Advanced Spectrum Sharing in 5G Cognitive Heterogeneous Networks

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Abstract

Spectrum utilization, energy consumption, and cost efficiency are three key performance metrics that should be jointly investigated in developing a sustainable 5G system. Advanced spectrum sharing can enhance both the spectral efficiency and energy efficiency in a cost-effective manner, which is expected to perform much better than conventional networks. In this article, we survey cognitive and cooperative spectrum sharing, and classify a multi-level spectrum exploitation, coordination, and utilization framework from both technical and economic perspectives. We specifically concentrate on spectrum trading and leasing, spectrum mobility, relaying, routing, and harvesting. Finally, a spectrum flowing scheme is proposed for 5G cognitive heterogeneous cellular networks, which improves both spectral and energy efficiency.

Introduction

Mobile wireless communications have experienced explosive traffic growth in the last decade. This has recently been further fueled by the popularity of various smart devices and Internet-based applications. The fifth generation (5G) mobile communication network is expected to meet unprecedented traffic demands and provide better quality of user experience. In sustainable 5G heterogeneous communication networks, spectrum utilization, energy consumption, and cost efficiency are three key performance metrics [1–4]. Some recent 5G vision activities commonly recognize that future mobile wireless communications should have the following efficiency enhancements compared to the current networks: spectrum efficiency: 5–15 times; energy efficiency: 100+ times; and cost efficiency: 100+ times.

Spectrum sharing can improve spectrum efficiency by allowing more than one node to use the same spectrum at the same time. Recently, dense deployment of small nodes over rich portions of low radio frequency has been investigated as a promising method of spectrum sharing. Also, we know that cognitive-radio-inspired spectrum sharing schemes can utilize unused or underutilized spectrum temporally and geographically, which will significantly enhance the spectral efficiency. In the emerging 5G communication era, energy efficiency should be another critical performance metric, which is motivated by both financial and environmental considerations. Energy efficiency is critical, especially when extremely small nodes are densely deployed. However, it has not received much research attention in the current spectral efficient spectrum sharing schemes.

Advanced spectrum sharing schemes have been creatively proposed to improve the spectrum utilization including spectrum trading [5–9] and leasing [10], and the latest spectrum mobility [11, 12], relaying [13], routing [14], and harvesting [15]. Compared to the conventional themes, they can both enhance capacity and save energy, and thus improve both spectral and energy efficiency. It is known that spectrum sharing can improve spectral efficiency, although there is little doubt that spectrum sharing can enhance energy efficiency. In fact, advanced spectrum sharing (i.e., bandwidth exchange) can well save energy, details of which can be found in [4].

In this work, advanced spectrum sharing always combines other technical methods with respect to the channel/interference state information and the traffic situation. Advanced spectrum sharing schemes are both energy and cost efficient.

First, advanced spectrum sharing schemes can save energy. It is proved that an advanced spectrum sharing scheme, called bandwidth exchange in [4], saves energy more efficiently than power control. This is due to the shorter transmission distance, and the cooperative and selective diversity gains among different nodes. This spectrum sharing scheme is tightly combined with the cooperative relaying. For another example, by spectrum sharing in multi-tier cellular heterogeneous networks (HetNets), a user can associate with an access point that has a shorter transmission distance, requiring lower transmit power.

Second, advanced spectrum sharing schemes can allow more nodes/devices to share the same spectrum in multiple dimensions, thus enhancing cost efficiency from the spectrum license holders' perspective. This is mainly due to more nodes/devices sharing spectrum, meaning more revenue for wireless operators. Certainly, wireless operators should include the interference mitigation

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technique in the spectrum sharing case.

Although different communities in academia, industry, and standardization hold different points of view on 5G networks (e.g., green and soft from China Mobile), we hold the vision of the 5G mobile network as cognitive, cooperative, and multi-tier. We concentrate on the advanced spectrum sharing schemes in such kinds of wireless networks, aiming to optimize both spectral and energy efficiency. In summary, our contributions can be summarized as follows:

- We provide a comprehensive survey of advanced spectrum sharing and view it from both economic and technical perspectives. In particular, we summarize most recent spectrum sharing schemes from a cross-layer technical implementation perspective.
- We present a spectrum flowing scheme with cognition of both traffic status and channel state information. We provide simulation results to reflect the improved spectrum efficiency and energy efficiency of the presented scheme for different small cells with various locations and coverage.

The rest of our article is organized as follows. In the following section we summarize the emerging trends of advanced spectrum sharing in the 5G era. Then we provide a taxonomy for current advanced spectrum sharing schemes, emphasizing both technical and economic investigations on spectrum sharing. Following that, an advanced spectrum flow scheme is implemented in cognitive HetNets. Numerical results show the improved spectral and energy efficiency. Then we list a few future research issues. Finally, we conclude this work in the last section.

Emerging Trends of 5G Spectrum Sharing

Our view of advanced spectrum sharing is a cognitive, cooperative and multi-tier coordination process in 5G HetNets. How to explore the potential cognition and cooperation capabilities of multiple nodes in cognitive HetNets to improve spectral and energy efficiency is a key challenge but a good opportunity at the same time.

Network cognition and cooperation are employed as promising techniques to save energy and mitigate interference, thus improving spectral and energy efficiency. Different players participate in spectrum sharing of different frequency spectrum from various perspectives, which are summarized in Fig. 1.

In the following subsections, we provide the detailed basics of advanced spectrum sharing schemes with typical cooperation and cognition characteristics in the 5G era.

Cooperation-Based Spectrum Sharing

We should take a wider view of spectrum sharing in addition to wireless operators, which encourages us to seriously consider the multiple types of players' spectrum sharing technologies. For instance, the focus in [1] was on public-private spectrum sharing, which may complement the historical quality of service focus to bring the gigabits per second in 5G systems to home, office, and leisure quickly and efficiently. To improve the edge user experience quality, an integration of the local area with the wide area is regarded as a new form of cooperation between conventional macrocells in lower frequency bands and small cells deployed in higher frequency bands.

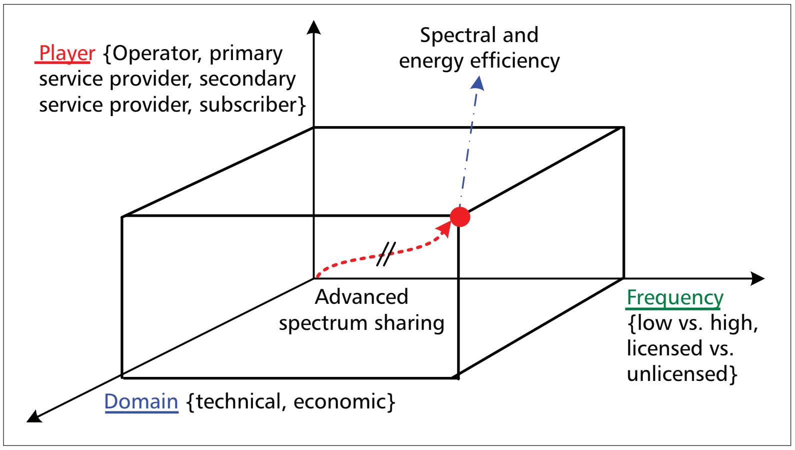

Figure 1. An advanced spectrum sharing scheme in the 5G era.

While traditional exclusive licensing continues to be a preferred option for mobile network operators, the new sharing-based licensed shared access concept is receiving growing interest in the research, regulation, and standardization communities. The licensed shared access method allows a wireless operator to share licensed spectrum with predetermined rules. Matinmikko *et al.* [2] reviewed different types of spectrum bands for Long Term Evolution (LTE)/LTE-Advanced (LTE-A) and beyond networks, and focused on licensed shared access as a spectrally efficient solution for spectrum access in the future.

Cognitive-Radio-Inspired Spectrum Sharing

With the ability to detect and adapt to the surrounding radio environment, cognitive radio has been recognized as a key technology to solve the spectrum scarcity problem. It temporally or spatially releases valuable and scarce spectrum from the shackles of authorized licenses and allows opportunistic usage of the vacant licensed bands. A lot of effort has been made to introduce cognitive radio capabilities into 5G HetNets; therefore, a large number of related new networking concepts have emerged, including cognitive cellular, cognitive WiFi, and cognitive femtocell.

For future mobile network operators, sharing the spectrum with other operators or other radio communication services is a disruptive change, especially when using cognitive radio system technologies. Building on alternative spectrum sharing scenarios, the authors in [3] discussed a set of simple rules for mobile network operators, both dominators and challengers, regarding spectrum sharing in future cognitive cellular networks. The HetNet architecture, device-to-device communications, and coexistence with existing wireless systems have been regarded as new communication paradigms introduced in LTE-A/LTE-B cellular networks. To facilitate these paradigms, considerable research has shown the promise of cognitive radio technology, particularly cognitive radio resource management on top of resource allocation to control layer 1 and layer 2 radio operations. Thus, this eliminates the concerns of potential system impacts and operation

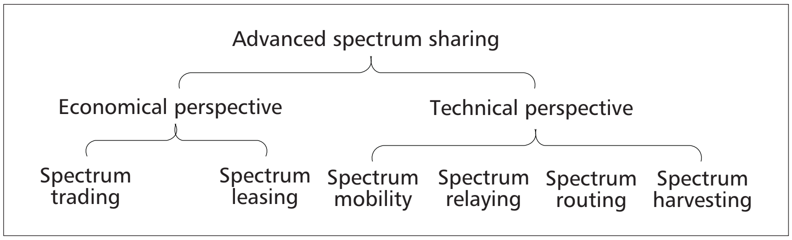

Figure 2. A taxonomy of the current advanced spectrum sharing schemes.

unreliability to bridge the gap between cellular and cognitive radio technologies. To support diverse communication paradigms with different challenges, a variety of cognitive radio resource management schemes have recently been proposed [5]. In addition, as the number of distributive deployed femtocell access points increases rapidly, interference coordination becomes the primary challenge in such HetNets. Several cognitive-radio-inspired approaches have been proposed to enhance the interference coordination in cognitive femtocell networks.

Diverse Approaches to Spectrum Sharing

We provide a taxonomy for spectrum sharing schemes with the emphasis on both technical and economic investigations in spectrum sharing. This article discusses spectrum harvesting, mobility, relaying, spectrum trading, and leasing. The available literature on spectrum sharing schemes tackles the issue of sharing spectrum from different aspects. Most of these aspects are sub-classes of two major categories: an economic marketing perspective and a cross-layer technical implementation perspective, as shown in Fig. 2.

An Economic Marketing Perspective

The first category covers proposals that aim to improve the spectrum revenue of operators or spectrum owners. The research work under this category is divided into subcategories of spectrum trading and spectrum leasing. Both of these categories are considered as novel and dynamic spectrum sharing paradigms that have appeared in recent literature.

Spectrum Trading: Spectrum trading is the process of buying, selling, and exchanging the rights of the radio spectrum. It can be widely used in a variety of communication scenarios, including broadcasting, emergency services, and telecommunication. Spectrum trading enhances the radio spectrum utilization. It provides more chance of better provision of wireless services and economic growth, and opens up new opportunities for businesses, giving consumers better experience of new services with lower prices. The spectrum trading process is similar to a marketing transaction process, which is why some market-driven spectrum trading schemes have been proposed in game theoretic terminology.

First, spectrum trading can enhance spectrum utilization via dynamic spectrum sharing from a marketing perspective. The problem of a spectrum owner trading spectrum to multiple secondary users was investigated in [6]. The spectrum owner acts as a monopolist in the trading process, and sets the qualities and prices. Secondary users act as consumers, and purchase spectrum according to the appropriate quality and right price. Once consumers find that such a purchase is feasibly rewarding for all secondary users, a contract is then produced with the monopolist. Moreover, customers can adapt their spectrum buying behaviors with respect to the spectrum price and quality variations offered by different sellers [7]. In this case, sellers can also adjust their selling behaviors toward spectrum opportunities. Researchers can use the theory of evolutionary game to analyze the dynamic behaviors of the customers and sellers. Meanwhile, the authors of [7] discussed the scope of spectrum trading for different spectrum sharing models, where the research issues and the corresponding related solutions were also outlined.

Second, there are different timescales of spectrum trading, including long-term spectrum macro-trading, medium-term spectrum meso-trading, and short-term spectrum micro-trading. Short-term spectrum micro-trading enables trading of spectrum on the micro scale, three dimensions of which can be implemented, including the micro-spatial, micro-temporal, and micro-frequency scales. The conditions for viability of spectrum trading are important to the formulated markets. The authors of [9] focused on determining such conditions, where the authors analyzed different market scenarios and the behaviors of the participants.

Third, spectrum trading schemes have been well studied in centralized networks. For instance, spectrum trading occurs between primary and secondary users in a cognitive radio network, or between macrocells and small cells in HetNets, which really creates more access opportunities and economic benefits. It is proved to be challenging to implement a spectrum trading scheme in a multihop network. This is significantly due to different spectrum requirements from secondary users, uncertain spectrum supply from primary users, and the complex competition relationship between them. Meanwhile, there are different types of radio frequency trading of spectrum including the open, licensed, and unlicensed spectrum. For instance, in [8], the authors discussed a spectrum trading mechanism implemented by the spectrum broker in the licensed TV white spaces.

Spectrum Leasing: The primary user owns a given licensed spectrum bandwidth and may decide to lease parts of bandwidth to secondary users in exchange for appropriate technical cooperation or economic revenue. An implementation of such a framework was proposed and analyzed in [10], where a primary link temporarily leased its owned spectrum to the secondary nodes in exchange for coding cooperation.

Different from the above described spectrum trading, primary users participate and allow secondary users access to the spectrum in dynamic spectrum leasing. For instance, a game theoretic framework was formulated in [10] for dynamic spectrum leasing where primary users actively participate with secondary users. In fact, cross-tier user cooperation occurs during the spectrum leasing process. That is why there was a cooperative communication-aware spectrum leasing framework, where the primary network leveraged secondary users as cooperative relays. The primary network would decide the optimal relay selection and the price for spectrum leasing. Based on the primary network's decision, the secondary network would determine spectrum access time. The above procedure is usually formulated as a Stackelberg game, where the primary users act as the leaders and the secondary users as the followers.

Multi-Tier Spectrum Trading and Leasing: With an overview of the typical literature above, we present a multi-tier spectrum trading and leasing architecture with the upper, medium, and lower tiers, as shown in Fig. 3. Different tiers of spectrum trading and leasing correspond to long, medium, and short terms, respectively.

In Fig. 3, four types of players are involved in the multi-tier spectrum trading and leasing game. Those are the spectrum owner, primary service provider (PSP), secondary service provider (SSP), and user device. Here, the spectrum owner can be the wireless operator; the PSP is the existing infrastructure, such as macrocell eNodeBs (MeNBs) and WiFi access points with their own licensed spectrum. The SSP represents the small cell eNodeB (SeNB) or any cognitive access point. From the perspective of top to bottom, any upper entity can sense spectrum utilization and traffic, and then determine to lease or trade to a lower entity for more spectrum revenue or to improve the spectrum efficiency. Meanwhile, the lower entity decides who should rent and trade, and how much. In addition, if multiple players share the same tier, cooperation between them is crucial to further improve the spectrum utilization.

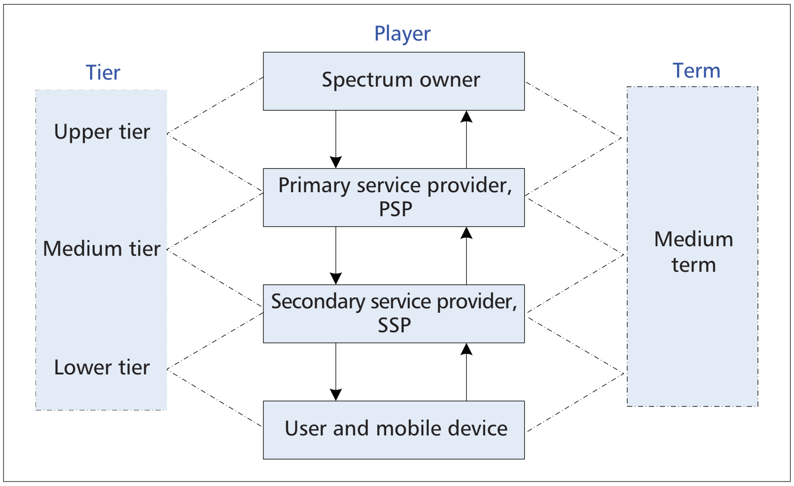

Figure 3. Multi-tier spectrum trading and leasing.

A Cross-Layer Technical Implementation Perspective

We have observed the trends of future spectrum sharing, and realized the flexible economical perspective of spectrum sharing schemes. In this subsection, we survey the recent technical implementation of these technologies taking a cross-layer communication protocol perspective.

Spectrum Mobility: Spectrum sharing coordinates the spectrum utilization among different nodes. In cognitive radio networks, if a primary user reclaims a licensed channel that has been temporarily leased or traded to a secondary user, spectrum mobility should suspend the secondary user's transmission and vacate the channel. The aim of spectrum mobility is to switch channels at the right time to guarantee the performance of both the secondary and primary users.

Spectrum mobility is a challenging topic during spectrum sharing, which has attracted lots of attention recently. Spectrum mobility is divided into two processes: spectrum handoff and connection management. Spectrum handoff is the process of transferring ongoing data transmission from the current channel to an alternative free channel. Southwell *et al.* have examined various spectrum handoff strategies, and reviewed and compared different strategies in [11].

During spectrum mobility, primary users have higher priority [12], which means that secondary users leave the licensed channel immediately once they cause interference. Certainly, secondary users can also perform spectrum mobility due to the link quality degradation.

Spectrum Relaying: Relaying is an important way to enlarge the coverage and extend the capacity in wireless communications, which can also facilitate the advanced spectrum sharing process. Relay-assisted protocols for spectrum mobility have been proposed. The authors of [13] developed a relay-assisted protocol for spectrum mobility in cognitive LTE networks. Under this protocol, each secondary user has more than one connection paths to the base station through dynamic spectrum relaying. Here, the path with the minimum expected transmission time is selected. The selection is made using multiple paths through a relay once the relay has plenty of spectrum holes. Therefore, it is possible for a spectrum hole to be occupied by multiple secondary users.

Spectrum Routing: Using TV white space sharing as an example, subscribers make a series of channel switching decisions if they have accurate foreknowledge of channel availabilities. This process of a series of channel switching decisions is more like the routing issue in wireless communication. In spectrum routing, each user decides when and how to switch channels with respect to both the information of channel availabilities and the opponents' strategies. The authors of [14] modeled the scenario as a game, where a network congestion game was formulated.

Spectrum Harvesting: Opportunistic sharing of unlicensed or licensed spectrum bands has initiated interesting research on spectrum trading systems. Most existing work focuses on user-centric spectrum trading, that is, each secondary user purchases available bands from primary users, and as a return primary users attain revenue or relief. Current designs of spectrum trading systems are confronted with several critical problems including different spectrum requests, changing spectrum availability, and dynamic behaviors of primary users, in particular when they are deployed in multihop wireless networks.

On the other hand, by now these advanced spectrum sharing schemes occur between the cognitive users and the primary users. In order to facilitate the spectrum trading between a wider

Spectrum sharing is shifting from transmitter-based regulation to transmitter and receiver regulation, which is a promising full-duplex technology. On the other hand, millimeter wave technology and interference-tolerant overall systems are also expected to contribute to the thousand-fold throughput enhancement.

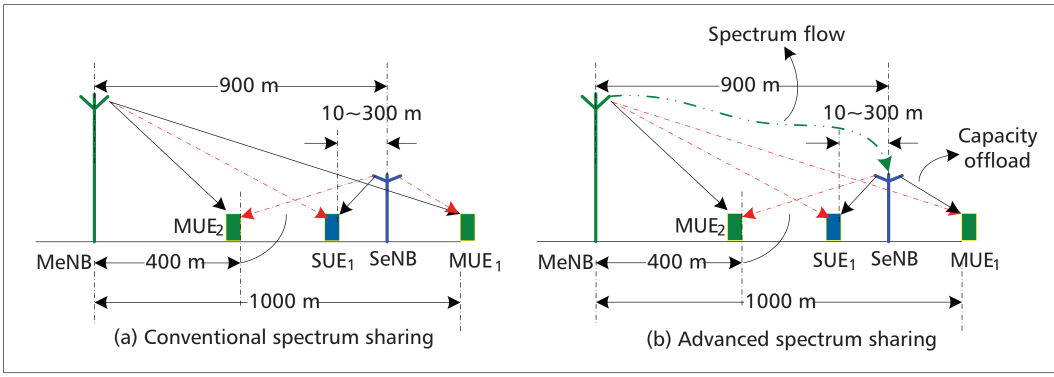

Figure 4. Conventional and advanced spectrum sharing scenarios: a) conventional spectrum sharing; b) advanced spectrum sharing.

1: Source Selection: The MeNB determines which MUEs should be offloaded to the SeNB, the decision of which depends on the ratio of the achieved SINR and the predefined SINR threshold.
2: Target Selection: The MeNB selects the SeNB who introduces the most interference as the offloading target.
3: Spectrum Leasing: In return, the MeNB will lease some of its dedicated channels to each selected SeNB according to its offloaded MUEs.

Table 1. An advanced spectrum sharing scheme.

number of users without cognitive radio capabilities, novel network architectures and new network entities should be introduced during spectrum sharing.

A new service provider is introduced in [15] to facilitate the access of secondary users. It is referred to as the secondary service provider, and it harvests the available spectrum bands with cognitive radio capabilities.

Spectrum Flow in 5G Cognitive HetNets

An advanced spectrum flow scheme is implemented in cognitive HetNets, and numerical results show the improved spectral and energy efficiency in this section.

5G Cognitive HetNets

First, we illustrate the conventional spectrum sharing HetNets, shown in Fig. 4a, where multiple small cell eNodeBs (SeNBs) are overlaid on an existing macrocell controlled by macrocell eNodeB (MeNB). HetNets hold great promise, however, both the SeNB and MeNB may suffer significant performance degradation due to inter/intra-tier interference. For instance, in Fig. 4a macro user equipment 2 (MUE2) and smal cell UE1 (SUE1) are seriously interfering with each other. In particular, MUE1 is an edge MUE associated with MeNB. It is too far away from the MeNB; however, it is close to a specific SeNB. Therefore, its achieved capacity is very low since the received effective downlink power from the MeNB is low, and the interference power from the SeNB is high.

In 5G cognitive HetNets, we assume that both the MeNB and SeNB have cognitive capabilities, and they can engage in cooperation. In Fig. 4b, the cognitive capabilities are referred to as MeNB and can sense the achieved capacity/signal-to-interference-plus-noise (SINR) of its associated MUEs and the spectrum utilization situation, and then offloads the MUEs with poor SINR and leases some of its underutilized dedicated spectrum to the SeNBs. Also, the cognitive SeNB can sense the requirements of access from offloading MUEs, and then determine how to allow the MUEs access. In this article, we term the spectrum exchange in Fig. 4b as the spectrum flow among different nodes in the network.

Proposed Scheme and Simulation Settings

We propose an advanced spectrum sharing scheme to mitigate interference and save energy between the MeNB and the SeNBs. The proposed scheme combines both the economic and technical considerations, described in Table 1.

In fact, the presented advanced spectrum sharing scheme implements both cooperative capacity offload and spectrum leasing. We investigate a simple two-tier cognitive HetNet to verify the improved performance, where we assume that there are one MeNB underlaid by several SeNBs. The MeNB covers a 1000 m radius area, and SeNBs are distributed around 100 m to the MeNB edge. The downlink powers of both the SeNB and MeNB are static, and 20 dBm and 46 dBm, respectively. The propagation models for the MeNB and SeNB are $153 + 376 \times \log_{10}(d)$ and $384.6 + 200 \times \log_{10}(d)$, respectively, where d is the distance between the node and its associated subscribers.

There are three kinds of conventional spectrum sharing frameworks including dedicated, full, and hybrid spectrum sharing schemes, where wireless networks operators are favored for the full spectrum sharing scheme due to high capacity improvement. That is why in this work we set conventional spectrum sharing as the full frequency reuse case among the MeNB and multiple SeNBs, where we assume that 20 MHz with the LTE orthogonal frequency-division multiple access (OFDMA) settings is fully shared by both the MeNB and the SeNBs.

The advanced spectrum sharing schemes always involve spectrum collaboration and buying and selling behaviors between different players;

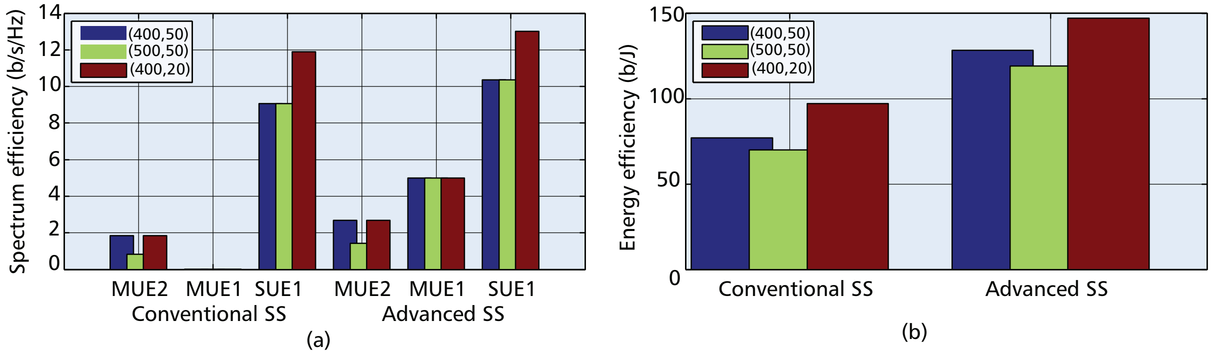

Figure 5. Individual spectrum efficiency and system energy efficiency of both conventional and advanced spectrum sharing schemes: a) individual spectrum efficiency; b) system energy efficiency.

therefore, we implement the proposed scheme with the hybrid spectrum sharing scheme. Here, the MeNB uses 10 MHz as its dedicated spectrum, and the other 10 MHz is fully shared by the MeNB and SeNBs. According to the proposed scheme, we can compute the achieved capacity with different SINR forms with different interference situations.

Numerical Results

In this subsection, typical scenarios are set to reflect the improved performance of the presented scheme for both spectrum efficiency and energy efficiency. We simulate three different cases, where we choose different settings of local area radius of the MeNB and coverage radius of the SeNB. The first case is (400, 50), which means that the local area radius of the MeNB is 400 m, and the coverage radius of an SeNB is 50 m. Also, the other two cases are (500, 50) and (400, 20) with the same definitions. Here, we choose the individual spectrum efficiency and the system energy efficiency as performance metrics due to the promising requirements of the user-centric quality of experience provision and systematic network-wide energy consumption.

We compute the corresponding individual spectrum efficiency achieved by MUE2, MUE1, and SUE1, which is illustrated in Fig. 5a, and the system energy efficiency performance in Fig. 5b.

From Fig. 5a, we conclude that the proposed spectrum sharing scheme can achieve a win-win performance for MUE2, MUE1, and SUE1. In particular, for MUE1, the wide edge MUE1 obtains significantly improved spectrum efficiency compared to that of the conventional spectrum sharing one. This is mainly due to the maximum interferer SeNB, which becomes the new associated node of the MUE with poor SINR. At this time, the MUE receives more effective and useful power from its previous interferer SeNB but low interference power from its previously associated MeNB.

Here, the spectral efficiency performance values in Fig. 5a are achieved without considering the performance effects on other SUEs in the SeNB. In summary, if the MeNB can always offload multiple MUEs with the worst spectral efficiency performance to the selected SeNB that introduces the strongest interference power, this brings SE performance improvement to both sides of the MeNB and SeNB. On the other hand, the MeNB can opportunistically be more energy efficient. Finally, we depict the system energy efficiency in the unit of bits per Joule. Then we conclude that the advanced spectrum sharing saves some power compared to that of the conventional one. Due to the fact that extensive MUEs are offloaded to the SeNBs, the MeNB only needs to serve the MUEs. Then the MeNB does not need a large downlink transmission power, which can save energy and also reduce the mutual interference to multiple SeNBs. Therefore, the presented advanced spectrum sharing will achieve win-win performance improvement in both spectral and energy efficiency.

Future Research Issues

It is important for researchers to recognize that in addition to established spectrum bands, 5G will require new bands. On the other hand, the availability of new bands is not guaranteed. Different bands will serve different purposes, and a key aspect of 5G will be to integrate the various approaches and bands within a harmonized global framework. During the LTE standardization process, carrier aggregation makes it possible for mobile operators to aggregate two or more radio frequency carriers to boost the throughput of user data.

Also, spectrum sharing is shifting from transmitter-based regulation to transmitter and receiver regulation, which is a promising full-duplex technology. On the other hand, millimeter-wave technology and interference-tolerant overall systems are also expected to contribute to the thousand-fold throughput enhancement.

Extensive research has been carried out in spectrum sharing; in particular, the cognition and cooperation incentives have attracted wider interest in 5G spectrum sharing. However, we feel that there are still problems that deserve attention in this area and need to be resolved. Hence, we look forward to the following two aspects being further combined with advanced spectrum sharing.

Small cell deployments will play an important role in the 5G era, which can provide the spectrum- and energy-efficient through-

More types of cognition can be explored to combine the promising uthorized/licensed shared access and co-primary sharing, for instance, the traffic cognition and spectrum resource reserving technology. In addition, spectrum sharing involves multiple domains of players.

put enhancement in a cost-effective manner. Extreme deployment of small cells will further explore both spacial and frequency diversities in the co-channel sharing case. Certainly, it introduces technical challenges including serious interference and high energy consumption; however, challenges come with opportunities. Both inter- and intra-cooperation between small cells and macrocells, or among themselves, can be explored to share the spectrum well. Here, we list a few of them including cooperative capacity offload with spectrum leasing, small cell range expansion with cooperative power coordination, and cooperative relay with spectrum trading and virtual currency or belief as incentives.

Device-to-device (D2D) communications are proposed as one of the most important paradigms to improve the experience of proximity-based user pairs. Extensive D2D pairs are an underlay to cellular networks or HetNets. Three spectrum sharing schemes are designed for the D2D and cellular users, including dedicated spectrum sharing, and full and hybrid spectrum sharing. Wireless network operators prefer full spectrum sharing due to more capacity improvement. However, it always involves interference avoidance, cancellation, mitigation, or even interference alignment in the multi-antenna case. Basically, we know that on one hand, elimination of conventional base stations as relays will reduce the uplink and downlink channels to one direct channel, which helps improve the spectrum utilization. On the other hand, a spectrum utilization hierarchy always exists between the macrocell user equipment and the D2D communication pairs, where the spectrum trading and spectrum leasing summarized in this work can find wide application and thus improve spectrum efficiency.

Last but not least, cognitive radio technologies make it possible to share this spectrum by using radio environmental awareness techniques and interference management that allow multiple systems to occupy the same spectrum. Meanwhile, more types of cognition can be explored to combine the promising uthorized/licensed shared access and co-primary sharing, for instance, traffic cognition and spectrum resource reserving technology. In addition, spectrum sharing involves multiple domains of players.

Conclusion

Spectrum sharing is expected to play a more important role in the 5G era. In this article, the surveyed advanced spectrum sharing schemes can enhance both spectral and energy efficiency. We present unified spectrum exploitation, coordination, and utilization for spectral and energy efficiency in 5G cognitive heterogeneous networks. We emphasize both technical and economic perspectives on spectrum sharing. An advanced spectrum flow scheme was implemented in cognitive heterogeneous cellular networks, and numerical results verified that our proposed scheme could improve both spectral and energy efficiency.

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Biographies

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