Device-to-Device Relaying: Optimization, Performance Perspectives, and Open Challenges towards 6G Networks

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***Abstract*—A relaying can significantly improve performance of contemporary mobile networks in terms of capacity and/or energy consumption. Nevertheless, an incorporation of conventional relay stations into the mobile networks is usually expensive in terms of both capital and operational expenditures for the mobile operators. With an evolution of Device-to-device (D2D) communication, the relaying can be also facilitated via a user equipment (UE) by means of D2D relaying. In the D2D relaying, the users relay data for others, thus significantly cutting the mobile network operators' expenditures. The D2D relaying also offers a plenty of opportunities for the relaying as, in theory, each UE can play a role of the relay. To fully unlock all benefits of the D2D relaying, however, there are still many challenges to be addressed, such as an efficient radio resource and interference management, mobility management, security and trust issues, or finding proper incentives to motivate users to help others. In this survey, we introduce a detailed taxonomy of the D2D relaying concept encompassing an overview of various relaying scenarios, types of relays, and radio resource management techniques to be optimized. Then, we provide a comprehensive overview of research works targeting the D2D relaying addressing the above-mentioned challenges, compare these works from various perspectives, identify their potential drawbacks and limitations, and also draw some interesting lessons for the readers. Last, based on the gaps in the current literature, we identify key open research challenges deserving further attention of the researches to make the D2D relaying feasible and attractive option for mobile network operators as well as end-users in emerging 6G networks.**

***Index Terms*—device-to-device relaying, radio resource management, incentives, optimization, performance, 6G.**

I. Introduction

The idea of relaying in the mobile networks has been conceived already during the development of Worldwide Interoperability for Microwave Access (WiMAX), pushed by IEEE, and Long Term Evolution-Advanced (LTE-A), promoted by 3rd Generation Partnership Project (3GPP) towards 4G mobile networks. The main perceived benefit of the relaying is a potential to increase the network's coverage and capacity, since the users with a low channel quality to a base station (BS), or even out of its coverage, can attach to a close-by relay station (RS) that offers significantly higher channel quality to the BS. The RSs are not connected to the operator's core network by expensive wired connections (as it is done in case of the BSs), but are wirelessly attached to the BS.

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In order to enable the operation of the RSs in WiMAX-based networks, 802.16j-2009 standard was approved in 2009 [1]. The 802.16j-2009 standard distinguishes two types of RSs: *transparent* and *non-transparent*. The transparent RSs are very simple relays transmitting neither control nor management signaling. The non-transparent RSs, in contrast, are BS-like nodes handling functionalities similar to the conventional BSs, including own control and management signaling.

The 3GPP followed the IEEE 802.16j-2009 and incorporated the RSs into Release 10 in 2011. Analogously to 802.16j-2009 standard, both non-transparent (also known as Type I) and transparent (Type II) RSs have been initially considered. Nevertheless, only the non-transparent RSs are now fully standardized while the transparent RSs are still being problematic, because these transmit no control information, such as synchronization or reference signals [2]. Consequently, there is no easy way to manage efficiently users' association or handover [3][4]. Depending on mobility, the RSs can be further classified as *fixed*, *nomadic*, or *mobile*. The Fixed RSs are supposed to be located at the strategic locations, where the coverage of conventional BSs is not sufficient and a deployment of entirely new BSs is uneconomical. Even if the non-transparent RSs have BS-like functionalities, their deployment is still much cheaper than the conventional BSs, as the non-transparent RSs do not require a wired connection either to the operator's core network or to other parts of the network infrastructure whatsoever. The second type of RSs, the nomadic ones, are also fixed during their operation, but are deployed only temporarily to boost the performance of the network during peak/busy hours (such as during concert, football match, etc.). While Fixed and Nomadic RSs are immobile during their operation, the last type of RSs (i.e., Mobile RSs) are assumed to move during their operation. The Mobile RSs can be mounted on vehicles, such as buses or trams, thus improving quality of service (QoS) of the users on board or in their close proximity. Besides, 3GPP has been studying the possibility to deploy fully Mobile RSs at high speed trains [5][6].

With the recent technological evolution of unmanned aerial vehicles (UAVs), an interesting option to deal with a dynamicity of the mobile users is to exploit the UAVs acting as the Flying RSs. Such Flying RSs are able to relay data between the mobile users and the fixed BSs [7]. When compared to the Mobile RSs, the Flying RSs' locations are fully adaptable in

TABLE I: The comparison of individual relaying concepts adopted by the cellular networks.

Aspect/relay type	Fixed RSs	Mobile RSs	Flying RSs	Relay UEs (D2D relaying)
Deployment cost for operators	**Very high**	**Medium**	**High (due to potential high OPEX wrt Mobile RSs)**	**No or minimal cost**
Number of potential relays	**Several RSs per cell** at most	Usually more than the number of fixed RSs, but still limited	**Several Flying RSs per cell** at most	**Many as each UE in the cell is a potential relay**
Ownership	Mobile operators	Mobile operators	Mobile operators	Mobile users
Location	Fixed or nomadic	Usually predetermined (according to vehicle/train scheduled trajectory)	**Highly adaptable** depending on users' needs and requirements	Changing with current user's location disregarding needs of other users
Requirements imposed on users exploiting relays	No requirements	No requirements	No requirements	Support D2D functionality by the UE is required
Security	**High**	**High**	**High**	**Low** (depending on the trustworthiness of relaying users)
Necessity to provide incentive to relay	**No** (RSs are owned by the operator)	**No** (RSs are owned by the operator)	**No** (RSs are owned by the operator)	**Yes** (to motivate often selfish users)

3D space in order to manage fluidity of users' needs and their requirements, as considered in many recent papers [8].

Besides various RS's options discussed above, the mobile networks can also leverage on device-to-device (D2D) functionality of a user equipment (UE), incorporated into 3GPP for the first time in scope of Release 12 in 2015, allowing even the UEs to relay data for other UEs. This concept is often referred to as a *D2D relaying*. The authors in [9] show that the use of UEs as relaying devices (labeled as Relay UEs in the rest of the paper) is a convenient way to improve the coverage and capacity of cell-edge UEs, i.e., the UEs experiencing a low channel quality to the BS. In such case, the Relay UE acts as a go-between the cell-edge UE and the BSs in a form of a *UE-to-Network* relaying. Moreover, the relaying via other UEs can play a critical role in a public safety scenarios. For example, in [10], the authors discuss a possibility to exploit multi-hop D2D communication in the areas affected by a natural disaster, where the UEs can relay messages of other UEs to notify their family members and friends of their safety. In case the Relay UEs retransmit data between two UEs (labeled as Source UE and Destination UE, respectively), we speak about a relay-assisted D2D communication or about a *UE-to-UE* relaying.

In comparison to other relaying concepts, the D2D relaying has two *key advantages*:

- The D2D relaying introduces no (or very limited) deployment cost at the mobile operators' side, since the operators do not need to deploy *any additional nodes* (see Table I). In contrast, the Fixed RSs are supposed to have similar functionalities as the BSs, thus, the deployment cost of the Fixed RSs with respect to the D2D relaying is seen as a "very high". Then, although the price of the Flying RSs is lower with respect to the Fixed RSs, the operating expenses (OPEX) of the Flying RSs may be notable, hence we classify the deployment cost of the FlyRSs as "high". Even though the cost of Mobile RSs could be further reduced due its lower OPEX compared to the Flying RSs (e.g., if mounted on public vehicles, such as buses and trams), their deployment cost is still not negligible and classified as "medium".
- There are *many UEs* in the network making, theoretically, *plenty of opportunities and options* for selection of a suitable Relay UE(s). Thus, the D2D relaying has a high potential to improve the capacity of mobile networks.

Of course, the advantages of D2D relaying goes hand-in-hand with some *drawbacks* and *challenges*:

- While the Fixed RSs, Mobile RSs, and Flying RSs are supposed to be *owned and fully controlled* by the mobile operators, the Relay UEs are commonly in the ownership of the mobile users. Hence, the mobile operators can only plan deployment of the Fixed RSs or trajectories of the Flying/Mobile RSs (provided that Mobile RSs are mounted at moving public transport vehicles with known trajectory). The positions of the Relay UEs, on the other hand, solely depend on the users owning each particular UE.
- The D2D relaying requires both the relaying users and the users requesting the relaying services to be equipped with *D2D-enabled UEs* [11]. Still, D2D communication is expected to be widespread and supported by a common UE in the near future, thus eliminating this slight drawback.
- The relaying through the Fixed, Mobile, and Flying RSs is relatively secure as the communication traverses only though operator's node(s), while the Relay UEs are owned by the users themselves. Consequently, the security measures at the Fixed RSs, the Mobile, and Flying RSs are considered to be "high" when compared to the Relay UEs, as the Fixed, Mobile, and Flying RSs have basically the same security-related functionalities as the BSs. Even though the D2D relaying is supposed to adopt security mechanisms commonly used in D2D communication [12] or general relaying [13], there are still trust issues to be addressed, as the users may not be willing to entrust they data to others.

From comparison given in Table I, we observe that the D2D relaying is very intriguing from the operators' point of view to enhance the performance of the mobile networks while at no or only minimal cost. To fully unlock all benefits of the D2D relaying, following crucial aspects should be handled: *(i)* radio resource management (RRM), including relay selection and radio resources/power allocation, *(ii)* interference management if the relaying D2D links underlay conventional cellular communication, *(iii)* reduction of power/energy consumption of the Relay UEs, *(iv)* mobility management, as the inherent

TABLE II: The focus of most relevant surveys dealing with D2D communication or general relaying (✓: primary focus, (✓): only brief focus.

	[14]	[15]	[16]	[17]	[12]	[18]	[19]	[20]	[21]	[13]	[22]	[23]	[24]	[25]	[26]	**Our survey**
D2D communication																
General principles	✓	✓	✓	✓												
Privacy & security aspects				✓	✓											
Separation framework						✓										
Social aspects							✓									
Mobility aspects								✓								
Network coding									✓							
General relaying																
PHY security in coop. relaying										✓						
Buffer-aided relay selection											✓					
Lossy forwarding coop. relaying												✓				
Wireless relay networks													✓			
D2D relaying																
Taxonomy on D2D relaying																✓
3GPP standardization on D2D relaying																✓
Routing in multi-hop comm.		(✓)												✓		
RRM for D2D relaying	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)						(✓)	(✓)	✓
Incentives (incl. security & trust issues)		(✓)											(✓)	(✓)		✓

characteristic of the Relay UE is their mobility that is often very hard to predict, *(v)* security and trust issues, or *(vi)* the motivation of usually selfish users to relay data for others.

In the following section, we overview most relevant surveys and discuss how these tackle the problem of D2D relaying.

A. Most relevant related surveys

Although there are many surveys overviewing the advancements in D2D communication and/or relaying, none of these focuses primarily on the D2D relaying and the challenges described above. For example, the surveys on general D2D communication are delivered in [14]-[17]. The authors in [14] give an overview of papers addressing both in-band and out-band D2D communication managed either by the network or autonomously controlled by the UEs. The paper also briefly reviews D2D architecture and discusses its implementation in the real world. Nevertheless, only several works on D2D relaying are surveyed in [14]. The survey presented in [15] is oriented more on the performance evaluation techniques, application/services for D2D communication, and existing initial prototypes and experiments. The D2D relaying is described only superficially for multicasting and incentives to motivate Relay UEs are discussed only in open research challenges. The authors in [16] focus on in-band D2D communication giving more insight into the D2D mode selection (i.e., the selection between conventional cellular communication and D2D communication) and interference management. Regarding D2D relaying, only works focusing on multicast/broadcast services are described very briefly. Besides, there are overviewed several works enhancing capacity and/or extending coverage by means of the Relay UEs. Finally, the authors in [17] focus on more recent research issues and challenges in D2D communication, such as security and economic aspects. Nevertheless, the topic of D2D relaying is again discussed only briefly. Despite all surveys [14]-[17] target various aspects of D2D communication, we can see that the D2D relaying is considered and treated only superficially.

Other surveys considering D2D communication in more specific way are presented in [12][18]-[21]. In [12], the authors provide an extensive overview of security and privacy issues in D2D communication. Besides, the authors identify number of open problems towards full D2D security and privacy. The authors in [18] focus on data and control separation architecture that is seen as an enabler for 5G networks. The authors in [19] further survey the works considering social-aware aspects of general D2D communication, such as social-ties, social community, social trust, and selfishness. Then, the authors overview in detail social-aware D2D peer discovery, D2D resource allocation, and interference management. A general impact of mobility on D2D communication is contemplated in [20]. The authors first discuss various mobility models used for D2D communication. After that, the works focusing on mobility-aware throughput optimization, data offloading/caching, energy efficiency, or latency are overviewed. Besides, the survey [21] summarizes network coding principle and discusses its applicability also for D2D communication. However, all these surveys focus on conventional D2D communication and do not address D2D relaying.

Further, there are several surveys considering relaying for general wireless networks, not specifically in terms of the D2D relaying [13][22]-[24]. A survey on cooperative relaying and jamming strategies in order to ensure physical layer security is delivered in [13]. The survey [22] overviews works on buffer-aided relay selection that are able to improve various performance metrics, such as outage probability, power reduction, or throughput, at the cost of increased packet delay. The authors in [23] provide a tutorial on lossy forwarding cooperative relaying for general relaying systems. Further, the survey in [24] analyses the impact of selfish and malicious behaviour on routing in the non-cooperative wireless relay networks. Even if also some incentive mechanisms used in

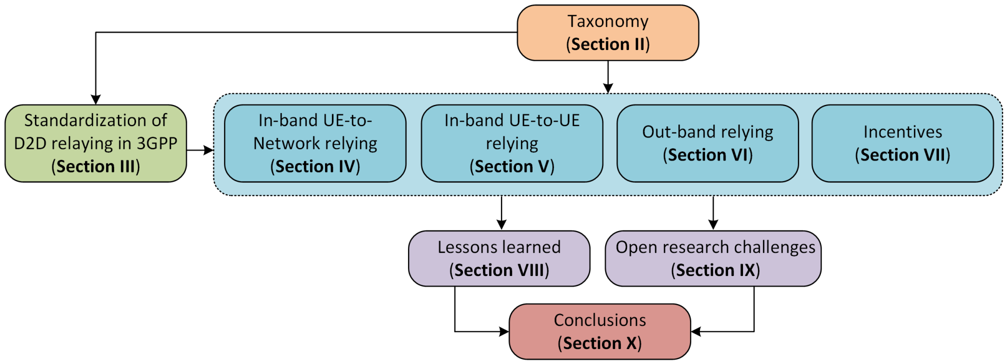

Fig. 1: High-level structure of our survey.

wireless relay networks, such as credit-based, "tit-for-tat", and reputation incentives are surveyed, most of the incentive works described in [24] do not target the D2D relaying.

The relaying in D2D communication is addressed in [25], where the authors focus specifically on multi-hop routing in D2D communication, such as social connection-based routing, security-based routing, topology-based routing, reactive/proactive routing, etc. Nevertheless, the authors do not survey works addressing challenges introduced by the D2D relaying described above. Even though, the paper briefly mentions some approaches to motive the users relay data for others, no survey on this topic is provided in [25].

In [26], the authors focus on various techniques extending the coverage of cellular networks. In this regard, the authors dedicate a brief section to the D2D communication for coverage extension, but the survey deals with the D2D relaying only superficially.

To summarize, none of the surveys described above specifically focuses on the D2D relaying, as illustrated also in Table II. The only survey zooming on the D2D relaying is [25], but its sole target is the multi-hop routing while other challenges introduces by the D2D relaying, such as the relay/mode selection, power and resource allocation, or incentivization of the D2D users are omitted. Even though there are several surveys targeting the relaying systems in common mobile networks, the D2D relaying is quite specific with respect to those, as the users exploiting the D2D relaying usually co-exist with legacy cellular UEs. Thus, the research works on D2D relaying should address specific challenges related to the optimization of radio resource management shown in challenges *(i)*-*(vi)* described above. Note that since [25] focuses in a very high detail on routing problem in multi-hop relaying, we do not cover this area specifically in our survey to avoid substantial overlapping.

B. Contributions of the survey

The previous section and Table II uncover the fact that, as of now, there is no thorough survey focusing specifically on D2D relaying. Thus, we provide a unique and a comprehensive survey of the research focused on advancements in the D2D relaying underlying the mobile networks that has not been surveyed in detail yet. Our key contributions are summarized as follows:

- We introduce a ***taxonomy classifying D2D relaying*** from several perspectives, including D2D relaying use-cases, access and allocation of radio resources by D2D relaying, or number of UEs involved in the relaying. Further we classify relays also according to relaying protocol, duplex, relaying direction, and activity of relaying users. Finally, we describe radio resource management techniques usually optimized in the surveyed works focusing on D2D relaying together with key performance indicators.
- We shed light on the recent developments and ***standardization efforts*** in the D2D communication, and D2D relaying in particular, by 3GPP organization encompassing its evolution, envisioned relying scenarios, or establishment and maintenance of D2D relaying links.
- We provide a ***detailed overview*** of research works focusing on in- and out-band relaying and on the incentive mechanisms to motivate/encourage the users to relay data for others. We sort and compare the research works in line with the taxonomy introduced earlier. We also highlight their advantages, show their performance perspectives, and point out their potential ***drawbacks and limitations***, if any.
- Based on the reviewed literature, we draw a number of practical and interesting ***lessons*** to be learned for in-band relaying, out-band relaying, and incentives.
- We identify ***open research challenges*** in order to fill the gaps in the current state-of-the-art research and to make the D2D relaying attractive solution in emerging 6G that will cope with unprecedented requirements on data rates, latency, or energy/spectral efficiency.

C. Structure of the survey

This section gives a high-level overview of the survey's organization, as illustrated in Fig. 1. First, ***Section II*** introduces the taxonomy used in the rest of the survey for the classification and comparison of individual works on D2D relaying. The following section, ***Section III***, summarizes the standardization efforts in 3GPP organization related to D2D communication and D2D relaying, as the standardization process is vital for the promotion of D2D relaying in contemporary and future mobile networks.

The core part of this paper surveys in detail recent advancements and efforts of the researchers all around the globe dealing with D2D relaying. In particular, ***Section IV*** overviews

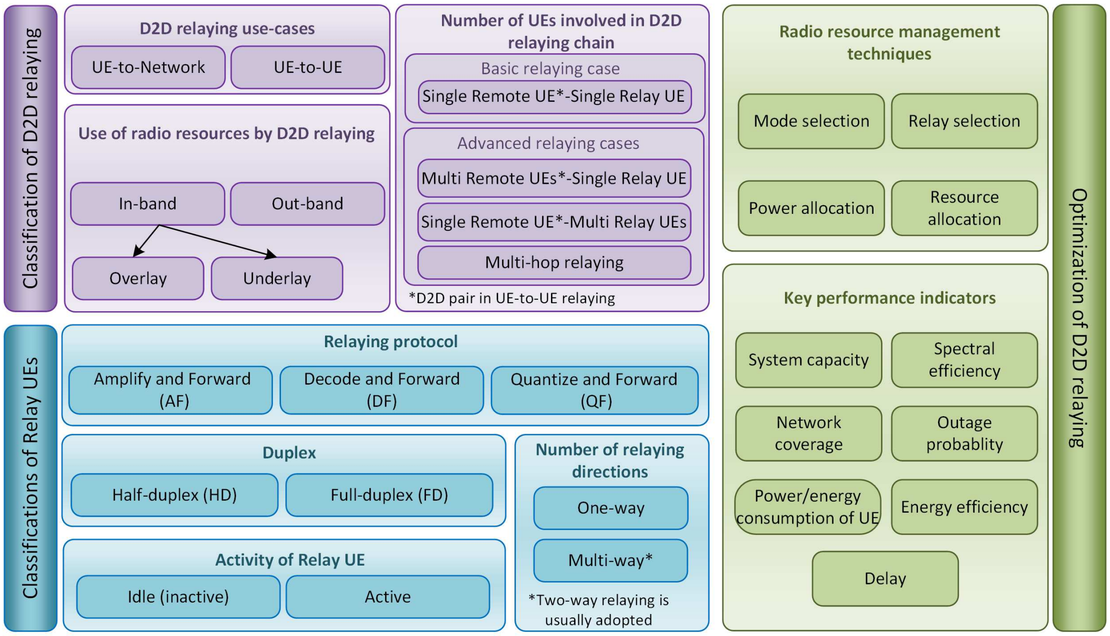

Fig. 2: Taxonomy used in the rest of the survey.

the works focusing specifically on the in-band UE-to-Network relaying, where the Relay UE acts as a go-between the Remote UE(s) and the network (represented by the BS). The in-band UE-to-UE relaying, where the Relay UE assists the D2D communication, is tackled in ***Section V***. While both previous sections track the current progress in the in-band D2D relaying, we demonstrate in ***Section VI*** that there are also works dealing with the out-band D2D relaying. The last "core" section, ***Section VII***, focuses on a crucial aspect of the whole D2D relaying concept: the incentives. The incentives serve not just to motivate users to act as the relays, but also partly address security, privacy, and trust issues.

Based on the overview of research works in Sections IV-VII, we draw in ***Section VIII*** number of lessons to be learned related especially to the in-band/out-band D2D relaying and the incentives. Besides, we also emphasize several facts regarding the radio resource management techniques in D2D relaying, relay selection, and general relaying. Further, in ***Section IX***, we identify open research challenges to fill the gaps of current state-of-the-art so that the D2D relaying will help to meet the unprecedented requirements on ultra-high data rates, ultra-low latency, or high energy/spectral efficiency, expected in the emerging 6G networks. Finally, ***Section X*** concludes our survey with several remarks and observations.

II. Taxonomy

Before we embark on a detailed survey of works addressing challenges of the D2D relaying, we introduce a taxonomy used in the rest of the survey, see Fig. 2. First, we describe various D2D relaying use-cases and scenarios (Section II-A). Second, we also explain classification of the Relay UEs based on the relaying protocols, duplex, and whether these operate in one- or multi-way relaying manner (Section II-B). Finally, we outline key radio resource management techniques and key

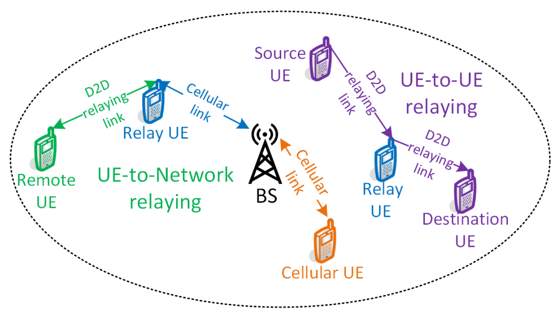

Fig. 3: Classification of D2D relaying use-cases on UE-to-Network and UE-to-UE relaying.

performance indicators optimized by current research works on D2D relaying (Section II-C).

A. *Classification of D2D relaying*

This subsection describes key differences between the UE-to-Network and UE-to-UE relaying use cases, shows that D2D relaying can exploit both in-band and out-band frequencies, and discusses in detail the relaying scenarios differing in the number of UEs involved in the relaying chain.

1) D2D relaying use-cases

In general, D2D relaying can be classified depending on whether the Relay UEs assist the conventional *cellular users* or *D2D users* (see Fig. 3[1]):

- **UE-to-Network relaying** – The Relay UE helps to the conventional *cellular users*, denoted in the rest of the

[1]Note that from now, we distinguish the Remote UEs and D2D relaying links in UE-to-Network relaying by green color; the Source UEs, the Destination UEs, and corresponding D2D relaying links in UE-to-UE relaying by violet color; the Relay UEs and cellular link between the Relay UE and the BS by blue color; the Cellular UE and corresponding cellular link by orange color.

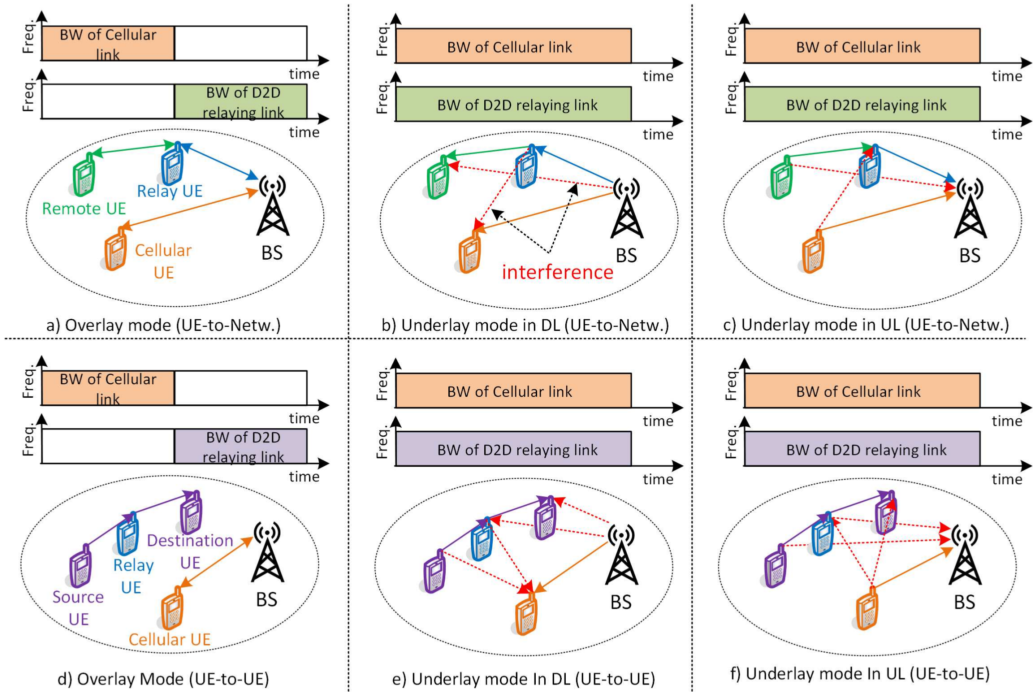

Fig. 4: Underlay vs overlay relaying modes in D2D relaying showing victim of interference in underlay relaying depending on whether relaying links use bandwidth (BW) in underlay or overlay manner while exploiting either downlink (DL) or uplink (UL).

survey as the Remote UEs, transmitting (or receiving) data to (or from) the BS. While the D2D relaying link *between the Remote UE and the Relay UE* is facilitated by D2D communication (thus labeled as D2D relaying link), *the Relay UE communicates with the BS* over a conventional cellular link. The objective of the UE-to-Network relaying is to improve the performance of the Remote UEs with a low channel quality to the BS.

- **UE-to-UE relaying** – The objective of the Relay UE is to enhance the performance of *D2D communication* by retransmitting data from a Source UE to a Destination UE. Note that the roles of the Source and Destination UEs can be swapped over time. The communication link between the Source UE (Destination UE) and the Relay UE is enabled by means of D2D relaying link. The radio resource management in UE-to-UE relaying is handled differently when compared to UE-to-Network relaying. The main reason is that D2D communication should not negatively affect the cellular communication. Thus, one of the key issues in UE-to-UE relaying is to minimize the negative impact of D2D communication on cellular communication by means of proper radio resource management for the D2D relaying links (i.e., power allocation/control at Source and Relay UEs and channel allocation).

2) Allocation of bands/resources for D2D relaying

Another classification of the D2D relaying distinguishes type of band exploited for relaying. Thus, the D2D relaying is classified to:

- **In-band relaying** – The D2D relaying links use *licensed* frequency band allocated to the mobile networks. As a result, QoS is ensured as for legacy mobile users. The in-band relaying can be further classified according to the resource allocation for the D2D relaying links with respect to the legacy mobile users to:
  - **Overlay mode** – The D2D relaying links use different radio resources with respect to the Cellular UEs (see Fig. 4a and 4d). Hence, there is no interference between the relaying links and the cellular users disregarding whether DL or UL resources are used by the relaying links. Of course, a spectral efficiency can be deteriorated and no dedicated resources may be even available to the relaying links in the case of high load periods.
  - **Underlay mode** – The D2D relaying links reuse the resources of the Cellular UEs either in DL (Fig. 4b and 4e) or in UL (Fig. 4c and Fig. 4f) resulting in mutual interference between the D2D relaying links and the cellular links. The victim of interference in both UE-to-Network and UE-to-UE relaying depends on whether DL or UL is reused by the D2D relaying links (see Fig. 4b,c,e,f). For the sake of Fig. 4 simplicity, we illustrate the case, where each relaying link reuses resources of just one UE. Nevertheless, to increase the spectral efficiency, multiple D2D relaying links can reuse the resources of the same Cellular UE, or the same D2D relaying link can reuse the resources of multiple Cellular UEs.
- **Out-band relaying** – The D2D relaying links exploit *unlicensed* frequencies, such as those allocated to WiFi. Hence, QoS is hard to be ensured.

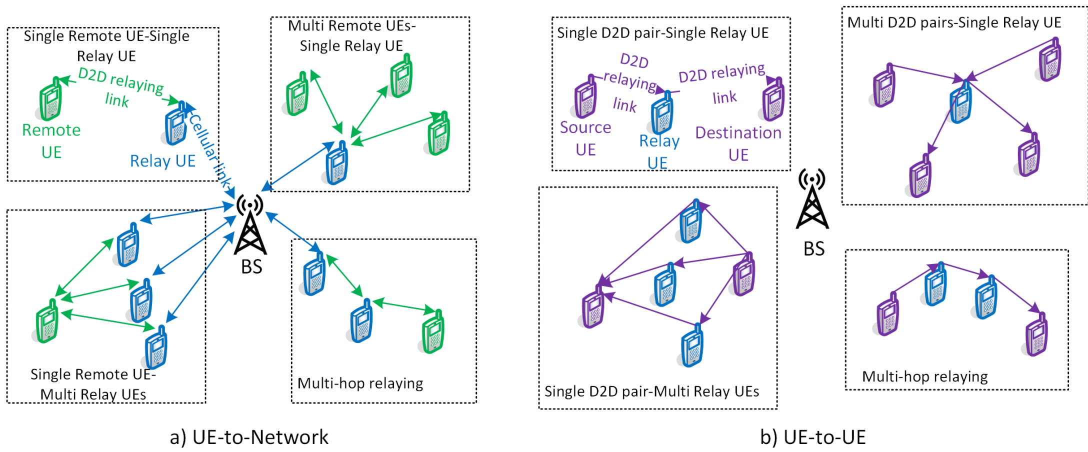

Fig. 5: Number of UEs involved in relaying.

3) Number of UEs involved in relaying chain

Another aspect of D2D relaying is to distinguish the number of Relay UEs and the number of Remote UEs[2] involved in the D2D relaying (see Fig. 5). According to the number of individual types of UEs, we distinguish the following cases:

- **Single Remote UE–Single Relay UE** – This is a "basic" relaying mode, where one Remote UE is helped by one Relay UE.
- **Multi Remote UEs–Single Relay UE** – In this case, one Relay UE serves multiple Remote UEs. This relaying case is very suitable for scenarios with significantly higher number of the Remote UEs compared to the number of potential candidate Relay UEs. Multiple Remote UEs served by single Relay UE is also of a benefit if the Relay UE has a very good channel to the BS, since the very good channel to BS makes the Relay UE potentially a good relaying candidate for multiple Remote UEs. Besides this relaying case is often exploited if the Relay UE is retransmitting multicast/broadcast content from the BS.
- **Single Remote UE–Multi Relay UEs** – This corresponds to the situation when Multiple Relay UEs serve single Remote UE. This is rather rare D2D relaying case due to overall energy consumption of all involved Relay UEs. Still, multiple Relay UEs serving single Remote UE can be of an advantage in deep fading scenarios, where each Relay UE participating in the relaying uses only a part of the bandwidth allocated for the relaying (e.g., only subset of available resource blocks or subcarriers).
- **Multi-hop relaying** – Similarly as in the previous relaying case, more than one Relay UE is exploited between the Remote UE and the BS. The main difference is, however, that data is relayed in a sequential manner in multi-hop relaying and the Remote UE sends data just to the first Relay UE in the communication path. The multi-hop relaying is convenient especially for coverage extension where the Remote UEs is at (or even beyond) a cell edge and, thus, it is helped by several Relay UEs to reach the BS.

[2]Note that for simplicity, we explain individual relaying cases only for UE-to-Network relaying. But all general explanations can be extended also to UE-to-UE relaying with only difference that the Remote UE would be substituted by D2D pair and the BS would be replaced by the Source/Destination UE.

Although the more advanced relaying cases with multiple Relay UEs or multiple Remote UEs can potentially bring more notable benefits than the "basic" relaying with just single Remote UE and single Relay UE, these are also more complex in terms of radio resource management. For example, if multiple Remote UEs are served by single Relay UE, the relaying gain can be affected by the number of served Remote UEs. Thus, during the relay selection, the most beneficial Relay UE for each Remote UE can change. The relay selection can be also complicated in the multi-hop relaying, as the selection of one Relay UE affects subsequently the selection of another Relay UE. Besides, the use of all advanced relaying cases basically results in more D2D relaying links to be managed (i.e., in UE-to-Network relaying, one D2D relaying link per each Remote UE-Relay UE connection). Consequently, the power and resource allocation is significantly more complex compared to the basic relaying case with just one Relay UE helping one Remote UE, especially if the D2D relaying links reuse resources of the Cellular UEs in the underlay mode (see Fig. 4) and interference between the cellular and D2D links needs to be managed.

B. Classification of relays

This section describes classifications of the Relay UEs considered in the works on D2D relaying from a perspective of adopted relaying protocols, duplex, whether the Relay UE is able to receive (transmit) data from (to) multiple sources (destinations) or not, and activity of the relaying user.

1) Relaying protocol

The Relay UEs can be classified according to an adopted relaying protocol to:

- **Amplify-and-Forward (AF)** – The received signal at the Relay UE is simply amplified and forwarded to the destination. The main advantage of the AF relaying is a low complexity, as nearly no processing is involved in the relaying itself [27]. As a result, the AF relaying is also characterized by a low energy consumption. The problem of AF relaying is, however, that the received noise (and potentially also interference) is amplified and forwarded to the destination. Besides, the AF relay requires a large memory to store the received signals with a high precision before forwarding [28]. The AF relaying is beneficial if the received signal at the Relay UE is significantly stronger than the received noise (plus interference) and/or if a low energy consumption at the Relay UE is required.

- **Decode-and-Forward (DF)** – The Relay UE using the DF relaying protocol first decodes and re-modulates the received signal before its retransmission to the destination. Hence, the DF relaying is superior in terms of the communication capacity in comparison to the AF relaying and, at the same time, the DF relaying does not require large memory as the AF relaying. However, the complexity of the DF relaying is significantly higher than that of the AF relaying resulting in a higher energy consumption of the Relay UE.
- **Quantized-and-Forward (QF)** – The Relay UE first quantizes and compresses the received signal before it is forwarded to the destination. The QF relaying is sometimes also called compress-and-forward, as the received signal is compressed before its retransmission [29]. The QF relaying is able to reduce bit error rate even without any coding by means of flexible setting of quantization level [30].

2) Duplex

Another classification of the Relay UE is according to the duplex. In this regard, the Relay UEs can work in:

- **Half-duplex** – The Relay UE first receives data from the source node (e.g., Remote UE or BS in case of the UE-to-Network relaying) during the first time slot (t_1 in Fig. 6). Then, the Relay UE forwards the received data to the destination node (BS or Remote UE) during the second time slot (t_2). The major advantage of the half-duplex can be seen in its low complexity. Nevertheless, the spectral efficiency is degraded, as two time slots are consumed to relay data between two nodes.
- **Full-duplex** – The Relay UE receives and transmits data simultaneously, thus, improves significantly the spectral efficiency compared to the half-duplex. Still, the full-duplex is plagued by a self-interference, i.e., by the interference caused from the transmitter to the receiver of the same device (see Fig. 6b,d). Fortunately, there are quite significant advancements in mitigation of self-interference making the full-duplex a promising option for the future mobile networks, such as 6G [31]. Moreover, it is worth to note that the full-duplex Relay UE cannot violate a "relaying causality", that is, the Relay UE can relay only already received data. Consequently, even the full-duplex Relay UE works in the half-duplex mode at the very beginning of a transmission session (to receive "first data" from the source while it has no data to retransmit) and at the very end of the transmission session (to relay the "last data" when the source node is already inactive).

3) Number of relaying directions

The Relay UE can be further classified depending on its ability to either receive (transmit) data from (to) single source (destination) or multiple sources (destinations) simultaneously. In this regard, we classify the relays into:

- **One-way relay** – This is a usual mode of operation when the Relay UE receives/transmits data just from one source at the moment (see Fig. 7a,c). Thus, in case of the UE-to-Network relaying, the Relay UE either retransmits data in DL or UL. Similarly, in case of the UE-to-UE relaying, the Relay UE forwards data from the Source UE to the Destination UE.
- **Multi-way relay** – This advanced mode of operation allows the Relay UE to receive/transmit data from/to multiple

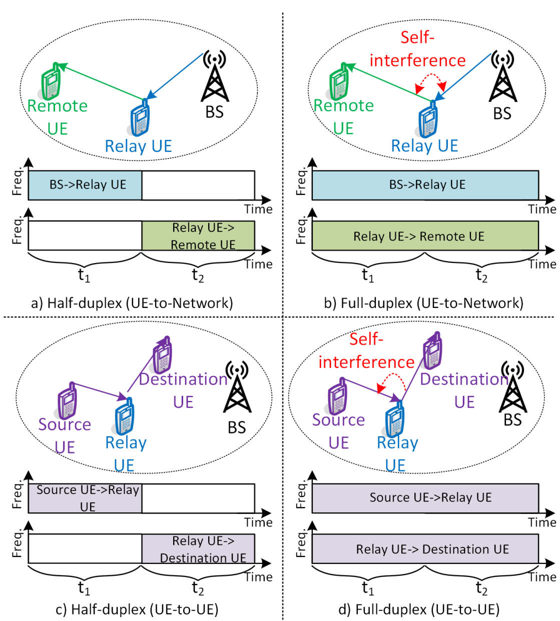

Fig. 6: Comparison of half-duplex and full-duplex relaying for DL transmissions.

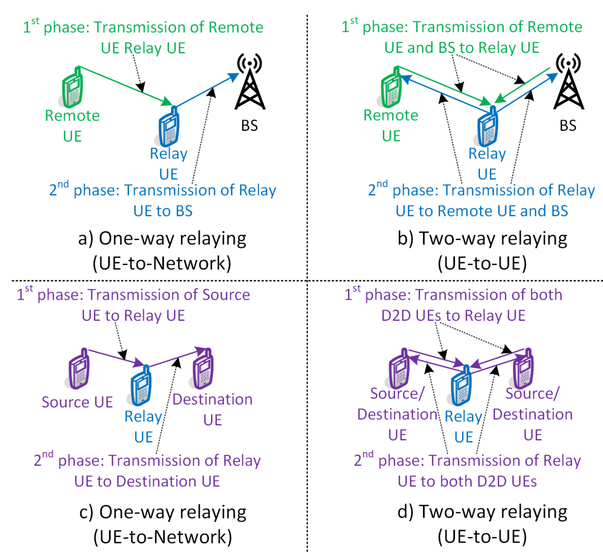

Fig. 7: Illustrative example of one way and multi-way relay in UE-to-Network and UE-to-UE relaying use cases. For simplicity, we show only two-way relaying that is commonly adopted in D2D relaying.

sources/destinations simultaneously. The works on D2D relaying usually adopts two-way Relay UEs where data is first received from both the BS and the Remote UE (in case of the UE-to-Network) or from both UEs of the same D2D pair (in case of the UE-to-UE) simultaneously (see Fig. 7b,d). Then, the Relay UE retransmits data simultaneously to both destination nodes (e.g, Remote UE and BS as shown in Fig. 7b). However, to enable two-way relaying, the Relay UE should support a physical-layer network coding (PNC) that requires more complex UE [32].

4) Activity of Relay UE

The last relay classification is according to the activity/inactivity of the Relay UEs. In particular, we distinguish:

- **Idle (inactive) Relay UE** – The relaying user is idle and has no own data to send/receive at the moment of relying. Thus, the whole power and radio resources can be dedicated for the relaying of data between two other communicating nodes. In practice, however, it may not be easy to motivate the idle Relay UE to retransmits data for others, as the consumed energy of the Relay UE is significantly increased compared to the idle state.
- **Active Relay UE** – The relaying user has own data to send/receive together with relayed data. Hence, it is necessary to determine whether the Relay UE is able to accommodate its own transmission while, at the same time, help other Remote UE(s)/D2D pair(s).

C. Optimization of D2D relaying

This subsection describes the radio resource management techniques to be optimized in order to smoothly incorporate D2D relaying into contemporary mobile networks. Furthermore, key performance indicators are outlined in this subsection.

1) Radio resource management techniques

Following four radio resource management techniques are usually addressed in the current state-of-the-art research (see Fig. 8):

- **Mode selection** - The mode selection decides whether the Remote UE (in case of the UE-to-Network relaying) or the D2D pair (UE-to-UE relaying) should be assisted by the Relay UE. The usage of the Relay UE is commonly beneficial if the Remote UE is either at the cell edge or out of the BS's coverage. In such case, the Relay UE can increase the BS's capacity or extend the BS's coverage. Similarly, the D2D pair may enjoy an assistance of the Relay UE if the Source UE and the Destination UE either would like to improve their performance or if they are far from each other and direct communication is not feasible.
- **Relay selection** – If the relaying is required to improve the performance of the Remote UE or the D2D pair, an appropriate Relay UE should be selected. The relay selection depends on many parameters, such as the relaying gain enabled by the Relay UE, power/energy consumption of the UEs in the relaying chain, remaining battery state of the Relay UE, its buffer state, etc.
- **Power allocation** – The power allocation manages the allocation of the transmission power at the transmitting node, i.e., at the BS and UEs. The power allocation targets to improve the performance of all UEs (e.g., their throughput, energy consumption, etc.) and, at the same time, to mitigate interference among UEs provided the same radio resources are exploited by them. Hence, the power allocation is especially critical in the underlay relaying mode, where mutual interference between the D2D relaying links and the cellular links should be mitigated (see Section II-A2).
- **Resource allocation** – The resource allocation determines which "physical" radio resources of the BS (e.g., channels or resource blocks in orthogonal frequency division multiple access) are allocated to the cellular and D2D relaying links. Similarly as the power allocation, also the resource allocation is of a high importance in the underlay relaying mode, where the aim is to select the radio resources that are reused by each D2D relaying link (see Fig. 8d, where the Remote UE reuses resources of the Cellular UE2 to transmit its data to the Relay UE).

The individual radio resource management technique can be handled centrally by the BS or in a distributed way by the UEs. The centralized solution is often highly demanding in terms of signaling, as the BS should have full knowledge of the channels among all involved users (i.e., full channel state information). In contrast, the distributed solution often leads to sub-optimal performance.

2) Key performance indicators

The objective of the radio resource management is to enhance the system performance that is typically measured in terms of following common key performance indicators in the research works on D2D relaying:

- **System capacity** – The system capacity (measured in bits/s) represents the sum capacity of all UEs in the system.
- **Spectral efficiency** – The spectral efficiency (bits/s/Hz) corresponds to the amount of bits transmitted per one second and per one Hz of bandwidth.
- **Network coverage** – The network coverage refers to the area covered by the BSs or by the RSs. The coverage itself can be defined by several parameters such as, required received signal strength from the BSs, required signal to noise ratio (SNR) or signal to interference and noise ratio (SINR), required bit rate, and required bit error rate or block error rate.
- **Outage probability** – The outage probability is related to the network coverage and represents the probability that the UE is out of the network coverage.
- **Power/energy consumption of UE** – The power or energy consumption of the UE (measured in W or J, respectively) encompasses the consumption of the signal processing part, radio communication part, and communication circuitry part [33].
- **Power/Energy efficiency** – The power or energy efficiency stands for the number of bits transmitted while consuming a certain amount of power/energy, usually measured in bits/W [34] or bits/J [35].
- **Delay** - The delay is composed of several components: *(i)* queuing time representing the time a packet is waiting in a buffer of BS, Remote UE, Source UE, or Relay UE [36],

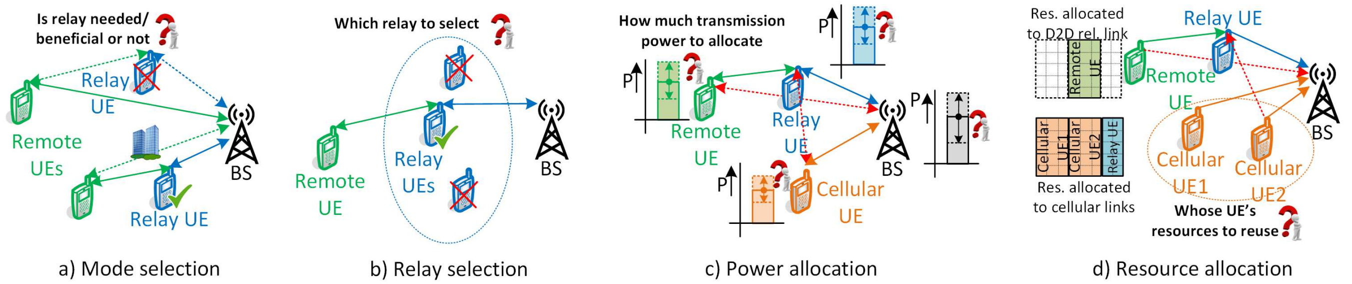

Fig. 8: Illustrative example of radio resource management techniques for UE-to-Network relaying. The radio resource management for UE-to-UE is analogous to UE-to-Network relaying, but Relay UE acts as go-between Source UE and Destination UE.

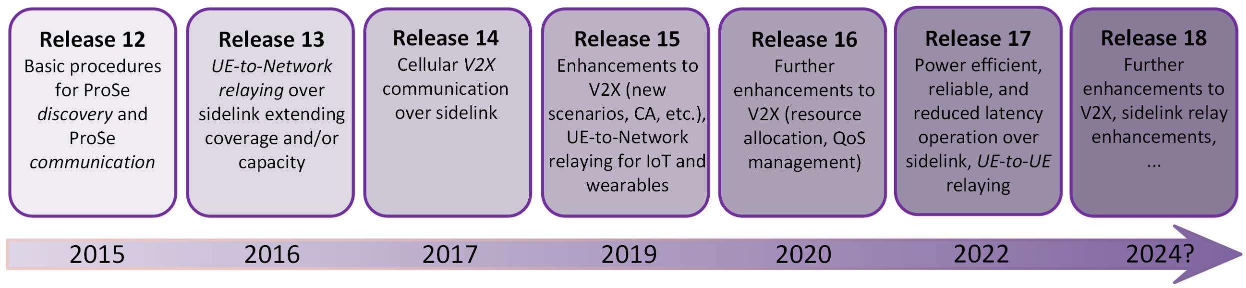

Fig. 9: The evolution of D2D communication in 3GPP standardization.

(ii) a processing time at the Relay UEs, such as the time needed for decoding/coding at the Relay UE (in case of DF relaying protocol), and *(iii)* transmission time.

III. Standardization of D2D Relaying in 3GPP

The standardization of the D2D communication in the 3GPP is a key step in promoting and implementation of the D2D relaying into the mobile networks. This section first describes an evolution of the D2D communication within 3GPP (Section III-A). Then, we briefly depict the D2D relaying scenarios envisioned by the 3GPP (Section III-B) and we explain types of the relays expected to be supported in the 3GPP standards (Section III-C). Finally, we outline the process of the relay link establishment and maintenance in Section IV-D.

A. Evolution of D2D communication in 3GPP

The D2D communication was introduced into 3GPP standards for the first time in ***Release 12*** in 2015 by means of a proximity-based services (ProSe) [37][38] (see Fig. 9). The ProSe enables the direct communication of two UEs in proximity using a new PC5 interface, thus, bypassing the BS and offloading its traffic. Note that the D2D link between the UEs is often referred to as a sidelink in 3GPP terminology. Release 12 defines basic procedures enabling ProSe discovery and ProSe communication. While the purpose of ProSe discovery is to find UEs that can potentially communicate with each other directly, the objective of ProSe communication is to establish and maintain the direct communication via a sidelink.

In 2016, 3GPP organization came up with ***Release 13*** enhancing ProSe/D2D by relaying capabilities via the UE-to-Network relaying use-case [39]. It is worth to mention that the UE-to-Network relaying would not be possible without the ProSe, as the communication between the Remote and Relay UEs is facilitated by the sidelink using the PC5 interface.

Further evolution of D2D/ProSe within 3GPP is a more radical one as ***Release 14***, approved in 2017, extends an applicability of the D2D communication to the vehicle-to-everything (V2X) communication through the PC5 interface [40]. The V2X encompasses vehicle-to-vehicle (V2V) enabling cooperative automated driving, vehicle-to-infrastructure (V2I) facilitating communication of vehicles with infrastructure (e.g., with the BSs), and vehicle-to-pedestrian (V2P) communication. The V2X is designed to satisfy the latency requirements of high speed vehicles and to combat Doppler effect [41]. Regarding the D2D relaying, new study on further enhancements of the UE-to-Network relaying for Internet of Things (IoT) and wearables is initiated [42]. Still, at this stage, the study only defines several initial scenarios and requirements specific for IoT devices and wearables, such as requirement on low power consumption, low device complexity, or coexistence with public safety UEs.

Release 15, approved in 2019, continues with the development of V2X communication over the sidelink including support of V2X services in safety and non-safety scenarios [43], the use of new bands, and carrier aggregation for sidelink [44]. Release 15 also significantly enhances the architecture for the UE-to-Network relaying by addressing several key issues including security (authentication/authorization), relay discovery and selection, service continuity, idle mode operation, or support for emergency calls [45][46]. In addition, Release 15 also elaborates more on an enhancement of UE-to-Network

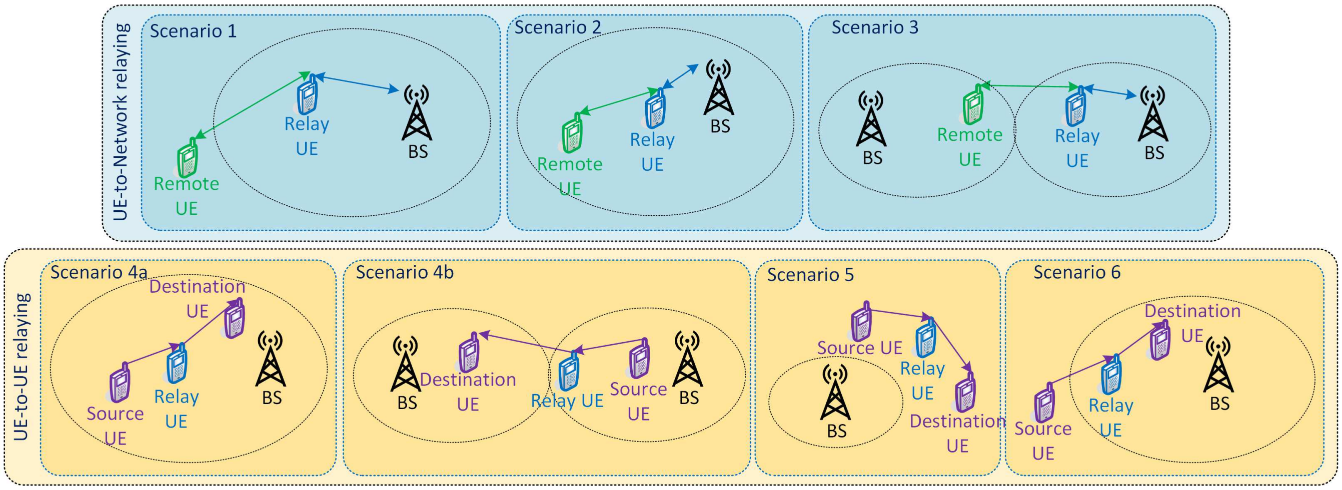

Fig. 10: Relaying scenarios supported by 3GPP [50].

relaying and studies/analyzes both discovery and communication performance while taking specific requirements of IoT devices and wearables into account [47].

The evolution of D2D/ProSe also continues within ***Release 16*** finalized in 2020. Most of the effort is dedicated to further improvement of V2X communication, such as enhancements for advanced V2X use cases, resource allocation, and QoS management [48]. Note that there is no substantial work on the UE-to-Network relaying at this stage.

The further evolution of D2D communication within 3GPP continues in ***Release 17*** approved in 2022. The previous releases support "always-on" sidelink operation, which is acceptable for the UEs with a sufficient battery capacity, but this kind of operation is not suitable for the UEs with limited battery capacity in many public or commercial use cases. Thus, one of the enhancements delivered by Release 17 is the reduced energy consumption during the sidelink operation [49]. Besides, a low reliability and high latency (e.g., due to high load) limits often operation over the sidelink. To this end, the objective of Release 17 is to significantly improve reliability and to reduce latency towards URLLC (Ultra-Reliable Low-Latency Communication) type of applications [49]. Moreover, Release 17 also introduces significant enhancements to the relaying over the sidelink, including relay discovery, relay (re-)selection, and authorization [50]. Also, it defines an architecture and a protocol stack not just for the UE-to-Network relaying, but also for the UE-to-UE relaying use-case.

Since the work on Release 17 has been finalized, there is already identified a tentative plan with priority items towards ***Release 18*** [51], expected to be completed during 2024. In case of D2D communication, further enhancements of V2X communication to enable vertical applications are expected. Besides, sidelink relay enhancements are also expected in terms of radio resource control.

B. 3GPP D2D relaying scenarios

In Section II-A, we have described several general relaying cases differing in the number of Remote UEs (D2D pairs) and the number of Relay UEs involved in the relaying. The 3GPP further distinguishes several relaying scenarios depending on whether the users involved in the relaying are in the coverage of BS or not (see Fig. 10) [50]. In case of the UE-to-Network relaying, following scenarios are envisioned by 3GPP:

- ***Scenario 1*** – The Relay UE is in coverage of the BS while the Remote UE is out of the BS's coverage. Hence, this scenario represents a coverage extension, as the users far away from the BS can still communicate with the BS via an intermediate Relay UE.
- ***Scenario 2*** – Both the Relay UE and the Remote UE are in coverage of the same BS. The Remote UE is at the cell edge, thus, with a low channel quality. Hence, the Relay UE enhances the capacity and/or decreases the energy consumption of the Remote UE.
- ***Scenario 3*** – The Relay UE and the Remote UE are under coverage of different BSs. Consequently, this scenario is suitable for a load balancing among adjacent BSs or for an energy saving via switching off an underutilized BS during a light traffic load period(s).

Similarly, also the UE-to-UE relaying is assumed by 3GPP to be exploited in following scenarios, mostly analogical to the UE-to-Network relaying:

- ***Scenario 4*** – All UEs involved in the relaying (i.e., Source UE, Destination UE, Relay UE) are under coverage of the BS. This scenario can be divided into two sub-scenarios with: *(i)* all UEs in the coverage of the same BS (***Scenario 4a)*** and *(ii)* the UEs in the coverage of different BSs (***Scenario 4b***). Both scenarios help facilitating D2D communication between Source and Destination UE to offload traffic from the BS(s).
- ***Scenario 5*** – All UEs are out of the BS's coverage. This scenario is tailored for public safety situations and use cases, e.g., if a disaster disables all BSs in the vicinity of the users.
- ***Scenario 6*** – Either Source UE or Destination UE is in coverage of the BS while the other UE is out the BS's coverage. Fig. 10 shows just one example, where the Destination UE and the Relay UE are in coverage while the Source UE is out of coverage. This scenario is

again profitable if both Source UE and Destination UE are not able to ensure reliable D2D communication or just to improve their performance.

C. Relay types

In Section II-B, various classifications of the relays are outlined from the perspective of the relaying protocol, duplex, and activity of the relaying users. On top of this, the 3GPP in Release 17 also defines the relays depending on the supported (sub)-layers in the protocol stack to:

- ***Layer-2 Relay UE*** – This type of relay is specified for both UE-to-Network and UE-to-UE relaying (see Fig. 11). The Relay UE covers only bottom two layer according to the open systems interconnection (OSI) model including physical (PHY) layer, medium access control (MAC) layer, and radio link control (RLC) layer. Besides, also adaptation layer (Adapt) is included on top of RLC to enable exchange information between RLC channels [50].
- ***Layer-3 Relay UE*** – Compared to the Layer-2 Relay UE, the Layer-3 Relay UE includes additional sub-layers from the protocol stack including packet data convergence protocol layer (PDCP), service data application protocol layer (SDAP), and protocol data unit layer (PDU) sub-layers. The SDAP is a new sub-layer introduced in 5G new radio (NR) to manage QoS. The protocol stack for the Layer-3 Relay UE in the UE-to-UE relaying is not available at this moment in 3GPP. Thus, Fig. 11b depicts only the UE-to-Network relaying between the Remote UE and the BS.

D. Process of relaying establishment and maintenance

This subsection describes the process during which the D2D relaying link (i.e., sidelink) is being established and subsequently maintained. This process includes following steps:

- ***Authorization and provisioning*** – At the beginning, authorization of the UE and identification of its role in the relaying (either the Relay UE or the Remote UE) is done.
- ***Relay discovery and selection*** – After the authorization is done, the Relay UEs are discovered by means of a physical sidelink discovery channel (PSDCH). The 3GPP defines two models for relay discovery, Model A and Model B. In the Model A, the Relay UE periodically announces its presence by broadcasting a discovery message. Contrary, in the Model B, the Remote UE sends its own request in order to find the available Relay UEs in communication proximity while the Relay UEs answer to this request. The potential Relay UEs are those whose response message is received with a satisfactory strength [52]. The relay discovery via the Model B takes 2-4 times longer than the relay discovery via the Model A depending on parameters setting, as demonstrated in [53][54]. However, the Model A reduces a signalling overhead and presumably also an energy consumption of the Relay UEs. It is worth to note that 3GPP does not specify any concrete relay selection process, which is out of standardization scope.
- ***Relaying link establishment*** – When a suitable Relay UE is found, establishment of the D2D relaying link is done over the PC5 interface that is commonly used for any D2D link in 3GPP, as defined in Release 12 [55].
- ***IP configuration*** – During this step, an IP configuration of the established relaying link is done using either IPv4 or IPv6.
- ***Data transmissions and resource management/allocation*** – Once the relaying link is established and IP is configured, data can be transmitted in both relaying link directions over a physical sidelink shared channel (PSSCH). The management and allocation of resources exploiting PSSCH is done by a physical sidelink control channel (PSCCH). In particular, the BS allocates specific pool of resources for the sidelink operation within the data frame (i.e., specific amount of physical resource blocks in each subframe). Then, the allocation of these resource blocks is done in two modes. In *mode 1*, the BS centrally indicates resources to be used for the UE exploiting sidelink (targeted for the case, where the UE accessing the resources is within the BS's coverage). In *mode 2*, the UE selects the pre-allocated resources from the resource pool by itself, hence, this mode can be used even if the UE is out of BS's coverage.
- ***Relaying link maintenance and channel estimation*** - During the data transmissions over the sidelink, it is also necessary to maintain the connection as users are usually changing their positions. As a result, the relay re-selection process needs to be initiated if the received signal strength at the D2D relaying link drops below a preconfigured threshold due to deteoriated channel quality [56]. To this end, the estimation of D2D relaying link channel quality is done through demodulation reference signals transmitted within PSSCH (see [44]).

IV. In-band UE-to-Network relaying

This section overviews the works focused on in-band UE-to-Network relaying, where the Relay UE acts as a go-between the UE and the network while exploiting in-band frequency resources. This section is organized in the following way (illustrated also in Fig. 12). First, we overview the works focused on a "basic" relaying case with single Remote UE being helped by single Relay UE (Section IV-A). After that, we target studies contemplating "advanced" relaying cases, that is, single Relay UE assisting multiple Remote UEs, multiple Relay UEs helping one Remote UE, and multi-hop relaying (Section IV-B). Notice that these advanced relaying cases are significantly more complex in terms of radio resource and/or interference management. Besides, we also discuss several practical use-cases of the UE-to-Network relaying in mobile networks (Section IV-C). Last, we compare the existing research works from several key perspectives and identify their gaps and limitations (Section IV-D).

A. Basic relaying case

This subsection overviews first the works on the UE-to-Network relaying assuming a *single-cell* scenario (Section IV-A1). Further, we focus on several works extending the

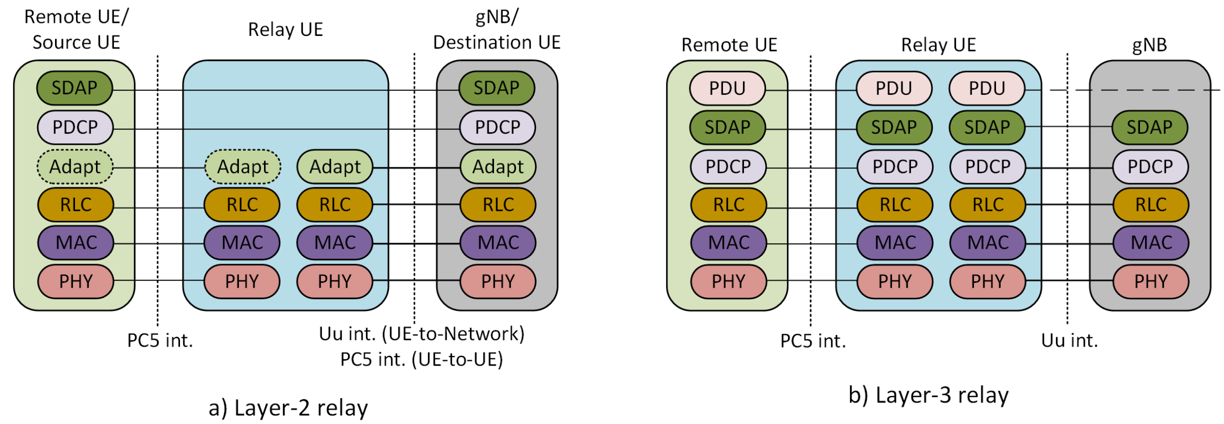

Fig. 11: Protocol stack for layer-2 and layer-3 relays according to [50]. The PC5 interface represents interface between the Remote/Source UE and Relay UE while Uu interface is used between Relay UE and BS.

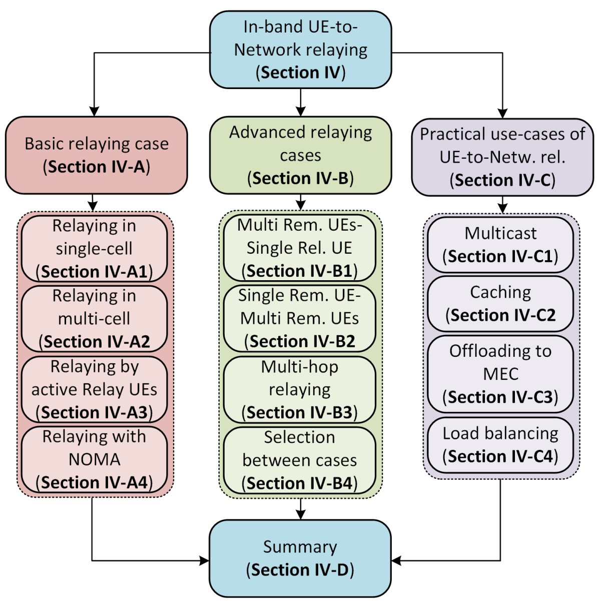

Fig. 12: Structure of Section IV.

single-cell scenario to *multi-cell*, where interference from neighboring cells impacts radio resource management for D2D relaying (Section IV-A2). Moreover, Section IV-A3 targets the works assuming active Relay UEs, as the activity of the Relay UEs affects the radio resource management. Finally, Section IV-A4 is dedicated to D2D relaying exploiting non-orthogonal multiple access (NOMA), since NOMA brings a new aspects that need to be addressed, including transmission power allocation among the users, pairing of users, etc.

1) Relaying in single-cell

One of the pioneering works in the area of UE-to-Network relaying is [57]. This study has been quite ahead of 3GPP standardization, which at that time just approved the use of Fixed RSs in Release 10 (as mentioned in Section I). The authors of [57] argue that the Relay UEs can significantly increase the network capacity and coverage to cut the infrastructure's cost and operational expenses implied by the BSs' densification, as expected in 5G and beyond networks [58]. The authors propose a simple relay selection scheme, where all idle UEs with path loss less than 105 dB to the Remote UEs are assumed to be the candidate Relay UEs. Then, the candidate Relay UEs are further ranked based on a long term path loss measurement and assigned to the Remote UEs in a greedy way so that the candidate Relay UE providing the highest throughput is always selected. The proposed greedy scheme improves the capacity of Remote UEs by more than 200% (in DL) and more than 300% (in UL) while the coverage is expanded by up to 20%.

The encouraging results shown in [57] give a motivation to further investigate benefits of the UE-to-Network relaying. Hence, in [59], the authors propose a joint relay selection and resource allocation scheme maximizing the capacity and extending the network coverage. The proposed solution exploits opportunistic network architecture with the UEs managing both the relay selection and the spectrum allocation in a cognitive radio fashion [60]. Following functional components of the proposed framework are considered:

- *Context aware entity* - The purpose of this entity is to: *(i)* discover the potential Relay UEs by sending "*hello*" messages and monitor responses from potential Relay UEs, *(ii)* identify available spectrum exploiting spectrum sensing and dynamic spectrum management, and *(iii)* monitor achievable capacity of individual D2D relaying links.
- *Knowledge management entity* - The entity exploits Q-learning approach to learn from past experiences when the Remote UE selected Relay UE while utilizing a specific frequency resources.
- *Decision making entity* - The entity responsible for the relay selection and spectrum allocation based on the inputs from the knowledge management entity exploiting softmax decision policy [61].
- *Control entity* - This entity manages the interaction among individual entities.

The proposed framework discussed above outperforms a random relay selection strategy by 200% in terms of the capacity while performing only by 1.4% worse than the optimal solution.

The joint relay selection and resource allocation is also considered in [62]. The authors maximize the system capacity and limit the interference between the D2D relaying links and the cellular links (each D2D relaying link is assumed to reuse resources of just one Cellular UE). In order to solve the defined problem, the paper adopts two-level game model. In the inner level, the Stackelberg game manages the relay selection and transmission power allocation for the Relay UEs. In context of the Stackleberg game, the Relay UEs are leaders while the Remote UEs are followers. In the outer level, the coalition formation game is applied to allocate the radio resources between the individual D2D relaying links. The relay selection and the spectrum allocation are affected by the price of the Relay UEs' power consumption so the idle Relay UEs helping others do not deplete their battery significantly. The proposed scheme improves the capacity by up to 15% when compared to no relaying case (i.e., all Remote UEs transmit data directly to the BS). Unfortunately, the paper does not show a convergence of the iterative Stackelberg algorithm to give an insight into its applicability in real networks.

Besides maximization of the system capacity and/or coverage, the UE-to-Network relaying can also significantly reduce the energy and/or power consumption of the Remote UEs. The minimization of the transmission power consumption via mode selection is the main objective of the authors in [63]. In this regard, an idle user acting as the Relay UE is exploited only if the total power consumption of the Remote and Relay UEs is lower than the power consumption of the Remote UE transmitting data directly to the BS. The authors first propose a tractable analytical approach to model the relay selection based on the minimal transmission power through stochastic geometry. Then, closed form expressions of the outage probability and the average transmission power are derived. The probability the relay is selected decreases if the distance between the Relay UE and the Remote UE increases (from 50% to 35% if the distance increases from 0 to 30m). The reason is that with the increasing distance between the users, the probability that the total transmission power is decreased due to the relaying is lowered. Although the paper proposes a power efficient relay selection, this is of benefit only to the Remote UE, not the *idle* Relay UE. The idle Relay UE, on the other hand, always increases its energy consumption when helping others with respect to no relaying case.

The objective to minimize the total energy consumption of all Remote and active Relay UEs, while guaranteeing the minimum data rate to each, is assumed in [64]. The authors formulate a joint transmission mode selection, relay selection, and power allocation at the UEs. The defined problem is a mixed integer nonlinear programming (MINLP) problem that is NP-hard and, thus, hard to be solved in polynomial time. Therefore, the original problem is transformed to a weighted one-to-one matching problem using bipartite graph. The weight represents the amount of reduced transmission power if the Remote UE is matched with one of the Relay UE. Subsequently, the matching problem is optimally solved by Hungarian algorithm. The proposal decreases the energy consumption more than two times compared to the case without relaying.

The UE-to-Network relaying can be also used to increase the energy efficiency of the network. To this end, the authors in [65] aim to achieve an energy efficient and proportional fair environment among the users through a relay selection adopting symmetry pairing theory. The relay selection is done in an iterative way as follows. First, each Remote UE stores the list of potential idle Relay UEs that are able to increase its throughput. Similarly, each Relay UE has a list of potential Remote UE(s) to whom it can help. Then, in the first round, each Remote UE sends a request to the Relay UE providing the highest gain according to its estimation. When individual Relay UEs receive these requests, each selects single Remote UE according to their priorities. In the second round, the Remote UEs still not paired with any Relay UE proceed in the same fashion as in the first round. The whole process is repeated as long as there is at least one available Relay UE or as long as there is at least one Remote UE still not paired with any Relay UE. If the number of available Relay UEs is much higher than the number of the Remote UEs, energy efficiency is increased roughly by 50% compared to the case where only 10% of all users are the Relay UEs.

2) *Relaying in multi-cell*

Thus far, all papers assumed the scenario with just single cell, i.e., without considering inter-cell interference. The inter-cell interference, however, plays a crucial role in both the relay selection and resource allocation. Especially, the Remote UEs situated at the cell edge may be experiencing quite strong interference from adjacent cells.

A thorough coverage probability and ergodic data rate analysis of multi-cell multi-channel DL cellular network using stochastic geometry is delivered in [66]. The authors first determine analytically the probability of the UE being communicating directly with the BS (if the received signal strength from the BS is above the threshold β) and the probability of the communication through intermediate Relay UE. Several interesting following findings are observed:

- The probability that the UE will exploit intermediate Relay UE increases first with β and, then, it starts decreasing. The initial increase in probability that Remote UE uses the Relay UE to reach the BS is due to the fact that Remote UE is not able to receive signal from the BS with required strength, thus, a help from the Relay UEs is necessary. With further increase of β, however, the probability that Remote UE is able to utilize one of the Relay UEs decreases, since less and less UEs (even those close to the BS) are able to receive signal from the BS with enough strength.
- If the transmission power of the BS increases, the probability that the Remote UE exploits the Relay UE follows similar trend as with the increase of β. The initial increase is due to the fact that there are more available potential Relay UEs in the cell. Then, at a certain point, further increase in the BS's transmission power decreases the probability that the Remote UEs need a help from the Relay UEs in the first place.

Then, the authors in [66] also perform an analysis of the coverage probability and ergodic data rate for two basic channel assignment schemes: *(i)* random channel assignment and *(ii)* sequential channel assignment, where the channel with index n_{i+1} is assigned to the cellular link right after the channel with index n_i. The numerical results show the outage probability and/or data rates of the system with and without UE-to-Network relaying depending on various parameters, such as β, transmission power of BSs and UEs, or density of BSs and UEs. The results demonstrate that if β and the transmission power of BSs and UEs are tuned properly, the coverage probability can be increased by tens of percent due to the use of Relay UEs. Moreover, the ergodic data rate is increased roughly by up to 30% if the Relay UEs are exploited.

While [66] analyzes benefits of the UE-to-Network relaying for DL, the paper [67] further analyses the coverage probability and the average data rates in UL under fractional channel inversion uplink power control. Similarly to [66], the paper first derives the probability with which the UE communicates directly with the BS and the probability that the Relay UE is used to help the Remote UE reaching the BS depending on β and the transmission power of UEs. Then, a complementary cumulative distribution function of SINR for both cellular and D2D relaying links is derived together with the coverage probability and the average rate. The numerical results validate the superiority of the system performance with the UE-to-Network relaying compared to the conventional cellular communication without relaying provided that β is tuned well together with the transmission power of the UEs. In particular, the coverage probability is increased by tens of percent with respect to the case without relaying (roughly up to 30% if maximum allowed distance between the Remote and Relay UEs is 60 m). Similarly, the average data rate is improved by approximately 40%.

The performance of uplink UE-to-Network relaying in multi-cell scenario is further analyzed in [68]. The authors derive probability density function of the cellular transmission power (i.e., the Cellular UEs and Relay UEs transmitting to the BS) under channel inversion power control. Afterward, the probability that the received power at the BS (for the cellular transmission) and at the Relay UE (for the D2D transmission) is above a specified threshold is obtained. Then, similarly as in [67], the complementary cumulative distribution function of SINR of the cellular and D2D relaying links is derived together with the coverage probability and the ergodic rate of the cellular and D2D transmissions. The simulation results uncover a fact that the number of channels allocated for the D2D communication (out of all available channels) can fairly optimize both the coverage probability and the average rate of the system. The reason is that although the coverage probability and data rate of D2D transmission increases with the number of channels allocated for the D2D, the cellular transmissions are negatively affected, as less channels is available for it.

The problem of throughput maximization in multi-cell case is addressed in [69]. First, the authors analyze an achievable throughput for a simple setting with fixed Remote UE and BS while the position of the Relay UE is changing. The analysis shows that the optimal position of the Relay UE is in the middle between the Remote UE and the BS. Then, a joint relay selection and resource allocation algorithm is proposed aiming to allocate a proper amount of radio resources to each user. The algorithm allocates resources first to the user having the highest path loss to the BS, second to the user with the second highest path loss, and so on until all users are served. The proposal improves the capacity of the Remote UEs by more than 300%, but at the cost of a slight decrease (3.8%) in the average system capacity.

The multi-cell case is further considered in [70], where quality of experience (QoE) of the users is enhanced by means of software defined networking (SDN) architecture. The proposed architecture consists of: *(i)* data plane with the BSs and the UEs, *(ii)* control plane encompassing application modules for mobility management, resource allocation, load balancing, and routing setup, and *(i)* SDN controller. Whenever the UE can not be served directly by any BSs in its vicinity (either in DL or in UL), it is served by the Relay UE that is already connected to the BS if an appropriate Relay UE can be found. The relay selection and an establishment of D2D links are managed by control plane modules. The authors also discuss several research challenges of the proposed framework, e.g., a stability of D2D links, incetivization of the Relay UEs, or privacy issues. Then, the simulations demonstrate that the QoE of users measured by mean opinion score (MOS) can be increased by more than 1 (on the scale from 1 to 5) for various users' densities and various required signal to interference ratios.

3) Relaying by active Relay UEs

As explained in Section II-B, the Relay UEs are not always idle at the moment of relaying, as considered so far, but can have own data to be sent/received affecting the radio resource management. Hence, besides the energy consumption of the Relay UEs, also QoS requirements of the Relay UEs should be taken into account.

The active Relay UEs are assumed in [71], where the UEs with favorable channel quality from the BS can help the Remote UEs. The Relay UE receives data from the BS in one time slot and, then, retransmits data to the Remote UE in another time slot. The objective of the paper is to maximize the network throughput by determining the resource allocation and the transmission intervals of the BS and all Relay UEs. The problem is decomposed into two simpler sub-problems: *(i)* active time reuse pattern selection and *(ii)* resource allocation. The first sub-problem is solved centrally by Frank-Wolfe method [72] assuming all channels are known at the BS. Since the problem is convex, common convex optimization technique CVX in Matlab [73] is used. Then, the second sub-problem is formulated as one consensus-building problem [74] solved in a distributed way by implying the alternating-direction method of multipliers [75]. The proposed algorithm iteratively updates allocation patterns of all Relay UEs and the BSs until a network-wide consensus on the resource allocation is reached. The throughput of the UEs is increased more than 10 times compared to the case without the relaying and 80% of the UEs reach a higher throughput than the one provided by the scheme without relaying. However, the algorithm typically converges after 500 iterations, which may limit its applicability in a dynamic scenarios.

The active Relay UEs are considered also in [36]. Both the Remote and Relay UEs operate in full-duplex, thus, the capacity can be theoretically doubled in comparison to half-duplex relays considered so far. Although the full-duplex is plagued by the problem of self-interference, this interference can be mitigated making the full-duplex an interesting choice for the UEs [76][77]. The authors in [36] formulate the relay selection problem as a stable marriage matching problem. In such problem, the Remote UEs are willing to be matched with the most profitable Relay UEs and vice versa. The Remote UEs rank the Relay UEs according to the following parameters: *(i)* throughput of the link between the Remote UE and the Relay UE), *(ii)* packet delay, *(iii)* amount of residual energy at the Relay UEs to ensure that these are able to forward reliably data, and *(iv)* buffer state of the Relay UEs. Similarly, the Relay UEs rank each Remote UE according to: *(i)* throughput derived in the same way as by the Remote UE, *(ii)* requirements of the Remote UE to assess volume of data to be re-transmitted, and *(iii)* benefit from the relaying. Then, the aforementioned parameters are weighted according to individual user's profile and requirements. Finally, the distributed matching algorithm based on Gale-Shapley matching is proposed to pair each Remote UE with at most one Relay UE. The proposal increases throughput by up to 70% and 186% compared to random and distance-based relay selections, respectively, while losing only 4.6% with respect to the optimal relay selection. A potential limitation of the proposed scheme is, however, that even the distributed approach generates relatively high signaling overhead, since the Remote UEs and the Relay UEs are expected to exchange information about their preferences.

The active relays are also considered in [78], where the aim is to select appropriate communication mode of each active user. To this end, the authors assume that the UEs have self-organization capabilities to reach pure and mixed Nash equilibrium. Then, two decentralized reinforcement learning algorithms are proposed: *(i)* linear reward-inaction algorithm to learn pure Nash equilibrium and *(ii)* Boltzmann–Gibbs-Based Payoff-reinforcement learning algorithm [79]. The simulation results investigate the convergence of the proposed approach which, however, often takes more than 1000 iterations.

4) Relaying with NOMA

This section reviews the works, where NOMA is adopted to boost the performance of the UE-to-Network relaying. The NOMA leverages from the concepts of superposition coding at the transmitter and successive interference cancellation (SIC) at the receiver [80]. This way, NOMA allows transmitting data to several users over the same radio resources.

The principle of the UE-to-Network relaying with NOMA is shown in Fig. 13. The transmission to the users occurs in two consecutive phases. In the first transmission phase, the BS sends a superposed signal to both the Relay UE and the Remote UE. Since the Remote UE has a role of the "far" user, more transmission power is allocated to the Remote UE than to the Relay UE. The transmission power allocated to the Remote and Relay UEs is determined by a splitting factor α). The Relay UE is considered to be a "near" user due to its superior channel quality to the BS. In the second transmission phase, the Relay UE decodes the signal from the BS using SIC and forwards data to the Remote UE. Finally, the Remote UE combines the received signals from both phases by means of maximum ratio combining (MRC) [81].

The NOMA exploited for the UE-to-Network relaying is considered in [82]. The objective is to maximize the capacity of both the Remote and Relay UEs by means of the power allocation splitting defined by α (see Fig. 13). The problem is analyzed for two cases: *(i)* data rate of the Relay UE is lower than that of the Remote UE and *(ii)* data rate of the Relay UE is higher than the data rate of the Remote UE. In the former case, the optimal solution cannot be found as the principle of NOMA would be violated, since the whole power should be allocated only to the Relay UE (i.e., capacity is maximized for $\alpha = 1$). In the latter case, however, the optimal solution maximizing the capacity is obtained considering the inequality constraints of the problem, where at least local optimum is reached using Karush-Kuhn-Tucker conditions and Lagrange multipliers. The sum capacity of the Relay and Remote UEs is increased roughly by up to 10% and 35% compared to the case with NOMA but without relaying and to the case with neither NOMA nor relaying, respectively.

While [82] assumes only one pair of users (one Relay UE and one Remote UE), the authors in [83] extends the problem to multi-user scenario. Hence, besides the power allocation between the Relay UE and the Remote UE (as managed by the authors in [82]), also a pairing of the Relay UEs with the Remote UEs is addressed. The joint power allocation and users pairing is mixed integer non-linear programming problem. The problem is decomposed into two sub-problems. The first sub-problem is to allocate the power for any two users being in the same pair with the objective to maximize the minimum capacity of both the Relay UE and the Remote UE. The optimal power is derived analytically using root finding method. The second sub-problem is to find the optimal pairing. Hence, the users' channel gains to the BS are first sorted from the lowest to the highest. Then, the first half of the users with relatively small channel gains are assumed to be the set of "far" users while the users from the other half creates the set of "near" users. Finally, the users from both sets are

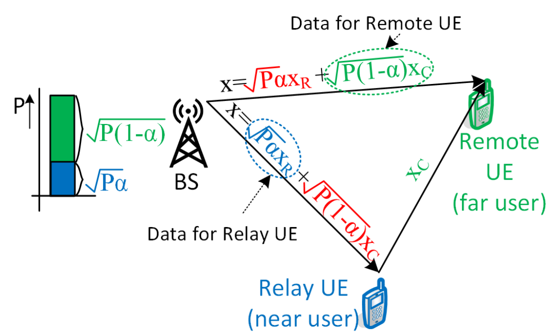

Fig. 13: Principle of the UE-to-Network relaying with NOMA
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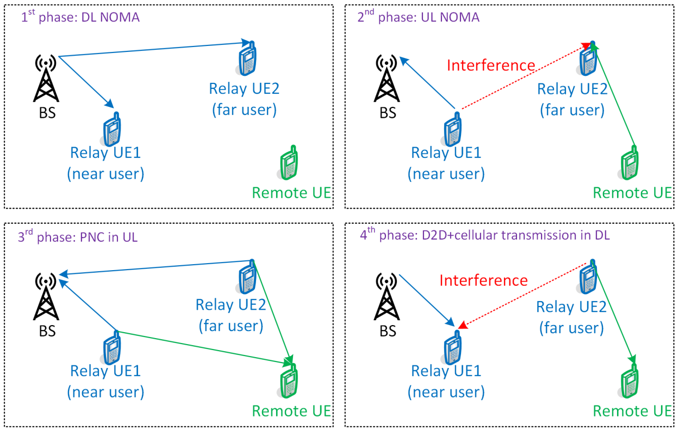

Fig. 14: The concept exploiting UL and DL NOMA for D2D relaying [84].

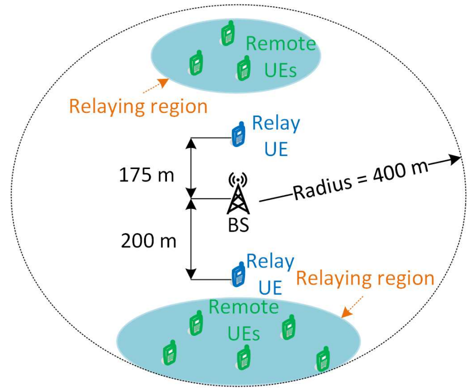

Fig. 15: The illustrative example of size and shape of the relaying region depending on BS-Relay UE distance [85].

matched together in a way that each user from the first set is matched with exactly one user from the second set. Since the problem leads to one-to-one matching, it is solved optimally by Hungarian method. The sum of minimum rates is increased up to approximately 130% compared to the conventional NOMA with relaying. Moreover, the proposed pairing outperforms also the state-of-the-art benchmark pairing scheme roughly by 20%.

While both previous papers assume solely DL NOMA for the relaying, a spectral efficient scheme combining DL and UL NOMA is proposed in [84]. The scheme is composed of four subsequent phases (see Fig. 14): *(i)* the BS transmits superposed signal to the Relay UE1 (near user) and the Relay UE2 (far user) in DL NOMA phase, *(ii)* the Relay UE1 transmits its UL data to the BS while the Remote UE sends its own data to the Relay UE2 during UL NOMA phase, *(iii)* the Relay UE1 and the Relay UE2 exploit PNC, i.e., the Relay UE1 sends both its own UL data to the BS and retransmits DL data for the Remote UE while the Relay UE2 retransmits both DL and UL data on behalf of the Remote UE, and *(iv)* the Relay UE1 receives another DL data from the BS while the Relay UE2 can send its own data to the Remote UE by means of D2D relaying link to further enhance the spectral efficiency of the system. The proposed concept enhances the average spectral efficiency roughly by up to 70% when compared to the case without NOMA.

B. Advanced relaying cases

All papers in the previous section assume basic relaying case with single Remote UE being helped by just one Relay UE. To fully exploit potential benefits of the UE-to-Network relaying, also advanced cases with multiple Remote UEs being helped by one Relay UEs or multiple Relay UEs helping one Remote UE should be considered. Of course, these advanced relaying cases add extra complexity to radio resource and interference management, as discussed in Section II-A3. In this section, we first survey the works focusing on the case where multiple Remote UEs use the same Relay UE simultaneously (Section IV-B1). Then, we also overview the works with single Remote UE exploiting multiple Relay UEs (Section IV-B2). Also multi-hop relaying, where more than two-hops transmission occur between the Remote and Relay UEs is addressed as well (Section IV-B3). Finally, we also describe an initial work selecting between the relaying cases in Section IV-B4.

1) Multi Remote UEs-Single Relay UE

A theoretical analysis of the relay coverage exploiting stochastic geometry while assuming that *one Relay UE* helps to retransmit data from the BS to *multiple Remote UEs* is provided in [85]. The objective of the provided analysis is to find a region, where the Remote UEs benefit from the relaying in terms of an increased throughput. Such relaying region is roughly of ellipsoid shape and its size depends on the position of the Relay UE with respect to the BS. The size of the relaying region increases if the Relay UE is farther from the BS (see Fig. 15). The reason is that the Relay UE's coverage depends on both the channel quality between the BS and the Relay UE and the channel quality between the Relay UE and the Remote UEs. The cell spectral efficiency first increases with the distance between the BS and the Relay UE (up to 0.5 bits/s/Hz gain when compared to no relaying). If the distance between the BS and the Relay UE, however, reaches a critical point, the spectral efficiency starts decreasing, since the channel quality between the BS and the Relay UE decreases as well making the link between the BS and the Relay UE a bottleneck.

A possibility to connect multiple Remote UEs via single Relay UE is also considered in [86]. The authors aim to maximize the DL throughput by an association of each Remote UE with the appropriate Relay UE (i.e., the relay selection). Since the defined problem is an integer programming and, thus, NP-hard, the authors solve the problem via an algorithm based on a hedonistic coalition game [87] composed of four steps. In the first step, the maximum number of Remote UEs allowed to be associated with the same Relay UE is derived. During the second step, each Remote UE selects several potential Relay UEs yielding the highest throughput gains. The proposed game is played in the third step, where each Remote UE is associated with the Relay UE with the aim to reach Nash equilibrium (i.e., state where switching any Remote UE to different Relay UE decreases the Remote UE's throughput). In the last step, an "admission control" is done ensuring that the number of Remote UEs per Relay UE does not exceed the maximum allowed number derived in the first step. The proposed algorithm increases the throughput by up to 10% and 27% compared to the most efficient competitive scheme and a traditional mobile network without relaying, respectively. The simulation results also show that the capacity is decreased roughly by 6% if the speed of UEs is increased from 1 m/s to 5 m/s.

2) Single Remote UE-Multi Relay UEs

The relaying scenario with *multiple Relay UEs* serving *one Remote UE* is considered in [88]. Such scenario can be especially of benefit if the users are moving, when the reliability of single Relay UE may be compromised. The problem of relay selection is defined as a partially observable Markov decision process, since only exact locations of the selected Relay UEs are assumed to be always known while the positions of not selected Relay UEs are not known to reduce signaling overhead. Since the whole problem is intractable and cannot be solved optimally for high number of users in the system, the authors propose a sub-optimal greedy algorithm based on point-based value iteration method [89] and prove its sub-modularity properties. The proposal offers throughput gain with respect to the no relaying up to roughly 55% and 30% for single Remote UE and multiple Remote UEs deployed in the system, respectively. Unfortunately, the authors do not discuss the approximation guarantees to the optimal relay selection.

3) Multi-hop relaying

The *multi-hop* relaying also assumes multiple Relay UEs serving one Remote UEs like the works presented in previous subsection, but the Relay UEs transmit data sequentially between the BS and the Remote UE. Such scenario is considered in [90]. The main objective of the paper is again to maximize the throughput. To this end, the authors propose a three-stage mechanism. In the first stage, the relay channel pre-allocation is done centrally at the BS to ensure that no adjacent hops in the communication path use the same channel. Moreover, the same channel cannot be used by the UEs close to each other to avoid co-channel interference. In the second stage, the power allocation at the BS and the Relay UEs is set using an ordinal potential game [91], where potential communication links are the players. The authors also improve game decision making process by reducing the size of action space (i.e., the set of transmission power levels) by binary search followed by sequential search. In the last stage, the relays are finally selected for each Remote UE in order to maximize the throughput while ensuring all Relay UEs in the relaying path have enough remaining energy and the transmission delay constraint is satisfied as well. The proposal increases average data rate by up to 30% with respect to competitive greedy algorithm. The impact of multi-hop communication on possible power consumption reduction is analyzed in [30]. While AF or DF are usually used as the relaying protocol at the Relay UE, the authors adopt the QF relaying protocol instead. In case of the QF protocol, the relay first quantizes the received signal and then forwards it to the next Relay UE or the BS. The QF is of a lower complexity than the DF but still more efficient than the AF (which also amplifies the noise, as explained earlier in Section II-C). The authors derive analytically transmission power consumption of the Remote and Relay UEs to ensure QoS (expressed by data rate and outage probability) for the Remote UEs. After that, a power efficiency, represented by the transmission power savings if the Relay UE(s) are exploited instead of the direct transmission, is also analyzed. The results indicate that the total transmission power can be reduced by up to 23%, 43%, and 53% if one, two, and three Relay UEs are used, respectively.

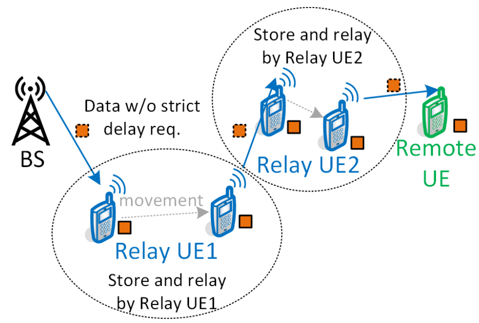

Fig. 16: The principle of store and forward relaying for data having no strict delay requirements [92]. The data is first send to the Relay UE1, which stores it and after some time (and distance covered) relay the data to the Relay UE2. Finally, the Relay UE2 opportunistically relay data to the Remote UE.

The multi-hop communication is addressed also in [92]. The paper analyses benefits of opportunistic networks with the Relay UEs first storing data and relaying it later (see Fig. 16). This "store and relay" data delivery is applicable only if data has no strict latency requirements. If data should be immediately forwarded to the Remote UE, either the conventional cellular mode (the BS sends data directly to the Remote UE) or the UE-to-network relay mode should be adopted. Thus, the authors select the communication mode, which should be used depending on the maximal delivery time when data is required by the Remote UE. Besides, the Relay UEs moving in the direction of the Remote UE are preferentially selected. The mode selection is based on BRISK scheme [93] balancing the benefits and the risks. While the benefits are represented by the gain introduced by exploiting the Relay UE(s), the risks stands for the probability that the expected benefits are not achieved. The results indicate that the proposed mode selection outperforms the conventional cellular communication without relaying by up to 125% in terms of throughput. Moreover, if the Relay UEs are moving in the direction of the Remote UE, the proposed "store and relay" mechanism may significantly (by up to 70%) decrease the energy consumption if compared to no relaying. The main reason is that the energy consumed by the transmissions is much larger than the energy consumed during the store and carry processes. This demonstrates that the mobility does not have to be always an obstacle (in contrast to [88], where the mobility impairs the system throughput), but it can actually be a helping factor in the opportunistic relaying of the delay-tolerant data.

4) Selection between relaying cases

The selection between individual relaying cases, that is, between the single Remote UE-Single Relay UE (e.g., [57]), the multi Remote UEs-Single Relay UE [85][88], and the multi-hop relaying [90][92] is considered in [94]. The paper exploits a distributed artificial intelligence-based solution capitalizing on a belief desire intention concept, where the UEs (agents) act independently and autonomously according to their best beliefs [95]. In such concept, each UE decides whether it should act as the Relay UE or rather being served by some of the Relay UE instead. The proposed scheme increases the spectral efficiency by 20% and 28% compared to the random mode selection and the conventional communication without relays, respectively.

C. Practical use-cases of UE-to-Network relaying

In general, the UE-to-Network relaying does not have to be used necessarily for transmission of conventional users' data (as contemplated in the previous sections), but it can improve the performance of multicast services, caching, make computation offloading to edge servers in multi-access edge computing (MEC) concept more efficient [96], or to smartly balance load among several cells.

1) Multicast services

In case of multicast services, the BS transmits the same content to the multiple UEs. If the UEs are far from the BS or if the signal from the BS is significantly attenuated due to obstacle(s) in the communication path, these UEs are not able to receive data correctly. This problem is addressed in [97], where the Relay UEs help to retransmit multicast data to the UEs with low channel quality to the BS. To this end, the UEs are classified into those who can decode data from the BS correctly (i.e., potential Relay UEs) and those who are not (i.e., the Remote UEs). The fundamental idea of the proposal is to select one or several UEs from the first group to act as the Relay UE(s) for the users from the second group. When the Relay UE retransmits data to multiple Remote UEs, the "worst" channel between the Relay and Remote UEs determines the efficiency of the retransmission. Thus, the authors propose an iterative sub-cluster partitioning algorithm in order to select a proper number of retransmitting Relay UEs, each retransmitting data to either single Remote UE or multiple Remote UEs. The proposed clustering decreases the retransmission cost by approximately 40% compared to the benchmark algorithm assuming just two Relay UEs help Remote UEs. A drawback of the approach proposed in [97] is that the Remote UEs are clustered with the Relay UEs only based on the channel quality between them. Hence, if the Remote UEs do not need retransmissions often, the created D2D clusters are underutilized.

The idea in [97] is enhanced in [98] so that the clustering algorithm does not consider only the channel quality, but also the number of lost packets of individual Remote UEs. The paper proposes a greedy "worst-out-first" algorithm that works in the following way. All Remote UEs not able to receive data directly from the BS are assumed to be potentially clustered with all available Relay UEs. Then, the Remote UEs are step-by-step weeded out from the clusters if the cost of the retransmission is too high until each Remote UE remains in just single cluster with the lowest retransmission cost. The proposed greedy approach outperforms the scheme introduced in [97] by up to 15% in terms of the normalized resource cost.

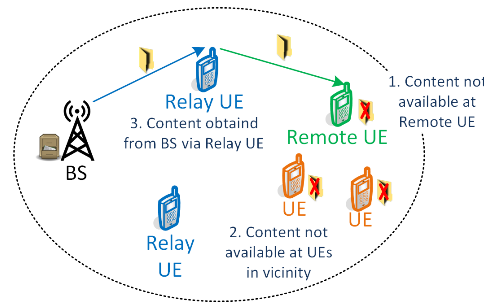

Fig. 17: Caching aided by UE-to-Network relaying [100].

2) Caching

The UE-to-Network relaying does not have to be used exclusively for transmission of conventional user data, but it can be also used to enhance the caching (see more information on caching, e.g., in [99]). In this sense, the relaying through other users is exploited whenever any active user is searching for some cashed content (e.g., video file) that is available at neither his/her own device nor at some inactive device in proximity [100]. In such a case, the cashed content is requested directly from the BS (see Fig. 17). The authors provide a throughout mathematical analyses using stochastic geometry. Since the main objective of the paper is the mathematical analyses of the UE-to-Network caching, it does not optimize the relay selection, as most of the works in Sections III-A and III-B. Thus, the authors consider only simple and impractical random relay selection that is usually far from the optimal selection. Hence, the probability of successful transmission can be even increased if a more sophisticated relay selection would be considered. The analyses show that despite the random relay selection, the UE-to-Network relaying is actually able to improve the probability of successful transmission by up to nearly 20% compared to the case without relaying.

3) Computation offloading to MEC

Very intriguing use-case, where the UE-to-Network relaying may be of a significant help is the computation offloading to MEC. If the UEs are not able to process/compute some task or application in a specified time or if the local computation is too energy demanding, the UEs can send these tasks to MEC server(s) in their vicinity, as considered in many recent studies (see, e.g., [96]). Of course, even the transmission to the MEC server(s) itself can be energy demanding and time consuming if the channel to the BS is not of a high quality. In such case, the UE-to-Network relaying can be of a significant help in forwarding the computing tasks to the MEC servers.

Benefits of the computation offloading to the MEC servers via the Relay UEs are investigated in [101], as illustrated in Fig. 18. The offloading via the Relay UEs is of benefit *especially* if the energy consumption at the offloading UE is required to be low and, at the same time, a strict latency deadline needs to be met. In such a case, the UE-to-Network

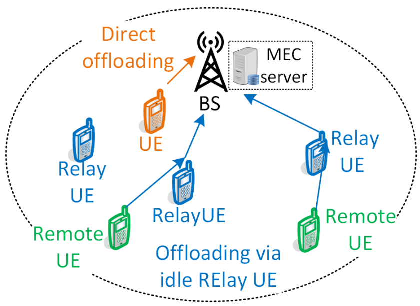

Fig. 18: Computation offloading enhanced by UE-to-Network relaying [101].

relaying assists in offloading of up to 30% tasks sent to the MEC servers. On the contrary, if constraints on the energy consumption and the latency are alleviated, even the direct offloading without relaying is able to accommodate the UE's requirements.

The problem of computation offloading to the MEC servers with the help of the Relay UEs is also considered in [102]. The main objective is to ensure a reliable offloading in the scenario with the users moving in vehicles while enjoying computing-intensive and delay-sensitive application (e.g., virtual reality game [103]). The problem, however, is that such users are often in the area without coverage of the MEC servers. Hence, the authors propose a relay-assisted offloading approach with other users helping to offload the computation. The paper first proposes a relay selection algorithm, where the Relay UEs should fulfill the following two conditions: *(i)* the Relay UE is able to communicate with both the Remote UE requesting the relaying service and the MEC server and *(ii)* the Relay UE is moving in the same direction as the Remote UE. This maximizes the probability that the Relay UE is in the communication distance to the Remote UE during the offloading, thus making the relaying reliable. The simulation results corroborate the effectiveness of the proposed approach, which is able to increase the percentage of tasks satisfying the delay constraint by up to 15% and 33% compared to competitive and greedy schemes, respectively.

4) Load balancing

Another interesting use-case where the UE-to-Network relaying can be of a great advantage is load balancing among adjacent cells, as proposed in [104]. The authors consider fully heterogeneous network deployment with the macro- and small- cells. To balance the load, the traffic of overloaded cells is routed via the Relay UEs to underloaded cells. This way, the BSs are able to serve additional users who could not be served with required QoS otherwise. Of course, the feasibility of load balancing depends on the current load of adjacent cells, location of the UE(s) for whom the traffic is being offloaded, and availability of the Relay UEs. The authors propose four load balancing steps differing in efficiency, applicability, and complexity of implementation:

- *Step 1*: The Macro BS1 in Fig. 19 is overloaded and cannot serve the Remote UE1. Hence, the BS1 first localizes the Remote UE1 and investigates whether there are some underloaded cells in the vicinity of the Remote UE1. If this is the case, the Macro BS1 multicasts the location of the Remote UE1 to all candidate cells (i.e., macro BS2) via X2 interface. Then, if there is found a suitable Relay UE (i.e., Relay UE1), D2D link between the Remote UE1 and the Relay UE1 is established and the Macro BS2 subsequently allocates some of its resources for the transmission.
- *Step 2*: If there are no underloaded cells and/or no available Relay UEs in the vicinity of the Remote UE, the BS first tries to alleviate its traffic. This is accomplished in a way that another UE's traffic is being offloaded to any adjacent cell. After the resources of this UE are released, the Remote UE can be served. In Fig. 19, the Remote UE2 is first connected to the Pico BS2 via the Relay UE2. Then, the Cellular UE1 can be served by the Macro BS2.
- *Step 3*: The principle is similar as in the Step 2, but two Relay UEs are subsequently utilized to alleviate resources of the Macro BS. For example, the Macro BS3 is not able to serve the Remote UE4 (see Fig. 19). Thus, the Remote UE3 is relayed to Pico BS4 first and, then, the Remote UE4 uses the Relay UE4 to be served by the Pico BS3.
- *Step 4*: Again, the similar principle as in the Step 3, but the difference is that two Relay UEs are utilized to offload traffic of the Remote UE4 from the Macro BS4 so that the Cellular UE2 can be served by the Macro BS4.

Notice that during the load balancing process, the BS tries first offload traffic by means of Step 1, if unsuccessful Step 2 is tried, and so on. In order to manage above mentioned cases, there are several practical issues that needs to be addressed, such as obtaining current position of Remote UEs whose traffic is being offloaded to adjacent cells, exchange of signalling of involved BSs, resources allocation for D2D and cellular links, incentivization of Relay UEs, or security and trust issues. The simulations show that the offloading by means of D2D relaying increases ratio of UEs able to access Internet by more than 20% if all four cases are used in the load balancing.

D. Summary

This section and Table III give a brief summary and comparison of works focusing on the UE-to-Network relaying

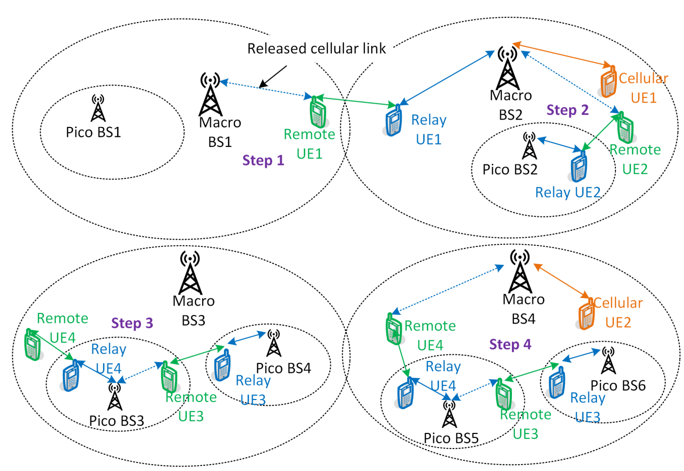

Fig. 19: The principle of load balancing by UE-to-Network relaying [104].

in line with the taxonomy introduced in Section II. To this end, we first compare the works on UE-to-Network relaying based on classification of D2D relaying introduced in Section II-A, that is, whether overlay or underlay use of the resources is employed and distinguish between basic and advanced relaying cases (note that Table III includes only information on which advanced relaying case is used since basic relaying is considered as a default case). Then we compare the works according to the classification of Relay UEs, such as relaying protocol, duplex, activity of Relay UEs, and whether two-way relaying is employed, as described in Section II-B. Finally, we compare the works in relation to the optimization of D2D relaying, including radio resource management techniques that are optimized, optimization/math tool(s), and key performance indicator(s) introduced in Section II-C.

Below, we compare in more detail the works on UE-to-Network relaying from above-mentioned aspects:

- **Classification of D2D relaying** – The overview of works on the UE-to-Network relaying shows the relaying is done usually in the ***overlay*** mode, where the D2D relaying links (i.e., links between the Remote and Relay UEs) use ***dedicated*** radio resources with respect to the Cellular UEs. The reason is that the Remote UEs are commonly seen as other Cellular UEs for whom QoS should be guaranteed. Unfortunately, the use of ***overlay mode*** makes the D2D relaying ***less spectral efficient*** and ***not sufficient for future mobile networks, such as emerging 6G***. Thus, the underlay mode should be properly investigated as well. Besides, although the most common D2D relying case is the single Remote UE-single Relay UE, there is actually number of works exploring also the advanced relaying cases, such as multi Remote UEs-single Relay UE [85][86][98], single Remote UE-multi Relay UEs [88], multi-hop relaying [90][92], or initial attempt to select among several relaying cases [94]. Still, a very promising D2D relaying scenario with ***one Relay UE helping multiple Remote UEs*** while each ***Remote UE can exploit multiple Relay UEs*** simultaneously is not explored thus far. Such scenario is, however, supposed to increase spectral efficiency and data rates.
- **Classification of Relay UEs** – Usually, the Relay UEs are assumed to operate in half-duplex mode, since it is less complex and less energy demanding. The research focusing on full-duplex relaying adopted for D2D is still rather at its initial stage [36][94]. Moreover, the Relay UEs are usually assumed to employ DF relaying protocol, where data is first decoded at the Relay UE and then forwarded to the destination node (BS, Remote UE, or other Relay UE). Our survey demonstrates that other relaying protocols, such as AF or QF, are used only rarely [62]. The other important fact is that the Relay UEs are usually assumed to be idle and no data is transmitted by these users. The active Relay UEs are considered only in a limited number of studies [36][71][82]-[84]. Last, all works but one [84] solely focus on one-way relaying while ***two-way*** relaying (see Section II-C for more detail) is ***neglected despite its high spectral efficiency*** required in future mobile networks.
- **Optimized RRM technique** – Majority of works on the UE-to-Network relaying optimizes the relay selection (see, e.g., [57][86][88][36][102]). This finding is not that surprising and confirms the fact that the relay selection plays a key role in the UE-to-Network relaying in order to benefit from this concept. Besides the relay selection, some works also focus on other RRM techniques, such as power allocation at the UEs, Remote UEs, Relay UEs, and/or BS [82][84], allocation of radio resources in time/frequency domain [71], and mode selection [94]. Still, individual RRM techniques are usually optimized ***separately*** leading to sub-optimal solutions. Hence, ***joint solution optimizing all RRM techniques is still missing*** in the current research.
- **Optimization/math tool** – Most commonly, the optimization of relay selection exploits various matching [64][36], clustering [98], or pairing approaches [65], where the Remote UEs are matched/paired with the specific Relay UE. Moreover, game theory is a convenient tool to solve some problems in a centralized way (e.g., using Stackelberg game [62]) or, even in a decentralized way (hedonistic game [86] or ordinal potential game for power allocation [90]). Besides, stochastic geometry is commonly used to analyze the performance of the UE-to-Network relaying [85][63][66][67]. Even though ***machine learning*** and ***artificial intelligence*** approaches are a very strong tool to solve various radio resource management problems, only ***limited amount of works*** exploit these approaches, such as reinforcement learning used in [59][78] or artificial intelligence-based framework using “believe desire intention” concept in [94]. This may be rather surprising considering the fact that optimization problem are often of very high complexity and a joint solution is hard, if not impossible, to be found by “conventional“ optimization tools. Besides, machine learning and artificial intelligence are seen as enablers for advanced low-complexity management of future networks serving many heterogeneous devices.
- **Performance** – The existing studies prove many times that the UE-to-Network relaying can significantly enhance the performance of contemporary mobile networks. In particular, relaying is able to increase system capacity in orders of tens or even hundreds of percent. For example, the authors in [57], [59], and [71] show that the capacity can been increased by up 200%, 300%, and even 10 times, respectively, when compared to no relaying. In addition, the UE-to-Network relaying allows to significantly decrease the energy/power consumption at the side of the UEs (more than two times) [64]. Last, the relaying also significantly decreases the retransmission cost in multicast services (up to dozens of percent [97]), increases success transmission probability of cached content (by tens of percent [100]), enhances the performance of the users enjoying MEC services [101][102], or improve load balancing on the network [104].

V. In-band UE-to-UE relaying

While the previous section surveys and discusses advancements in the in-band UE-to-Network relaying, this section

TABLE III: Comparison of state-of-the-art works on UE-to-Network relaying; ReS – relay selection, RA – resource allocation, MS – mode selection, PA – power allocation, HD – half-duplex, FD – full duplex, C - capacity, SE - Spectral Efficiency, EE - Energy Efficiency, PC - Power Consumption, EC - Energy Consumption.

	Classification of D2D relaying	Class. of Relay UEs	Optimized RRM tech.	Optimization/math tool	Performance
[57]	Overlay	DF, HD, idle	ReS	-	$C \uparrow$ by up to **200%** in DL and **300%** in UL
[59]	Overlay	HD, idle	ReS, RA	Reinforcement learning (Q-learning, softmax)	Reward $\uparrow$ by **200%**, only **1.4%** is lost wrt to optimum
[62]	Underlay	AF, HD, idle	ReS, RA	Game theory (Stackelberg game)	$C \uparrow$ by **15%** wrt no relaying
[63]	Overlay	HD, idle	MS	Stochastic geometry	The probability or relay selection is $\downarrow$ if distance between Remote UE and Relay UE is $\uparrow$
[64]	Underlay	HD, active	MS, ReS, PA	Weighted one-to-one matching (Hungarian method)	EC $\downarrow$ by **more than two times** wrt no relaying
[65]	Overlay	HD, idle	ReS	Symmetry pairing theory	EE $\uparrow$ by **50%** wrt benchmark
[66]	Overlay	-	MS, RA	Stochastic geometry	Coverage prob. $\uparrow$ by **tens** of %, $C \uparrow$ by **30%** wrt no relaying
[67]	Overlay	-	MS, RA, PA	Stochastic geometry	Coverage prob. $\uparrow$ by **30%**, $C \uparrow$ by **40%** wrt no relaying
[68]	Overlay	-	MS, RA, PA	Stochastic geometry	Coverage prob. and C can be optimized by No. of channels allocated for the D2D comm.
[69]	Overlay	HD, idle	ReS, RA, PA	-	C of cell edge UEs $\uparrow$ by **300%**, average $C \downarrow$ by **3.8%**
[70]	-	-	MS, ReS, RA	-	QoE of users $\uparrow$ by more than **1** (on the scale from 1 to 5)
[71]	Overlay/ underlay	HD, active	RA	Frank-Wolfe method, alternating-direction method of multipliers	$C \uparrow$ **10x** wrt no relaying
[36]	Underlay	DF, FD, active	ReS	Matching (Gale-Shapley)	$C \uparrow$ by **186%** wrt distance-based ReS, $\downarrow$ **4.6%** wrt optimal ReS
[78]	Overlay	HD, active	MS	Game theory, machine learning	Convergence in orders of hundreds or thousands of iterations
[82]	Overlay	DF, HD, active	PA	Lagrange multipliers	$C \uparrow$ by up to **35%** wrt case w/o NOMA and w/o relaying
[83]	Overlay	DF, HD, active	PA, ReS	Root finding method (PA), Hungarian (ReS)	$C \uparrow$ by **130%** wrt NOMA w/o relaying
[84]	Overlay, single Remote UE-multi Relay UE	DF, HD, two-way, active	PA	-	Average SE $\uparrow$ by up to **70%**
[85]	Overlay, multi Remote UEs-single Relay UE	HD, idle	-	Stochastic geometry	SE $\uparrow$ by up to **0.5 bits/s/Hz** wrt no relaying
[86]	Overlay, multi Remote UEs-single Relay UE	HD, idle	ReS	Game theory (hedonistic coalition game)	$C \uparrow$ up to **27%** wrt no relaying
[88]	Overlay, single Remote UE-multi Relay UEs	HD, idle	ReS	Constrained partially observable Markov decision process	$C \uparrow$ by **55%** in single CUE scenario and by **30%** in multiple CUEs scenario wrt no relaying
[90]	Overlay, multi-hop relaying	HD, idle	ReS, PA, RA	Ordinal potential game (for PA only)	$C \uparrow$ by up to **3%** for <400 UEs
[30]	Overlay, multi-hop relaying	HD, QF, idle	-	-	Outage probability $\downarrow$ to **0.6%** wrt no relaying, PC $\downarrow$ by **53%** wrt no relaying
[92]	Overlay, multi-hop relaying	HD, idle	MS, ReS	-	$C \uparrow$ by up to **125%**, EC $\downarrow$ by up to **70%** wrt scheme w/o relaying
[94]	Overlay/Underlay, multi Remote UEs-single Relay UE, multi-hop relaying	FD	MS	Artificial intelligence (belief desire intention concept)	SE $\uparrow$ by **28%**, EC $\downarrow$ by **200%** wrt no relaying
[97]	Overlay, multi Remote UEs-single Relay UE	D, DF, idle	ReS	Iterative subcluster partitioningH	Normalized resource cost $\downarrow$ by **40%**
[98]	Overlay, multi Remote UEs-single Relay UE	HD, idle	ReS	Clustering	Normalized resource cost $\downarrow$ by **15%** wrt [97], cost $\uparrow$ by up to **5%** wrt optimum
[100]	Overlay	HD, DF, idle	ReS	Stochastic geometry	Successful transmission probability $\uparrow$ by up to **20%** wrt no relaying
[101]	Overlay	Idle	-	-	Relay UEs help **30%** of offloaded tasks
[102]	Overlay	-	ReS	-	No. of tasks satisfying delay const. $\uparrow$ by up to **33%** wrt greedy algorithm
[104]	Overlay	-	ReS	-	Offloading $\uparrow$ ratio of UEs able to access Internet by up to more than **20%**

zooms-in on the research performed in the in-band UE-to-UE relaying scenario. As explained in Section II, the fundamental difference between the UE-to-UE relaying and the UE-to-Network relaying is that, in the former, the Relay UEs help to the D2D UEs while the Cellular UEs are assisted by the relays in the latter. Since the D2D UEs are usually treated differently when compared to the Cellular UEs, also related radio resource management techniques need to take a different angle in solving various optimization problems. The structure of this section is shown in see Fig. 20. The basic relaying case, where single D2D pair is helped by single Relay UE, is tackled first in Section V-A. Furthermore, several more advanced relaying cases with either multiple D2D pairs or multiple Relay UEs involved in the relaying are discussed in Section V-B. Finally, we compare all the surveyed works and also identify the gaps and missing links in the current research in Section V-C.

A. Basic relaying case

In this subsection, we first overview initial advancements in the UE-to-UE relaying aiming to improve the performance of D2D users in terms of capacity, energy consumption, or outage (Section V-A1). Then, we also pinpoint various aspects targeted by the individual works on UE-to-UE relaying, including multi-criteria relay selection (Section V-A2), more advanced reuse of cellular resources by D2D relaying links in the underlay mode (Section V-A3), performance comparison of underlay and overlay modes (Section V-A4), utilization of full duplex (Section V-A5) and/or two-way Relay UEs (Section V-A6), and the use of NOMA by the UE-to-UE relaying concept (Section V-A7).

1) Initial advancements in UE-to-UE relaying

One of the first works showing a potential to enhance the capacity of D2D pair by intermediate Relay UE is presented in [105]. The authors assume the underlay mode resulting in mutual interference between the cellular users and the D2D communication (see Fig. 21). Thus, to mitigate this interference and to maximize the capacity of D2D pair(s), the authors formulate the problem of joint relay selection, power allocation, and resource allocation. Finding the optimal solution of such problem is extremely hard, as the problem is a mixed integer programming. Hence, the problem is decomposed into two sub-problems solved sequentially: *(i)* the power allocation sub-problem, and *(ii)* joint relay selection and channel assignment sub-problem. The purpose of the first sub-problem is to mitigate mutual interference between the D2D and cellular communication (in Fig. 21, interference caused by the Source UE and the Relay UE2 and interference to the Relay UE2 and the Destination UE by the Cellular UE). The power allocation sub-problem is solved optimally, as the objective function is either monotone or convex over the transmission power. The second sub-problem is a 3-dimensional matching problem that is still NP-complete. Hence, the problem is further transformed to a 2-dimensional problem and solved subsequently by an iterative Hungarian algorithm. The average throughput is increased roughly by 10% compared to a greedy algorithm while the gap to the optimal exhaustive search is only approximately 2%.

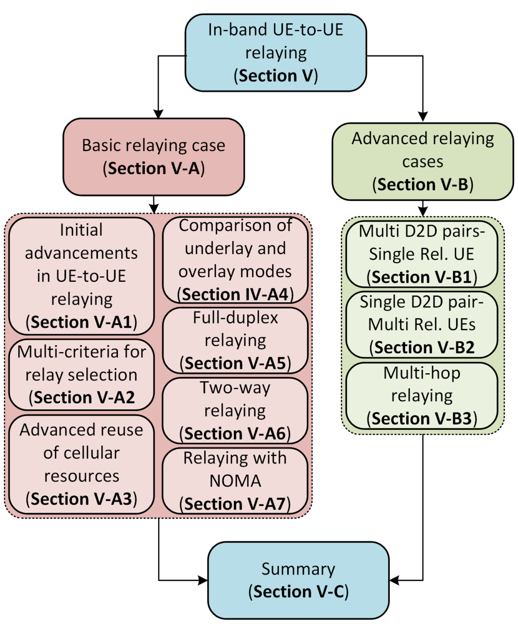

Fig. 20: Structure of Section V.

In [106], the authors introduce an enhancement to the power allocation initially proposed in [105]. To this end, the authors maximize capacity as a subject to the required energy efficiency at the D2D pair and the maximal allowed interference at the BS from D2D communication. The power allocation problem at the Source UE and the Relay UE is first solved for the unconstrained interference problem, where the interference from the Source UE and the Relay UE to the BS is not considered. The optimal solution is obtained by Lagrange multipliers method. In sequel, the authors solve the power allocation problem also for the case when the interference constraint is assumed. If the optimal power obtained for the unconstrained problem does not violate the maximal allowed interference at the BS, the optimal power for the interference-constrained problem is the same as for the unconstrained one. In the opposite case, the problem is simplified into a power-constrained capacity maximization problem having solution only if the required energy efficiency can be guaranteed at the D2D pair even if the transmission power is decreased to ensure the maximal allowed interference at the BS is not exceeded. The proposed power allocation improves spectral efficiency with respect to [105] roughly by up to 45%.

The objective to maximize the sum capacity of the Cellular UEs and the D2D pairs while guaranteeing the minimum capacity to the Cellular UEs is also the focus of [107]. The maximization of sum capacity is achieved by a relay selection. The authors also consider a power allocation problem, but the power allocation itself is fully based on [108]. The proposed

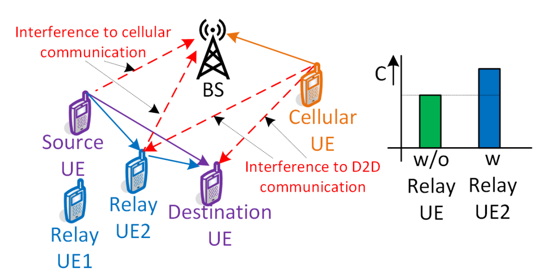

Fig. 21: Illustrative example of the capacity maximization by means of power allocation at individual UEs (i.e., Source UE, Relay UE2, Cellular UE), relay selection, and resource allocation [105]. The capacity is maximized by exploiting the Relay UE2 while both Source UE and Relay UE2 reuse resources allocated to the Cellular UE.

relay selection is done by a stable Shapley matching algorithm (similarly as in [36]). In particular, each D2D pair indicates preferred most beneficial Relay UE in terms of capacity gain and the Relay UEs also give their preferences to which D2D pairs they should be assigned in order to maximize their utility. Then, greedy algorithm matches the D2D pairs with the Relay UEs according to their preferences. The proposed relay selection algorithm increases the system capacity by up to 100% compared to no relaying case, but it losses almost 30% with respect to the optimal Hungarian method.

The same objective as in [107], i.e., joint mode selection, resource allocation, and power allocation, is pursued also in [109]. The problem solved in [109] is formulated as a complex MINLP problem, thus hard to be solved jointly. Consequently, the authors first solve the problem of power allocation optimally assuming given resource allocation and mode selection using Dinkelbach optimization method [110]. Then, the resource allocation is transformed into one-to-one matching problem that is optimally solvable by Hungarian algorithm (similarly as [107]). The scheme proposed in [109] enhances the capacity roughly up to 25% compared to the case without relays.

Even more complex problem than that solved in [109] is considered in [111][112][113], where joint mode selection, relay selection, power allocation, and resource allocation is targeted. Since the optimization problem in [111] is a non-convex combinatorial problem, the authors split it into several sub-problems solved sequentially. First, the authors derive the transmission power allocation for the Source and Relay UEs. Second, the authors optimally select the Relay UE from the candidate set of the Relay UEs to optimize the capacity of D2D pair. To limit the number of potential candidate Relay UEs from which the actual Relay UE is selected, only those candidate Relay UEs located in the area given by the intersection of two circles (one originating from the Source UE and the other one originating from the Destination UE) can be selected. Afterword, a brute force algorithm is employed to find the optimal relay. In the third step, it is decided if the D2D pair should communicate directly through the relay selected in the second step or if the communication through the BS should be used. Finally, resources are allocated via matching the D2D pairs with the Cellular UEs to maximize the capacity of the former while ensuring the minimum required capacity of the latter. The matching of the D2D pairs with the Cellular UEs is based on interference-limited area [114], where the D2D pairs should be sufficiently far from the BS. The proposal increases data rate by up to 100% compared with a random relays selection and a random resources allocation, while losing less than 2% with respect to the exhaustive search.

As in [111], also in [112], the authors decouple the optimization problem into several sub-problems. The first sub-problem to be solved is the relay selection. As the authors consider a perfect channel state information (CSI) knowledge of all links at the BS, the relay selection can be a demanding process in terms of signaling overhead. Thus, only the Relay UEs inside the delineated area, derived exactly in the same way as in [111], are considered as the candidate relays. Then, the Relay UEs are matched with the D2D pairs in a way that the D2D pairs having the lowest number of candidate Relay UEs are matched with the Relay UE preferentially. The second sub-problem, the power allocation, assigns the transmission power at the Source UE and the Relay UE. As a matter of fact, this problem is a partial fractional optimization problem and the optimal solution is obtained by Dinkelbach method [110] similarly as in [109]. Last, the mode selection and channel allocation is solved jointly by a low complexity greedy algorithm. The proposal outperforms the scheme selecting the relays and allocating resources randomly by up to 30% in terms of the capacity. A slight drawback of the delineation area limiting the number of candidate Relay UEs in both [111] and [112] is that even the Relay UEs having a high attenuation to the Source UE, the Destination UE, or both are still considered as the candidate relays. More importantly, it may not be always feasible to distinguish which Relay UEs are in the delineation area, as the users may not be willing to share their exact positions. Another study focusing on joint power allocation, mode selection, relay selection, and resource allocation in order to maximize the capacity is delivered in [113]. Since the defined problem is MINLP, the authors decompose it into the following two sub-problems to make it tractable: *(i)* power allocation sub-problem and *(ii)* joint mode selection, relay selection, and resource allocation sub-problem. The first sub-problem is further divided to the problem of power allocation for the case when the D2D pair does not exploit any Relay UE and the case if the Relay UE is enabled. For the former case, the lower and upper bound transmission powers are derived. For the latter case, the algorithm proposed in [109] is adopted. Afterward, the second sub-problem is transformed from integer nonlinear programming into integer linear programming by introduction of auxiliary variables. Hence, the problem can be solve by simplex or Balas methods [115]. The capacity is increased by up to 200% and 10% compared to the scheme with no relays and [109], respectively.

Besides the objective to maximize the capacity of D2D users, there is also an ongoing effort to maximize the D2D users' energy efficiency. For example, the authors in [116] aim to maximize the energy efficiency by means of relay selection and power allocation. In order to select the relay, adaptive neuro fuzzy inference system (ANFIS) architecture based on a supervised learning is adopted. The architecture is composed from five layers: *(i)* fuzzification layer, *(ii)* rule layer, *(iii)* implication layer, *(iv)* aggregation layer, and *(v)* defuzzification layer. Basically, the inputs to the fuzzification layer of ANFIS architecture are the SINR at the Relay UE (i.e., first hop transmission), SINR at the Destination UE (second hop transmission) and SINR at the BS. Then, the output coming from the defuzzification layer is the relay selection decision. When the Relay UE offering the highest energy efficiency is selected, power allocation is applied to both Source UE and Relay UE to further maximize the energy efficiency of the whole system. The transmission powers at the Source UE and the Relay UE do not affect only the D2D users, but also the performance of the Cellular UE(s) due to interference. The power allocation is done via particle swarm optimization (PSO) algorithm and the transmission power is found iteratively. However, the authors give no insight on how long the PSO-based power allocation takes to converge, but the PSO is known generally for a slow convergence [117]. The proposal increases energy efficiency compared to the opportunistic random relay selection and the random relay selection benchmark schemes by up to 25% and 50%, respectively.

Another study focusing on the power allocation and the relay selection with the objectives to maximize the energy efficiency while ensuring QoS of both the Cellular UEs and the D2D pairs is presented in [34]. The formulated problem is, due to its NP-hardness properties, decomposed into two sub-problems solved separately. The first sub-problem, the power allocation, is non-convex as the aim is to determine concurrently the transmission powers at the Cellular, Source, and Relay UEs. Hence, the sub-problem is further transformed into an equivalent subtracting form and solved by Dinkelbach method (similarly as in, e.g., [109][112]) and Lagrangian dual decomposition. The important aspect of the power allocation at the Source UE and the Relay UE is that it addresses the bottleneck problem. More specifically, the power allocation is set to achieve equal capacity at both transmission hops to maximize the energy efficiency of the connection. The relay selection sub-problem is solved by employing reinforcement learning (i.e., Q-learning). The optimal action is obtained by updating the Q-value consisting agent, action, strategy, state, and reward. In particular, the agent (i.e., D2D pair) learns from taken actions (i.e., relay selection) depending on the current strategy to maximize its reward (i.e., energy efficiency). The proposal outperforms state-of-the-art scheme by up to roughly 40% in terms of the energy efficiency. Solving the bottleneck problem yields addition 6% gain in the energy efficiency compared to the equal power allocation.

The energy efficiency of the UE-to-UE relaying is significantly influenced by the mobility of users, as studied in [118]. In particular, the objective of the paper is to maximize the energy efficiency of the system while ensuring the minimum required spectral efficiency of each user. The authors solve the optimization problem by relay selection, resource allocation, and power allocation. The authors propose a non-cooperative finite game that aims to reach Nash equilibrium among all the players (i.e., the Cellular UEs, D2D pairs not needing relay assistance, D2D pairs needing relay assistance, and the Relay UEs). To this end, each player acts independently with respect to other players and maximizes its own utility. The game is finished when the utility of any player cannot be increased if decision of any other user changes. The advantage of the solution can be seen in the fact that full CSI does not have to be known at the BS, as the game is done in a distributed way. The proposed scheme more than doubles the energy efficiency when compared to the competitive schemes if a high spectral efficiency is required (10 bits/s/Hz). Furthermore, it is shown that a high mobility of the users (emulated by dynamic channel variations) decreases their energy efficiency by up to roughly 300%, thus, coping with the high mobility of users is still a challenge to be addressed in relaying.

Besides the capacity and the energy efficiency, the UE-to-UE relaying is able to minimize the outage probability, as analysed in [119]. The authors in [119] derive an approximate closed form expression for the UE-to-UE relaying with the AF relaying protocol for the three following scenarios:

- *high SNR* - the Source UE and the Destination UE are close to each other,
- *weak interference from the BS* - the Source UE, the Destination UE, and the Relay UE are at the cell edge and, thus interference from the BS at the second hop (i.e., when the Relay UE transmits data to the Destination UE) is ignored,
- *weak interference from both cellular UE and BS* - the D2D pair is far from the BS and the UE causing the interference to D2D communication is far from the Relay UE.

It is shown that the AF relaying decreases the outage probability by up to 15% when compared to the DF relaying, provided that the channel quality between the Source and Relay UEs is of a high quality (i.e., high SNR). The reason for this phenomenon is that the transmitted signal is significantly stronger than the noise. Consequently, even if the noise is also amplified in the AF process, it does not have a significant effect on the retransmission quality. Contrary, the DF relaying is far better choice if the first-hop channel is of low SNR.

2) Multi-criteria for relay selection

The works dealing with relay selection problem in the previous section usually consider only channel quality among individual nodes as a relay selection criterion. Nevertheless, as the Relay UEs are owned by other users and devices are battery constrained, it is of advantage to consider application- and/or use-case-related criteria in the relay selection process, such as delay, reliability, or battery state of the Relay UEs.

Hence, the authors in [120] consider a *remaining operation time of the Relay UE* and *transmission delay* in the relay selection process besides the throughput. The remaining operation time of the Relay UEs is derived by empirical Peukert's Law model [121] considering transmission power, energy conversion efficiency (i.e., energy loss in its circuitry), and remaining battery capacity. To model the transmission delay between the Source and Destination UEs, the queuing model at the Source and Relay UEs is adopted exploiting finite state Markov chain. The Relay UEs having more remaining battery energy are selected preferentially as long as: *(i)* the throughput improvement satisfies D2D pair's requirements and *(ii)* maximum transmission delay is not exceeded. This way, the total amount of data transmitted via the selected relay is increased and the relaying is more reliable (i.e., the probability that the Relay UE terminates the relaying due to a low battery is minimized). A thorough delay analysis indicates that considering multiple criteria in the relay selection increases the amount of total transmitted data by up to 40% at the cost of slight increase of average delay approximately by 10%.

Multiple relay selection criteria are also considered in [122], where the relay selection takes the following aspects into the account: *(i)* SNR of both transmission hops *(ii)* SINR of both transmission hops, *(iii)* the remaining battery of the Relay UEs, *(iv)* buffer status of the Relay UEs, and finally *(v)* a reliability indicating if the Relay UE has been willing to act as relay in the past (the reliability is increase by 1 if the Relay UE act as relays and the reliability is decrease by 0.5

if not). The paper defines several relay selection strategies, where individual parameters are weighted depending on the application case and the scenario. For example, if the Remote UE requires high throughput while delay of data is not an issue, higher weight is given to the channel quality (i.e., SINR of both transmission hops) while the buffer status of the Relay UE is not that important. Further, the authors also propose a relay selection strategy based on multi-parameter decision making and the Mahalanobis distance vector [123]. Then, the most suitable Relay UE is selected. The capacity (measured by the success of delivered packets) is increased by 30% compared to the scheme selecting relays only according to the capacity. Although the paper addresses the mobility of users, which is usually neglected by the relay selection schemes, it does not cope with the problem if the Source UE and/or the Destination UE moves in a way that the use of the selected Relay UE is no longer viable. In such a case, yet another Relay UE should be found to maintain D2D communication.

The idea presented in [122] is farther enhanced in [124], where the authors aim to increase the reliability of relaying by selecting two relays instead of one. The relay selection takes into account the same criteria as considered already in [122]. Then, the Relay UE enabling the highest capacity while guaranteeing the same criteria as considered in [122] (i.e., battery status, buffer status, and reliability) is selected as a *primary* Relay UE. In addition, the Relay UE offering the second highest capacity and fulfilling all other requirements is selected as a *backup* relay. The backup relay is, then, used if the first Relay UE becomes unavailable for any reason, e.g., if it moves too far due to its mobility. The proposed "backup" relay selection increases the probability that the suitable relay is selected by up to 50% leading further to roughly 15% capacity gain when compared to state-of-the-art schemes. Still, the disadvantage of the approach may be seen in relatively high signaling overhead, as the relay selection is done centrally with all nodes reporting the required information to the BS. Moreover, even the "backup" relay may become unsuitable due to users' mobility eventually.

3) Advanced reuse of cellular resources

In the previous sections, all the channel allocation schemes adopting underlay mode assume that *both transmission hops* (i.e., the first hop between the Source UE and the Relay UE and the second hop between the Relay UE and the Destination UE) *reuse the resources allocated to the same Cellular UE*. Nevertheless, as the Relay UE and the Destination UE are interfered differently by the Cellular UE due to different channel propagation conditions, it is more efficient to reuse resources of different Cellular UE at each transmission hop. Nevertheless, this leads to more complicated resource management, as both Cellular UEs cause interference to both Relay and Destination UEs (in case of UL) or both Cellular UEs are interfered by the Source and Relay UEs (in case of DL). In addition, this option may not be always possible if there is significantly more D2D pairs assisted by the Relay UEs than the number of the Cellular UEs whose resources are reused.

The reuse of resources of different Cellular UEs at the first and the second transmission hop is assumed in [125]. For example in Fig. 22, the Source UE2 reuses the resources of

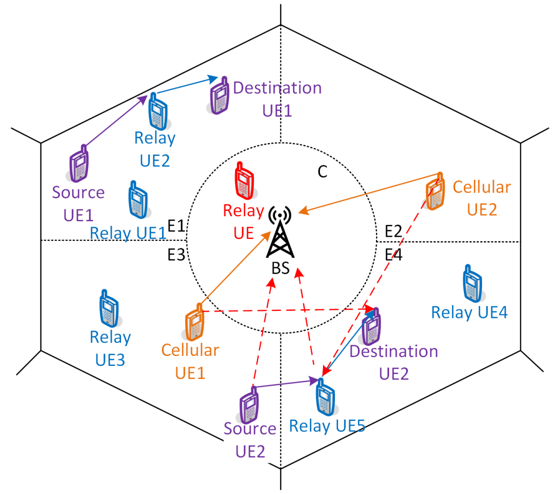

Fig. 22: Illustrative example of the candidate Relay UEs selection and allocation of resources of different CUEs to each transmission hop in line with [125].

the Cellular UE2 while the Relay UE5 exploits the resources allocated to the Cellular UE1 when re-transmitting data to the Destination UE2. The paper focuses on joint relay selection and resource allocation scheme composed of two following stages. In the first stage, the objective is to select several candidate Relay UEs. To this end, cell area is divided into five smaller areas as illustrated in Fig. 22. The candidate Relay UEs cannot be in a close vicinity of the BS (area C) to avoid strong interference originating from the Relay UE to the BS. Also, the candidate Relay UEs have to be in the same area as the Source UE and/or the Destination UE. During the second stage, the optimal relay is selected from the set of candidate relays in order to maximize the throughput of D2D users and the Cellular UE(s) whose resources are reused. The proposed scheme enhances the throughput roughly by 100% when compared to the random relay selection. The drawback of the proposed scheme, however, can be seen in the first stage, where quite many Relay UEs are still considered in the relay selection process. For example, the Relay UE3 is not located geographically well to serve as the relay for the Source UE2 and the Destination UE2 (see Fig. 22).

Reusing different resources at each transmission hop is also assumed in [126], where the authors aim to increase energy efficiency. The authors solve the problem by relay selection, resource allocation, and power control. The overall problem is MINLP, thus it is again solved in two subsequent steps. In the first step, the authors propose a two-dimensional matching, where the Destination UEs are assigned resources initially allocated to the Cellular UEs in order to minimize interference from the Cellular UEs to the Destination UEs. The Source UEs first establish their preferences by indicating which resources they prefer to use when transmitting to the Relay UE. Then, a pricing strategy is proposed to resolve conflicts between the Source UEs preferring the same resources. If more Source UEs are in contention over some resources, the virtual price of these resources iteratively increases until just one Source UE is willing to pay the price. In the second step, a three dimensional matching is performed as the Source UEs are matched with the Relay UEs and the Cellular UEs, whose radio resources are used. Then, the transmission power of the Source UE and the Relay UE is set optimally to maximize the energy efficiency. The proposal increases energy efficiency by up to 120% compared to the matching without any power optimization (i.e., with a fixed power), but the gap with the optimal exhaustive search is quite high (up to 27%).

4) Comparison of underlay and overlay modes

Thus far, most of the studies assume the underlay mode (i.e., the D2D users and the Relay UEs reuse resources of the Cellular UEs) while overlay mode is not found as attractive. A *comparison of the underlay and overlay modes* for the UE-to-UE relaying is done in [127]. The authors provide in depth and thorough mathematical analysis of the D2D transmission capacity enhanced by the relaying in both the underlay and overlay modes using stochastic geometry. The simulation results yield the following conclusions: *(i)* the relaying in *overlay mode brings significant benefits* especially if the Source UE and the Destination UE are relatively far from each other (throughput gain up to 600% compared to the case without relaying); *(ii)* the relying in *underlay mode is beneficial* even for a short distance between the Source UE and the Destination UE, as these are interfered by the Cellular UEs resulting in throughput gain up to 140% for a short distance between the Source and the Destination UE and up to 350% for a long distance between the Source UE and the Destination UE with respect to no relaying; *(iii)* the *overlay mode significantly increases throughput* compared to the *underlay mode* by more than 300%, albeit at the *cost of dedicating extra resources* for the relaying.

A thorough analysis of the underlay and overlay modes using stochastic geometry is delivered also in [128]. The authors confirm the fact that the capacity of D2D users is significantly higher in the overlay mode than in the underlay mode. In addition, the paper also analyses performance of two interference cancellation techniques, since the D2D pairs are assumed to reuse the same radio resources and, thus, cause mutual interference to each other. In this regard, the first interference cancellation method, close interferer cancelation, mitigates interference from an interfering user in proximity. This is accomplished in a way that the users within a certain radius from each other are forbidden to use the same radio resources. The second interference cancellation technique, strong interferer cancelaltion, combats interference from the strong interferer, which does not have to be necessarily close to the interfered one. The simulation results uncover the following facts: *(i)* close interferer cancelation increases the capacity when compared to no relaying by up to 120% for the underlay mode and by 430% for the overlay mode; *(ii)* strong interferer cancelaltion is able to improve the capacity in the underlay and overlay modes by 120% and 400%, respectively; *(iii)* close interferer cancelation enhanced by an adaptive setting of interference cancellation radius farther boosts the capacity gain with respect to no relaying by up to 660% for the underlay mode and up to 450% for the overlay mode.

5) Full-duplex relaying

As already explained in Section II-B2 and demonstrated in Section IV, *full-duplex* relaying can notably improve performance of the UE-to-Network relaying (see, e.g., [36]). Hence, the authors in [129] maximize the system capacity via resource and power allocation for the full-duplex in the UE-to-UE relaying concept. Thanks to the full-duplex, the Source UE and the Relay UE transmit simultaneously while reusing the resources of the same Cellular UE. The formulated problem is mixed binary integer programming that is again NP-hard. Hence, the problem is decomposed into two independent sub-problems for power and resource allocation, and both are solved via linear relaxation. The system throughput is increased roughly by up to 20% compared to a centralized coordination scheme using statistical CSI while yielding the same performance as the optimal solution. Unfortunately, the paper neglects the problem of self-interference caused by the full-duplex relaying that can significantly compromise the gain (see Section II-B2).

The benefits of full-duplex relaying and its effect on energy efficiency considering also self-interference are analyzed in [130]. The optimization objective is addressed by joint resource (subcarrier) and power allocation. The defined problem is mixed combinatorial non-convex problem, thus it cannot be solved in polynomial time. Hence, the power and resource allocation problems are again solved separately. In order to solve the power allocation, the problem is transformed into a "difference of two concave functions" programming, which is solvable by iterative sequential convex optimization technique. The resource allocation is, then, formulated as one-to-one matching problem (i.e., one D2D pair can reuse only one subcarrier) and solved optimally by Hungarian method. The proposed scheme outperforms a random channel allocation with full-duplex relaying by up to 30% and half-duplex relaying by nearly 200% in terms of the energy efficiency. Even if considering strong self-interference in the full-duplex relaying, the energy efficiency is decreased only by less than 20% while still outperforming the half-duplex relaying by roughly 160%.

While previous papers considering full duplex relaying aim to maximize either system capacity or energy efficiency, the authors in [131] try to find a trade-off between these two. The objective is accomplished by power allocation while utilizing machine learning approach based on neural networks. The proposed neural network uses channel coefficients as input while optimal power allocation of Source UEs and Relay UEs is the output. Similarly as in previous study, it is shown that full-duplex Relay UEs outperform significantly half-duplex relay in terms of the capacity (by up to 150%) if there is insignificant self-interference.

The use of full-duplex relaying can also help to minimize the outage probability, as demonstrated in [132]. The authors first analyze an "exact" outage probability. Since there is no way how to obtain closed-form expression of exact outage probability, the authors find an "approximate" outage probability in closed-form that is valid as long as self-interference is negligible. Then, the authors aim to minimize the outage probability at the D2D pair while ensuring interference to the

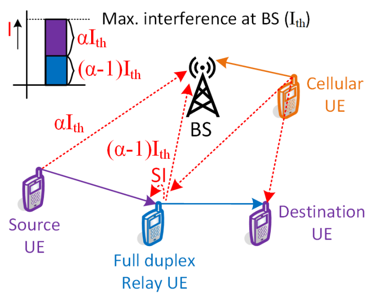

Fig. 23: Optimization of power allocation factor (α) at the Source and Relay UEs to ensure interference at the BS is not higher than allowed interference specified by I_{th} [132].

BS is not higher than the predefined threshold I_{th}. This is managed by optimization of power allocated factor α determining the amount of interference at the BS by both the Source and Relay UEs (see Fig. 23). Since the optimization of α is intractable, a sub-optimal solution is derived by disciplined convex programming [73]. The simulation results indicate that if self-interference is fully canceled, the full-duplex relaying decreases the outage probability approximately by half with respect to the half-duplex. If self-interference is significant, however, the full-duplex more than doubles the probability of the outage compared to the half-duplex.

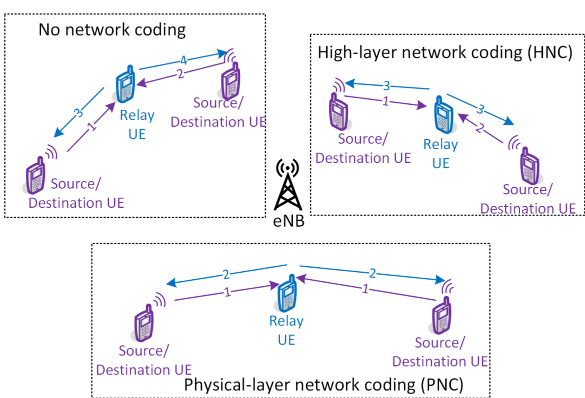

Fig. 24: The principle of two-way relaying without network coding, HNC, and PNC.

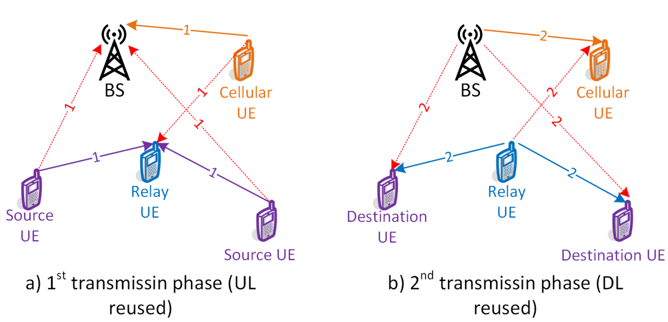

Fig. 25: Principle of two-way relaying adopted in [133].

6) Two-way relaying

So far, only *one-way* relaying has been assumed by all surveyed papers on the UE-to-UE relaying. In the one-way relaying, only one D2D user (i.e., Source UE) transmits data to another D2D user (i.e., Destination UE). The D2D communication is, however, tailored also for the cases with both D2D users within the same D2D pair exchanging data with each other. Then, *two-way* relaying can be used if such D2D pair is being helped by the Relay UE (see Section II-B3). Nevertheless, to facilitate exchange of data in both directions without any network coding, four time slots would be needed (See Fig. 24). Thus, high-layer network coding (HNC) is introduced to decrease the number of required time slots to three. Even more efficient data exchange between two D2D users is enabled by PNC [32], where only two time slots are needed (see bottom part of Fig. 24). In the following, we show that two-way relaying attracted quite a lot of attention of the researches.

The analysis of ergodic capacity for two-way relaying system with single Cellular UE, single Relay UE, and two D2D users is done in [133]. The principle of the two-way relaying adopted in [133] is as follows (see Fig. 25). In the first phase, both Source UEs send data concurrently to the Relay UE reusing uplink resources. Consequently, the Source UEs interfere the BS while the Cellular UE causes interference to the Relay UE. During the second phase, the D2D users switch their role from the Source UE to the Destination UE and receive relayed data from the Relay UE while the BS transmits to the Cellular UE. As a result, the Destination UEs and the Cellular UE become the victims of the interference from the BS and from the Relay UE, respectively. Then, the authors derive in a closed-form of the ergodic capacity for the case when only statistical CSI is available at the receivers for two cases: *(i)* weak interference scenario, where the D2D pair is at the cell edge (far from the UE whose radio resources are reused) and *(ii)* high SNR scenario, where the D2D users are close to each other. In addition, the power allocation maximizing the ergodic capacity is derived in closed form as well. The two-way relaying increases ergodic rate by up to 20% compared to the traditional D2D communication without relaying.

The power optimization and analysis of two-way relaying is also delivered in [134]. Similarly, as in [133], the analysis is done for simple system with just one Cellular UE, one Relay UE, and two D2D users. Two objectives defined in the paper are the maximization of minimal SINR of D2D pair and the capacity maximization of D2D pair. In both cases, the minimum QoS requirement of the Cellular UE with which the D2D pair and the Relay UE share resources should be satisfied. The first problem is analyzed and solved for three boundary cases: *(i)* transmission power of the first Source UE is set to the maximum value, *(ii)* transmission power of the second Source UE is set to the maximum value, and *(iii)* transmission power of both is set in a way that a minimum QoS of the Cellular UE is always ensured. Afterward, the optimal power allocation for all cases is derived by solving simple quadratic equations. The power is allocated at the Source UEs in a way that the capacity of both transmission hops is equal to maximize the relaying capacity so that none of the transmission hops pose a bottleneck in the relaying chain. The second optimization problem is of a “difference of convex structure” and can be solved iteratively by any convex optimization technique (e.g., interior-point method). The optimal power setting improves SINR of the D2D pair by up to 20% and the sum capacity by roughly 10% compared to the equal transmission power allocation. Both above works on the two-way relaying consider only a simple scenario with a limited number of users (one UE, one Relay UE, two D2D UEs). Thus, these works do not give enough insights to the two-way relaying's performance in a more realistic *multi-users scenario*. The relay selection in the multi-users two-way relaying scenario is considered in [135]. The relay selection is formulated as one-to-one problem, where the D2D pairs are matched with the Relay UEs in order to maximize the capacity (represented via relaying gain if the D2D pairs utilizes the Relay UE instead of the direct transmission between them). The authors also assume channel uncertainties during the matching process, such as imperfect channel estimation. To model the channel uncertainty, a column wise and ellipsoidal uncertainties [136] are introduced into estimated channel gains. The problem is solved by stable matching approach inspired by matching market considering the following four sets of users: the set of D2D pairs, the set of available Relay UEs, the set of potential Relay UEs that are preferred by the D2D pairs, and the set of potential D2D pairs preferred by the Relay UEs. The two-way relaying in multi-user scenario increases data rates up to 25% compared to the random relay selection scheme. Unfortunately, the authors do not give detailed insight into implementation of the matching algorithm.

The problem of joint relay selection, power allocation, and resource allocation for the two-way relaying in multi-user scenario is further studied in [137]. The paper first proposes a transmission power adjustment in a way that the Relay UE using PNC is able to successfully decode the signal from both the D2D UEs under time-varying channel conditions. To this end, both D2D UEs send test bits to the Relay UEs in order to measure received signal strength from both. Then, if the received power from the first D2D UE is higher (lower) than from the second D2D UE, the Relay UE commands the first D2D UE to decrease (increase) its transmission power to ensure equal received power from both. The authors also derive optimal SINR thresholds to maximize the transmission rates of D2D pair for all possible matchings of the D2D pair and the Cellular UEs in the first step. Then, in the second step, a bipartite-matching is adopted to further optimize the matching of the D2D pairs with the Cellular UEs. The authors also provide in-depth analyses of PNC's benefits with respect to no network coding and with a traditional HNC (see Fig. 24). It is demonstrated that the PNC indeed outperforms the case with no network coding (requiring four transmission phases) and high-layer network coding (needing three transmission phases) by more than 100%.

The performance analysis of two-way relaying for multi-users scenario is also given in [138]. The authors first provide a rigorous performance analysis for two-way relaying adopting XOR-based coding with focus on outage probability, average error probability, and average throughput for Rayleigh fading environment. Although the main contribution of the paper is the performance analysis, the authors also propose a simple relay selection for individual D2D pairs not able to communicate directly otherwise. The relay selection algorithm finds the optimal relay that maximizes the minimum SINR of two-hop communication path. Thus, the Relay UEs providing SINR value higher than a predefined threshold at the first hop are selected as the candidate Relay UEs. Then, the Relay UE resulting in the highest SINR at the second hop is selected from the candidate Relays. The simulation results validate the analysis and demonstrate that the PNC increases the capacity by up to 180% and 120% compared to the DF relaying without PNC and the AF relaying, respectively.

The energy efficiency of two-way relaying is addressed in [139], where the authors jointly optimize the transmission powers of the Relay UE and the Source UEs. Instead of PNC, however, only HNC is adopted. Thus, data is sent from the first Source UE to the Relay UE and from the second Source UE to the Relay UE within two consecutive time slots (see Fig. 24). Then, in the third time slot, the Relay UE decodes the transmissions and broadcasts it to both Source UEs. The authors first derive closed form expressions for successful transmission probability, total average transmission rate, and average energy efficiency of the UEs exploiting stochastic geometry. Then, the transmission power optimization is formulated. Since this problem is not convex, the authors adopt a sub-optimal derivative-based algorithm decomposing the objective function into K sub-functions that are maximized. The proposed scheme increases the energy efficiency approximately by up to 120% compared to no relaying case. Unfortunately, the paper does not assume two-time slots two-way relaying (i.e., PNC as considered, e.g., in [137]) to see whether the energy efficiency can be further increased or not.

Although the works above show the benefits offered by PNC or HNC, the potential disadvantage is the fact that enabling *advance coding techniques at the side of the Relay UEs requires more complex UEs*. Also the processing and decoding of the signal from the superposition of two received signals *deplete battery of the Relay UE* more quickly, which is, in fact, one of the most critical problems and also key challenge in the relaying via the UE.

7) Relaying with NOMA

The UE-to-UE relaying can also exploit *NOMA* transmission similarly as the UE-to-Network relaying concept. Hence, in [140], the D2D users that are not able to communicate directly with each other are helped by the Cellular UE. The Cellular UE/Relay UE is assumed to work in full-duplex and the transmission is composed of two phases: *(i)* the Source UE sends data to the UE and *(ii)* the UE decodes the received data and broadcasts both its own data and retransmitted data from the Source UE to the Destination UE. The Cellular UE also sets the power splitting factor between the transmission to the BS and the Destination UE. Since the Cellular UE works in full-duplex, both phases can happen concurrently, thus making the transmission more spectral efficient. The paper provides detailed performance analysis of the aforementioned system and derives an achievable rate region for the Cellular UE and the D2D pair, respectively. Moreover, an expression for the outage probability of both the UE and the D2D pair is derived analytically. Then, the authors formulate a problem as maximization of the minimum data rate of the Cellular UE and the D2D pair and solve it by joint transmission power allocation and power splitting at the Cellular UE. Finally, the authors also propose simple yet practical switching mechanism "compute-and-compare" to select between full-duplex and half-duplex mode in order to minimize the outage probability. The proposed algorithm results in a gain of 55% and 120% in the average achievable rate compared to the random power splitting and system without NOMA, respectively.

The relaying exploiting NOMA in DL is investigated in [141]. In fact, the Relay UE helps not just the D2D pair to improve its performance, but also performance of the Cellular UE is boosted thanks to the relaying, thus, the combination of the UE-to-UE and UE-to-Network relaying is considered in [141]. The relaying occurs in two consecutive phases, see Fig. 26. In the first phase, the BS transmits data to the Cellular UE and the Relay UE while the Source UE sends its own data to the Relay UE. During the second phase, the Relay UE broadcasts encoded data received in the first phase from both the BS and the Source UE. The objective of the paper is to maximize the capacity by the transmission power allocation at: *(i)* the BS while transmitting signal to the Cellular and Relay UEs during the first phase (indicated by a_1 and a_2 coefficients) and *(ii)* at the Relay UE while transmitting to the Cellular and Destination UEs during the second phase (indicated by b_1 and b_2 coefficients). The optimal transmission power allocation cannot be obtained in closed form. Thus, the authors derive the power allocation iteratively via one-dimensional search by setting first a_2 to fixed value while maximizing the capacity over b_2. Then, the process is repeated but b_2 is fixed while a_2 is changing. The proposal outperforms the equal power allocation (i.e., the BS allocates the same transmission power for the Cellular UE and the Relay UE in the first phase and the same power is allocated by the Relay UE when transmitting to the Cellular UE and the Destination UE in the second phase) by roughly 160%.

B. Advanced D2D relaying cases

Thus far, all works focusing on the UE-to-UE relaying assume just one Relay UE assisting one D2D pair. Similarly as in the UE-to-Network relaying, advanced relaying cases can be adopted also for the UE-to-UE relaying at a cost of a more complex radio resource management. To this end, we first discuss the case with multiple D2D pairs being helped by single Relay UE in Section V-B1. Further, the scenario with single D2D pair assisted by multiple Relay UEs and multi-hop relaying is discussed in Section V-B2 and Section V-B3, respectively.

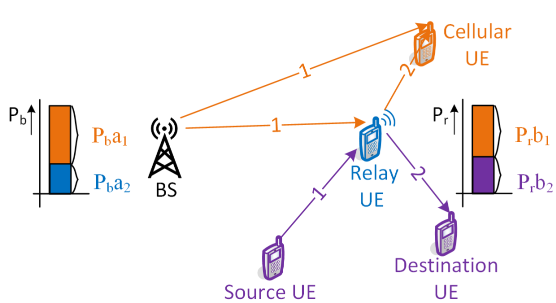

Fig. 26: DL NOMA aided relaying as proposed in [141].

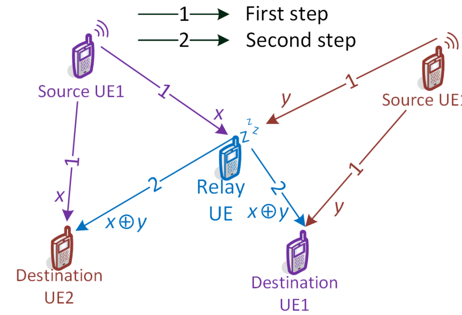

Fig. 27: Illustrative example of PNC exploited for data relaying to several D2D pairs by single Relay UE [142].

1) Multiple D2D pairs-Single Relay UE

A possibility to serve *multiple D2D pairs by single Relay UE* exploiting PNC is considered in [142]. The relaying itself is accomplished during two subsequent steps shown in Fig. 27. In the first step, the Source UE1 and the Source UE2 transmit simultaneously data to the Relay UE. At the same time, the Destination UE2 is supposed to receive data from the Source UE1 while data from the Source UE2 can be simultaneously received by the Destination UE1. Then, the Relay UE decodes data and broadcasts the XOR-coded data in the second step. Finally, the Destination UEs are able to decode data, as each Destination UE knows which part is intended for it. The PNC increases the capacity by up to 60% compared to the case without PNC requiring four time slots transmissions instead of just two. Although the paper brings an intriguing idea, where multiple D2D pairs can use the same Relay UE, the authors analyze this concept only for up to 70 Relay UEs and just two D2D pairs that are looking for relays. Hence, it would be interesting to investigate also the case where the number of Relay UEs is lower than the number of D2D pairs in need of relaying.

2) Single D2D pair-Multiple Relay UEs

The use of *multiple Relay UEs per single D2D pair* with the purpose to maximize energy efficiency is contemplated in [35]. The authors propose the optimal adaptive forwarding strategy constituting of two subsequent steps: *(i)* the most appropriate Relay UE is selected from all feasible Relay UEs and *(ii)* additional Relay UEs, besides the one selected during the first step, may be selected and perform cooperative beamforming provided that the energy efficiency is improved (i.e., several Relay UEs can help single D2D pair to improve its performance). Then, the proposed strategy dynamically selects between a best relay forwarding strategy [143] and a cooperative relay beamforming [144] in order to maximize the energy efficiency. To decrease the computational complexity of the optimal strategy, the authors also propose a sub-optimal low complexity adaptive forwarding strategy, where at most two Relay UEs are allowed to be used for the relaying. The proposed sub-optimal solution using only up to two Relay UEs outperforms the case without relays and best relay forwarding-only/cooperative relay beamforming-only strategies roughly by up to 200% and 20%, respectively, in terms of energy efficiency. Moreover, sub-optimal proposed strategy performs only slightly worse than the optimal one. Consequently, the use of *up to two Relay UEs per D2D pair* is usually a *good trade-off* between the energy efficiency and the complexity.

The use of several Relay UEs by single D2D pair can be of great benefit in deep fading scenarios as demonstrated in [145]. Each Relay UE exploits (different) subcarriers depending on signal to interference ratio at each subcarrier (see Fig. 28). The authors first provide a rigorous mathematical analysis of the outage probability. Then, relay selection and power optimization are carried out in order to minimize the outage probability of the D2D pairs while minimizing interference to the Cellular UEs. The power optimization problem is approximated so it becomes quasi-concave and is solvable by standard optimization techniques (the authors exploit CVX similarly as in [132]). The use of multiple Relay UEs per D2D pair decreases the outage probability by 75% compared to the case with one Relay UE for an average channel gain between Source UE and Relay UE of 10 dB if a deep fading effect at different subcarriers occurs. Although the proposed multicarrier relay selection provides a lower outage ratio, it is also by far more complex than conventional relaying schemes with just one Relay UE serving one D2D pair. Moreover, it is not easy to manage coordination and synchronization among multiple Relay UEs.

3) Multi-hop relaying

The multi-hop relaying in the UE-to-UE relaying concept allows direct communication of the Source and Destination UEs that are relatively far away from each other via several Relay UEs without any help from the BS. Of course, this advanced relaying option is challenging in terms of finding a proper Relay UEs and maintaining ongoing multi-hop communication due to users' mobility.

The multi-hop relaying is assumed in [146], where the main objective of the paper is to maximize end-to-end capacity in the scenario with moving UEs. The authors propose a square division allocation scheme based on a square tessellation technique, where the area is partitioned into small squares and the D2D relaying links can reuse the resources of the Cellular UEs far from them [147]. The size of each square is based on the maximum D2D communication distance ensuring that the Destination UE is able to communicate with the Source UE located in the adjacent square. The relay selection is done in a way that the first Relay UE is chosen randomly from all available Relay UEs located in the square that is: *(i)* adjacent to the one in which the Source UE is located and *(ii)* closest to the square with the Destination UE. The second Relay UE is again selected randomly from those located in the next square. This process is repeated until the last Relay UE is able to communicate directly with the Destination UE. Besides, the proposal deals with the mobility of users (both the Relay UEs and the D2D users) and updates the communication path by selecting new Relay UEs in the path. Hence, whenever the users move, it is checked whether multi-hop communication path should be updated or not. If such update is performed too often, relatively high signaling overhead is, however, generated. The proposed scheme outperforms state-of-the-art by 50% in terms of capacity.

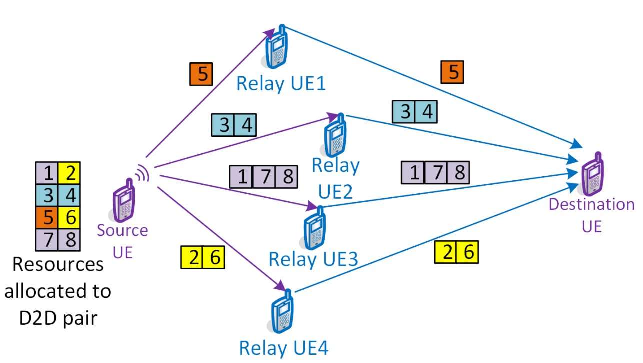

Fig. 28: Example of multicarrier relay selection, where each Relay UE exploits only those resources over which the outage is minimized [145].

The multi-hop relaying is further considered in [148]. The authors first develop a stochastic integer programming model to handle an uncertainty in the predictions of network parameters in the future time instances due to the users' mobility (such as channel quality between individual nodes). Then, a connectivity factor metric reflecting the D2D relaying links reliability and expected capacity is defined. The connectivity factor is calculated locally at each Relay UE involved in the relaying of data between any Source and Destination UEs. Finally, the perceived graph is created so that each node (i.e., the Source UE, the Destination UE, or the Relay UE) represents the vertex while the edge between any of two vertices is assigned with the connectivity factor. The paper also proposes a relay selection following two possible approaches: *(i)* centralized operator-controlled relay selection and *(ii)* distributed device-controlled relay selection. The purpose of the relay selection is, then, to find a proper trade-off between packet delay and packet loss. The proposed relay selection decreases both packet loss and delay roughly by 30% compared to a delay-based relay selection [149]. Further, it is demonstrated that the distributed relay selection performs only marginally worse than the centralized one.

The advantages of *two-way* relaying for multi-hop communication are explored by the authors in [150]. In particular, the paper investigates the performance of PNC with XOR coding in scenario with two D2D users exchanging data between themselves through several two-way Relay UEs. As discussed earlier in this section, the advantage of PNC is that the number of time slots required to exchange two packets between two users through single relay is shortened (see Fig. 24). In case of the multi-hop communication, the number of time slots is shortened from 2(M+1) to 2M+1, where M is the number of Relay UEs involved in the multi-hop communication. The paper yields the following outcomes: *(i)* XOR network coding

TABLE IV: Comparison of state-of-the-art works on UE-to-UE relaying; E2E - End-to-End.

	Classification of D2D relaying	Class. of Relay UEs	Optimized RRM tech.	Optimization/math tool	Performance
[105]	Underlay	HD, AF, idle	ReS, RA, PA	Iterative Hungarian	$C \uparrow$ by **10%** wrt greedy alg., $C \downarrow$ wrt optimal is **2%**
[106]	Underlay	HD, DF, idle	PA	Lagrange multipliers	SE $\uparrow$ by up to **45%** wrt [105] and [64]
[107]	Underlay	HD, DF, idle	ReS, PA	Stable marriage matching	$C \uparrow$ by **100%** wrt no relaying, **30%** $\downarrow$ wrt optimal
[109]	Underlay	HD, DF, idle	MS, RA, PA	Dinkelbach method, Hungarian alg.	$C \uparrow$ by up to **25%** wrt no relaying
[111]	Underlay	HD, DF, idle	ReS, MS, RA, PA	-	$C \uparrow$ by **100%** wrt random ReS and RA scheme, $\downarrow$ **2%** wrt optimal
[112]	Underlay	HD, DF, idle	MS, ReS, PA, RA	Dinkelbach method (PA)	$C \uparrow$ by up to **30%** wrt competitive schemes
[113]	Underlay	HD, DF, idle	MS, ReS, RA, PA	Simplex, Balas method	$C \uparrow$ by **200%** wrt no relaying, **10%** wrt [109]
[116]	Underlay	HD, DF, idle	ReS, PA	ANFIS, PSO	EE $\uparrow$ by **50%** wrt random ReS
[34]	Underlay	HD, AF, idle	ReS, PA	Dinkelbach met., Lagrang. dual decomp., Q-learning	EE $\uparrow$ by up to **40%** wrt benchmark
[118]	Underlay	HD, AF, idle	ReS, RA, PA	Game theory	SE $\uparrow$ more than **100%** wrt benchmark
[119]	Underlay	HD, AF, idle	-	-	Outage prob. $\downarrow$ by **15%**
[120]	Underlay	HD, DF, idle	ReS	Queuing theory (finite Markov state chain)	$C \uparrow$ by up to **40%** wrt benchmark, E2E delay $\uparrow$ by **10%**
[122]	Overlay	HD, idle	ReS	Multi-attribute decision process	Up to **30%** packets successfully delivered wrt benchmark
[124]	Underlay	HD, idle	ReS	-	$C \uparrow$ by **15%** wrt benchmark
[125]	Underlay	HD, idle	ReS, RA	-	$C \uparrow$ by **100%** wrt random relay selection
[126]	Underlay	HD, idle	ReS, RA, PA	Matching	EE $\uparrow$ by up to **120%** wrt matching with fixed power, but loss **27%** wrt optimal
[127]	Underlay/Overlay	HD, idle	-	Stochastic geometry	$C \uparrow$ by up to **600%** and **350%** wrt no relaying in Overlay and Underlay mode, resp.
[128]	Underlay/Overlay	HD, idle	-	Stochastic geometry	$C \uparrow$ by up to **450%** and **660%** wrt no relaying in Overlay and Underlay mode, resp.
[129]	Underlay	FD, DF, idle	RA, PA	Linear relaxation	$C \uparrow$ by **50%** wrt benchmark
[130]	Underlay	FD, DF, idle	PA,RA	Seq. convex opt. (PA), Hungarian (RA)	EE $\uparrow$ by up to **200%** wrt HD relays
[131]	Overlay	FD, AF	PA	Machine learning (neural networks)	C $\uparrow$ by up to **150%** wrt HD relays
[132]	Underlay	FD, DF, idle	PA	CVX in Matlab	Outage prob. $\downarrow$ **two times** wrt HD
[133]	Underlay	HD, DF, idle, two-way	PA	-	Ergodic $C \uparrow$ by up to **20%** wrt no relaying
[134]	Underlay	HD, AF, two-way, idle	PA	Interior-point method	$C \uparrow$ up to **10%** wrt equal power allocation
[135]	Underlay	HD, DF, idle, two-way	ReS, PA	Matching	$C \uparrow$ by **25%** wrt random relay selection
[137]	Underlay	HD, DF, idle, two-way	ReS, PA, RA	Hungarian algorithm	PNC outperforms HNC by more than **100%** in terms C
[138]	Underlay	HD, DF, idle, two-way	ReS, PA	-	Outage $\downarrow$ 2 times wrt cellular mode, $C \uparrow$ by up to **400%** wrt no relaying
[139]	Underlay	HD, DF, idle, two-way	PA	Stochastic geometry	EE $\uparrow$ by up to **120%** wrt no relaying
[140]	Underlay	FD, DF, active	PA	-	$C \uparrow$ by **120%** wrt OMA
[141]	Underlay	HD, DF, idle	PA	-	$C \uparrow$ **160%** wrt equal PA
[142]	Underlay, multi D2D pairs-single Relay UE	HD, DF, idle	ReS	-	$C \uparrow$ nearly **4 times** wrt conventional ReS
[35]	Overlay, multi Relay UEs-single D2D pair	HD, DF, idle	ReS	-	EE can be $\uparrow$ by up to **200%** compared to no relaying
[145]	Underlay/DL, multi Relay UEs- single D2D pair	FD, DF, idle	ReS	CVX in Matlab	Outage prob. $\downarrow$ by **3x times** wrt single relay scheme.
[146]	Underlay, multi-hop relaying	HD, idle	ReS, RA	Square tessellation technique (RA)	$C \uparrow$ by up to **50%** wrt competitive scheme
[148]	multi-hop relaying	HD, idle	ReS	Stoch. int. program., graph theory	packet loss and E2E delay $\downarrow$ by **30%** wrt benchmark
[150]	Underlay, multi-hop relaying	HD, idle, two way	-	-	$C \uparrow$, E2E packet loss $\downarrow$ by **30%** wrt benchmark

increases the capacity when compared to the case without coding roughly by 40% for 5 Relay UEs in the communication path, *(ii)* XOR coding increases the packet loss probability when compared to no coding scheme approximately by up to 30% for 5 Relay UEs, and *(iii)* the overall time during which the packets are exchanged between the users is decreased by XOR coding roughly by 30% for 5 Relay UEs.

C. Summary

This section has demonstrated that there are many works addressing various challenges in the UE-to-UE relaying. Similarly as in Section IV, we compare the surveyed works based on taxonomy introduced in Section II, including classification of D2D relaying described in Section II-A (i.e., according to the use of radio resources by D2D relaying links and number of UEs involved in the relaying chain), classification of Relay UEs introduced in Section II-B (i.e., according to the relaying protocol, duplex, activity of the Relay UEs, or whether two-way relaying is employed), and the used optimization tool and optimized RRM technique together with optimized metric(s) described in Section II-C (see Table IV):

- **Classification of D2D relaying** – Table IV illustrates that most of the surveyed works assume ***underlay*** communication mode. This trend is ***opposite to the UE-to-Network*** relaying, where the overlay mode is usually assumed. The reason is that, in the UE-to-UE relaying, the Source UEs and the Destination UEs are assumed to be of a lower priority, hence, dedicated resources are typically *not* allocated to these UEs. Still, the works on UE-to-UE relaying assume that each ***D2D relaying link always reuses resources of just one Cellular UE***. Thus, the resource allocation schemes with multiple D2D relaying links reusing the resources of the same Cellular UE should be farther investigated to increase spectral efficiency in future mobile networks. Also, like in the UE-to-Network relaying, the most common relaying scenario addressed in the papers is single D2D pair helped by single Relay UE. The advanced scenarios multi D2D pairs-single Relay UE [142], multi Relay UEs-single D2D pair [35], or multi-hop relaying [146], are assumed rather rarely.
- **Classification of Relay UEs** – As in the UE-to-Network relaying, the relaying users are typically supposed to be idle while exploiting half-duplex with the DF relaying protocol. Still, there are some works showing the benefits of the AF relaying over the DF relaying [119][34] or analyzing the merits of the full-duplex relaying [140][130][132][145]. Moreover, while ***two-way*** relaying is used only sporadically in the UE-to-Network relaying, it is of emph**high benefit** in the UE-to-UE relaying enhancing either the capacity or the energy efficiency [133]-[138][150][139].
- **Optimized RRM technique** – The surveyed papers focus especially on the relay selection and/or the transmission power allocation [105][107][137]. This finding is a little bit different with respect to the UE-to-Network relaying, where the sole optimization of the relay selection is predominant. The main reason for this difference is that the D2D pairs helped by the Relay UE(s) usually reuse the resources of the Cellular UEs and the transmission power allocation plays a crucial role in mitigating interference between the D2D and the cellular communication. Moreover, the resource allocation and the mode selection (i.e., deciding whether the D2D pair should be helped by the Relay UE or not) is tackled in some of the studies [111]-[113]. Further, similarly as in case of the UE-to-Network relaying, individual techniques are mostly ***optimized separately in sequential manner*** and joint solutions to the specified problems are not found.
- **Optimization/math tool** – There is a plethora of optimization and math tools employed for solving various optimization problems. The relay selection is very often solved by some kind of matching approaches (e.g., Hungarian method [105][137] or stable marriage matching [107]). Besides, many problems in the UE-to-UE relaying are hard to be solved in polynomial time, as these are often (mixed) integer (non)-linear programming. Thus, these problems are first transformed into more suitable forms that are, then, solved by various optimization techniques/methods, such as Lagrange multipliers [106], Dinkelbach [109], interior point [134], convex programming [132], etc. Also, similarly as in the UE-to-Network relaying, stochastic geometry is often used for analyzes of the system performance [127][128]. Last, machine learning is used only sporadically when optimizing performance of the UE-to-UE relaying. For example, ANFIS architecture using supervised learning approach and evolutionary algorithm using PSO is used for transmission power allocation in [116]. Besides, reinforcement learning (Q-learning) is exploited for the relay selection [34]. Still, machine learning, such as deep neural networks, has been adopted only sporadically ([131]) despite their potential to solve more complex problems.
- **Performance** – The works focusing on maximizing the capacity show that the relaying is able to increase the capacity in orders of tens of percent [109] or even hundreds of percent [111][113]. Besides, the energy efficiency can be also significantly increased (e.g., up to 200% as shown in [130][35]) and the outage probability can be decreased dramatically [145]. Still, the real gain in terms of capacity, energy efficiency, or outage probability introduced by the UE-to-UE relaying is strongly dependent on the selected scenario and/or parameters configurations.

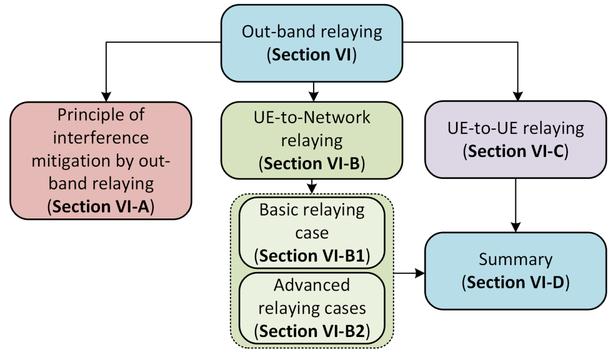

Fig. 29: Structure of Section VI.

VI. Out-band relaying

So far, we have seen many advantages of the in-band D2D relaying adopted either in the UE-to-Network or UE-to-UE relaying use-cases. In this section, we focus in detail on potential and benefits of the out-band relaying for both UE-to-Network and UE-to-UE relaying since work done in the former is rather limited and does not deserve dedicated section. First, we explain how the out-band relaying helps to avoid interference between the cellular and D2D communications (Section VI-A). Then, we overview the potential benefits of the out-band relaying for both UE-to-Network relaying (Section VI-B) and UE-to-UE relaying (Section VI-C). Finally, we also compare individual works focusing on the out-band relaying and identify some drawbacks in Section VI-D.

A. Principle of interference mitigation by out-band relaying

Due to an adoption of the underlay mode for the D2D relaying, severe mutual interference between the D2D relaying links and the cellular links may occur in the in-band relaying. This interference can be solved by the out-band relaying, where the D2D relaying links utilize WiFi or other frequency bands, such as millimeter Waves (mmWaves). The out-band relaying fully mitigates several types of interference (see Fig. 30):

- **I1** – interference from the Relay UE to the Cellular UE (in case of DL) and from the Cellular UE to the Relay UE (in case of UL)
- **I2** – interference from the BS to the Remote UE (DL) and from the Remote UE to the BS (UL)
- **I3** – interference from adjacent BS to the Remote UE (DL) and from the Remote UE to adjacent BS (UL)

In the following subsection we discuss in more detail individual works focusing on out-band relaying.

B. UE-to-Network relaying

Similarly as previous sections, we divide the works focusing on UE-to-Network relaying on those adopting basic relaying case with single Remote UE being helped by single Relay UE (Section VI-B1) and works assuming advanced relaying cases with either multiple Remote UEs or multiple Relay UEs involved in the relaying (Section VI-B2).

1) Basic relaying case

A thorough coverage probability and spectral efficiency analysis of the out-band UE-to-Network relaying encompassing single Remote UE-single Relay case is delivered in [151].

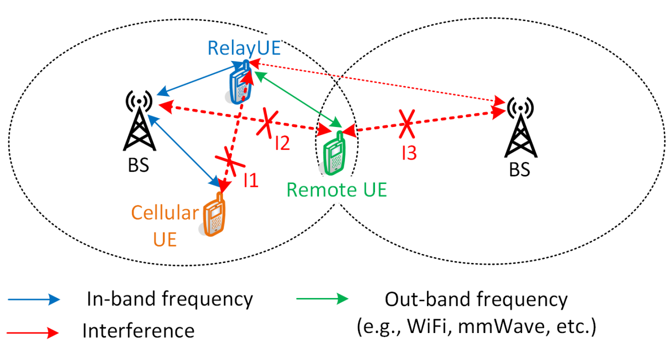

Fig. 30: Mitigation of various types of interference by exploitation of the out-band D2D relaying in the UE-to-Network case. In case of the UE-to-UE relaying, the source of interference is the Source UE while the victim is the Destination UE.

The coverage probability analysis employing stochastic geometry is done for: *(i)* the conventional cellular links exploiting mmWaves frequencies, *(ii)* D2D relaying links using in-band frequencies (in the paper referred to as microwave frequencies), and *(iii)* D2D relaying links facilitated by the mmWaves frequencies. The coverage probability defines whether the receiver (i.e., the Remote UE or the Relay UE) is able to receive the signal with SINR above specified threshold τ. The analysis itself is done for both interference-limited and noise-limited system. The authors conclude that in-band relaying outperforms the out-band relaying for an outdoor scenario by up to 35% in terms of coverage and by up to 8% in terms of spectral efficiency. Contrary, in an indoor scenario, the out-band relaying facilitated by mmWaves outperforms in-band relaying by up to 38% in terms of coverage and by up to 7% in terms of spectral efficiency. The reason why the in-band relaying outperforms the out-band relaying in the outdoor scenario is that the mmWaves relaying do not cope well with longer communication distances expected in the outdoor environment. In contrast, the out-band relaying outperforms the in-band relaying in the indoor scenario, where the communication distances are significantly shortened.

The coverage probability of the out-band UE-to-Network relaying exploiting mmWaves is also analyzed in [152]. Compared to [151], the authors of [152] answer the question whether the analysis error caused by ignoring spatial correlation is acceptable or not. The authors first derive SINR coverage probability for both the case where spatial correlation is accounted for and the case where spatial correlation is ignored. The performed analysis show that if the spatial correlation is ignored, there is severe overestimation of the coverage probability and also severe underestimation of the minimum number of antennas needed at the Destination UEs to achieve targeting SINR coverage probability. Besides, the provided results indicate that the out-band relaying exploiting mmWaves roughly doubles the SINR coverage when compared to the case without relays. The benefit of out-band relaying, however, decreases with an increasing transmission power of the BS (e.g., only 10% gain in the coverage is observed if the transmission power of the BS is 40 dBm). Although the increase in the transmission power of the BS can extend its coverage, it can also result in insufferable inter-cell interference in a multi-cell scenario with a dense BSs' deployment, as discussed in Section V-A. Hence, the authors in [153] maximize the spectral and energy efficiencies of the C-RAN network [154] encompassing multiple remote radio heads that cause interference to each other. Although the Relay UEs still retransmit data to the BS via in-band frequencies, the Relay UEs are much farther from the adjacent BSs than the Remote UEs and, thus, interference to the adjacent BSs is decreased. However, the D2D relaying link between Remote UE and Relay UE is facilitated by WiFi connection. The authors formulate the problem of the channel and power allocation as a non-cooperative game model, where each player (i.e., each UE) maximizes its own spectral efficiency. The non-concave problem is transformed into a concave one using a constraint relaxation and nonlinear fractional programming. Then, the problem is solved by Dinkelbach's method (similarly

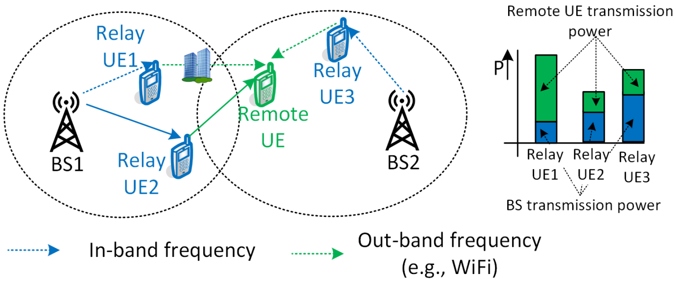

Fig. 31: Illustrative system model assumed in [156] with multiple cells. The Remote UE can select from Relay UE1, Relay UE2, and Relay UE3.

as in [112]) and Lagrangian duality theory. The authors demonstrate that the out-band relaying increases spectral and energy efficiencies of the cellular UEs by up to 65% and 25%, respectively.

The objective to maximize the system capacity while minimizing the interference by means of out-band relaying is also considered in [155]. When compared to [153], however, the out-band relaying in [155] helps to mitigate the *interference among the UEs inside the same cell* generated by *imperfect orthogonality* in uplink transmissions. The authors deliver Markov chain analysis to derive the probabilities of the Remote UEs' switching from the direct transmission (i.e., to the BS) to the relay transmission (i.e., data transmission in the out-band UE-to-Network mode using Relay UEs) and vice versa. Moreover, a steady state probability determining the average number of Remote UEs in the direct transmission mode and the relay transmission mode is performed. Finally, exploiting determined probabilities, the authors derive closed form expressions for the overall reliability and throughput. The provided analysis demonstrates that if the number of UEs in the network is low (less than 15 in a circular area with 2000 m radius) the maximal throughput is reached if the probability of switching from D2D mode to cellular is high (close to 1) while the probability that the UEs switching from the cellular mode to the D2D mode is low close to 0. This proves the fact that the relaying for a low density of UEs is not needed and the cellular mode is preferred, as there is no need to mitigate interference among the UEs. For higher densities of UEs, however, the throughput rises if the probability of the UEs being in the D2D mode increases.

The relaying is able not just to increase the capacity and coverage, but it can also help to reduce the transmission power of the UEs and the BSs. The objective to minimize the sum transmission power of the BSs and the Relay UEs via out-band relaying, while guaranteeing a minimum data rate for each UE, is considered in [156]. The out-band is again used only for the D2D communication enabling the transmission of the data from the Relay UE to the Remote UE (similarly as in above-discussed works). The authors define a relay selection problem, where the Remote UEs are attached to the BS either directly or via intermediate Relay UEs. The paper also assumes the case when the Relay UE and the Remote UE are served by different BSs, thus increasing the number of potential relays resulting in a higher reduction in the sum transmission power (see Fig. 31). Since the optimization problem is a non-linear binary problem (i.e., NP hard), the authors design a distributive selection algorithm based on Q-learning. In this algorithm, each Remote UE keeps its own record on past experience using the Relay UEs and computes a reward. The reward is based on the fulfillment of the optimization target in the past while ensuring bit rate requirements of the UEs. As a result, the lower power consumption of the BS and the Relay UEs leads to the higher reward and vice versa. Then, the relay selection is performed using softmax decision-making process [61] exploiting the information each UE already knows in order to obtain a reward, on one hand, and exploring ways to take the better actions in the future, on the other hand. The proposed algorithm decreases the total transmission power by up to 40% when compared to no relaying.

The minimization of the transmission power of Remote UEs is also contemplated in [157]. The UE is considered as a candidate Relay UE if and only if the saved transmission power of the Remote and Relay UEs is higher than a power saving threshold. First, the authors define a relaying region, where any potential Relay UE should be located to be considered as the candidate Relay UEs. To this end, the authors also derive analytically the probability of at least one Relay UE being in the relaying region. Further, the power consumptions at the Remote and the Relay UEs are derived in closed form using Green's theorem [158]. The paper demonstrates a trade-off between a success probability of the D2D relaying and the amount of power saved. In particular, if the power saving threshold increases, the success probability of the D2D relaying decreases while more notable savings are achieved (up to 45% when compared to no relaying case). Nevertheless, the power consumption starts increasing as the number of available relay decreases when the threshold reaches a critical value.

The systems exploiting mmWaves as the out-band relaying are known to have a very short reach and are *highly susceptible*

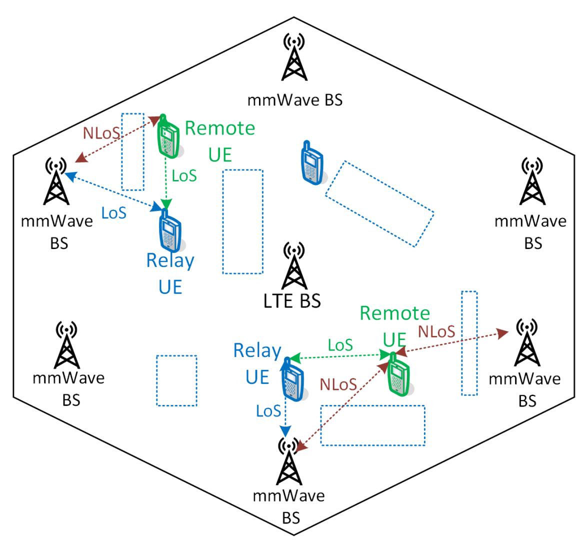

Fig. 32: System model based on [159] with the possible obstacles in the communication path.

to any obstacle in the communication path (i.e., to NLoS environment). To this end, the authors in [159] propose a relay selection for the UE-to-Network scenario with the objective to ensure LoS communication between the UEs and mmWaves-based BSs (see Fig. 32). If LoS between the UE and the BS cannot be guaranteed, the Relay UEs are selected in a way that the Remote UE and the Relay UE are able to communicate in LoS to ensure reliable transmissions in mmWaves. In order to facilitate the relay selection, the authors propose a learning based approach to determine both *fixed* and *moving obstacles* (like cars and humans) in the area and, then, select the Relay UEs accordingly. The input to the learning process is the channel quality between two communicating nodes from the past reflecting also whether the nodes communicated via LoS or NLoS channel. The output from the learning is the information whether LoS/NLoS environment is between any two nodes. During the learning phase, the BS assigns arbitrarily links to the UEs and, subsequently, SINR of these links is measured and reported. If the SINR of any link remains stable and significantly lower than a specified threshold, it is assumed that there is a static obstacle in the way (i.e., NLoS communication). Moving obstacles are distinguished by only temporal drop in the channel quality. The learned information is, then, exploited for the relay selection in order to ensure LoS between the Remote UE and Relay UE and between the Remote UE and BS to maximize the capacity. The proposed approach is close to optimal case with the position of fixed and moving obstacles assumed to be known (less than 10% inaccuracy in the relay selection), if the learning process is sufficiently long (at least 200 000 learning cycles).

2) Advanced relaying cases

The out-band relaying in the UE-to-Network concept can be also used for *multi-hop* communication, as considered in [160]. The main objective of the paper is to decrease bit error rate of the Remote UEs and, thus, to improve DL throughput. Similarly as in the above-discussed studies, the in-band frequency is used solely for the transmissions between the BS and the Cellular UEs. Then, data is relayed to the Remote UEs through WiFi. The Relay UEs in the communication path are not selected just with respect to the capacity gain, but also considering the remaining energy of the Relay UEs (similarly as in, e.g., [120]) to avoid the situation where one Relay UE would compromise the whole relaying chain. The authors propose a centralized heuristic algorithm divided into three parts: *(i)* the pre-selection of the first Relay UE in the communicating path (i.e., the Relay UE receiving data directly from the BS), *(ii)* the pre-selection of the second Relay UE (i.e., the Relay UE re-transmitting data to the Remote UE from the first Relay UE), and *(iii)* the verification of selected Relay UEs at the BS checking whether the pre-selected relays are suitable or not. The proposed multi-hop out-band relaying considering remaining energy of the Relay UEs increases the D2D link average lifetime with respect to competitive scheme by up to 30%.

So far, all listed studies evaluate the performance of the out-band relaying either analytically and/or by means of the simulations. The authors in [161], in contrast, provide an *experimental analysis* by means of a software defined radio platform LabVIEW. The paper designs a D2D opportunistic relaying with QoS enforcement framework. The main objective is to opportunistically select the communication mode (i.e., deciding whether the use of Relay UE is beneficial or not). If the relaying is beneficial, the Relay UE is selected while taking into account one of the most tangible problem of the out-band relaying, i.e., the problem of maintaining QoS in the unlicensed bands. The defined problem of relay selection is, however, a multidimensional knapsack problem, which is generally hard to be solved. Since even a modified brute force algorithm proposed by the authors is of very high (exponential) complexity, the greedy algorithm is adopted for the relay selection in order to keep low complexity for real networks implementation. The algorithm first estimates a potential throughput gain and delay. Then, the Relay UEs are selected prioritizing the Remote UE-Relay UE connections yielding the highest gain under the delay constraint. Thus, the UEs with good cellular links or the UEs having a channel to the candidate Relay UEs of a low quality are prevented from being matched with any Relay UE. The experiments yield the following conclusions:

- The used of WiFi as out-band technology *doubles end-to-end delay* (increase by 3.3 ms) and *increases CPU load* of the UEs by 5% on average due to WiFi processing.
- The capacity of out-band relaying can be significantly enhanced by enlarging the relaying group allowing one Relay UE to relay data of multiple Remote UEs (i.e., multi Remote UEs-single Relay UE case). This way, the capacity can be enhanced by 70% if one Relay UE helps four Remote UEs instead of just single Remote UE.

The experimental analysis and prototyping is also done in [162]. The authors first propose *eDirect* framework to minimize energy consumption and signaling overhead generated by short and frequent "heartbeat" messages (generated, e.g., by popular WhatsApp application). The objective of eDirect is to alleviate signaling by use of the D2D relaying, where multiple Remote UEs first send these messages to the Relay UE via WiFi and, then, the Relay UE retransmits the collected messages to the BS. The proposed framework is composed of three phases. The first phase is a *D2D discovery* during which the Remote UEs search for suitable Relay UEs candidates. During the second phase, a *D2D connection*, a matching of the Remote UEs with the Relay UEs is performed. The authors adopt a greedy approach, where the Remote UEs are matched with the Relay UEs guaranteeing the highest received signal strength. Besides, the matching algorithm also considers the number of Remote UEs that each Relay UE is willing to serve depending on the Relay UE battery status. Finally, the last phase, a *Message transmission*, encompasses a scheduling of the Relay UE's transmission to meet the delay deadlines of the received heartbeat messages while minimizing the signaling. The real-world experiments with the prototype implementation demonstrates a decrease of at least 50% in signaling overhead and saving of up to 36% in the energy consumption of the Remote and Relay UEs due to heartbeat transmissions.

C. UE-to-UE relaying

The impact of the moving obstacles on the relay selection in the UE-to-UE scenario is considered in [163]. The authors model the problem via finite horizon partially observable Markov decision process framework to learn whether the D2D relaying link is LoS or NLoS. The model learns the channel quality in online fashion and, thus, there is no need to train the model. The learning itself is facilitated by an exploration procedure during which the Source UE locally searches for a suitable Relay UE. In particular, the Source UE sequentially searches space in all directions to align transmitter and receiver beams (i.e., beam alignment). The actions that can be taken after the exploration are as follows: *(i)* the potential D2D link is of a bad quality (e.g., due to NLoS) and some other relay should be found instead, *(ii)* the potential D2D link is of a good quality and the relay is exploited for data transmission, and *(iii)* the decision on whether the D2D link should be used cannot be made immediately and exploration of D2D link channel quality continues for another specified period. The proposal minimizes the D2D link failure due to moving obstacles and the end-to-end delay roughly two times and three times, respectively, compared to the greedy selection based on received signal strength approach. This is at the cost of nearly three times longer exploration time lasting up to 10ms (i.e., the time to learn the quality of individual links).

D. Summary

This section and Table V give a brief summary of the works focusing on the out-band relaying in relation to the taxonomy introduced in Section II. In particular, we classify individual works on whether UE-to-Network or UE-to-UE relaying is exploited, if advanced relaying use-cases are utilized or not, and the use of out-band technology/frequency bands) according to Section II-A. Furthermore, we classify Relay UEs according to relaying protocol, duplex, or activity or Relay UEs in line with Section II-B (note that one-way relaying is always assumed in the works focused on out-band relaying). Finally, we show which RRM techniques are optimized by individual works, discuss optimization/math tools, and compare the performance following optimization aspects introduced in Section II-C. Now, let's discuss the individual above-mentioned aspects in more detail:

- **Classification of D2D relaying** – When compared to the in-band relaying, the studies focusing on the out-band relaying targets primarily the UE-to-Network relaying in the multi-cell scenario, as the out-band relaying is able to mitigate also inter-cell interference among adjacent cells. Still, the out-band relaying can be of an advantage also in the UE-to-UE relaying considering the fact that the underlay mode is used in this scenario predominantly. Beside, WiFi [153][160] or mmWaves [151][152] are usually considered for the out-band relaying. Surprisingly, there are ***no*** works exploring the use of ***terahertz bands*** and ***visible light communication*** (VLC), for the out-band relaying even though terahertz bands/VLC may provide superior capacity over conventional microwave bands, especially if communication is at short distances with LoS communication (see, e.g., [164]).
- **Classification of Relay UEs** – The Relay UEs exploiting the out-band frequencies are assumed to usually work in the half-duplex. Only the authors in [156] consider the full-duplex relaying. This finding is surprising, as the ***out-band relaying mitigates self-interference*** caused by the ***full-duplex*** provided that the Relay UE transmits/receives data via the in-band communication while it receives/transmits data by means of the out-band communication. In addition, we can observe that mostly the idle relays are considered while the active relays are assumed to be used only in few surveyed works [155][161].
- **Optimized RRM technique** – Similarly as in case of the in-band D2D relaying, the relay selection is the crucial radio resource management technique and, hence, it is optimized in a majority of the surveyed works [160]-[156][163]. Moreover, the mode selection (i.e., the selection between the cellular mode and the D2D relaying) is tackled by the authors in [155][161][157]. In addition, joint resource and power allocation is optimized in [153].
- **Optimization/math tool** – The works exploit various optimization and math tools ranging from the stochastic geometry [151] and Markov chain [155] to model a random behavior of the users and their deployment, via game theory [153], to various machine learning tools, such as reinforcement Q-learning in [156] for relay selection purposes or learning-based deterministic algorithm to determine whether the communication will be in LoS or NLoS [159][163].
- **Performance** – The simulation and experimental results show many benefits of the out-band relaying in terms of the capacity enhancement (up to 80% [161]), coverage extension (i.e., doubling the coverage probability [152]) or the transmission power reduction (by 40% [156]) when compared to no relaying scenario.

VII. Incentives

The previous sections demonstrate that D2D relaying is able to significantly boost performance of contemporary and future mobile networks in terms of capacity, energy efficiency, or energy consumption. Nevertheless, to unlock these benefits and gains, the key aspect of D2D relaying is to motivate the relaying users to act as the relays. At the same time, the users searching for the relays also expect certain level of privacy, security, and reliability to be willing exploit devices of other users to relay their own data. Both above-mentioned aspects can be addressed by proper incentive mechanisms. To this end, this section gives detailed overview of various incentive mechanisms and ideas (see Fig. 33).

We show that the incentive mechanisms can take inspiration from the economy (Section VII-A) or can be based on social trust and social relationship among the users (Section VII-B). Besides, a reputation of the relaying users or the users searching for relay can also be used to motivate the relaying (Section VII-C). In case the relaying users are active (i.e., transmit/receive their own data), a very convenient incentive

TABLE V: Comparison of state-of-the-art focusing on out-band relaying; Tx - transmission power.

	Classification of D2D relaying	Class. of Relay UEs	Optimized RRM tech.	Optimization/math tool	Performance
[151]	UE-to-Network, mmWave	HD, idle	-	Stochastic geometry	Indoor scenario: Coverage prob. and SE ↑ by **38%** and **7%**, resp.; Outdoor scenario: coverage prob. and SE ↓ by up to **35%** and **8%**, resp.
[152]	UE-to-Network, mmWave	DF, HD, idle	-	-	Coverage prob. ↑ by **100%** wrt no relaying
[153]	UE-to-Network, WiFi	HD, idle	RA, PA	Game theory, nonlinear fractional programming	SE ↑ by **65%**, EE ↑ by **25%**
[155]	UE-to-Network	HD, active	MS	Markov chain process	If $<$ 15 UEs ⇒ better stay in cellular mode, otherwise it is better to switch to D2D mode
[156]	UE-to-Network, WiFi	FD, idle/active	ReS	Reinforcement learning (Q-learning)	Tx ↓ by **40%** wrt no relaying
[157]	UE-to-Network, WiFi	DF, HD, idle	MS	Green's theorem	Tx ↓ by **45%** wrt no relaying
[159]	UE-to-Network, mmWave	-	ReS	Learning based deterministic algorithm	Less than **10%** inaccuracy in relay selection
[160]	UE-to-Network, multi-hop relaying, WiFi	HD, idle	ReS	-	D2D link lifetime ↑ up to **30%** wrt benchmark
[161]	UE-to-Network, multi Remote UEs-single Relay UE, WiFi	HD, active	MS, ReS	-	C ↑ by **80%** wrt no relaying; E2E delay is ↑ by **100%**, and CPU ↑ by **4%** wrt no relaying
[162]	UE-to-Network, multi Remote UEs-single Relay UE, WiFi	HD, active	ReS	-	Sig. overhead ↓ by **50%**, EC ↓ by up to **36%**
[163]	UE-to-UE, mmWave	HD, idle	ReS	Finite horizon partially observable Markov process	Link failure and E2E delay ↓ by **2 times** and **3 times**, resp.; exploration time ↑ **3 times** wrt benchmark

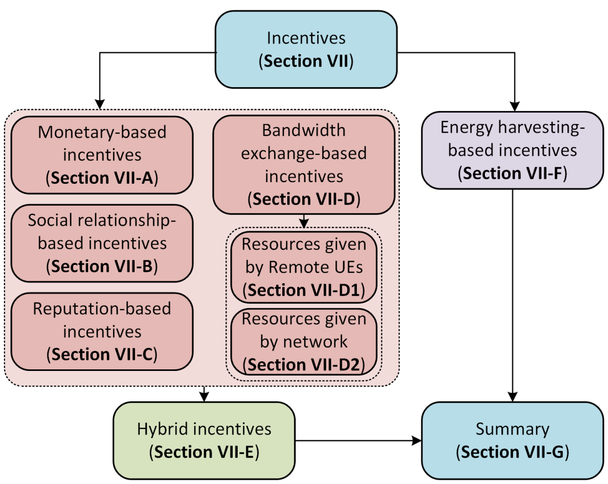

Fig. 33: Structure of Section VII.

is to pay the relaying users with an additional bandwidth or transmission opportunities (Section VII-D). Besides, we also overview some initial attempts to combine some of the above-discussed incentives into a hybrid incentive to better serve the need of the relaying users (Section VII-E). On top of that, Section VII-F illustrates that the relaying users can be motivated to relay data if allowed to harvest energy from radio frequency transmissions of other users or BS. Finally, we compare the surveyed studies from several key perspectives and identify their drawbacks, if any, in Section VII-G.

A. Monetary-based incentive

The monetary-based incentives are inspired by a natural "selling-buying" principle, where the relaying users sell their relaying services while the users exploiting the relays pay with some kind of a virtual currency.

The pioneering work on the monetary-based incentives for the UE-to-network relaying is [165] and its extension [166]. The motivation for the idle Relay UEs to relay data for the Remote UEs is a reception of a token. The received token(s) can be used by the Relay UEs in the future when asking for the relaying services. The objective of the papers is to maximize a long-term utility of each user represented as a difference between the gain in throughput due to relaying (i.e., when the Remote UE is being helped by the Relay UE) and the energy consumed by the relaying. The authors propose a low complexity supervised learning algorithm to learn a near optimal cooperation strategy. The algorithm considers three probabilities: *(i)* a probability that the Remote UE searches for a help from the Relay UE, *(ii)* a probability that the Relay UE is asked to relay for the Remote UE, and *(iii)* a conditional probability that the Remote UE gets help from the Relay UE provided that the Remote UE has enough tokens while, at the same time, the Relay UE has enough power budget for relaying. The proposed algorithm itself is composed from offline and online phases. During the offline phase each UE learns cooperation strategy, such as whether to relay data for others or not. Then, during the online phase, each UE selects the proper cooperation policy learned during the offline phase. The simulations show that if there are *too few or too many tokens* in the system, the relaying gain is decreased. If there are not enough tokens, users usually have no token(s) to pay to the Relay UEs. Contrary, if there are *too many tokens*, the users with enough tokens have no motivation to further help others. Another problem of the token-based mechanism is that single token is paid to the Relay UE disregarding the relaying gain or the amount of energy spent by the relaying.

The motivation of the Relay UEs in the UE-to-UE relaying use-case is the main scope of [146]. The authors assume multi-hop relaying, where the Source UE sends data to the Destination UE through several intermediate Relay UEs (see

Fig. 34). Obviously, an incentivization of multiple Relay UEs is more challenging than motivating just a single Relay UE. For example, the payment by tokens, as considered in [165], would not work, since multiple tokens would need to be paid by the users, making tokens hard-to-find commodity. To this end, the authors propose a credit-based incentive mechanism, where the BS acts as an account server (see Fig. 34). The Source UE and the Destination UE are charged based on the reporting of the "first" Relay UE in the communication path between the Source and Destination UEs (i.e., the Relay UE1 in Fig. 34) informing the BS about the number and the sizes of received packets from the Source UE. The reason why the first Relay UE is selected instead of another one is that the first Relay UE has the most precise knowledge of the number of packets actually transmitted by the Source UE. Similarly, the amount of credits to be paid to the Relay UEs is based on the reporting of the Destination UE to the BS giving the same type of information as the first Relay UE, that is, the number of received packets and their sizes. The disadvantage of the proposed approach, however, is that if there is just one relaying user not forwarding all packets, all other relaying users are punished as they will not get paid for packets not delivered to the Destination UE. In addition, the Source and Destination UEs may be required to pay credits even if the first Relay UE falsely informs the BS about the number of packets received.

B. Social relationship-based incentives

The social relationships among the users play a significant role in the willingness of the users to act as the relays. The users are more willing to help those with whom they have *close social ties*. Besides, users with strong social ties are supposed to be more *trustworthy* and *reliable* to each other, as these users will not (most likely) try to misuse and/or discard relayed data. As a result, the social relationships notably affect the *relay selection* mechanism itself.

The works focusing on the social relationship consider not just a *physical* domain, but also the aspects from a *social* domain. Both physical and social domains are represented by separate graphs (see Fig. 35) [167]. The physical domain represents the channel quality between any two users. Hence, if the users are able to communicate with each other, there exists an edge between them in the physical graph. The social domain reflects an existence of a social tie between the users. The social tie ordinarily exists between family members, friend, co-worker, etc. Besides, the social tie can also reflect past contacts (duration and frequency) among individual users. The users that have a mutual connection in both physical and social domains are suitable candidates to help each other by means of the relaying.

The social relationship for the UE-to-Network relaying is elaborated in [168]. Compared to [167], the social domain is further decomposed into two parts, each modelled by individual graph: *(i) online* social graph and *(ii) offline* social graph. The online social graph represents the social trust and willingness of the users to act as the relays. The authors assume that the social trust has a specific degree varying between 0 and 1 affecting the amount of the transmission power each Relay UE is willing to allocate for the relaying. Thus, the Relay UEs having no social trust with the Remote UEs transmit with the minimal transmission power resulting in only negligible relaying gain. The offline social graph indicates whether the users have met in the past or not. Hence, the offline social graph serves for the practical scenarios, where the users move, as the movement has a significant impact on the duration and stability of the D2D relaying link. The authors also propose a social-aware optimal stopping policy relay selection scheme. In particular, the Remote UEs search for potential Relay UEs during the probing phase, taking into account social aspects defined by online and offline social graphs. The objective is to stop the probing process when there is no better potential Relay UE than the selected one (i.e., when reward is maximized).

The social relationship impacting the relay selection is also considered by the authors in [169]. The main objective of the relay selection is to find a proper trade-off between latency and reliability. While a low latency is possible due to the relaying, the reliability is reflected by social trusts among the users quantified by the security of relaying. With an increasing level of social trust, the Relay UEs tolerate a higher degradation in their own data rate in order to help others.

So far, all works considering social ties and/or relationships target the in-band relaying, where the relaying is done over the bands exploited by the Cellular UEs. The authors in

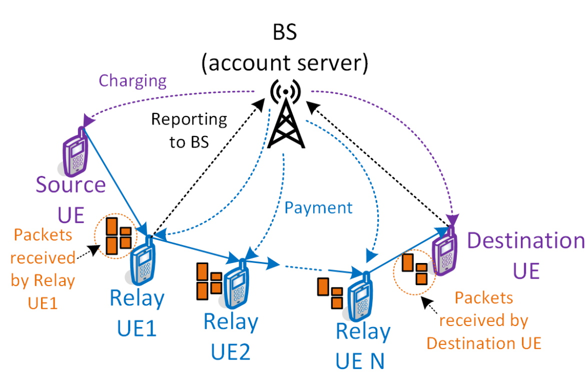

Fig. 34: Principle of incentive mechanism for multi-hop UE-to-UE relaying proposed in [146].

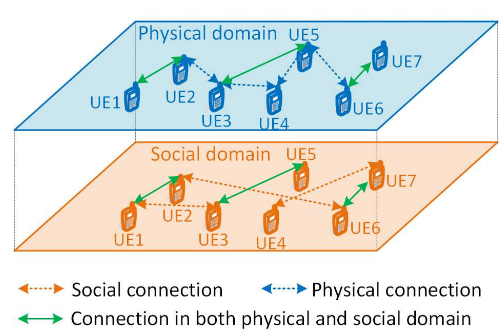

Fig. 35: Physical and social domains for D2D relaying based on [167].

[170][171], in contrast, explore the impact of social ties for the out-band relaying using mmWaves (as in several works described in Section V). The paper addresses the problem of mobility and changing of social behavior affecting both the physical and social domains. More specifically, the mobility of users affects the physical connection between the users while the changing social relationship among the users affects the social ties and their willingness to act as the Relay UEs. This dynamicity is modeled by Markov process, where the edges between individual users appear and disappear over time. Then, two approaches for establishing a trustworthy D2D relaying are proposed:

- *proactive approach* – The UEs having LoS communication with the BS are willing to act as the Relay UEs and, thus, proactively broadcast their availability to other users. After that, interested Remote UEs calculate trust level of the Relay UE and transmit their data that are subsequently retransmitted by the Relay UE.
- *reactive approach* – The Remote UEs that are in NLoS communication with the BS send a request to the trustworthy Relay UEs in their vicinity. The Relay UEs that are interested in provisioning of the relaying services respond to their preferred Relay UEs. Then, the Remote UE selects the Relay UE with the highest social trust.

One of the first studies exploring the impact of social relationship for the UE-to-UE relaying is presented in [172]. The social relationships are derived from the past interactions between the users. Then, the transmission power allocated by the Relay UE depends on the level of social trust between the users. The paper's objective is to maximize the throughput by relay selection mechanism while considering social relationship between the users. To this end, the authors devise a hybrid relay selection scheme considering both distance between the UEs and the social relations. Only the UEs with a strong social relation (i.e., the social relation above a specified threshold), can act as the Relay UEs. The UEs with a weak social relation are discarded as these may not meet data requirements due to a low transmission power allocated for the relaying.

The social ties can serve not just to measure the willingness of users to relay data for others, but they also impact the relaying users' reliability, as assumed in [173]. Moreover, the authors assume *asymmetric social ties* between users. Thus, the social tie between the users A and B and social tie between the users B and A does not have to be the same. This inequality means that if the user A is reliable for the user B, the user B may not be so reliable for the user A and vice versa. The objective of the paper is to maximize the capacity by saving the BS's resources, since data between the Source and Destination UEs is send through the Relay UE instead of through the BS. At the same time, only reliable Relay UEs (i.e., social tie between the Source UE and Relay UE is strong enough) can be selected. The asymmetric social ties between users are also assumed in [174]. The objective is to minimize the sum transmission power of all Relay UEs in a scenario with the Source UE sending some content to the Destination UE via multi-hop relaying (i.e., via more than one Relay UE). The authors propose a greedy geo-forwarding rule, where each Relay UE in the multi-hop path is closer to the Destination UE and satisfies both a constraint on social relationship (i.e., social tie is above specified threshold, similarly as in [173]) and a power constraint (i.e., the Source UE or the Relay UE is able to send content to newly selected Relay UE while the transmission power is below a certain threshold).

The social ties between UEs are also assumed in [175] to facilitate task offloading in industrial IoT. Similarly as in the previous works on social-aware incentives, a social domain representing strength of social tie among any two UEs is assumed, on top of the physical domain. The social tie between the UEs is modelled by weighted undirected graph, where the weight represents the strength of the social tie. In order to improve the task offloading from the UEs with insufficient computing resources to the UEs with idle computing resources, single Relay UE can be exploited. The interaction between the UEs is modelled as an auction mechanism, where the UEs with idle computing resources act as sellers while the UEs willing to offload their task are buyers. The authors propose a social-aware incentive mechanism composed of three phases: *(i)* relay selection phase (the Relay UE that can provide connection to the UE with the highest bid is selected), *(ii)* winner selection phase during which the UEs with idle computing resources decide to whom they allocate their computing resource to maximize social welfare, and finally *(iii)* price determination phase. The performance evaluation unveils the fact that the social motivated UEs are able to more than double the task offloading ratio if there are strong social ties among the UEs.

While the previous papers assumes a single community in a content delivery multi-hop scenario, the authors in [176] extend the problem to the case with the users that can belong to *several communities*. Then, the users having strong social ties in several overlapping communities are suitable candidates to relay content between different communities. The social ties among the users are based on frequency and duration of the contacts among users (same as in [168]). Each user is supposed to maintain local record containing the information about which users had been encountered and for how long (this information is updated on a regular basis). Then, the users are classified intro three categories: *(i)* often encountered users, *(ii)* users that have not been encountered for some time, and *(iii)* transitively encountered users. Then, based on the number of encounters in the past, a social tie among the users is extracted utilizing a deep sparse autoencoder [177] employing an offline unsupervised learning. Finally, the users belonging to several communities, labeled as "overlapping community users", are identified by means of fuzzy C-mean clustering [178].

The level of social trust among the users can also have an effect on the users' willingness to relay data in half- or full-duplex, as contemplated in [179]. Although the full-duplex offers higher transmission rates (i.e., higher relaying gain), it is also less energy efficient due to imposed self-interference (i.e., the transmission rate is not increased twice). To this end, the authors argue that the relaying users are more willing to use half duplex if the remaining battery level is below some threshold to avoid a quick depletion of their battery. The full-duplex is used only if the remaining battery energy of the Relay UE is above a certain threshold, otherwise, half-duplex is employed. Consequently, the proposed relay selection algorithm first classifies te candidate Relay UEs into two groups depending on whether the Relay UEs can work in full or half duplex. Then, the relaying gain provided by each potential Relay UE is proportional to: *(i)* transmission rate if the Relay UE would be exploited and *(ii)* social relationship strength measured by their encounters in the past. Finally, the Relay UE yielding maximum relaying is selected. So far, the social trust among the users has been "simply" derived by frequency and duration of encounters by the users or based on the relationships among the users (friends, family members, etc.). A different and more sophisticated approach for a determination of the social trust among individual users is contemplated in [180]. The trust level between any two users is based on both *objective* and *subjective* psychological aspects:

- *Cognitive trust* – Trust based on direct or indirect encounter/interaction between the users. For example, the direct interaction is represented by the willingness of other users to cooperate in the relaying. The indirect interaction/encounter is seen as a recommendation of others users and experience with them.
- *Emotional trust* – The users having similar interests are seen more trustworthy resulting in a stronger emotional trust.
- *Behavior trust* – Trust based on a gained experience from the past reflecting whether the users do not tend to "misuse" the offered help.

The reliable relaying users are found by means of naïve Bayes method [181] taking all three subjective psychological aspects into account. Only the reliable users are considered as the candidate Relay UEs and out of these the user maximizing the throughput is selected.

Similarly as the previous study, the authors of [182] dig deeper into the way how social relationships among the users are obtained. While both cognitive trust and emotional trust are considered, also a social trust based on *Triadic closure* is taken into account. The Triadic closure is a common phenomenon in social networks assuming if the user A is a friend with the user B and the user B is a friend with the user C, the user A is either already friend with the user C or become friends in the future. Thus, this paper brings an interesting new twist into social relationship-based incentives as the social relationship is ongoing changing process that is updated from time to time.

The drawback of the whole social relationship-based concept is the fact that usually only a *limited number of users* with strong social ties is in the vicinity of the users requiring the relaying services. Still, as already explained above, strong social ties help not just to motivate the users to act as the relays but also help to increase security of the relaying. Hence, the goal of the authors in [183] is to find a trade-off between the achievable relaying gain and security. The whole relay selection problem is solved by a modified stable matching, where the Source UEs are matched with the Relay UEs in two rounds. During the first round, the Source UEs can be matched only with the Relay UEs having strong social ties. Then, in the second round, the Source UEs not matched with any Relay UE during the first round still got the opportunity to be matched with the Relay UE without a strong social tie provided that there is enough D2D relaying links accommodated by users with strong social tie.

C. Reputation-based incentives

Other type of incentives is based on a reputation of the users. The seminal work on the reputation-based incentives for the UE-to-Network relaying is [184]. The authors propose an indirect reciprocity game, where the relaying users do not benefit immediately from their current actions, but the benefit is received in the future, similarly as in the virtual currency or social relationship incentives discussed in previous subsections. The users get a "good" reputation if they help others to relay data and a "bad" reputation is assigned to those users declining to act as the Relay UEs (see Fig. 36). The reputation of each relaying user is being stored and updated regularly at the BS to reflect their most recent actions (i.e., accepting/declining to relay). The authors also address the problem of potential cheating by the relaying users who promise to help to increase his/her reputation, but does not relay any data at the appointed intervals. To this end, the BS senses whether the Relay UE relays the data at the appointed interval(s) while using energy detection. Still, as the paper focuses on uplink communication, the energy detection itself may be redundant since the BS should be able to recognize whether Relay UE is relaying data or not. Thus, the energy detection rather should be exploited to determine if the Relay UE transmits with enough power.

The binary classification of the reputation to either good or bad, as proposed in [184], does not have to be sufficient, since people are not usually either solely good or bad. The authors in [185] partly address the problem of binary reputation by introduction of "medium" and "very good" reputation states in addition to bad and good. Consequently, there are more options of classification and to select the appropriate Relay UE. The paper also assumes two options how the reputation is applied. In the first option, only the reputation of the potential Relay UEs is considered in the relay selection. This option, however, does not motivate the users to relay data for others, since even the users with a bad reputation are being helped. The second option considers both the reputation of the Relay

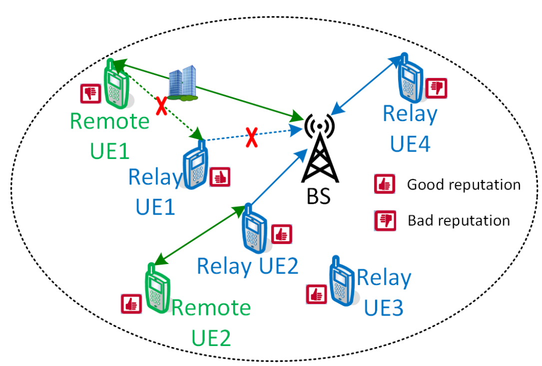

Fig. 36: Illustrative principle of the reputation-based incentives based on [184].

UEs as well as the Remote UEs. The Remote UE with a low reputation may not be able to find the Relay UE willing to help them. The paper unfortunately does not discuss impact of the reputations, like "good" and "very good"), on the relay selection process. The reputation-based incentive for UE-to-Network relaying is also assumed in [186], where the BS multicasts some content to multiple users, like in [97][98] (described in Section III). Similarly as in [184], the indirect reciprocity game is proposed to stimulate the cooperation between the users. When compared to the previous works on the reputation, the authors rate the reputation differently, as multiple Remote UEs can be served by single Relay UE. More specifically, the reputation of the Relay UEs is affected by: *(i)* the number of the Remote UEs served by the Relay UE and *(ii)* required service level of each Remote UE (i.e., the reputation is directly proportional to the effort the Relay UE has to make to serve individual users). Analogously to [184], the reputation is managed centrally by the BS, which updates and stores the reputation of each user. The interesting aspect considered in the paper is that it also assumes the reputation of the users can be negatively affected by *fading effects*. For example, some of the Remote UEs may not be able to successfully receive data from the Relay UE due to fading despite the Relay UE sets its transmission power to maximum value. To this end, the authors propose a reputation updating policy adjusting the Relay UEs reputation if fading occurs (i.e., the Relay UE is not automatically assigned with bad reputation if some of the Remote UEs are not able to receive the multimedia content). The common disadvantage of all incentives based on the reputation is the *additional signaling overhead* in order to assign reputation to Relay UEs.

D. Bandwidth exchange-based incentives

While all previously mentioned incentive approaches give *future benefits* to the relaying users, the bandwidth exchange-based incentives give an *immediate reward* to the relaying users. The additional bandwidth is given to the Relay UE by either the Remote UE(s) or the network itself as discussed in subsections VII-D1 and VII-D2, respectively.

1) Resources given by Remote UEs

In this subsection, we focus on the works where the Remote UEs give a part of bandwidth to the Relay UEs. The Relay UEs, then, use some of these additional resources for a transmission/reception of its own data while the rest is used for the relaying of the Remote UEs' data.

The bandwidth exchange incentive mechanism aiming to increase the energy efficiency of the users is proposed in [187]. The Remote and Relay UEs are assigned with a specific transmission times by the BS through a time division multiple access. The Relay UE is willing to act as the relay for the Remote UE as long as the Relay UEs' energy efficiency is increased. The whole problem is defined as a joint time and transmission power allocation problem with the aim to maximize the energy efficiency of the Relay UEs while maximizing the throughput of the Remote UEs. The authors prove that the energy efficiency of the Relay UEs increases with a longer transmission time and a lower transmission power.

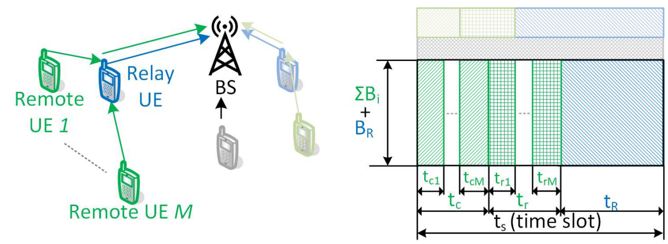

Fig. 37: Resource allocation scheme proposed in [189]. The Remote UEs first transmit data to the Relay UE with the transmission intervals t_{c1} to t_{cM}. Then, the Relay UE retransmits the Remote UEs' data and also sends its own data to the BS during t_{rM} and t_R, respectively.

Thus, the problem is solved by two-dimensional search over the transmission time of the Relay UE and its transmission power. Still, even if the energy efficiency of the Relay UEs is increased their energy consumption may be, in fact, increased.

The objective to decrease the energy consumption of both the Relay UEs and the Remote UEs by means of a cooperative relaying is proposed in [188]. Similarly as in [187], all the users are assumed to have the transmission time intervals pre-allocated in time division multiple access manner. Then, the objective is to allocate the transmission intervals for each Remote UE-Relay UE pair in a way that both users are able to decrease their energy consumption when compared to the case without the relaying. To this end, the authors adopt Nash bargaining solution and derive closed-form expression for the transmission time of any Remote UE and any Relay UE cooperating in the relaying. The possibility to decrease energy consumption for the scenario allowing *multiple Remote UEs served by single Relay UE* is contemplated in [189]. The channel bandwidth allocated initially to each user by the BS (i.e., B_i and B_R) is aggregated at the Relay UE, which uses this aggregated bandwidth for both relaying of the Remote UEs' data as well as for its own transmission (see Fig. 37). The paper first derives the lower and upper performance bounds when an increase in capacity and/or a decrease in energy consumption can be still ensured for all Remote as well as Relay UEs in a relaying group (i.e., group of the Relay UE and all Remote UEs attached to it). Then, the authors derive a closed form for the allocation of the transmission intervals to ensure that all users within each relaying group experience either the same relative or absolute gains in terms of the capacity or the energy consumption.

Another incentive scheme based on the bandwidth exchange with the aim to maximize the energy efficiency of the users is proposed in [190]. When compared to other works focusing on bandwidth exchange incentives, the authors in [190] assume completely different approach. More specifically, the Source UE is allowed to send data to the Destination UE by mean of D2D communication provided that the Source UE also acts as the Relay UE for the Remote UE (see Fig. 38). The bandwidth B_i initially allocated to the Remote UE's is used as follows: *(i)* a part of B_i is used solely for the D2D transmission of the Source UE to the Destination UE while *(ii)* the rest of the B_i is divided into two equal time slots, one used for the Remote

UE's transmission to the Relay UE and other half is exploited for the relaying of Remote UE's data from the Relay UE to the BS. Besides, the authors distinguish two types of Relay UEs: *(i)* the Relay UEs with *public interest* that are willing to share the bandwidth obtained from the relaying with other users (i.e., if the Relay UE is idle at the moment or is able to transmit its own data with less bandwidth) and *(ii)* the Relay UEs with *self-interest* that are not willing to share additional bandwidth even if they are not able to fully utilize it at the moment. The authors first solve the joint bandwidth and power allocation and subsequent Relay UE selection for the case with public interest Relay UEs. The problem is transformed in a form solvable optimally by Lagrange duality theory. Then, the authors show that the problem of the Relay UEs with self-interest is a special case of the problem with public interest Relay UEs and, thus, the same solution as for the Relay UEs with public interest can be applied.

Similar concept as in [190] is also proposed in [191], but considering full-duplex Relay UEs. Consequently, if the Source UE acts as the Relay UE for the Remote UE, whole bandwidth of the Remote UE is used by the Source UE in time division duplex as follows : *(i)* the first part of the time slot (with a duration of α) is dedicated to the full duplex transmission between the Remote UE-Relay UE link and the Relay UE-BS link, and *(ii)* in the rest of the time slot (i.e., duration of $1-\alpha$), the Source UE and the Destination UE exchange data in full-duplex. The authors define the transmission power-bandwidth exchange problem taking into account both QoS of the UEs and the transmission power constraint. The original non-convex problem is transform into convex one via concave-convex procedure. Then, the optimal resource allocation and the optimal relay selection are obtained by a maximum weight bipartite scheme.

2) *Resources given by the network*

This section surveys the works, where the network (usually the BS) grants some resources or transmission opportunities to the Relay UEs. For example, the authors in [192] propose similar principle considered in [190][191]. The main difference with [191], however, is that the Remote UE does not give the channel bandwidth to the Source UE. The data transmission occurs in two subsequent phases. In the first phase, data sent by the BS is received simultaneously by the Remote UE, the Source UE (also acting as the Relay UE), and the Destination UE. In the second phase, the Source UE broadcasts encoded data to both the Remote UE and the Destination UE. Since the Remote UE receives the same "useful" data twice, it can apply MRC to maximize its own data rate similarly as in the case of relaying with NOMA (see Section IV-A4). The authors also derive closed form expressions for the optimal power allocation if: *(i)* SNR at the first hop between the BS and the Relay UEs is higher than SNR at the second hop between the Relay and Remote UEs and *(i)* SNR at the first hop is lower than SNR on the second hop.

The extension of [192] to the case with full-duplex Relay UEs is presented in [193]. Due to the full-duplex, two-phase transmission is reduced to one-phase transmission, since the Relay UE/Source UE is able to receive data from the BS and transmit to both Remote and Destination UEs simultaneously. The authors again manage to derive closed form expression for the optimal power allocation for the same two cases as in [192].

The authors in [194] propose a concept, where the full-duplex relaying is accomplished even though the Remote UE works only in half-duplex mode. The transmissions are divided into even and odd time slots (see Fig. 39). Within the even time slots, the BS transmits data to the Source UE1, the Source UE2 retransmits data to the Remote UE (i.e., data received from the BS in previous odd time slot), and the Source UE1 sends data to its counterpart Source UE2. During the odd time slots, the BS sends data to the Source UE2, the Source UE1 retransmits data to the Remote UE obtained within the even time slot, and the Source UE2 transmits its own data to the Source UE1. This way, the Remote UE continuously receives relayed data from the BS while not working in full duplex. The authors further propose a novel hybrid complex field network coding to support this concept for following two different cases:

- *First case*: Both Source UEs are able to successfully decode signal from the BS and data are relayed successively to the Remote UE in odd and even time slots. At the same time, the Source UEs can alternately exchange data between themselves as they work in full-duplex.
- *Second case*: Only one Source UE is able to decode data from the BS and, thus, acts as the Relay UE between the BS and the Remote UE in odd transmission slots while sending/receiving data in the even transmission slots.

The potential drawback of the proposed idea is its limited use as both D2D users should be active, otherwise only second

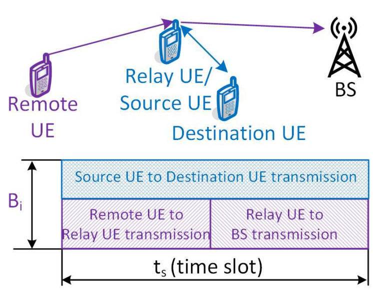

Fig. 38: Proposed relaying concept in [190] where part of the Remote UE's bandwidth is utilized by the Relay UE to transmits its own data to the Destination UE.

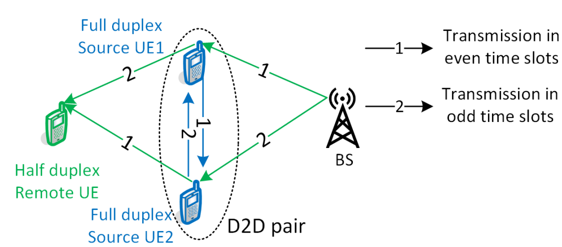

Fig. 39: Illustrative example of successive spectrum sharing scheme where both Relay UEs are able to successfully decode signal from the BS [194].

case can be exploited. Also the proposed principle assumes a tight transmission synchronization so that the D2D UEs perfectly alternate between transmission/reception phases.

A similar concept as considered in [192][193] is introduced in [195], where NOMA is exploited (see Fig. 40). Thus, the BS sends superposition-coded signal to the Relay UE (in Fig. 40 x_{B1}) and to the Remote UE (x_{B2}) in the first transmission phase (similarly as, e.g., in [82]). In the second phase, the proposed D2D-aided cooperative NOMA is adopted and the Relay UE performs superposition-coding of its own signal x_R intended for the Destination UE together with the signal received from the BS in the first phase (x_{B1}). In both phases, the Remote UE is assumed to be far user and, thus, more than a half of the transmission power is allocated to the transmissions of the Remote UE's signal (see Fig. 40). The D2D-aided cooperative NOMA concept proposed in [195] is further enhanced in [196], where also the Destination UE is assumed to be able to receive/decode the superposition-coded signal from the BS during the first transmission phase. This leads to more efficient decoding of the signal at the Destination UE that knows the signal BS already transmitted during the first phase.

Another use-case where giving additional resources to the relaying users can enhance the capacity is considered in [197]. The paper covers a topic of renting a network provider's physical infrastructure to multiple virtual network providers. Then, the virtual network provider share the physical infrastructure via slicing (see more details on the slicing concept, e.g., in [198]). Consequently, each virtual network provider dedicates some amount of radio resources that can be used only by the UEs within each slice. The objective of the work is, then, to maximize the average system capacity by motivating the UEs to act as the Relay UEs even if the Relay UEs are served by different slices than the Remote UEs. The authors propose two-layer incentive mechanism to motivate such relaying. The first layer rewards the cooperating slices with more radio resources. In other words, the slice with the users willing to act as the Relay UEs for the Remote UEs in different slice(s) are rewarded with an additional bandwidth. The second layer, then, rewards the Relay UEs that helps the Remote UEs within different slices.

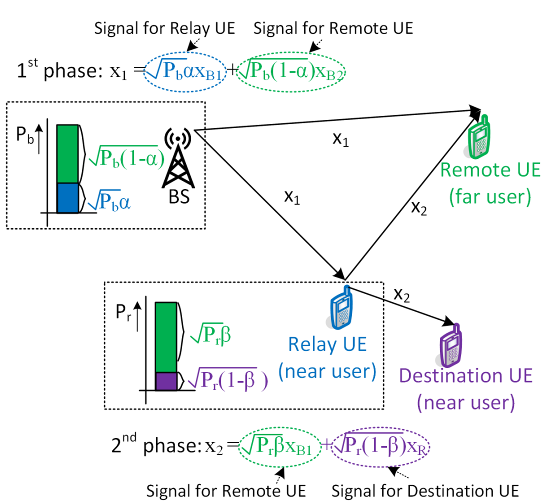

Fig. 40: Principle of proposed D2D-aided cooperative-NOMA incentivizing the Source UE to relay data to the Remote UE by transmission of its own data to the Destination UE [195].

E. Hybrid incentives

The previous sections describe various ways of incentivization of the Relay UEs. This section further contemplates several works that combine some of the above-discussed incentive strategies into a hybrid incentive.

The common hybrid incentive concepts combine social relationship- and virtual currency-based incentives [199][200][201]. In particular, the authors in [199] propose a social similarity-aware relay selection for the UE-to-Network scenario. The social similarity helps to distinguish whether the users have the same interests, such as sport, music, education, etc. Then, the users having the same interest have social factor equal to 1, while in the opposite case, the social factor is set to 0. Then, a user-centric relay selection considering both objective information and the subjective users' preferences is proposed. The objective information is related to the channel capacity between the Remote UEs and the Relay UEs, relaying cost, or buffer state of the Relay UE. The subjective preferences, then, relate to the social similarity reflecting the social factor explained above. Since the users do not have to be necessarily friends, family members, or co-workers (as assumed in [167]), the users are still expected to pay for the relaying services by the virtual currency as in [166].

The price to be paid to the relaying users depending on a trust level is contemplated in [200]. The stronger social trust level between users, the higher discount is applied to the Remote UE. Besides, the relay selection process is affected by a "D2D average duration" metric reflecting frequency and contact time of individual users, this is similar to the offline social graph proposed in [168]. The relay selection process is proposed taking different users' requirements into account towards maximizing quality of experience (QoE). The

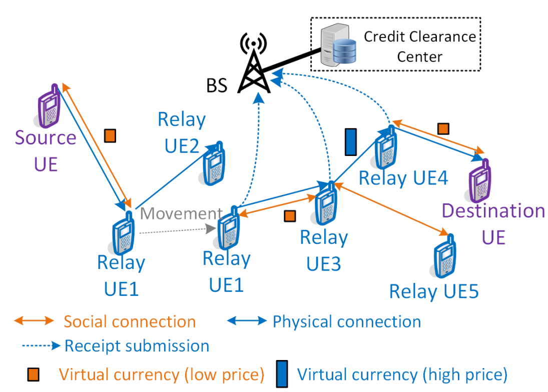

Fig. 41: Proposed hybrid incentive scheme where social ties affect the price of relaying [201]. The Relay UE1 waits until it moves to a communication distance with the Relay UE3 and only then relay the data. On the other hand, Relay UE3 sends data to Relay UE4 with high price since TTL is close low.

authors assume multi-demands framework, where all users' requirements, such as required capacity, packet delay, energy efficiency, or security are reflected in the proposed user's satisfaction function.

The authors in [201] use virtual currency-based incentives while considering social ties in the opportunistic wireless networks with UE-to-UE relaying, similarly as in [92] (see Section III). In such scenario, the Source UEs send data in the form of the bundles that are identified by time to live (TTL), which indicates the time when the bundle should reach the Destination UE. The Relay UEs are rewarded by credits, similarly as in [199]. To this end, a credit clearance center, placed in the network, manages accounts of each user (see Fig. 41). Whenever the user acts as the Relay UE, he/she submits a receipt via the BS and his/her account is updated at the CCC accordingly. The users with some social ties, such as friends, are supposed to relay data for each other at much lower price than for a complete stranger similarly as considered in [200]. Consequently, if the user has a bundle to be delivered to the Destination UE while TTL is high, the user rather waits for some friend(s) to move into the transmission proximity to pay less for the relaying. If the bundle expected delivery time, however, is close to its expiration, even strangers are exploited despite much higher relaying price. The price paid by the user looking for the relay is modeled as a bargaining game, where the buyers (i.e., the user looking for relay) and sellers (i.e., users selling the relaying service) negotiate the price.

Another hybrid incentive approach is proposed in [202], where a combination of the social relationship and bandwidth exchange-based incentives for the UE-to-Network is considered. The authors distinguish whether the Relay UE is active or idle and adapt the incentive mechanism as follows:

- *The Relay UE is active* – The Relay UE sends its own data directly to the Destination UE while also relays data of the Remote UE, similarly as in [71]. Nevertheless, the amount of bandwidth given to the Relay UE by the Remote UE and, at the same time, the amount of transmission power allocated by the Relay UE to relay data of the Remote UE is directly proportional to the level of social trust between the users. Hence, with a stronger social tie between the Relay and Remote UEs, the Relay UE obtains more bandwidth from the Remote US while the Relay UE allocates more transmission power to relay data to the BS and vice versa.
- *The Relay UE is idle* – The Relay UE has no data to send to its Destination UE counterpart. Consequently, the Remote UE dedicates whole bandwidth to the Relay UE, which allocates all its transmission power for the relaying.

The objective of the paper is to dynamically select the Relay UEs so that the average energy efficiency of the Remote UEs is minimized while a minimum data rate constraint on the Remote UEs and the D2D users is guaranteed. The authors formulate the problem as infinite-horizon time-average renewal-reward problem. The problem is solved by Lyapunov optimization based on drift-plus-penalty algorithm.

F. Energy harvesting-based incentives

So far, we have seen that most of the existing incentive mechanisms, with only several exceptions (e.g., [188][189]), are not able to cope with the increased energy consumption of the Relay UEs. Thus, the very interesting and convenient approach motivating the relaying users is built upon the recent energy harvesting and simultaneous wireless information and power transfer (SWIPT) concepts, initially proposed in [203].

The seminal work on exploitation of SWIPT for the UE-to-Network relaying scenario is delivered in [204]. The authors adopt relaying with NOMA similarly as [82][83] (see Section III-A). The key difference with these two works, however, is that the Relay UEs relay data to the Remote UEs using only the harvested energy from the BS's transmission. Hence, during the first transmission phase, the aim is to split the transmission power at the BS in a way that the Relay UE is able to decode the signal for the Remote UE while the harvested energy from the rest of BS's transmission power is maximized. Then, during the second transmission phase, the Relay UE relays data to the Remote UE similarly as already described in [82][83], but using the harvested energy only.

The authors in [205] further analyze the outage probability for the AF, DF, and hybrid AF/DF relaying protocols considering NOMA and the Relay UEs that harvest the energy for retransmission of data to the Remote UEs. To this end, the authors propose best-near best-far scheme pairing the near users with the best channel quality with the far users having also the best channel conditions. Then, the authors derive closed form expressions for the outage probability of the proposed pairing.

In addition, the authors in [206] enhance the proposed NOMA with the energy harvesting by an adaptive selection between a conventional NOMA (i.e., without relaying) and the cooperative NOMA transmission. In particular, if the link between the BS and the Remote UE has SNR above a specified threshold, the Remote UE notifies both the BS and the Relay UE that the relaying is not needed and data is send to the Relay UE and the Remote UE, as in the conventional NOMA transmission. Contrary, if SNR of the BS-Remote UE link drops below the threshold, the cooperative NOMA is employed and the Relay UE exploits the harvested energy for the relaying. While all above works assume a power splitting energy harvesting, where a part of the transmitted power from the BS is energy harvested at the Relay UE, the authors in [207] propose to exploit a hybrid time-switching and power-splitting energy harvesting (TS/PS EH) at the Relay UEs in order to minimize the outage probability. The principle of TS/PS EH at the Relay UE is shown in the Fig. 42. Any specific time interval T is divided into three parts. In the first part (i.e., during αT) the whole power from the BS is harvested at the Relay UE. Then, during the second part, the power splitting energy harvesting is employed by a power splitting coefficient β. Finally, the Relay UE retransmits data to the Remote UE within the third transmission interval. In principle, the second and third transmission intervals follow the same transmission rules as used, e.g., in [204].

The use of energy harvesting to incentivize users in the

TABLE VI: Comparison of state-of-the-art works on incentives; VC – Virtual Currency, SR – Social Reputation.

	Incentive mech.	Benefits of Remote UEs/D2D UEs	Benefit (reward) of Relay UEs	Cost to Relay UEs	Classification of D2D relaying	Classification of Relay UEs
[165] [166]	VC	↑ C	Token	↑ EC	UE-to-Network, DL	HD, AF, idle
[146]	VC	↑ C	Credits	↑ EC	UE-to-UE, multi-hop relaying	HD, idle
[167]	SR	↑ C	Same help in future	↑ EC	UE-to-Network/UE-to-UE	FD, DF
[168]	SR	↑ C, security/reliability	Same help in future	↑ EC	UE-to-Network	FD, DF, idle
[169]	SR	Min. delay, sec./rel.	Same help in future	↑ EC	UE-to-Network	HD, DF, idle/active
[170] [171]	SR	↑ C, security/reliability	Same help in future	↑ EC	UE-to-Network	HD, idle
[172]	SR	↑ C, security/reliability	Same help in future	↑ EC	UE-to-Network	HD, DF, idle
[173]	SR	↑ C, security/reliability	Same help in future	↑ EC	UE-to-UE	HD, DF, idle
[174]	SR	Content delivered to D2D-R, security/reliability	Same help in future	↑ EC	UE-to-UE, multi-hop relaying,	HD, idle
[175]	SR	Computation offloading	-	↑ EC	UE-to-UE	-
[176]	SR	Content delivered to D2D-R, security/reliability	Same help in future	↑ EC	UE-to-UE, multi-hop relaying	FD, idle
[179]	SR	↑ C, security/reliability	Same help in future	↑ EC	UE-to-UE	HD/FD, DF, idle
[180]	SR	↑ C, security/reliability	Same help in future	N/A	UE-to-UE	HD
[182]	SR	↑ C, security/reliability	Same help in future	↑ EC	UE-to-UE	FD, DF, idle
[183]	SR	↑ C, security/reliability	Same help in future	↑ EC	UE-to-UE	FD, DF, idle
[184]	Rep.	↑ C	↑ rep.	↑ EC	UE-to-Network	HD, AF, active
[185]	Rep.	↑ C	↑ rep.	↑ EC	UE-to-Network	HD, AF/DF, idle
[186]	Rep.	Multicast content delivered	↑ rep.	↑ EC	UE-to-Network, multi Remote UEs-single Relay UE	HD, DF, idle
[187]	Res.	↑ C	↑ EE	↑ EC	UE-to-Network	FD, AF, active
[188]	Res.	↓ EC	↓ EC	No cost	UE-to-Network	HD, DF, active
[189]	Res.	↑ C and/or ↓ EC	↑ C and/or ↓ EC	No cost	UE-to-Network, multi Remote UEs-single Relay UE	HD, DF, active
[190]	Res.	↑ EE	↑ EE	↑ EC	UE-to-Network	HD, AF, active
[191]	Res.	↑ C and EE	Source UE may send data to Dest. UE	↑ EC	UE-to-Network	FD, DF, active
[192]	Res.	↑ C	Source UE may send data to Dest. UE	↑ EC	UE-to-Network	HD, DF, active
[193]	Res.	↑ C	Source UE may send data to Dest. UE	↑ EC	UE-to-Network	FD, DF, active
[194]	Res.	↑ C	Relay UEs may exchange data	↑ EC	UE-to-Network	FD, DF, active
[195]	Res.	↑ C	Source UE may send data to Dest. UE	↑ EC	UE-to-Network	HD, DF, active
[196]	Res.	↑ C	Source UE may send data to Dest. UE	↑ EC	UE-to-Network	HD, DF, active
[199]	SR + VC	↑ C	Token	↑ EC	UE-to-Network	HD, idle
[200]	SR + VC	↑ C	Credits	↑ EC	UE-to-Network	HD, AF, active
[201]	SR + VC	Max. delivery ratio, min. delay	Credits	↑ EC	UE-to-UE, multiple UEs, multi-hop relaying	HD, idle
[202]	SR + Res.	Max. EE	↑ C	↑ EC	UE-to-Network	HD, idle/active
[204]	EH	↑ C	Same help in future	No cost	UE-to-Network	HD, DF, active
[205]	EH	↓ outage prob.	Same help in future	No cost	UE-to-Network	HD, hybrid AF/DF, active
[206]	EH	↑ C and ↓ outage prob.	Same help in future	No cost	UE-to-Network	HD, DF, DF, active
[207]	EH	↓ outage prob.	Same help in future	No cost	UE-to-Network	HD, DF, DF, active
[208]	EH	↑ C	Same help in future	No cost	UE-to-UE	HD, DF, idle
[209]	EH	↑ C	Same help in future	No cost	UE-to-UE	HD, DF, idle, two-way

UE-to-UE relaying is considered in [208][209]. The Relay UE employs PS EH model, analogously to [204]. Hence, during the first transmission interval, the transmission power is split to two parts: a part of the transmission is used for reception of data from the Source UE while the rest of the transmission power is exploited for the energy harvesting. Then, during the second transmission phase, the Relay UE re-transmits data to the Destination UE while using the harvested energy. The interesting edge of the proposal is that the Relay UE is also assumed to harvest energy from *renewable sources* (like solar source) during the whole time to maximize the amount of harvested energy. Besides, other interesting approach considered in the paper is that the energy harvesting is performed not just by the selected Relay UE, but also by other idle Relay UEs provided that these are close enough to receive the transmission either from the BS or the selected Relay UE. Besides, any idle Relay UE also harvests the energy from renewable sources all the time.

The work in [208] is further extended by considering a two-way relaying in [209]. One of the concerns related to the two-way relaying concept is its potential high energy consumption at the Relay UE. Thus, to employ the energy harvesting at the side of two-way Relay UEs is a convenient way to address their high energy consumption. The authors propose an iterative algorithm exploiting PSO to derive the ratio of the power used by the Relay UE for the energy harvesting and for

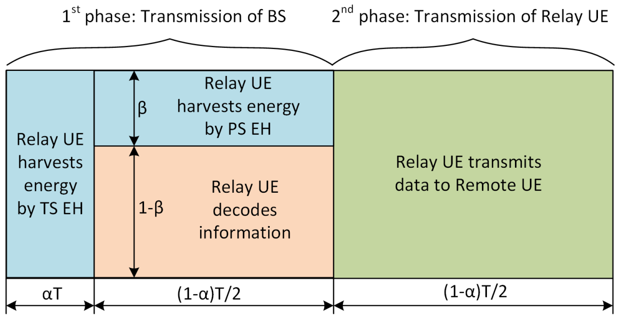

Fig. 42: Hybrid TS/PS EH at the Relay UE proposed in [207].

the decoding of the information from the Source UE.

G. Summary

This section compares individual incentive ideas from several perspectives (see Table VI). We have illustrated that the main purpose of individual incentive mechanisms is to give some benefits (rewards) to the Relay UEs while still ensuring that the Remote UEs/D2D pairs profit from the relaying as well. Besides, the crucial aspect of the relaying is the cost incurred at the side of the Relay UEs. Thus, contrary to Sections IV-VI, we primarily compare the works according to the utilized incentive mechanism, benefits experienced by the Remote UEs/D2D pairs, benefits given to the Relay UEs and relaying cost, while the classification of D2D relaying and Relay UEs itself introduced in the taxonomy are only secondary aspects:

- **Incentive mechanism** – There is actually a plethora of incentive mechanisms and ideas motivating the users to relay data for others. The most straightforward and natural incentive is to pay the relaying users with some kind of virtual currency (e.g., credits [146] or tokens [166]). Moreover, the users' reputation and the social relationship are used as a convenient way to motivate the users to act as the relays [167]-[183]. Besides, if the relaying users are active (either communicating directly with BS or exchanging data via D2D communication), the bandwidth-based incentive is very efficient way to reduce energy consumption of both Remote as well as Relay UEs [187]-[197]. Moreover, the energy harvesting is another interesting approach to solve the problem of increased energy consumption of the relaying users [204]-[209]. Last but not least, we have seen that each incentive mechanism has some ***pros*** and ***cons***. Thus, to fully benefit from the relaying individual ***"incentive worlds" should be smartly combined*** to capitalize on their advantages while suppressing their disadvantages. Although, there are already few initial attempts to combine some incentive ideas, like the social relationship-based incentives with the virtual currency [199]-[201] or bandwidth exchange-based incentives [202], there is still plenty room for improvement to better motivate the relaying users and, thus, to maximize the benefits introduced by D2D relaying.
- **Benefits for Remote UEs/D2D UEs** – The most common benefit at the side of the Remote UEs and the D2D users is enhanced capacity (see, e.g., [165][192]-[194]). Besides, the surveyed papers also illustrate that there are actually other potential benefits for the Remote UEs/D2D pair, such as increased energy efficiency [190][191][202], decreased energy consumption [188][189], decreased outage probability [207], or decreased delay [169] experienced by the Remote UEs/D2D pairs. Moreover, the by-product of the social relationship-based incentive is making the relaying more secure and reliable, if the relaying is done by close friends or family members.
- **Benefits (rewards) for the Relay UEs** – The reward of the Relay UEs strongly depends on their activity/inactivity. In particular, existing bandwidth exchange-based incentives (discussed in Section VI-D) are tailored only for the active relaying users, where the active Relay UEs obtain immediate benefit in the form of additional bandwidth or transmission opportunities in order to send their own data (see, e.g., [187]-[195]). In contrast, the idle users can be hardly motivated by such incentives, as these users do not need any resource at the moment. Fortunately, there exist various other incentive mechanisms and ideas applicable also for the idle users, where the reward in some kind of virtual currency (credits/tokens) or increased reputation is given. The ***important aspect*** of all incentive mechanisms, excluding the bandwidth exchange ones, is that the ***benefit*** for the Relay UE is ***always in the future***. Consequently, there is always an uncertainty if the future benefits outweigh the immediate relaying cost.
- **Cost to the Relay UEs** – The cost at the side of the Relay UEs is usually represented by an increased energy consumption due to relaying. Most of the incentives do not combat the increased energy consumption of the Relay UEs. Still, there are several works, where the relaying users at least do not increase their energy consumption as only the energy harvested from the received transmission is exploited for the relaying [204]-[209]. Besides, there are already some works, where the energy consumption of the relays can be even decreased, as demonstrated in [188][189].
- **Classification of D2D relaying** – There exist various incentive mechanisms applicable to the UE-to-Network relaying, the UE-to-UE relaying, or both. Usually, the Remote UE/D2D pair exploits single Relay UE for the relaying while the Relay UE relays data for just one Remote UE/D2D pair. Still, there are already some efforts to incentivize multiple Relay UEs serving single D2D pair [174][176][201] or one Relay UE serves multiple Remote UEs [186][189]. Besides, some works also address the problem of user's mobility having a significant impact on the relaying reliability [166][168][169][171][186].
- **Classification of Relay UEs** – The works on incentive mechanism assume both half-duplex and full duplex relays exploiting either AF or DF relaying protocol. In [179] the authors assume that the selection between half and full duplex is influenced by the level of social ties between users and remaining energy of relaying device. Moreover, hybrid AF/DF relaying is considered in [205]. Last, the works on incentives assume that both active and idle relays are used and the active users are solely used by the

bandwidth exchange-based incentives, as already discussed before.

VIII. Lessons learned

Throughout this survey, we have illustrated a significant ongoing effort focusing on D2D relaying. In this section, we summarize key and interesting lessons for a reader to remember. First, lets start with general observations on the in-band relaying:

- ***Lesson 1***: The ***fundamental difference*** between the ***UE-to-Network*** relaying and the ***UE-to-UE*** relaying use-cases is that, in the UE-to-Network relaying, the ***Relay UE helps*** to improve the performance of conventional ***cellular users*** transmitting/receiving data to/from the BS while in the UE-to-UE relaying, the Relay UE helps to ***D2D users***. Consequently, also the radio resource management for the UE-to-UE relaying is approached differently when compared to the UE-to-Network relaying, as the D2D users should not impair QoS of the cellular users
- ***Lesson 2***: The geographical relaying region, where the UE-to-Network relaying is of a benefit strongly depends on the mutual position of the Relay UE and the BS. In LoS scenario without obstacles, the area where the relaying is beneficial has ***an ellipsoid shape*** and increases if the Relay UE is farther from the BS. In the scenarios with obstacles (such as in urban area with buildings), the relaying introduces gain especially if the Relay UE has LoS or close to LoS connection with both the BS and the Remote UE while the Remote UE is in NLoS with the BS.
- ***Lesson 3***: The performance of mobile networks augmented by the UE-to-Network relaying can be optimized in terms of ***coverage probability*** and ***data rates*** by controlling: *(i)* ***received signal strength threshold*** deciding whether the UE should communicate directly with the BS or if the Relay UE should be used, *(ii)* ***transmission power*** of the BSs and the Relay UEs in DL and transmission power of the Remote and the Relay UEs in uplink, and *(iii)* ***number*** of orthogonal ***channels allocated*** to both the cellular and D2D links.
- ***Lesson 4***: The UE-to-Network relaying concept works well with ***NOMA*** towards ***cooperative*** relaying. In such case, a synergy between both is observed and the ***spectral efficiency*** is further ***enhanced*** compared to the conventional NOMA without relaying or, alternatively, compared to the relaying without NOMA.
- ***Lesson 5***: The UE-to-UE relaying is more beneficial in the underlay mode compared to the overlay mode. The reason is that, in the underlay mode, the D2D users are interfered by the Cellular UEs. Hence, the intermediate Relay UE may not just boost the capacity of D2D communication but, in fact, may enable D2D communication that would not be otherwise possible without a help from the Relay UE.
- ***Lesson 6***: Even though the relaying use-case with multiple Relay UEs helping single Remote UE/D2D pair can improve the performance, this improvement is not that significant. Thus, in most of the scenarios, up to ***two Relay UEs are seen as a good trade-off between complexity and relaying gain***. However, exploiting ***more than two Relay UEs*** helping just one Remote UE/D2D pair is very convenient to combat deep ***fading***.
- ***Lesson 7***: Multi-hop D2D relaying is able to ***decrease*** significantly the ***outage probability and power consumption***. The reason is that the distance between the communicating devices is significantly decreased by multi-hop relaying. Still, the communication through many Relay UEs may not be practical in most of the scenarios due to a high complexity of radio resource management. Thus, the multi-hop communication with “only” two or three Relay UEs between the BS and the Remote UE is envisioned to be used in real networks.

Further, we also uncover following key lessons related to the out-band relaying:

- ***Lesson 8***: The ***key benefit*** of the out-band relaying is its ability to fully ***mitigate*** mutual ***interference*** between the ***D2D and cellular communication***, provided that the D2D relaying links (i.e., the links between the Relay UEs and the Remote UEs) are facilitated by the out-band frequencies while the in-band frequencies are used solely for the communication with the BS.
- ***Lesson 9***: The out-band relaying can help mitigating intra-cell interference if the ***ideal orthogonality*** in the UEs' transmissions cannot be ensured (i.e., in practical scenarios). Then, if the number of UEs reaches some critical point, the out-band relaying can significantly decrease the outage probability of individual users.
- ***Lesson 10***: The use of frequency bands above 6 GHz, such as mmWaves, is beneficial mostly in the ***indoor scenario***, where mmWaves can outperform the more conventional in-band (microwave) frequencies in terms of both coverage probability and spectral efficiency. Contrary, in the ***outdoor scenarios***, the utilization of ***in-band relaying is more beneficial*** with respect to mmWaves, especially if the communication distances increases.
- ***Lesson 11***: The potential drawback of the ***out-band relaying*** is ***difficulty to ensure QoS*** on the D2D relaying link(s), especially if WiFi is considered as the out-band technology. Hence, QoS should not be overlooked when the out-band relay is selected.

The relaying usually goes hand-in-hand with increased energy/power consumption at the Relay UE. To this end, we summarize also key lessons learned regarding the motivation and incentives for the users to act as the Relay UE:

- ***Lesson 12***: In the monetary-based incentives, ***Number of tokens should be*** fairly ***regulated*** as too few or too much tokens in the system is a contra-productive. On one hand, if there are too few tokens, the users do not have enough tokens to pay for the relaying. On the other hand, if there are too many tokens, the users have no or limited motivation to earn another extra token(s).
- ***Lesson 13***: The social relationship-based incentives consider not just the ***physical domain*** representing the channel quality among the users, but also the ***social domain*** is taken

into account during selection of the Relay UE(s). The social domain may distinguish various aspects, such as whether the users are close friends, family members, or co-workers. Besides, the social domain may be defined also by ***social similarities***, that is, the time during which the users are in vicinity of each other during various social activities like attending concerts, sport events, or time spent in gym/pub, etc.

- ***Lesson 14***: The key benefit of the ***social relationship-based incentives*** is that these ***bring*** a certain level of ***security and reliability to the relaying***. The reason is that the users with strong social ties will not try to misuse the relayed data or drop data during ongoing relaying process. Hence, even the users looking for relays that would not be enthused to entrust their data to complete strangers become more open to exploit the relaying.
- ***Lesson 15***: If ***only the users with some social relationship*** are considered as potential candidate relays, the ***relaying gain can be significantly degraded*** as many potential relays are excluded from the relaying. Hence, there is a trade-off between the achievable relaying gain and the level of security/reliability offered by the relaying.
- ***Lesson 16***: The incentive mechanisms based on indirect reciprocity, that is, the relaying users receives a benefit in the ***future*** (i.e., monetary-, social relationship-, and reputation-based incentives), ***introduce an uncertainty*** whether the future benefit (reward) for relaying will outweigh the immediate cost of the relaying. Thus, unless radio channel characteristics and traffic demands are uniformly distributed among all UEs over time, these mechanisms can lead to deadlocks.
- ***Lesson 17***: The ***bandwidth exchange-based incentives*** are the only ones that can give ***immediate (guaranteed) benefits*** to the relaying users (e.g., in terms of capacity enhancement and/or energy reduction). The reason is that the Relay UEs exploit the acquired resources (such as additional bandwidth or transmission opportunities) at the moment of the relaying. At the same time, however, this narrows down the applicability of the bandwidth exchange-based incentives to the active UEs only, since the idle UE, obviously, could not be motivated by receiving any additional radio resources at the moment of relaying.
- ***Lesson 18***: Only the ***bandwidth exchange-based incentives*** are able to, under certain circumstances, ***decrease the power/energy consumption of the relays***. This is due to the fact that the use of additional resources can decrease either the transmission power of the Relay UEs or its transmission time.
- ***Lesson 19***: ***Energy*** harvesting helps to ***combat*** the problem of ***increased energy consumption of the relaying users***, as the relaying users are usually obliged to relay data using only the harvested energy. To this end, the Relay UEs can exploit time splitting, power splitting, or combination of both techniques. Of course, time/power splitting should be optimized to get a proper trade-off between the energy harvested by the Relay UEs and the relaying gain.

Besides the lessons specifically related to in- and out-band relaying or incentives, we would like to draw also several general lessons related to key radio resource management technique, that is, relay selection:

- ***Lesson 20***: There is always a ***trade-off*** between the ***performance*** and ***complexity*** related to the number of candidate Relay UEs considered for relaying. The ***number of candidate Relay UEs*** out of which one Relay UE is selected can ***be reduced to lower the complexity*** of the relay selection process. If this reduction is done smartly and the Relay UEs that are probably far from the optimum are weeded-out, the throughput degradation is negligible while the complexity of the relay selection is decreased significantly.
- ***Lesson 21***: The relay selection should not consider just channel quality at individual relaying hops, but also other aspects, such as ***remaining battery capacity*** of the Relay UE, ***transmission delay***, or ***reliability***, should be also taken into account. Especially the battery state of the Relay UE is of utmost importance, as the selection of the Relay UEs ensuring the highest relaying gain can be short-sighted in the long run due to battery depletion of the Relay UE(s). Consequently, if the relay selection considers also the battery's state, both data rate and reliability of the D2D relaying can be increased.
- ***Lesson 22***: Users' ***mobility*** can be both ***a foe and a friend*** in the relaying. On one hand, the mobility of users can make the relaying less reliable due to a potential degradation in the D2D relaying link quality or even its eventual disconnection. On the other hand, a high mobility of users can be considered as a virtue helping to deliver delay-tolerant data. Thus, considering also users' mobility-related aspects, such as velocity or moving direction, in the relay selection process allows a significant energy savings.

Last, lets discuss also several general lessons related to the relaying devices themselves:

- ***Lesson 23***: The ***AF relaying*** can result in a ***lower outage probability*** than the ***DF relaying*** if the first-hop transmission is over a ***high quality channel*** (i.e., of high SNR), since the amplified noise does not degrade the quality on the second hop. If the first-hop is, however, of a low channel quality (i.e., low SINR), the DF always reaches lower outage probability than the AF.
- ***Lesson 24***: ***Full-duplex*** relaying is able to significantly ***improve the capacity*** and the ***energy efficiency*** while ***minimizing the outage probability*** as long as self-interference can be mitigated. Otherwise, half-duplex is usually better choice if one considers the full-duplex requires more complex devices.
- ***Lesson 25***: The ***two-way*** Relay UEs with ***PNC*** provide the means to reduce the number of time slots required to exchange data between two nodes, thus, to significantly ***enhance capacity*** and ***energy efficiency***. Nevertheless, the PNC ***increases*** packet loss probability in multi-hop scenario when compared to no coding and also ***requires more complex Relay UEs***.

IX. Open research challenges towards 6G

This paper surveys current research oriented on D2D relaying. The tremendous effort of the researches around the globe makes the D2D relaying an integral part of contemporary 5G mobile networks due to its potential to significantly enhance the system capacity and spectrum or energy efficiency while, at the same time, decrease energy/power consumption or outage probability. Nevertheless, we have also identified many gaps in the current literature (as indicated in each summary throughout Sections IV-VII) limiting the achievable gains of the D2D relaying, thus, making the D2D relaying insufficient for future 6G networks. The main reason is that 6G networks, already taking more tangible shapes, will have to cope with unprecedented requirements on ultra-high data rates, ultra-low latency, high energy and spectral efficiency, or very high mobility [210][211]. To satisfy these requirements, the 6G mobile networks are expected to:

- incorporate an advanced interference and radio resource management techniques to handle further networks densification [211],
- use significantly broader bands by taping from terahertz and VLC frequencies that cope with a very high path loss and subsequent very short communication distances [211],
- exploit AI- and ML-based techniques to manage and optimize highly complex 6G networks [212].

According to [213], the D2D communication as well as the D2D relaying will play a significant role in 6G helping to meet the aforementioned requirements. Still, to make D2D relaying essential and useful part of 6G, number of open research challenges should be addressed to fill the gaps uncovered by our survey. In this regard, we discuss below the open research challenges to be addressed and we also suggest the ways how to tackle them.

A. Enhancements to in-band D2D relaying

The overview of works on in-band UE-to-Network relaying in Section IV demonstrates that the D2D relaying uses predominantly the overlay resources with respect to the legacy cellular communication. Unfortunately, the overlay use of cellular resources is not spectral efficient and, in general, not perspective in the long run due to the scarcity of radio resources. Thus, in order to ensure high spectral efficiency, as expected in 6G networks, it is worth to further dig deeper into the utilization of the underlay mode utilized by the UE-to-Network relaying, where the D2D relaying reuses resources already allocated to the Cellular UEs. Moreover, although many works on the UE-to-UE relaying already adopt the underlay use of radio resources, the D2D relaying links still usually reuse just the resources of single Cellular UE (see Section V). Hence, to bring the spectral efficiency to another level, it is worth to explore also the cases, where individual D2D relaying links reuse resources of multiple Cellular UEs, while multiple D2D relaying links can reuse the radio resources of the same Cellular UE (e.g., the same channel, same set of resource blocks, etc.).

Moreover, the predominant relaying scenario in current state-of-the-art oriented on D2D relaying is the single Relay UE helping single Remote UE (in case of UE-to-Network relaying) or single D2D pair (in case of UE-to-UE relaying). Although this relaying scenario is less complex in terms of radio resource management than the single Relay UE helping multiple Remote UEs or multi-hop relaying, the benefits of D2D relaying are usually fairly limited. In contrast, more advanced relaying cases, such as the Multi Remote UEs-Single Relay UE or the Single Remote UE-Multi Relay UEs are able to notably enhance the capacity, spectral/energy efficiency, or minimize outage probability (see Sections IV-B and V-B). However, most of the existing works assume just one relaying case. Consequently, to accommodate ultra high requirements in the 6G networks on spectral and/or energy efficiency, a promising D2D relaying scenario, albeit very challenging at the same time, is the one with one Relay UE helping multiple Remote UEs while each Remote UE can exploit multiple Relay UEs simultaneously.

Last, we show in Section IV that two-way relaying is practically not used in the UE-to-Network relaying even though two-way relaying is able to improve spectral efficiency significantly. Hence, in 6G networks, it may be of particular interest to simultaneously relay both UL and DL data in just two time slots instead of four times slots capitalizing on two-way relaying. In particular, the two-way Relay UE first receives DL data from the BS and UL data from the Remote UE in first time slot. Then, in the next time slot, the two-way Relay UE retransmits simultaneously DL data to the Remote UE and UL data to the BS.

Of course, in order to promote advanced radio resource management envisioned above, it is necessary to address various radio resource management related problems, such as resource allocation (i.e., matching many D2D relaying links with many cellular links in order to maximize the reuse gain), relay selection (i.e., matching many Remote UEs or D2D pairs with many Relay UEs), and/or transmission power allocation to manage interference among huge number of D2D and cellular links.

B. Enhancements to out-band D2D relaying

As we discussed earlier, much broader (out)-bands is expected to be used in the 6G networks. As of now, the works exploring the possibility to use out-band frequencies for the D2D relaying assumes solely either WiFi or mmWaves (see Section VI). Nevertheless, we believe that especially VLC finds its uses in D2D relaying, as the VLC is able to provide superior capacities, especially at short distances (in orders of meter or tens o meters). To this end, the D2D relaying augmented by the VLC has great potentials in indoor environment and in industrial or vehicular scenarios. Still, the main challenge of VLC is its high sensitivity to even small changes of irradiance and incidence angles resulting in a very significant, and often abrupt, capacity degradation.

Besides, a combination of several out-band technologies and/or frequency bands can be very interesting research direction in D2D relaying, as mmWaves and VLC are very efficient for LoS communication while, e.g., unlicensed WiFi frequencies can be exploited in NLoS environment. Hence, a dynamic selection between in-band and several out-band technologies can bring significant improvement in the experienced quality of service, especially if the users are moving with high speeds (as also foreseen in the 6G networks) and LoS is frequently alternated with NLoS. To this end, new techniques and mechanisms should be devised to handle jointly mobility management with band selection in an efficient way.

Another interesting option where the out-band D2D relaying may be of benefit is when combined with full-duplex relaying. Although full-duplex Relay UEs are able to offer superior performance with respect to half-duplex Relay UEs, the former are still plagued by self interference that can notably hinder benefits offered by the full-duplex relaying. Consequently, the out-band relaying can fully eliminate self interference as one transmission hop can be done via conventional radio frequency while another relaying hop exploits one of the out-band technologies.

C. Enhancements to incentive mechanisms

The alpha and omega of the whole D2D relaying concept is to provide proper incentives to the relaying users, as discussed in Section VII. One of the critical point not addressed properly thus far by the research works on incentives is the impact of users' mobility on the given incentive(s). Especially, in case of high mobility scenarios foreseen in the future 6G networks, the incentivization of the relaying users may be often problematic if the relaying itself is of benefit for only a limited amount of time. Then the challenge is to determine a cost paid by the users to the relaying user if the improvement in the capacity is only temporary and not easily predictable. In case of the bandwidth exchange incentives, it may not be even feasible to always ensure that both the relaying user and the user exploiting the relay benefit in accordance with their expectations. This may at the end affect the reputation of the relaying users. Thus, the relay selection algorithms should be adapted accordingly to cope with the mobility of users so that all users involved in the relaying still benefit.

Besides, another challenge regarding the incentives is how to properly motivate the relaying users in the advanced relaying cases, where multiple Remote UEs (or D2D pairs) are being helped by single Relay UE and/or multiple Relay UEs assist single Remote UE (or D2D pair), as we believe will be used commonly in 6G networks to increase spectral efficiency (see Section IX-A). The users may be highly motivated to relay data on behalf of others if multiple benefits come their way depending on their current needs and preferences. For example, the relaying user can be partly paid by an additional bandwidth just to satiate his/her actual willingness to increase the capacity, or to compensate increased energy consumption, while other users pay with the virtual currency for future benefits of the relaying user. This option is highly desirable to motivate the users relaying for multiple other users, thus maximizing the benefits from the relaying. Moreover, the social ties among the users can be also exploited in a "collaborative relaying", with several users having the mutual social ties with each other helping to just one user within the same social group. Such collaborative relaying is able to not just split the energy consumption caused by the relaying among several users, but is a great asset in fading propagation environment as each relaying user exploits only a part of the resources not affected by the fading.

D. Use of artificial intelligence and machine learning

The use of AI- and ML-based techniques to solve various optimization problems in the mobile networks have gained significant momentum during recent couple of years. The main reason is that AI approaches and ML approaches (supervised learning, unsupervised learning, or reinforcement learning), have a great potential to solve complex, and often seemingly unsolvable, optimization problems. Despite this fact, this survey uncovers an interesting fact that AI approaches, and particularly ML techniques, are used only very rarely in solving the problems introduced by the D2D relaying. This fact is about to change in the emerging 6G networks that will strongly rely on AI/ML, as discussed earlier in this section. Hence, we believe that AI/ML can contribute significantly to solve hard and complex radio resource management problems, such as various (mixed) integer (non)-linear programming problems, that are decomposed to sub-problems resulting in sub-optimal solutions while joint solutions are not derived.

Besides helping to solve various complex radio resource management problem, AI/ML techniques can help significantly in channel prediction/estimation. The knowledge of channel quality between individual UEs involved in or affected by the relaying, such as the Remote UEs, the Source/Destination UEs, the Relay UEs, or even the Cellular UEs is of paramount importance for radio resource management including mode selection, relay selection, and power/resource allocation. In particular, it is not trivial to estimate the channel quality if the potential Relay UEs are idle and/or moving with a high velocity expected in the 6G networks. Besides, the signaling overhead required to estimate the channel quality in a conventional way may consume too much radio resources. To this end, an efficient estimation of the channels between any UEs should be developed so that the improvement to the users with a low channel quality to the base station is ensured. One feasible way to solve this problem is to exploit supervised learning technique based on deep neural networks using a regression model, which is proven to be a strong tool for solving such problem [214].

E. Joint optimization of D2D relaying with emerging communication paradigms

Thus far, the D2D relaying is handled separately as a standalone optimization problem. Nevertheless, with the emergence of new communication paradigms, such as UAV communication, MEC, V2X communication, or reconfigurable intelligent surfaces (RIS), the D2D relaying should be "smartly" and jointly optimized with these emerging paradigms to cope with unprecedented requirements imposed on 6G networks. We discuss the ways of joint optimization of the D2D relaying with these above-mentioned paradigms in the following subsections.

1) Optimization of D2D relaying with UAV communication

There is a lot of effort dedicated to an optimization of the UAV communication, where the Flying BSs/RSs assist either the cellular UEs to relay data from/to the BS (analogous to the UE-to-Network relaying) [7] or the D2D communication so that the Source UE is able to reach the Destination UE (analogous to the UE-to-UE relaying) [215][216]. Nevertheless, there is so far no synergy effect gained from the joint optimization of D2D relaying and the UAV relaying. In particular, one of the crucial problem related to the UAV communication is the positioning of Flying BSs/RSs with respect to users' locations [217]. Then, the D2D relay selection can be optimized jointly with the Flying BSs/RSs positioning, where the Remote UEs with unfavorable channel conditions are helped by intermediate Relay UEs forwarding data to/from the Flying BS/RS. As a result, the Flying BS/RS positions do not have to be optimized with respect to weak users and, thus, an overall performance can be improved.

2) Optimization of D2D relaying with MEC

One of the key aspects regarding MEC is to decide whether to offload or not while considering energy and latency requirements of the UEs [96]. Since the D2D relaying itself is able to decrease an offloading time (due to enhanced capacity) and/or decrease an energy consumption of the UEs, the computation offloading decision is strongly affected by the relaying as well. In fact, joint D2D relay selection and the computation offloading decision can help achieving ultra low latency and energy efficiency, as required by the 6G networks.

Moreover, the fact that the offloading to MEC is able to significantly decrease the energy consumption of the cellular UEs can be exploited as an incentive for the relaying users. More specifically, the users needing to offload high demanding computation to MEC can be motivated to relay data for others provided that the energy savings due to offloading are higher than the energy consumed by the relaying.

Last, with increasing computing capabilities of the UEs, it is expected that computing clusters composed of multiple UEs will be formed and, thus, further augment computing power of MEC in 6G networks [213]. To effectively distribute and collect computing tasks among the UEs, multi-way relaying can find its usage, as not all UEs within the same D2D cluster may be in a communication distance of each other. In particular, a strategically selected UE acting as the Relay UE receives the offloaded tasks from multiple UEs in the first time slot and distribute them to multiple computing UEs during the second time slot using PNC. Similarly, after the computing is done, the Relay UE receives computed data from all UEs involved in computing and, subsequently, distributes the computed data back to multiple UEs.

3) Optimization of D2D relaying with V2X

We have illustrated that 3GPP already considers the D2D relaying and V2X communication to be closely related problems, as mentioned in Section III. Hence, we believe that also the future research should target practical aspects of the use-cases, where the D2D relaying can be actually exploited, such as V2V communication. More specifically, the vehicles can be the relay nodes for the cellular users and vice versa. Although this arrangement makes the radio resource management more complex, it would also offer significantly more relaying options potentially leading to higher relaying gains.

4) Optimization of D2D relaying and RIS

Recently, the RIS started to attract significant attention among the researches, since the RIS is able to, among others, mitigate mutual interference among cellular and D2D communication [218]. To this end, RIS can be exploited for mitigation of interference also between D2D relaying links and cellular links. Especially if multiple Relay UEs use the resources allocated to single cellular link while each D2D relaying link exploits resources of multiple cellular link, as we envision to be the case in 6G networks to achieve ultra-spectral efficiency. Besides, the RIS can also be utilized to relay data between the Source and Destination UEs [219]. Hence, the Relay UE selection deciding whether to exploit the Relay UE or the RIS for the relaying should be devised jointly with controlling the reflection, refraction, and scattering of the electromagnetic waves.

F. Experiments and practical testing

All surveyed works but two ([161][162]) demonstrate benefits of the D2D relaying analytically and/or via the simulations. However, a verification in more realistic environment at lab or in real-world is still missing. To this end, an effort towards initial verification in open source-based emulated mobile networks should be a first step to prove feasibility and efficiency of the general concept and to motivate various industries to push a deployment and support of the D2D relaying into the real-wold networks.

X. Conclusion

The D2D relaying concept facilitates relaying by "simple" user equipments owned by every mobile users. The D2D relaying offers a very convenient benefits for both the mobile operators, who are able to significantly reduce operational costs of the relaying, and mobile users, who can benefit from notably boosted performance. Still, since the inception of D2D relaying concept, there are number of research challenges to be addressed. To this end, we have provided a comprehensive survey on the up-to-date effort of the researches addressing these challenges via many interesting ideas and solutions. We have also drawn number of practical lessons to be learned synthesizing the pros and cons of D2D relaying concept. Last, based on the gaps and missing links in the current state-of-the-art, we have also identified key open challenges and research directions deserving further attention to make the D2D relaying concept feasible and efficient tool in emerging 6G mobile networks.

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TABLE VII: The list of acronyms.

Acronym	Meaning	Acronym	Meaning
3GPP	3rd Generation Partnership Project	PNC	Physical-layer Network Coding
AF	Amplify-and-Forward	PSCCH	Physical Sidelink Control Channel
AI	Artificial Intelligence	PSDCH	Physical Sidelink Discovery Channel
ANFIS	Adaptive Neuro Fuzzy Inference System	PSO	Particle Swarm Optimization
BS	Base Station	PS-EH	Power Switching Energy Harvesting
BW	Bandwidth	PSSCH	Physical Sidelink Shared Channel
C	Capacity	ProSe	Proximity-based Services
CCDF	Complementary Cumulative Distribution Function	QF	Quantized-and-Forward
CSI	Channel State Information	QoE	Quality of Experience
D2D	Device-to-Device	QoS	Quality of Service
DF	Decode-and-Forward	RA	Resource Allocation
DL	Downlink	RIS	Reconfigurable Intelligence Surface
E2E	End-to-End	RLC	Radio Link Control
EC	Energy Consumption	RRM	Radio Resource Management
EE	Energy Efficiency	ReS	Relay Selection
FD	Full-duplex	RS	Relay Station
HD	Half-duplex	SDAP	Service Data Application Protocol
HNC	High-layer Network Coding	SDN	Software Defined Networking
IoT	Internet of Things	SE	Spectral efficiency
LoS	Line-of-Sight	SIC	Successive Interference Cancellation
MAC	Medium Access Control	SINR	Signal to Interference plus Noise Ratio
MEC	Multi-Access Edge Computing	SNR	Signal to Noise Ratio
MINLP	Mixed Integer Nonlinear Programming	SR	Social Reputation
ML	Machine Learning	SWIPT	Simultaneous Wireless Information and Power Transfer
mmWaves	millimeter Waves	TS-EH	Time Switching Energy Harvesting
MOS	Mean Opinion Score	TTL	Time To Live
MRC	Maximum Ratio Combining	Tx	Transmission power
MS	Mode Selection	UAV	Unmanned Aerial Vehicle
NLoS	Non Line-of-Sight	UE	User Equipment
NOMA	Non-Orthogonal Multiple Access	UL	Uplink
NR	New Radio	URLLC	Ultra-Reliable Low-Latency Communication
OPEX	Operating Expenses	V2I	Vehicle-to-Infrastructure
OSI	Open Systems Interconnection	V2P	Vehicle-to-Pedestrian
PA	Power Allocation	V2V	Vehicle-to-Vehicle
PC	Power Consumption	V2X	Vehicle-to-Everything
PDCP	Packet Data Convergence Protocol	VC	Virtual currency
PDU	Protocol Data Unit	VLC	Visible Light Communication
PHY layer	Physical layer	WiMAX	Worldwide Interoperability for Microwave Access

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