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An Overview of Device-to-Device Communications Technology Components in METIS

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ABSTRACT As the standardization of network-assisted device-to-device (D2D) communications by the Third Generation Partnership Project progresses, the research community has started to explore the technology potential of new advanced features that will largely impact the performance of 5G networks. For 5G, D2D is becoming an integrative term of emerging technologies that take an advantage of the proximity of communicating entities in licensed and unlicensed spectra. The European 5G research project Mobile and Wireless Communication Enablers for the 2020 Information Society (METIS) has identified advanced D2D as a key enabler for a variety of 5G services, including cellular coverage extension, social proximity, and communicating vehicles. In this paper, we review the METIS D2D technology components in three key areas of proximal communications—network-assisted multi-hop, full-duplex, and multi-antenna D2D communications—and argue that the advantages of properly combining cellular and *ad hoc* technologies help to meet the challenges of the information society beyond 2020.

INDEX TERMS Device-to-device communications, cooperative communications, network coding, full duplex, MIMO systems, vehicular communications.

I. INTRODUCTION

Proximal communications represent an important set of use cases, including machine type communications (MTC) (massive as well as critical), national security and public safety situations, and vehicle-to-vehicle and intelligent transportation system applications, and also support local social networking. Although the idea of cellular controlled short range and device-to-device (D2D) communications underlaying cellular networks is not new [1], the industrial standardization of D2D technology has only recently been started. While the 3rd Generation Partnership Project (3GPP) has been busy agreeing on use cases and technology components and on developing protocols to support proximal communications, the research community has already started to explore new avenues and further developments for device-to-device (D2D) in the context of fifth-generation (5G) networks [2]–[4]. Indeed, the potential of network-controlled device-to-device (D2D) communications is expected to evolve as standardization and research activities define the next steps of D2D. In Europe, for example, the 5G research project METIS has extensively studied the applications of cellular network-assisted D2D technology in scenarios such as vehicle-to-infrastructure (V2X) communications, national security and public safety (NSPS) situations, and critical machine type communications (C-MTC) [5].

The early work on underlay D2D communications primarily focused on harvesting the following gains (see [1]–[4], [6], [7] and the references therein): *proximity gain* (high rates, low delays, low power), *reuse* of the cellular spectrum, and *hop gain* (spared uplink/downlink resources due to the direct D2D transmission). Recently, the original scope of D2D research has been substantially extended by advances in diverse areas, such as cooperative and full-duplex communications, massive multiple-input multiple-output (MIMO) systems and the advancements of user equipment (UE) capabilities. In this article we review three areas of D2D communications that we expect to become important elements of 5G networks and that have received relatively little attention in previous studies:

- Cellular network-assisted D2D-enabled multi-hop, cooperative and network coding (NWC) schemes in licensed spectrum;
- D2D as a means of exploiting the potential of full-duplex communications;
- Integration of multi-antenna technologies and D2D to enhance the capacity and coverage of cellular networks.

Each of these technology components takes advantage of the proximity of communicating entities and also use various forms of assistance from a cellular infrastructure. For example, a cellular network can make device discovery more energy-efficient and have a longer range than in ad hoc networks, help maintain session continuity, or play an important role in establishing secure connections. In this paper, we examine three technologies that are part of the METIS 5G concept and their interplay and coexistence with D2D communications from the perspective of performance gains in terms of spectral and energy efficiency, scalability and reliability.

Sections II and III discuss the potential for employing network coding in D2D-enabled cellular networks and using multi-hop D2D paths for cellular range extension, respectively. Both of these applications are examples of cellular network-assisted cooperative communications that create a win-win situation for both the cellular and the proximal communicating entities. Sections IV and V examine the potential of full-duplex and multiple antenna technologies, respectively, that can boost the capacity of short-range communication and the coverage of long-range communication. Section VI discusses the application of infrastructure assisted D2D communications to provide efficient communication services for vehicular user equipment (VUE). Finally, Section VII describes the D2D testbed developed in METIS and Section VIII concludes the paper.

II. D2D COMMUNICATIONS AND NETWORK CODING FOR PROXIMAL COMMUNICATIONS

A. COOPERATIVE D2D SCHEMES

In the presence of proximal communication opportunities, network-assisted D2D communications and physical layer network coding (PLNC) both have the potential to harvest the proximity and reuse gains, but they differ in terms of taking advantage of the hop gain. In traditional cellular networks, a bidirectional packet exchange between UE1 and UE2 requires two orthogonal resources, such as time slots or physical resource block (RB), in both uplink (UL) and downlink (DL); that is a total of four resource units.

As illustrated in Figure 1A and Figure 2, when two communicating UEs (UE1 and UE2) are close to each other, three time-slot (3-TS) and 2-TS PLNC by the cellular base station (BS) can reduce the number of required time slots to three and two respectively. An often overlooked aspect of employing PLNC is that in order to maintain orthogonality to the cellular layer, the UL resources used by UE1 and UE2 cannot be reused by users transmitting in the UL (UE3). As it can be seen in Figure 1A, when UE1 and UE2 use the 2-TS PLNC scheme, they transmit their respective packets (x_1 and x_2) simultaneously during the first UL time division duplex (TDD) slot. Subsequently, the BS transmits network coded data ($f(x_1, x_2)$) during the first DL TDD slot. In contrast, when using the 3-TS scheme, UE1 uses the first UL time slot, whereas UE2 uses the second UL time slot for transmitting x_1 and x_2 respectively, while the BS must await x_2 to send the network coded data packet during the second DL slot.

In contrast, network-assisted bidirectional underlay D2D communications in cellular spectrum not only reduce the necessary resources for proximal communications between UE1 and UE2, but they also allow for the well-known reuse gain, as illustrated in Figure 1B. On the other hand, D2D communications require a larger path gain between UE1 and UE2 than BS-assisted PLNC thanks to the basic cell geometry (the maximum distance of two UEs served by the same BS is twice the cell radius and thereby twice the maximum distance between a BS and a served UE) and the larger coverage of a BS.

In order to take advantage of both D2D and PLNC, recent works have proposed a joint D2D physical layer network coding scheme, as shown in Figure 1C and Figure 2 [8]. According to this scheme, UE1 and UE2 establish a bidirectional D2D link while utilizing the broadcast nature of wireless communications to transmit their packets (x_1 and x_2 respectively) to the cellular BS as well. The BS employs 3-TS PLNC and broadcasts network-coded data ($f(x_1, x_2)$) using a DL resource. This scheme is similar to the 3-TS scheme (Figure 1A) in terms of resource usage, but it improves the reliability of the communication between UE1 and UE2. Figure 1C shows the transmission of x_1 to the BS and UE2 during the first UL time slot and the transmission of x_2 to the BS and UE1 during the second slot. Similarly to Figure 1A, the BS broadcasts the network coded data during the second DL slot.

In overlay D2D communications, the cellular and D2D layers maintain resource orthogonality and do not cause any interference to each other, at the expense of losing the reuse gain [9]. In the METIS overlay approach, utilizing superposition coding (Figure 1D), the D2D devices devote part of their

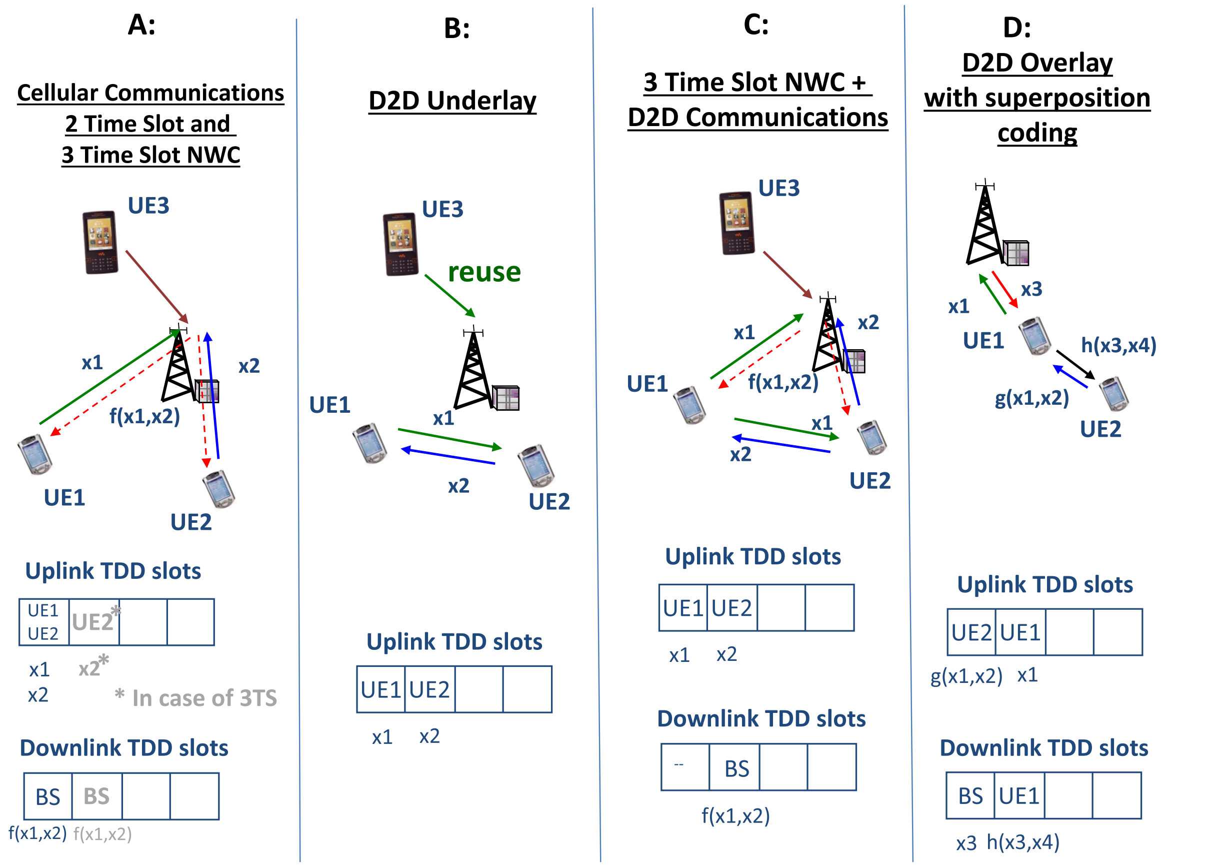

FIGURE 1. Proximal communication options using 2-TS or 3-TS network coding (A), D2D underlay (B), combined NWC and D2D (C) and D2D overlay with superposition coding (D). These schemes differ in terms of the time/frequency resources used, functional distribution at the BS and the devices, complexity, and impact on the cellular layer. In particular, underlay D2D communications reuse the resources used for cellular communications, while overlay D2D communications use orthogonal resources.

transmit power to enhance the cellular signal and facilitate its detection at the cellular receiver (BS or UE). In exchange, they may be allowed to transmit their own data using direct D2D communications. There is no dedicated channel for direct communications between D2D UEs which improves the spectrum usage, and at the same time the D2D link remains orthogonal to the cellular links, as explained below.

As illustrated in Figure 1D, UE1 enhances the communication between the BS and UE2 that want to exchange the packets x_1 (UL) and x_3 (DL), while managing its D2D communications with UE2 to send x_4 and receive x_2. Using D2D communications, UE1 can assist the BS-UE2 communication and exchange the packets x_2 and x_4 with UE2 without dedicated D2D resources. As shown in Figure 1D, the BS transmits x_3 in the first DL time slot. Next, UE2 uses superposition coding to transmit packet x_1 intended to the BS and x_2 intended to UE1 using a single UL resource to transmit $g(x_1, x_2)$. Subsequently, the D2D transmitter (UE1) transmits $h(x_3, x_4)$ in the second DL time slot. The two transmitted packets x_3 and x_4 can be multiplexed at the D2D transmitter (UE1) using superposition coding [10]. Finally, the relaying device decodes x_1 and x_2 and forwards x_1 to the BS during the second UL time slot. This way, D2D communications remain transparent to the cellular layer.

The basic principle of the overlay scheme is that the D2D devices that are close to the cellular transmitter (BS or UE) have access to a high-quality cellular signal that they are able to successfully decode. They then use knowledge of the cellular message to produce a signal that complements the cellular signal and improves the detection probability of the cellular receiver. At the same time, the D2D transmitter communicates with the D2D receiver with a low-power signal. Depending on their proximity, either the D2D transmitter or the D2D receiver, or both, have knowledge of the cellular signal. Hence, several techniques, such as dirty paper coding, or successive interference cancellation, may be applied at the D2D transmitter/receiver.

The main advantage of the D2D overlay approach is better interference control within the cell, better detection of the cellular signal, and an increased number of connections within the cell without any extra spectrum. This scheme may require knowledge of the channel state in order to guarantee that the cellular signal is successfully detected. Finally, a power control mechanism must be put in place that determines the

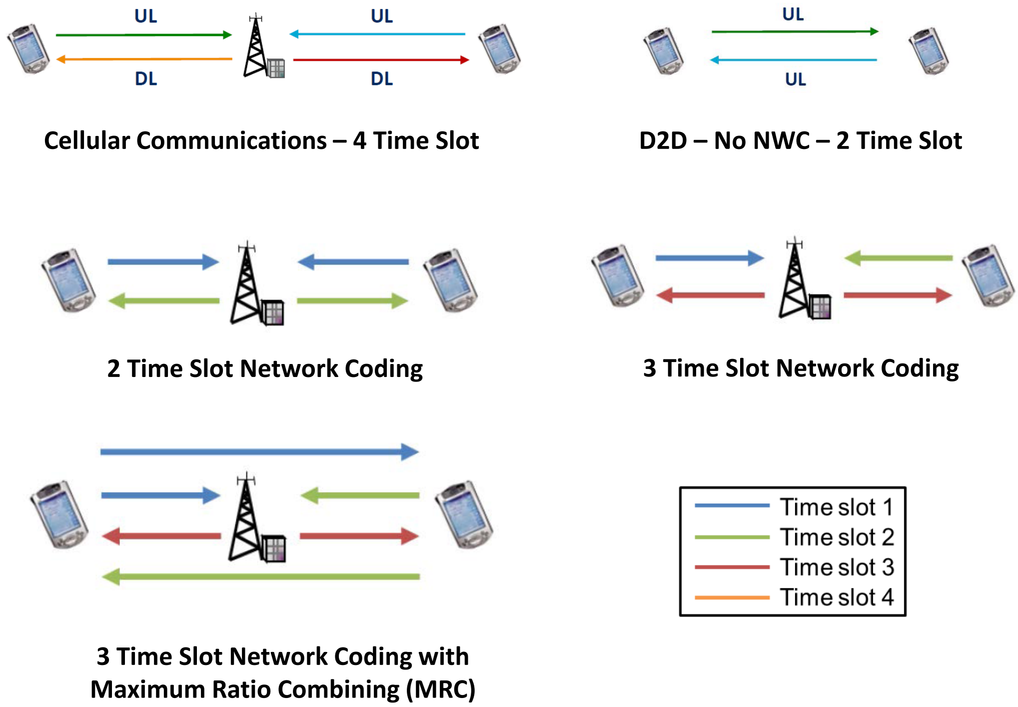

FIGURE 2. The number of time slots required by the proximal communication options using 2-TS or 3-TS network coding and D2D communications. While traditional cellular communications require 4 time slots, 2-TS and 3-TS PLNC can reduce the number of required time slots and take advantage of MRC.

power that D2D transmitters devote to the cellular and D2D signals, respectively.

B. MODE SELECTION FOR COOPERATIVE D2D SCHEMES

While there have been numerous studies of mode selection (MS) schemes for classical D2D communications, less attention has been devoted to MS in hybrid D2D and NWC-capable networks. Such an extended MS scheme must consider the following operational modes for proximal communications (see Figure 2):

1) Cellular Mode (4-TS scheme): In this case, UE1 and UE2 communicate using traditional cellular UL and DL transmissions and utilizing four time slots for bidirectional communications (upper left).
2) 2-TS and 3-TS and PLNC schemes: For these schemes, the BS manages the necessary UL and DL resources in addition to performing the PLNC operation and transmitting the network-coded signal in the DL (middle left and middle right).
3) D2D - No network coding (NWC): In the classical D2D mode, the BS manages the resources, typically over a longer time scale, while the devices themselves can perform the link layer operations within the resource and power constraints set up by the BS (upper right).
4) 3-TS NWC with maximum ratio combining (MRC): 3-TS physical layer network coding by the cellular BS can be advantageously combined with D2D communications by allowing user equipment to combine the received network-coded signals from a BS and a direct signal from a peer UE. This technique has been demonstrated to reduce the bit error rate compared with employing NWC or D2D communication alone [8] (lower left);
5) Overlay D2D with superposition coding: In this mode, the D2D transmitter acts as an in-band relay for a cellular link and, at the same time, transmits its own data by employing superposition coding as a form of multiplexing technique.

As Figure 2 shows, 2-TS and 3-TS PLNC in combination with D2D communications can reduce the number of resources (time slots) required for bidirectional communications and may also take advantage of receive diversity. Mode selection algorithms that can adapt the best communication mode in terms of resource utilization and achieved spectral and energy efficiency will likely attract future research.

III. NETWORK-ASSISTED MULTI-HOP D2D COMMUNICATIONS

Although multi-hop D2D communication requirements have been primarily defined with NSPS scenarios in mind [11], it is clear that commercial and traditional broadband Internet services can also benefit from range extension or multi-hop proximity communications, as illustrated in Figure 3. 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 3, different line types indicate different

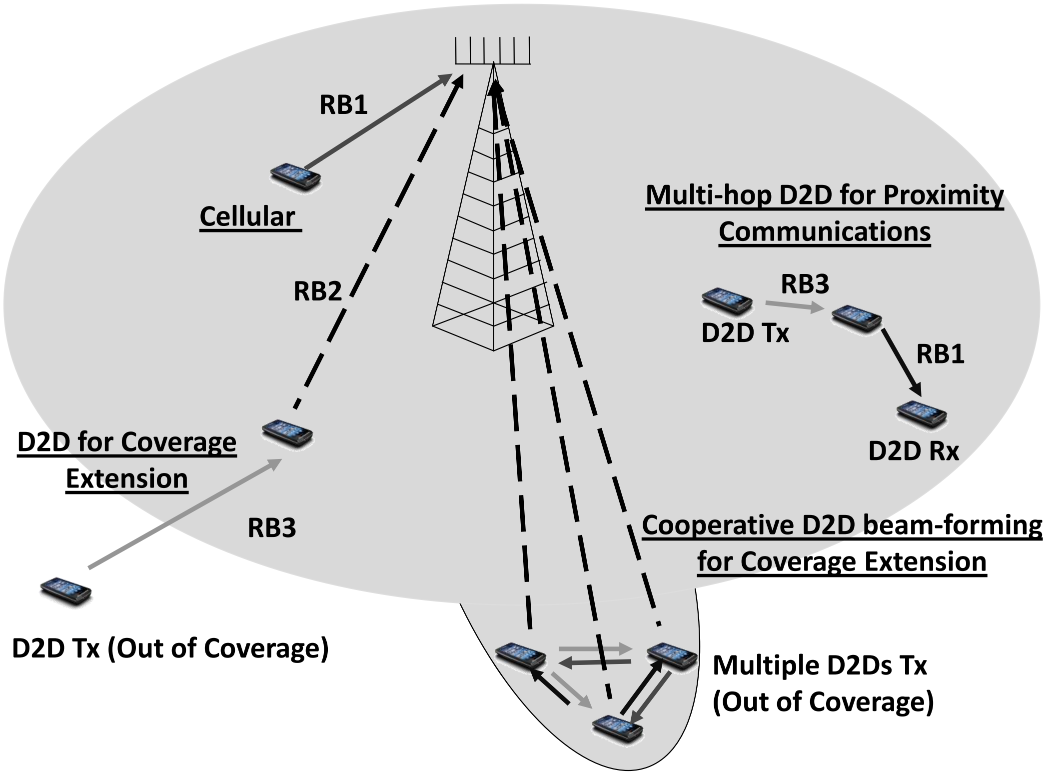

FIGURE 3. Network-assisted multi-hop D2D communications can facilitate cellular coverage extension and in-band relaying within cellular coverage. D2D capable user devices can also cooperate to realize a virtual antenna array and achieve distributed beamforming with limited feedback to achieve coverage extension.

time and frequency resources (that is RBs), while the same line type for different links indicates RB reuse (for example RB1 is used for a cellular UL and a D2D transmission). We have 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 base station or using single- or multi-hop D2D communications.

Recall that for D2D communications in a cellular spectrum, mode selection, RB allocation (scheduling), and power control are essential. However, extending these key RRM algorithms to MH D2D communication is non-trivial, for the following reasons:

- Existing single-hop mode selection (MS) algorithms must be extended to select between the single-hop D2D link, MH D2D paths, and cellular communications.
- 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.
- Available D2D power control (PC) algorithms must be 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.

The key aspect that distinguishes D2D-based range extension and multi-hop communications from relay-assisted cellular communications is the fact that, in the case of D2D communications, the relaying device has its own traffic to transmit (in UL) and receive (in DL), in addition to providing relaying service to a peer UE. Although D2D for coverage extension is a key application in NSPS situations, further research is required into radio resource management algorithms to handle the traffic of the relaying device as well as the peer devices [12], [13], [27]. Cooperating devices using limited feedback can also realize distributed or collaborative beamforming over multiple relaying devices and jointly achieve multiple-input single-output (MISO) beamfoming for cellular coverage extension. In such a scheme D2D communications are used to achieve spatial diversity among multiple devices without requiring that an antenna array be present at each node [14], [15]. As observed in, for example, [13], when D2D communications are used to extend the coverage and improve the quality of cellular services, user equipment temporarily become part of the infrastructure.

Another important issue of D2D-based range extension and multi-hop communications is the general assumption that all UEs are willing to cooperate selflessly. However, communicating nodes are often autonomous and aim to maximize their welfare hence minimizing their cooperation. Indeed, collaboration consumes resources like energy and

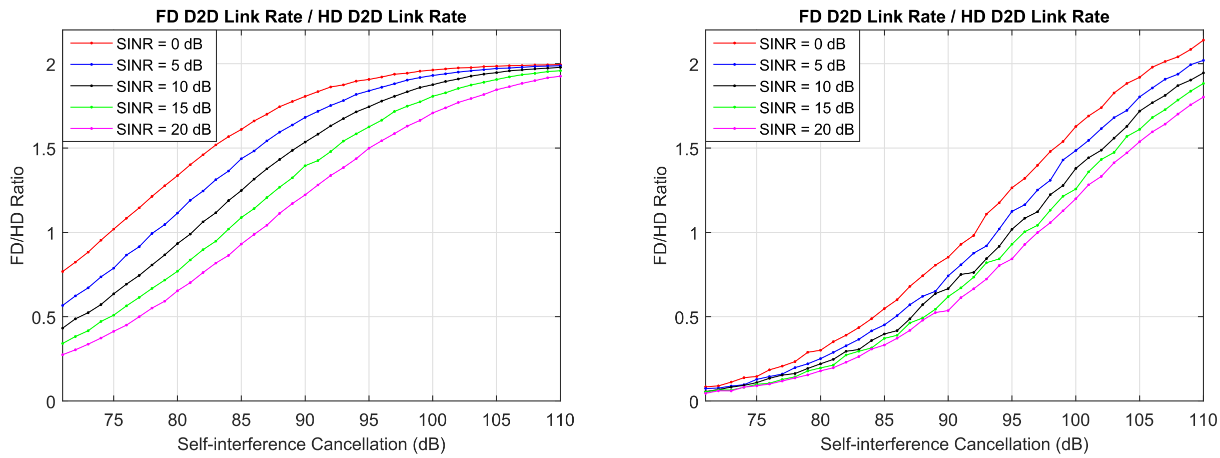

FIGURE 4. Ratio of full-duplex D2D link rate over half-duplex D2D link rate for different D2D SINR targets. A (left): UL radio resource reuse with uncontrolled interference on D2D from UL transmissions (this leads to higher interference-plus-noise level, which means that full-duplex radio needs less SI cancellation in order to double the rate). B (right): DL radio resource reuse when interference on D2D is minimized by beam-forming in base station (which leads to a very low interference-plus-noise level and full-duplex radio requires larger SI cancellation in order to double the rate).

computing power and does not provide immediate benefits. Therefore, UEs may not be interested in cooperation without an incentive [16]. Over the last decade, several techniques have been proposed to encourage cooperation and improve the efficiency of wireless networks using relaying. One approach is to encourage cooperation through the dissemination of reputation information about each node. Then, a certain node helps another node depending on its reputation. However, this approach is not always beneficial due to several reasons. First, there is room for possible misinterpretations of the nodes' behavior. Second, node complexity will increase due to the monitoring of others' behavior. Finally, reputation messages must be propagated, what increases signaling overhead. An alternative approach is to use a virtual currency that allows nodes to be remunerated for relaying. Nodes accumulate credit through cooperative behavior and use this credit to purchase cooperation from other nodes [17]. Moreover, incentive mechanisms can discourage launching exhaustive requests because the nodes pay for relaying their packets. On the other hand, a possibility is that operators give monetary incentives to their users acting as relays, as a less expensive option than investing on infrastructure.

IV. FULL-DUPLEX D2D COMMUNICATIONS

Transmission and reception at the same time and on the same frequency band can, in theory, double the spectral efficiency of wireless communication systems compared to conventional frequency-division-duplex (FDD) or time-division-duplex (TDD) half-duplex schemes. In traditional systems, when a radio is transmitting, it cannot receive on the same frequency at the same time because the receiver of the node gets its own transmit signal (self-interference, SI), which is much stronger than the signal of interest. However, recent research efforts – especially in the context of small cells and proximal communications – targeted at cancelling the self-interference have paved the way for making full-duplex transmission possible in practice. According to these results, SI can be mitigated in three stages [18]. In the *propagation domain*, either by using separate antennas for transmission and reception or using a circulator it is possible to isolate the transmit and receive chains. The second stage involves *analog-domain* active cancellation. The propagation and analog active cancelation is important because the self-interference signal can be reduced to the dynamic range of analog-to-digital (ADC) convertor. After the signal passes through ADC, the third stage is self-interference cancellation in the *digital domain*.

So far, the problem of SI in full-duplex radio design has been solved for systems with low transmit power levels such as Wi-Fi. Due to the small distance between users in D2D communication, which leads to small transmit powers, full-duplex radios can be implemented to increase the spectral efficiency of D2D systems. Initial studies on full-duplex D2D communication for single and multiple antenna base stations are reported in [19] and [20], respectively. In both of these papers, underlay D2D communication is considered and the results clearly indicate the increase in the rate of the system with different level of SI cancellation. These studies show that 110 dB self-interference cancellation leads to the throughput of the D2D link being doubled. An important insight is the benefit of full-duplex radios in environments with high interference. Since the main challenge of full-duplex radio design is to reduce the self-interference to the noise-plus-interference floor, less self-interference cancellation is required in the presence of interference. In [19] and [20] it was observed that different methods of limiting interference in underlay D2D communication affect the performance of full-duplex D2D compared to half-duplex D2D. One example from the results of [20] is shown in Figure 4. The simulation scenario is sum-power minimization in a single cell

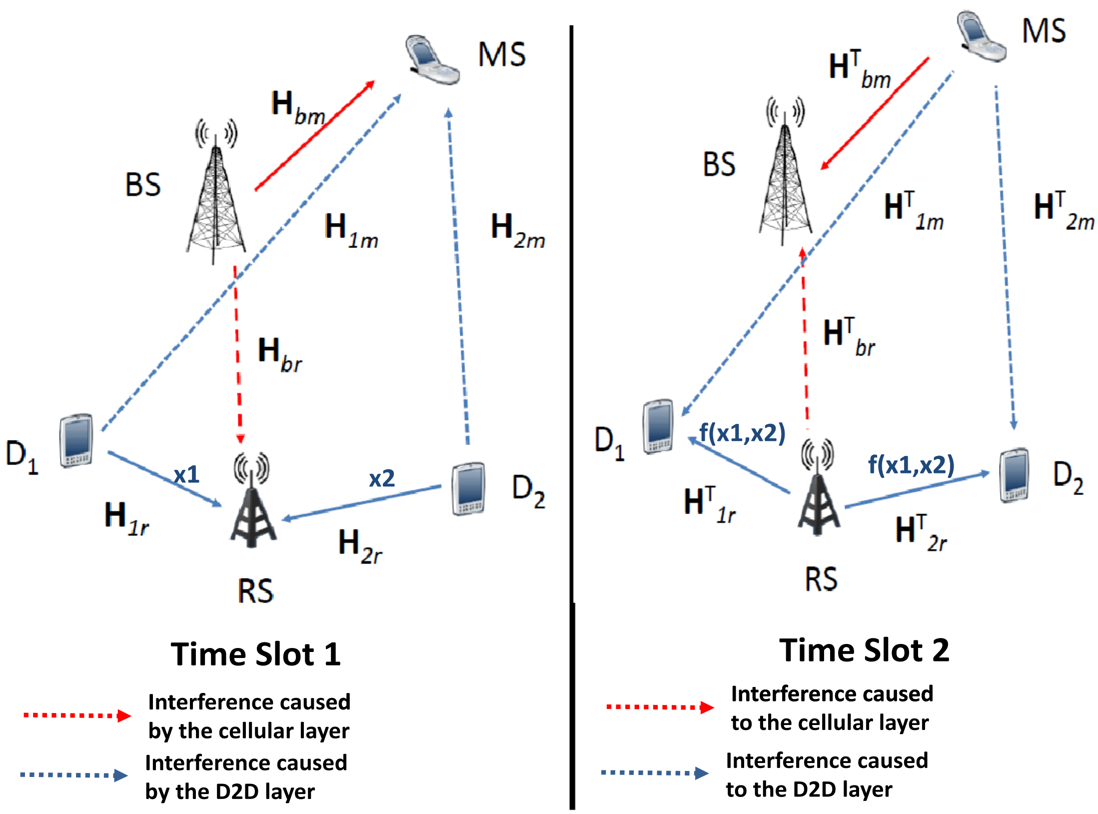

FIGURE 5. PHY layer network coding based underlay D2D Communication: (A) First time slot; (B) Second time slot. During the first time slot the BS transmits DL data to the served mobile station, while D_1 and D_2 transmit to the relay station. During the second time slot, the mobile station transmits UL data to the BS, while the relay station transmits network coded data to D1 and D2. MIMO techniques help reduce the interference between the cellular and D2D layers.

system with multi-antenna base station and single antenna users. In the UL (Figure 4, left), joint power control and receive beamformer are designed using fixed point iterations. In the DL (Figure 4, right), sum power control minimization is solved using convex optimization methods. Simulation parameters include the cell radius of 500 meters, maximum distance of 25 meters between D2D users and two Long Term Evolution (LTE) RBs for each simulation period.

Also, full-duplex radios are good candidates for relaying and range extension use cases of D2D communications. The main conclusion is that the reported full-duplex radios are good enough for D2D communication and should be utilized to increase the spectral efficiency of D2D systems. Finally, it is noted that full duplex enables a device to detect a collision while transmitting. This enables timely detection of transmissions in the cellular layer and thus expands the overall space for strategies for coexistence between the D2D and the cellular transmissions.

V. INTEGRATION OF MULTI-ANTENNA TECHNOLOGIES WITH D2D

A. INFRASTRUCTURE-RELAY-ASSISTED D2D MIMO COMMUNICATION

In an infrastructure-relay-assisted system supporting D2D underlay communications, cellular devices and peer devices using D2D communication mode can take advantage of multiple antenna relays (Figure 5). The number of antennas at the devices and the relay is considered to be the same facilitating equal number of spatial streams from the devices [21]. The scenario considered here for exchanging information between the devices D_1 and D_2 consists of two time slots where the activity begins with time slot 1 and finishes with time slot 2. The MIMO channel matrices corresponding to the relevant link are given as **H**.

As the name implies, the underlaid part of the system is subject to interference caused by the cellular layer (Figure 5A). Compared with traditional relay schemes, in the case of an underlaid D2D communication system, cooperative MIMO systems supporting network coding have the potential to increase the spectral efficiency by utilizing the spatial domain and the inherent resource efficiency of PLNC.

The D2D communication system shown in Figure 5A employing MIMO and PLNC can achieve very high spectral efficiency, provided that suitable interference cancellation techniques and low-complexity PLNC at the BS to create the network-coded data ($f(x_1, x_2)$) are employed (Figure 5B). To this end, a joint precoder-decoder design is an effective way to mitigate interference and reduce the complexity of the PLNC operation where the relay estimates the sum of the modulated signals by the devices. This is explained as follows. As mentioned, the bidirectional communication between two proximal devices is carried out in two time slots (Figures 5A and Figure 5B). In the first time slot the precoded signals from each device are transmitted to the infrastructure relay which employs a suitable decoder to estimate the sum signal ($s_1 + s_2$) from the devices. In the second time slot the estimated sum signal is transmitted to *both* devices after precoding at the relay. The devices then utilize their decoders to recover the signal from the peer devices after subtracting their own signal.

The performance of this scheme critically depends on the accuracy of PLNC mapping at the relay and therefore on the estimate of the sum of two symbol streams from the devices ($s_1 + s_2$). This estimation can be carried out by minimizing the mean square error (MSE) between the received signal and the sum of the possible transmitted signals. A similar MSE procedure can also be applied at each terminal to recover the signals.

A design example of a joint precoder-decoder applicable in an infrastructure-relay-assisted D2D system is provided by [21] and has been further investigated in the METIS project [3]. These initial results indicate the great technological potential of combining MIMO and PLNC technologies, although efficient and practically feasible mode selection algorithms applicable in such systems remain a challenge. PLNC based D2D has been shown to have better bit error rate performance than direct D2D, as well as traditional network coding, which uses three time slots and is therefore spectrally inefficient [21].

B. MULTI-HOP MIMO D2D RELAYING

As discussed in Section III, an important use case of proximal communications is MH D2D relaying, where the UEs provide a virtual infrastructure that can improve the cell edge performance and infrastructure-based coverage. Although UE relays require higher management complexity than fixed relays due to their changing location, they are more flexible and can adapt to continuous changes in the network.

Utilizing MIMO techniques in relay networks is a natural step that can enhance the performance of network-assisted MH D2D relaying, as MIMO is well-known to significantly improve spectral efficiency and link reliability through spatial multiplexing and space-time coding (STC). In fact, it has been shown that, in an MH MIMO setup using multiple relays at each hop, the capacity increases logarithmically with the number of relays, for a fixed SINR and a fixed number of antennas at the source, relays, and destination [22]. However, achieving the capacity upper bound of this system requires perfect channel state information (CSI) at all the involved nodes; each relay needs perfect CSI of its backward channel (i.e., between source and relay) and forward channel (i.e., between relay and destination). Furthermore, full cooperation among the relays (that is, joint processing) is required, to allow for a joint data decoding like in MIMO point-to-point systems.

It is worth noting that the aforementioned capacity upper bound is difficult to reach in practical cellular systems with UE relays. Cooperation among the UE relays involve extra control information, which penalizes the data rate. Besides, UE relays are typically transparent to the destination UE and, consequently, they do not have a cell-specific reference signal for forward CSI acquisition. Due to the absence of CSI on the forward channel and to the inherent mobility of UEs, such types of UE relays generally operate in open-loop mode (that is, without CSI at the transmitter side). In such a scenario, it is very important to identify a trade-off between signaling overhead and performance.

A suitable technique to exploit MIMO gains with less stringent CSI requirements in an MH D2D network is STC. It does not require CSI at the transmitters, thereby it reduces the signaling overhead while increases robustness against UE mobility. Many solutions to carry out distributed STC in a relay network have been proposed, most of them based on implementing a virtual MIMO transmitter with the antennas of different relays. A wide variety of STC designs applicable in this setup can be found in the literature, such as the well-known Alamouti code for two transmitter antennas or the fully orthogonal or quasi-orthogonal space-time block-codes for a generic number of antennas. An alternative but related solution to provide open-loop MH MIMO D2D relaying was proposed in [23], where STC and open-loop beamforming are combined based on the idea of multi-functional MIMO communication. In multi-functional MIMO systems, the total available antennas at each communication hop are divided into groups, each of them in charge of a different set of spatial streams. In the solution proposed in [23], the set of antennas of each UE relay is considered a group which is assigned a set of data streams to be processed. This scheme improves the bit error rate of the destination UE with respect to MH D2D relaying techniques based exclusively on distributed STC.

C. COOPERATIVE D2D BEAMFORMING FOR COVERAGE EXTENSION

If we assume that several UEs can exchange their UL data by using D2D communications, another opportunity for coverage extension using D2D is that multiple D2D UEs collaborate and jointly steer the transmit signal towards the BS, as shown in Figure 3. In this way, the received signal-to-noise ratio (SNR) at the BS can be improved significantly. This can be regarded as a MIMO system with distributed antennas at the transmitter side, which is also denoted as Virtual MIMO. Such a cooperative beamforming approach is particularly relevant for indoor scenarios (such as in an office or in a shopping mall), or any other situation where several users face coverage problems. The potential benefit is to lower the outage probability, and improve the energy efficiency for the D2D capable UEs. Alternatively, the beamforming gains can be used to improve the area fairness among the cellular UEs and the D2D-capable cell edge UEs, or to meet a required QoS for the cell edge UEs and use the freed up resources for the cellular UEs to boost the overall spectral efficiency.

The communication takes place in two phases. First, each UE exchanges its data with all other UEs by using D2D communication. Second, UEs cooperate to send the data to the BS. In order to implement phase two, the CSI of all the UL channels needs to be available to calculate the beamforming weights on the UE transmit antennas, which, depending on the scenario, might be difficult to obtain. In TDD channel reciprocity can be utilized, and in FDD the BS can either signal the channel information to each of the cooperative D2D UEs in the DL or to a particular cooperative D2D UE, which can share the channel information or the calculated precoding weights to the other cooperative D2D UEs over the D2D links.

D. INTEGRATION OF D2D IN DEPLOYMENTS WITH MASSIVE MIMO ARRAYS AT THE BS

In the DL of a massive MIMO cellular deployment with an underlay D2D network (as in Figure 5), the use of highly directional beamforming at the BS can steer nulls towards the receivers of the D2D communication pairs. This efficiently mitigates the interference caused over the D2D communication. Indeed, as shown in [24], in such a setup the D2D links are quite robust to the cellular-to-D2D interference, even if there are many cochannel cellular users. Furthermore, if the number of antennas at the BS is significantly larger than the number of served users, the channel of each user to/from the BS tends to become orthogonal to that of any other user. This key aspect of massive MIMO communication enables interference cancellation also in the UL. If multi-user UL communication with a large antenna array at the BS is employed, the interference caused by the D2D pairs to the cellular users during the UL transmission is, in most practical cases, close to zero [24].

VI. ENHANCING VEHICLE USERS' UPLINK COMMUNICATION

Due to the high penetration of smartphones and tablets and the increasing portability of laptops, public transportation vehicles, such as buses, trams, and trains, have become natural hotspots for wireless data traffic. The rapid development of cloud computing has lead to more of the computation burden being shifted from the UEs to the server side. Consequently, people are expecting to access remote services not only at home or in the office, but also when commuting at higher speeds, especially on their way to work or for connected driving of their cars. Hence, reliable communication between a user terminal and the server needs to be guaranteed for these VUE devices. A significant problem faced by VUE devices is the vehicular penetration loss (VPL), which substantially attenuates the radio signals traveling between the VUE devices inside vehicles and the base station (BS). Measurements show that VPL can be as high as 25 dB in a minivan at the frequency of 2.4 GHz and more than 30 dB VPL is expected for well isolated high speed trains. Even higher VPLs are foreseeable if higher frequency bands are used in next-generation mobile communication systems.

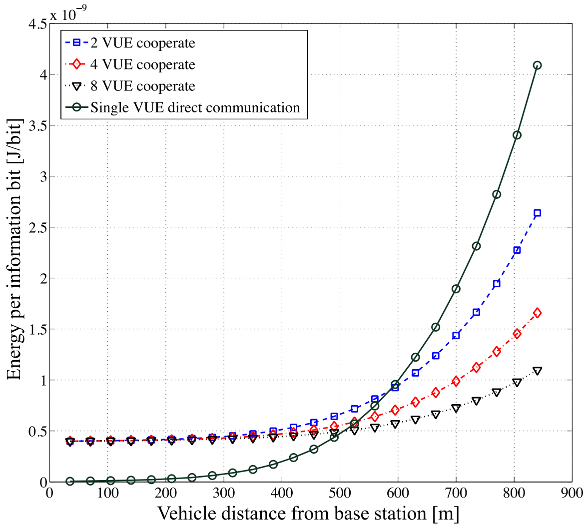

FIGURE 6. Required RF energy per information bit with vehicular penetration loss 30 dB for the cases of no cooperation and cooperation with two, four and eight items of vehicular user equipment. There is a loss with cooperation close to the base station, but in the outer part of a cell there are large gains, ranging from around 55 percent to 270 percent with two to eight items of cooperative vehicular user equipment.

Thus, in combination with the high data volumes, the battery life of VUEs is severely affected.

As shown in METIS, a promising solution to support the needs of VUEs is to deploy moving base stations in the vehicles and use the vehicles as gateways to assist the communication of VUEs. In this way, the VPL can be circumvented by separate outdoor and indoor antennas, and the Quality of Service (QoS) of VUE devices can be noticeably improved. However, there are challenges related to deployment, operation, and business models of moving BSs. Meanwhile, one promising solution could be cooperative D2D beamforming (as shown in Figure 3 and described in Section V) to enhance the UL of VUEs. VUEs in public transports like buses, trams, and trains are particularly good candidates for cooperative D2D for two main reasons. First, users are typically very active mobile broadband users while commuting in such vehicles, so the overhead to setup the cooperative D2D scheme can be motivated. Second, the proximity discovery is easier, since most UEs are rather static for a substantial amount of time within the vehicle. Cooperative D2D beamforming using a generalized co-phasing approach – using closed loop MIMO with constant peak power per transmit antenna and optimized transmitter phases and MRC at the receiver – was investigated in [25], with the aim of optimizing the overall RF energy efficiency for the VUEs UL data transfer. This particular cooperative D2D beamforming approach was adopted in order to limit the required CSI to only the phase information and to maximize the total transmit power capability of the cooperative D2D cluster of VUEs. The required RF energy of the system was evaluated assuming flat fading non-line-of-sight VUE-BS and line-of-sight VUE-VUE channels with realistic pathloss at 2.6 GHz. Single antenna VUEs and two antennas per BS were assumed. The conclusion of that study was that when the VPL is moderate, the VUEs should still perform individual UL communication with the BS, as the overhead of D2D communications is too large. At high VPL (in the order of 30 dB), however, the VUEs involved in the D2D cooperation can make substantial energy savings by cooperating with each other. The gain increases with the number of cooperative VUEs, ranging from around 55 percent with two VUEs to 270 percent with eight cooperative VUEs (Figure 6).

VII. D2D TEST-BED

Although the theoretical aspects of the METIS D2D technology components described in this work were mainly validated through simulations, the METIS project also developed hardware test-beds related to D2D communications [26]. In particular, the test-beds were able to show-case key aspects of a future D2D-based communication system such as a direct network controlled D2D communication, a D2D communication with mode selection and a D2D communication in a Heterogeneous Network (HetNet).

The first test-bed demonstrated the impact of interference cancellation (IC) in direct network controlled D2D, where a system using successive interference cancellation at the BS was considered. The main conclusion of the demonstration was that the LTE segmentation and encoding does not support a simple implementation of the IC functionality. The second D2D related test-bed enriched the first one with mode selection, and studied the system gain with D2D and IC at the D2D nodes. The results of the studies suggested that including the considered IC in the D2D communication setup could double the system capacity. Finally, the third D2D related test-bed concerned D2D in a HetNet scenario which used the resources based on Reference Signal Received Power (RSRP) measurements. The demonstration was assisted with an initial measurement campaign, where it was noticed that subframe-level RSRP values varied a lot. The METIS project testbed activity subsequently investigated how to average these values such that the interference probability at both macro and picocells could be controlled. Overall, the D2D test-beds were indeed useful to evaluate important aspects such as processing delays, control signalling, and hardware implementation complexity and impairments, which are generally hard to verify through software simulations.

VIII. CONCLUDING REMARKS

D2D communications have evolved from a technology that utilizes the proximity of communicating devices and realizes the proximity-, reuse-, and hop gains to become key enablers of national security and public safety and intelligent transportation systems. Recent advances in such diverse fields as cooperative communications, multiple antenna systems and full-duplex transceivers greatly affect the potential of D2D communications and call for solutions beyond the classical mode selection, resource allocation, and power control approaches that are well known in the literature and are currently standardized. Specifically, cooperative D2D communications – including schemes using network coding, superposition coding, mode selection for cooperative D2D schemes, multi-hop D2D communications, and virtual MIMO, as exemplified in Sections II and V – allow user equipment to extend the coverage of cellular networks and thereby to become part of the cellular infrastructure in addition to managing its own cellular or local traffic. This new role of user equipment gives rise to exciting questions regarding not only *how* such cooperation among user equipment and between user equipment and the cellular infrastructure should take place, but also mechanisms that provide *incentives* and rewards for undertaking such new roles. In parallel with this evolution, the deployment of large antenna arrays and advanced receiver structures, both on the infrastructure and user equipment side, call for new algorithms and protocols that enable the cellular infrastructure to maximize spectral and energy efficiency and enhance the end-user experience in terms of end-to-end throughput and packet delay.

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