Cooperation in 5G HetNets: Advanced Spectrum Access and D2D Assisted Communications

Georgios I. Tsiropoulos, Animesh Yadav, Ming Zeng, and Octavia A. Dobre

Abstract

The evolution of conventional wireless communication networks to 5G is driven by an explosive increase in the number of wireless mobile devices and services, as well as their demand for any time and everywhere connectivity, high data rates, low latency, high energy efficiency, and improved quality of service. To address these challenges, 5G relies on key technologies, such as full duplex, D2D communications, and network densification. In this article, a heterogeneous networking architecture is envisioned, where cells of different sizes and radio access technologies coexist. Specifically, collaboration for spectrum access is explored for both full-duplex and cognitive-based approaches, and cooperation among devices is discussed in the context of the state-of-the-art D2D assisted communication paradigm. The presented cooperative framework is expected to advance the understandings of the critical technical issues toward dynamic spectrum management for 5G heterogeneous networks.

Introduction

Recently, the Groupe Speciale Mobile Association predicted that 8.9 billion connections (excluding machine-to-machine) will serve 5.6 billion unique subscribers by 2020 [1]. To cater to ever increasing demands for higher data rates in the fifth generation (5G) era, and given that wireless link efficiency is approaching its fundamental limit, researchers are seeking new paradigms to revolutionize the traditional communication technologies and employ unconventional thinking for 5G. The emerging networks are expected to be a mixture of nodes with different transmission powers and coverage sizes, as well as multiple tiers and different radio access technologies. Using technologies such as full-duplex (FD), device-to-device (D2D), and carrier aggregation (CA), as well as exploiting shared frequency bands belonging to the TV white spaces and radar, and unlicensed bands both below and above 6 GHz is envisioned. The Third Generation Partnership Project (3GPP) has defined the specification of licensed-assisted access [2] in Release 13 (LTE-Advanced Pro) to address the issue of unlicensed spectrum utilization by wireless networks while fairly coexisting with Wi-Fi and other technologies in the 5 GHz unlicensed band. The use of unlicensed bands above 6 GHz is considered in terms of specification initiatives for 5G New Radio (NR), which will become the foundation for the next generation of mobile networks. The NR standardization procedure is split into two phases: phase 1 for sub-40 GHz and phase 2 for sub-100 GHz, which will be defined in Releases 15 and 16, respectively. Accordingly, cooperation and coordination in terms of spectrum access are a vital access road for 5G network evolution.

Cooperative communications facilitate the collaboration among terminals in a wireless network where nodes assist each other’s information transmission. Originally, relays were employed to realize cooperative communications with an idea not only to overcome path loss, but also to achieve diversity gain. However, the 5G vision recognizes that cooperation in future mobile wireless networks will not be strictly limited to assisting the information transmission. Users may collaborate in terms of accessing the common wireless medium, exchanging information regarding the network and channels status, forming small groups where increased cooperative operations are applied to each other, and employing new technologies in favor of coordinated communication.

From this perspective, in this article we investigate the cooperation in 5G heterogeneous networks (HetNets), aiming to improve the system spectral efficiency (SE) while addressing the challenges of future mobile systems in terms of quality of service (QoS) provision. Our contributions can be summarized as follows:

• We present dynamic spectrum access (DSA) techniques that involve collaboration and interaction among users. Furthermore, we discuss the cooperative aspect of FD-based DSA, as well as explore cognitive-inspired spectrum access and CA techniques that enable more flexibility and improve spectrum utilization. Additionally, we examine recent advances for cooperative access of licensed bands focusing on spectrum trading techniques.

• We investigate the cooperation among devices in terms of D2D communications. We provide the taxonomy of cooperative D2D communications for 5G HetNets based on the level of centralization, use case scenarios, and spectrum band utilization.

• Different scenarios are considered for link establishment for the end-to-end connection in cooperative 5G networks. The impact of the
signal-to-interference-plus-noise ratio (SINR) threshold and the distance between nodes on network performance is studied in terms of ergodic throughput. Evidently, the distance among users may promote a certain cooperative option over the other factors, which in turn affects the throughput.

The rest of this article is organized as follows. First, we summarize the emerging trends in cooperative 5G HetNets from the perspective of spectrum access and D2D communications. We then describe diverse approaches to cooperative DSA, emphasizing FD, CA, and cognitive-inspired methods. Next, we present the state of the art in D2D communications, and a potential cooperative communication model employing D2D and FD techniques is proposed. Finally, the article is concluded.

**Emerging Trends in Cooperative 5G HetNets**

Our view of cooperation in 5G HetNets is a collaborative and coordinated process among network nodes that takes advantage of the FD and D2D technologies, as well as relay-assisted transmission, as summarized in Fig. 1. Furthermore, it can use either licensed or unlicensed, or shared spectrum bands. The basis and description of the network functionalities for cooperative processes in future 5G HetNets are presented below.

**Prospects for Advanced Cooperative Spectrum Access**

It is evident that the currently globally employed 40 license frequency bands exclusive to cellular use are not enough to cater to future traffic demands. Hence, 5G networks should be allowed to operate over unlicensed or shared spectrum bands. Shared bands in the TV white spaces (50–700 MHz) and radar bands (L/S/C bands) are among candidates. The unlicensed spectrum around 2.4 GHz, 5 GHz, and millimeter-wave (mmWave) bands (57–64 GHz) represent potential bands to support 5G. Further, an SE improving CA technology is already employed in the licensed band in 3GPP Release 10, and has been extended to aggregation between carriers in both licensed and unlicensed spectrum bands in Release 13 [2]. The application of CA in both uplink and downlink, along with users’ cooperation in terms of suitable carrier selection, may promote SE.

FD communication is another SE enhancing technology that has been considered as a promising candidate for 5G networks [3]. FD technology allows nodes to transmit and receive on the same frequency band simultaneously. FD communications can be incorporated with cooperative communications or/and underlay DSA techniques to improve spectrum utilization in 5G networks [4], [5].

Advanced spectrum access models tackle the issue of sharing spectrum through an economic market or social perspective based on technical, business, and social criteria. Licensed spectrum can be traded or leased among network nodes or tiers in a 5G HetNet [6] to minimize the spectrum holes in the time and frequency domains, thus increasing the system capacity.

**Device-to-Device Assisted Communications**

D2D communications in cellular networks are defined as direct or multihop communications between two incumbent users in the licensed or unlicensed, or shared bands without any or limited core network involvement. The cooperation among nearby devices offers considerable potential for network operators to offload traffic from the core network. At the same time, it represents a new communication paradigm to support social networking through localization.

D2D assisted communication is one of the highlights of 3GPP Releases 12 and 13 [2]. Devices will cooperate with each other operating as mobile relays, and exploiting their spatial diversity advantages. Moreover, D2D functionality and user cooperation are considered not only to improve SE, but also to address other potential use cases, such as

**FIGURE 1.** Schematic representation of cooperation in 5G HetNets.
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**DIVERSE APPROACHES TO COOPERATIVE DYNAMIC SPECTRUM ACCESS**

In this section, we discuss the way that cooperation among network nodes will revolutionize the DSA techniques.

**COOPERATIVE FULL-DUPLEX SPECTRUM ACCESS TECHNIQUES**

FD technology not only nearly doubles SE, but also reduces end-to-end delays and facilitates the evolution of conventional half-duplex (HD) technology into a denser HetNet environment with mobile relaying nodes, as shown in Fig. 2a. Because of the loop self-interference (SI), this technology can be practically feasible for short-range communication scenarios such as small cell base stations (BSs) and relay nodes. These nodes cooperate in the sense that while they exchange data, they acquire

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**FIGURE 2.** Schematic representation of HD vs. cooperative FD spectrum access techniques: a) several communication paradigms employing FD in 5G HetNets; b) conventional communication scenario employing HD; c) conventional communication scenario employing FD; d) relay-assisted communication employing HD; e) relay-assisted communication employing FD; f) relay-assisted communication with 5G and CR network coexistence employing HD; g) relay-assisted communication with 5G and CR network coexistence employing MIMO and HD; h) relay-assisted communication with 5G and CR network coexistence employing FD.
the channel state information (CSI) in real time, as shown in Figs. 2b and 2c. Moreover, there is a practical implementation of cooperation in terms of spectrum since downlink and uplink are transmitted over the same channel at the same time. Considering cognitive radio (CR)-based communication networks, FD technology is exceptionally useful since cognitive users can monitor the licensed users' activities, improve spectrum hole identification accuracy, and reduce the probability of false alarm.

Cooperative FD communication can be extensively applied in relay-assisted wireless networks. Specifically, dedicated relays or users with good channel condition act as relays to assist the users with bad channel conditions [7]. As illustrated in Figs. 2d and 2e, in HD-based wireless systems, a two-phase cooperation protocol is applied to realize the relay-assisted communication in the time and frequency domains. Particularly, in phases I and II, the relay node listens to and forwards the traffic of the user. The use of FD technology reduces the two-phase cooperation into one.

Recently, a new cooperative paradigm employing FD communication has been introduced in CR networks [8]. Cognitive users may act as relays to forward licensed users' signal, and in return, they can utilize the licensed spectrum to serve their own communication needs. The conventional HD-based cooperation scenario employing multiple-input multiple-output (MIMO) is realized in two phases, as shown in Figs. 2f and 2g:

1. The cognitive user receives the signal from the licensed user.
2. The cognitive user forwards the primary traffic and transmits its own signal at the same time. In the envisioned FD-based cooperative 5G networks, both phases can be realized simultaneously (Fig. 2h).

**Cognitive-Inspired Spectrum Access**

The licensed spectrum policies limit the flexibility of spectrum utilization, while this dynamically changes over different geographical areas and time [9]. By means of 5G HetNets, the CR technology may be employed in the following aspects:

- It allows smooth migration from legacy radio access networks (RANs) to the new 5G communication era. BSs can dynamically lease channels from the previous generation RANs through the CR technology.
- It allows small cells to opportunistically use a channel for a certain time to serve an incoming user.

To promote the CR technology application to 5G HetNets, spectrum sensing and mobility can play a vital role. However, the radio sensing process can be complex and expensive, and may not perform satisfactorily with single user information. Hence, cooperation can enhance the sensing performance via spatial diversity and reduce the detection time at each individual user.
Users with low social distance are expected to interact with increased frequency and are likely to be physically close. This information can be used by the D2D technology to form direct links among users. Moreover, socially close users are considered likely candidates to serve as relays in relay-assisted communications.

To promote the CR technology application to 5G HetNets, spectrum sensing and mobility can play a vital role. However, the radio sensing process can be complex and expensive, and may not perform satisfactorily with single user information. Hence, cooperation can enhance the sensing performance via spatial diversity and reduce the detection time at each individual user [11]. Furthermore, clustering of cognitive users based on their spatial distribution can reduce the energy consumption and overhead due to the sensing information exchange, as the users within the same group have similar sensing characteristics. On the other hand, neighboring groups of nodes can cooperate in terms of timely exchanging information with low overhead. Moreover, node grouping can facilitate the frequency reuse among those that are spatially remote and alleviate the data collisions. The leased bands may be used to accommodate the overload traffic when the network operates near congestion or to provide opportunistic services at low cost.

Cooperative relaying can be combined with CA techniques to allow the usage of multiple spectrum segments and exploit every slice of the frequency band [10]. Cooperation among nearby BSs facilitates a suitable selection of component carriers to mitigate the inter-cell interference. Since a communication path in 5G HetNets may not include the BS, the component carrier selection can be realized at the user devices. To this end, coordination between users is vital to ensure reliable communication.

**Cooperative Access of Licensed Band:**

**The Economic and Social-Based Perspective of Dynamic Spectrum Sharing**

To design an efficient and effective DSA, an economic marketing perspective is also considered, which is referred to as spectrum trading or leasing. Two examples of cooperative-based architectures that realize dynamic spectrum trading techniques are as follows:

- A multi-tier architecture is considered where the spectrum owner, primary service provider (PSP), secondary service provider (SSP), and end users are the trading entities. Such an architecture can be used in HetNets, where the spectrum owner, PSP, and SSP are the wireless operator, macro-cell, and small cell, respectively [6].
- The licensed users may directly decide to lease the spectrum access rights or parts of it to cognitive users. The profit of the licensed users may be either economic revenue or technical cooperation [12]. In the latter case, the cognitive users act as relays in exchange for a fraction of time on accessing the licensed spectrum. Likewise, a trade-off results for cognitive users consuming the power on the relay transmission and acquiring sensing information.

Apart from cooperative architectures, cooperative policies based on user credits can be applied. Users can earn credits when they operate in a collaborative manner. User credits can be spent to gain cooperation from other users. Emerging cooperative-based architectures can exploit the information of social networks to improve their performance and facilitate information dissemination [13]. To this end, users with low social distance are expected to interact with increased frequency and are likely to be physically close. This information can be used by the D2D technology to form direct links among users. Moreover, socially close users are considered likely candidates to serve as relays in relay-assisted communications.

**Inband or Outband, Above or Below 6 GHz?**

The user can choose either inband (licensed band) or outband (shared/unlicensed band) spectrum for communications. Inband spectrum, which is fully controlled by the BS or controller, can be accessed in centralized or distributed fashion. In the centralized case, devices cooperate with the controller for channel availability, the QoS is guaranteed, and interference management is easy. In contrast, in a distributed case, devices need to sense the wireless environment to use the channel. Neighboring devices may cooperate, facilitating sensing information exchange to increase spectrum sensing efficiency. The main challenges of distributed inband communications are the interference management and resource allocation, which usually require methods of high complexity. Inadequate interference management may waste cellular resources and deteriorate the conventional cellular communication.

In unlicensed bands, there are no exclusive rights for their use, and therefore, they may be employed by any independent device that is compliant with the usage rules, such as maximum power levels and bandwidth limitations. It does not interfere the cellular network users; however, interference within the band is uncontrollable. Besides, security and QoS are not guaranteed. On the other hand, in shared bands, non-incumbent users are allowed to use the spectrum in accordance with...
sharing rules to avoid or limit the interference to the incumbent users. The most popular use cases of in-band and out-of-band communications are shown in Fig. 3a. The spectrum below 6 GHz is generally recommended for long-distance communications. For instance, the IEEE 802.22 standard (shared band in the TV frequency spectrum) is used to provide broadband wireless access in rural areas for ranges up to 100 km. The spectrum bands above 6 GHz are useful for mid- and short-range links. For instance, the IEEE 802.11ad standard recommends the use of the unlicensed 60 GHz band for short distance, especially for indoor use, achieving multi-gigabit speeds. The standardization bodies and the operators are pushing the technology forward to use the above 6 GHz band through the upcoming 5G NR standards. In 5G NR, the combination of the two bands will be able to meet the wide range of 5G requirements.

D2D COMMUNICATIONS

D2D communications are considered from three perspectives: control plane, type of communication (i.e., information relay or direct communication), and application of FD technology, as depicted in Fig. 4.

LEVEL OF CENTRALIZATION:

CORE NETWORK-ASSISTED VS. AUTONOMOUS

Devices may be partially or fully assisted by the BSs or relay nodes of the core network to control the D2D connections, as depicted in Fig. 3b. The core network assistance improves the throughput, EE, and SE performance at the cost of extra computational and controlling load for BSs and relay nodes. Clearly, such a scenario is not beneficial for D2D deployments that involve out-of-core network coverage.

In autonomous D2D communications, devices are fully responsible for setting up, controlling, and coordinating the communication. Cooperation among devices is essential to allow distributed users to process and relay information in a coordinated fashion. Channels belonging to different bands (i.e., licensed or unlicensed) or shared may be employed for multiple hops, with different access methods (e.g., spectrum leasing or cognitive access). If the distance between communicating devices is small, they may prefer to select channels from bands above 6 GHz. In higher frequency bands, signal power attenuates significantly, and thus the interference is restricted within a small region, which can be managed by applying the simple frequency-division multiplexing technique within the region. It is worth mentioning that autonomous D2D systems are critical in natural disasters, such as earthquakes or hurricanes, since they can set up an urgent communication network replacing the damaged core network.

D2D USE CASE SCENARIOS:

DIRECT OR RELAY COMMUNICATION

The introduction of D2D functionality in 5G HetNets creates two main use case scenarios, as illustrated in Fig. 3c. In the first scenario, nearby devices may set up local links among them, which can potentially improve the user experience in terms of latency and power consumption, and lead to increased SE and EE by dense spectrum reuse. Multiple D2D links can operate over the same channel within the same cell, which increases spectrum reuse per cell beyond one. A challenging case is when multihop D2D communication links are involved, that is, more than two devices cooperate to establish an end-to-end communication path.

In the second scenario, a device with better performance is set up nearby to serve as a mobile relay. Devices may be partially or fully assisted by the BSs or relay nodes of the core network to control the D2D connections. The core network assistance improves the throughput, EE, and SE performance at the cost of extra computational and controlling load for BSs and relay nodes. Evidently, such a scenario is not beneficial for D2D deployments that involve out-of-core network coverage.

FIGURE 5. The cooperative D2D-assisted model for 5G HetNets: a) four use case scenarios; b) proposed algorithm for the selection among available communication alternatives.
transmission characteristics than the BS can act as relay to assist the communication of nearby devices. Cooperative relaying D2D communications can benefit from the spatial diversity of devices, exploit multiuser shadow diversity, and improve transmission range. D2D relay introduces new technical challenges, where devices should collaborate to discover the candidate relays, select the relay device, and minimize the power consumption of the relay device. It is envisioned that devices located within a cell can be clustered into several groups. A certain relay node aggregates the traffic from the devices within each group and applies multiplexing techniques to forward the traffic to the BS. As the transmission characteristics vary over time, the relay node selected within the group can change accordingly.

**FD D2D-Aided Cooperative NOMA**

The FD technology can be combined with non-orthogonal multiple access (NOMA) in terms of D2D communications to further improve the SE. In cooperative NOMA relay-assisted CR networks, cognitive users help the licensed ones by acting as relays, while at the same time they use the same spectrum band to transmit their messages exploiting the NOMA technology advantages [14]. In another scenario, the NOMA user with higher SINR can receive data from the BS and forward them toward the NOMA user with lower SINR employing the FD technology at the same time over the same channel [15]. The application of FD D2D-aided cooperative NOMA can significantly improve the downlink performance and the transmission reliability of the NOMA user with lower SINR. In a novel use case, a BS can communicate to its low SINR user via a relay device, which employs NOMA to forward the data to the BS user and its own destination user; SE can be further improved by using the FD relay.

**Performance Studies**

In this section, we present illustrative performance studies for cooperative 5G HetNets employing D2D and FD technologies. Four scenarios are set to reflect the different alternatives offered in 5G HetNets to establish a link between two nodes, as depicted in Fig. 5a. The spectrum below 6 GHz is considered. Two performance metrics, ergodic throughput vs. SINR and D2D distance, are studied to illustrate the performance of the algorithm described in Fig. 5b.

When the transmitter and receiver devices are close enough, an outband direct link is established, which corresponds to scenario A. If the direct link quality is not adequate to satisfy the QoS requirements, more than two devices cooperate to establish a communication path (i.e., scenario B). If a link is not feasible without the core network’s involvement, scenario C is used, which corresponds to the conventional link. D2D communication can be employed for distant users or users with poor communication characteristics to assist their communication with the BS, as considered in scenario D. For scenarios A and B, autonomous D2D links on the outband spectrum are used, which not only avoids interference but also improves the SE. On the other hand, inband is employed for scenarios C and D since they involve the core network. The 5G HetNet admits an incoming call request by the source device based on the SINR of the link, the QoS requirements and the potential availability of a relay device, as shown in Fig. 5b.

We assume a circular cell of radius $r = 1$ km with a macro BS at the center. The locations of the in-band and out-of-band D2D transmitters are modeled via a Poisson point process (PPP) with densities $\lambda_{in}$ and $\lambda_{out}$, respectively. A list of parameters and their values are summarized in Fig. 6a. In Fig. 6b, the ergodic throughput vs. the SINR is shown for the four scenarios. Scenarios B and D, which involve device cooperation, use the amplify-and-forward

![Figure 6](image-url)

**FIGURE 6.** Comparison of ergodic throughput performance for different use case scenarios in cooperative 5G HetNets: a) input parameter values; b) ergodic throughput vs. SINR threshold; c) ergodic throughput vs. D2D distance. Note that $\sigma_n^2$ and $\sigma_r^2$ represent the noise power and residual SI power, respectively.
coordination scheme should be devised to reap the benefits of the shared and unlicensed bands; finally, the number of collisions increases with load in the shared and unlicensed bands; and second, higher device density causes higher aggregate interference, and thus, the need for efficient mitigation techniques is inevitable, especially for shared and unlicensed bands; finally, the number of collisions increases with load in the shared and unlicensed bands, and hence, a clever spectrum coordination scheme should be devised to reap the full potential of these bands for cellular usage.

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Conclusions and Research Directions

This article provides a glimpse of cooperative communications in 5G HetNets. Cooperation aims to improve the network performance in terms of SE, latency, connectivity, EE, and QoS. Cooperation among the wide array of spectrum available in the shared and unlicensed bands, along with the link-distance-dependent access for enhancing the SE are beneficial. Furthermore, employing FD and D2D technologies facilitates the cooperation among the distributed devices and cognitive users, and leads to efficient DSA. Cooperative communications can be combined with 5G NR and provide the most out of every bit of diverse spectrum. The insights gained from the preliminary numerical investigations regarding the potential adoption of cooperative techniques demonstrate the significant improvement in terms of SE, which is essential to meet the unprecedented challenges of future mobile systems.

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Cooperative communications can be combined with 5G NR to get the most out of every bit of diverse spectrum. The insights gained from the preliminary numerical investigations regarding the potential adoption of cooperative techniques demonstrate the significant improvement in terms of SE, which is essential to meet the unprecedented challenges of future mobile systems.

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