In Figure 10, an example procedure that enables multi-operator D2D discovery is shown.

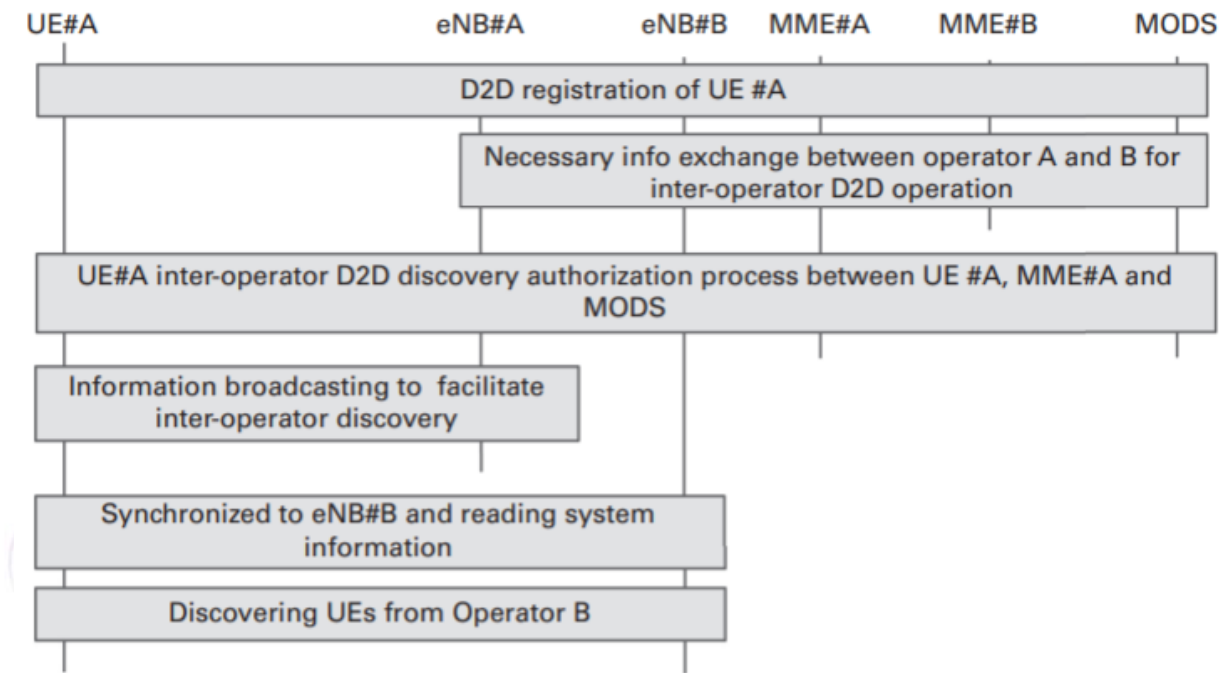


Figure 10. Procedure to enable multi-operator D2D discovery

In this example procedure, using LTE terminology, the D2D devices send discovery messages only on their home operator’s spectrum and hence no change to spectrum regulation or roaming rules is required. Taking the UE#A as an example, after registration of D2D operation and authorization process between UE#A, MME#A and MODS (Multi-operator D2D Server), UE#A can obtain information on discovery resources (both from the home operator and the other operators) based on the broadcasted information from its home operator. MODS is a new logical network entity which could be co-located with certain network elements within an operator’s network or running independently, e.g. as a network service provided by a 3rd party.

Example functionalities of MODS can include D2D subscription management, network access control, centralized security and radio resource management functions and so on. The broadcasted key parameters from the home operator include, for example, radio resource information related to different operators such as operator identifiers and the corresponding operating frequency bands to facilitate inter-operator discovery. UE#A will listen to both the home and the other operator’s resources to detect the presence of discovery messages.

4.2 Mode selection for multi-operator D2D

D2D mode selection algorithms developed for single-operator networks may not be directly applicable in a multi-operator system setup. Operators may not want to share information regarding the locations of users or path loss data as in [30], or CSI between the D2D users and their home operator’s BS. Moreover, operators

may not want to cooperate in order to estimate the D2D pairwise distance, see for instance [31], and use it as a criterion for mode selection.

In a single-operator network, either dedicated spectrum can be allocated to the D2D users (also known as D2D overlay), or D2D and cellular users can be allocated to the same resources (also known as D2D underlay). In a multi-operator D2D underlay, the cellular users are exposed to inter-operator interference generated from the D2D users involved in inter-operator communication sessions. The problem of inter-operator interference between cellular users and D2D users needs to be resolved without an excessive information exchange between the operators.

Clearly, at a first stage, an overlay multi-operator D2D scheme would be easier to implement. In the overlay D2D setting, the key design issue is the way to divide spectral resources between cellular and D2D users and the communication mode selection scheme. One method to select the communication mode without incurring excessive communication signaling overhead may rely on the received signal level at the D2D receiver. Such algorithm has been proposed in [32] and it is straightforward to extend it in a multi-operator setting because it does not require proprietary information exchange between the operators.

4.2.1 Mode selection algorithm

Given the spectral resources allocated for inter-operator D2D communication, the D2D receiver measures the interference level and communicates a quantized version of the interference to its home BS. The BS compares the measurement report with a decision threshold and chooses the D2D communication mode only if the measured interference is low. The D2D receiver should signal the selected communication mode back to the D2D transmitter, i.e. the source UE subscribed with the other operator, and the session in which it may start.

Note that the mode selection threshold impacts the overall network performance because it determines the amount of inter-operator D2D sessions and also the portion of users in cellular communication mode. The mode selection threshold should be a priori agreed i.e. optimized between the operators.

The mode selection algorithm described above could also be implemented in the following manner: the interference measurements could be carried out at the D2D transmitter instead of the receiver. In that case, the transmitter would be responsible for reporting the measurements to its home BS. While discussing the spectrum allocation algorithm for inter-operator D2D, it is assumed that the mode selection takes place at the transmitter, since the performance can be assessed using analytical means (as long as the D2D pair distance is short).

4.3 Spectrum allocation for multi-operator D2D

D2D communication can be enabled either over licensed or unlicensed spectrum. D2D communication in unlicensed bands would suffer from unpredictable interference. Licensed spectrum seems to be the way forward to enable LTE D2D communication, especially considering safety related scenarios such as vehicle-to-vehicle communication.

Overlay inter-operator D2D communication takes place over dedicated spectral resources possibly originating from both operators. For FDD operators, the spectral resources may refer to Orthogonal Frequency-Division Multiplexing (OFDM) subcarriers, while for the TDD operators they may refer to time-frequency resource blocks. In the TDD case, inter-operator D2D support would pose a requirement for time synchronization between the operators, which is more challenging. In Figure 11, two FDD operators contribute a part of their cellular spectrum, β_1 and β_2 respectively, for inter-operator D2D communication. Also, each operator $i = (1, 2)$ allocates fractions $[\beta_c i]$ and $[\beta_d i]$ for cellular and intra-operator D2D communication respectively.

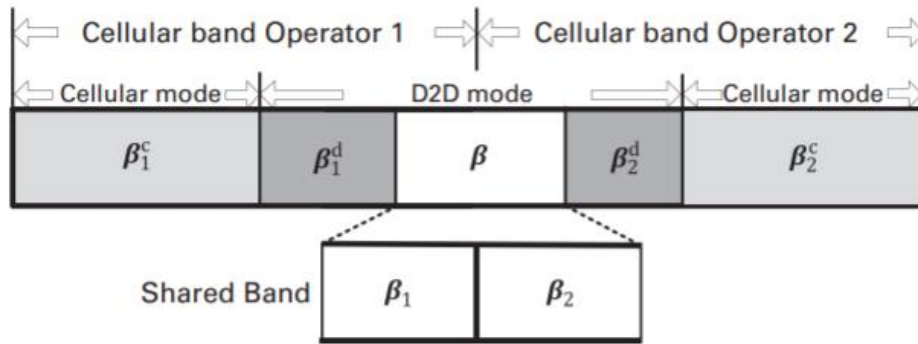


Figure 11. Spectrum divisions for two operators supporting inter-operator D2D communication.

When more than two operators are involved in spectrum sharing, it is possible to realize inter-operator D2D communication based on bilateral agreements between operators, or alternatively, all operators may commit some of their spectral resources in a common spectrum pool. The operators should negotiate the amount of resources they want to commit, but they should not be forced to take action. However, once the operators agree to share spectrum for some time and commit certain resources for multi-operator D2D, they are not allowed to break the agreement. The duration of the agreement should be set in advance and may depend on the expected network traffic dynamics.

In general, operators are competitors and they may not want to reveal proprietary information, e.g. utility functions, and network load. Ideally, the negotiations about spectrum allocation for multi-operator D2D should be completed without exchanging proprietary information. One possible way to do that is to model the operators as selfish players, and use a non-cooperative game theoretical approach. For instance, an operator can make a proposal about the amount of spectral resources it is willing to contribute, taking into consideration its own reward and the proposals made by the competitors. All operators can update their proposals based on the proposals submitted by the competitors until consensus is reached. This kind of updating procedure is also known as best response iteration and it is a common method to identify the Nash equilibrium of a one-shot non-cooperative game [33].

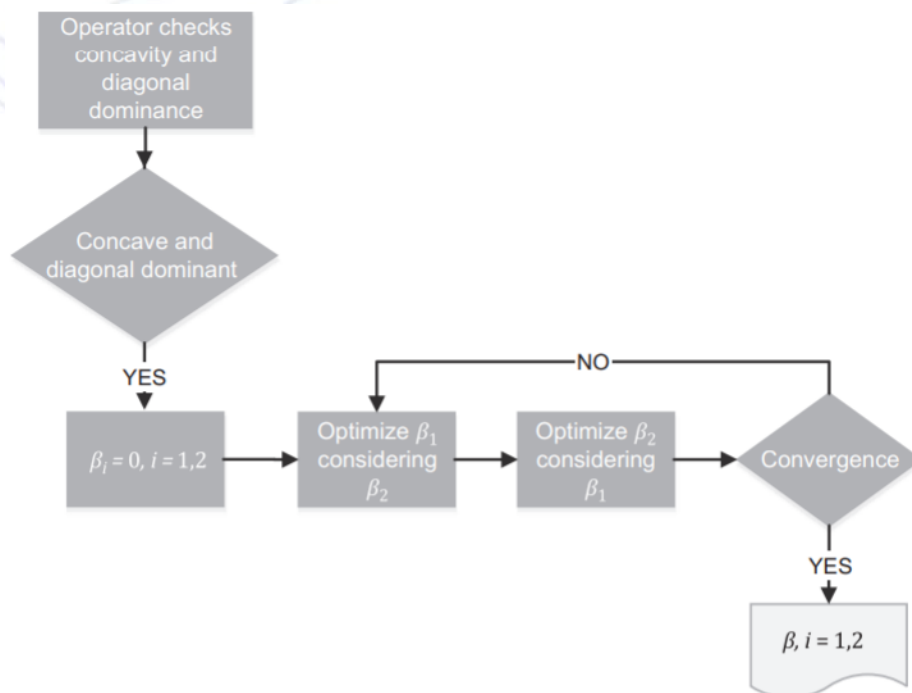


Figure 12. Best response iteration algorithm for spectrum allocation in multi-operator D2D communication.

In a non-cooperative game, one of the most important aspects is the existence and uniqueness of a Nash equilibrium. A situation where there are multiple equilibrium points may be undesirable because the realized equilibrium will depend on the selection order and the initial proposals of the operators. As a result, it is important to note that operators may be interested to share spectrum only if a unique Nash equilibrium exists. For the time being, the spectrum allocation algorithm does not support coupled constraints between the operators. In that case, there may exist infinite normalized equilibrium points [34]. Hence, some sort of extensive information exchange between the operators might be needed to obtain an efficient equilibrium.

4.3.1 Spectrum allocation algorithm

A sequential updating procedure is considered until consensus is reached where each operator strategy consists of responding to the others with the amount of spectrum each operator is willing to contribute for multi-operator D2D support. This strategy is one-dimensional. Further, each operator considers only its individual network utility and performance constraints. It is well known that, for concave utilities and constraints, an equilibrium exists. However, to establish uniqueness, the best response operator should also be a contraction [35]. For one-dimensional strategies, the contraction principle can be degenerated to the dominance solvability condition, which essentially means that an operator can control its own utility more than all other operators can do. Fortunately, each operator can check independently whether its optimization criteria are concave or not and whether the dominance solvability condition holds true. The operators can exchange binary messages regarding these conditions and provided that all indications are positive, the operators become automatically aware about the uniqueness of the equilibrium. Therefore, in that case, the best response iteration can start. Any operator can be ranked first. In case an operator experiences a performance loss as compared to no sharing, it should immediately break the agreement.

4.3.2 Numerical example

Assuming that each operator wants to maximize its average D2D user rate including own operator and inter-operator D2D users subject to transmission rate constraints for cellular communication mode and intra-operator D2D users. With the MoS scheme described in Section 2.3.1, it can be shown that the utilities as well as the constraint are concave [36]. Besides, in a spectrum-sharing scenario between two operators, the dominance solvability condition holds always true irrespective of the user densities [36].

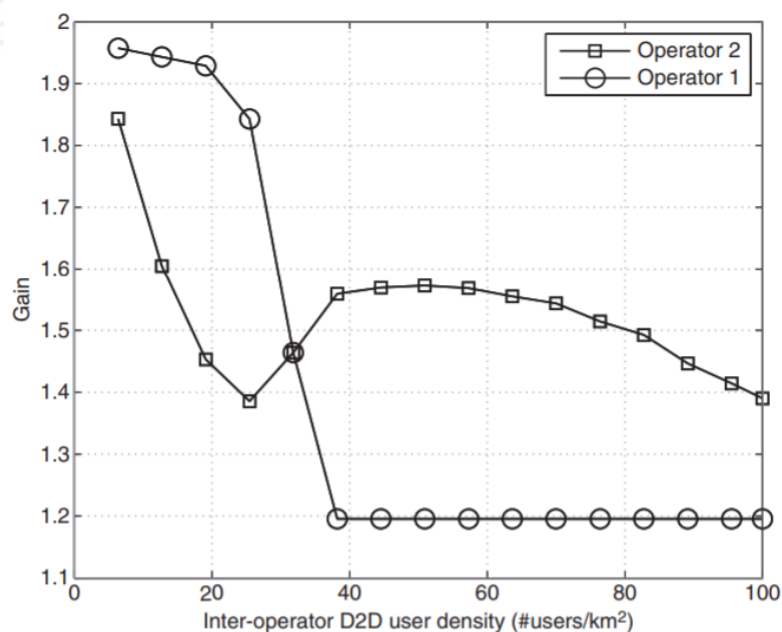


Figure13. Performance gain in terms of average user rate for two operators as compared to the case without multi-operator D2D support.

The network is modeled for each operator using a Voronoi tessellation² with an average inter-site distance of 100 m. Full-buffer traffic model is assumed, with the user density directly related to the network load. The densities of cellular and inter-operator D2D users is 30 users/km² (per operator) to model a scenario where the densities of the users are comparable to the densities of BSs. The density of intra-operator D2D users is 30 users/km² for Operator 1 and it varies for Operator 2 to model asymmetric network loads between the operators. A 3GPP propagation environment is used with Rayleigh fading. The average D2D link distance is 30 m. The MoS threshold is fixed to -72 dBm both for inter-operator and intra-operator D2D users. The decision threshold impacts the density of users selecting a D2D communication mode. A performance evaluation with other threshold values is available in [36]. The baseline scheme for comparison is not supporting multi-operator D2D communication. In that scheme, all inter-operator D2D traffic is routed toward the cellular infrastructure.

In Figure 13, the performance gain is shown in terms of average user rate for both operators. When both operators have an equal network load, they both experience around 50% performance gain. The gains for both operators become high when the network load of Operator 2 becomes low. In that case, Operator 2 is able to contribute a high amount of spectral resources for multi-operator D2D support, and both operators can enjoy performance gains close to 100% due to spectrum sharing and D2D proximity.

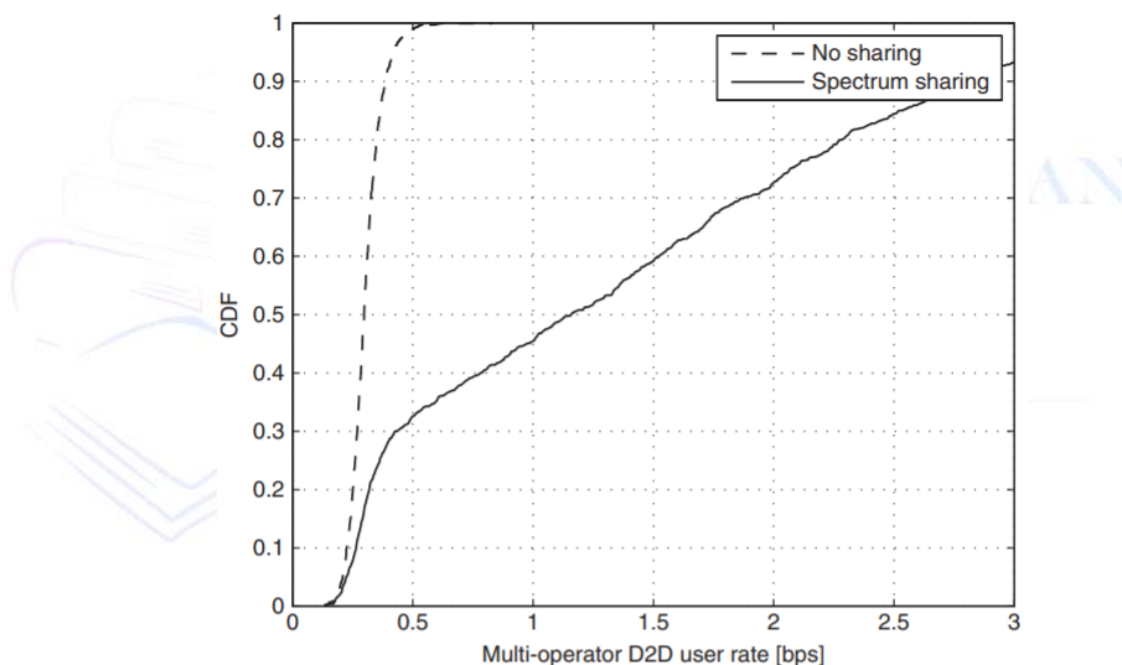


Figure 14. Rate distribution for multi-operator D2D users with and without multi-operator D2D support

Figure 14 depicts the rate distribution for multi-operator D2D users, where symmetric operators are assumed. Without spectrum sharing, all inter-operator D2D traffic is routed to the cellular infrastructure and the achievable D2D user rate is low. One can see that multi-operator D2D support can boost the median D2D user data rate by up to a factor of 4. Hence, multi-operator D2D support is required in order to harvest the business potential of D2D communications, e.g. in the context of vehicular communication for traffic efficiency and safety.

Conclusions

It is envisioned that integrated D2D communication will play a more important role in the future 5G system thanks to the promising benefits on both network and end-user sides, contributing to traffic offloading, very high throughput, significantly reduced latency and low power consumption. In addition, D2D has the potential to increase communication availability and reliability, and provide additional diversity. From a

service and application perspective, D2D possesses the capability of enabling a number of new applications such as V2V and machine-type communications. Finally, in order to capitalize on the full benefits of a system with native support of D2D operation, it is needed to address in the coming years additional challenges related to for example mobility management (exemplary solutions can be found in Chapter 11) and security.

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