Integrated Energy and Spectrum Harvesting for 5G Wireless Communications

Yi Liu, Yan Zhang, Rong Yu, and Shengli Xie

Abstract

Two important issues have arisen in 5G wireless communications: spectral efficiency and energy efficiency. The existing wireless communication architectures and technologies may not be able to address these two issues at the same time for 5G multi-tier networks where users in different tiers have different priorities for channel access. In this article, we first present the motivation for our proposal of a new paradigm of integrated spectrum and energy harvesting for 5G wireless networks, in which spectrum and energy resources are efficiently collected and intelligently managed. Then we present an integrated spectrum and energy harvesting 5G architecture for dealing with current challenges. After that, based on the proposed architecture, we provide integrated spectrum and energy control mechanisms for typical 5G networks. Finally, we propose a cooperative medium access control scheme for heterogeneous 5G networks that attracts cooperative sensing participants with heterogeneous energy harvesting capabilities. Illustrative results demonstrate significant energy and spectrum efficiency for 5G wireless networks.

The fifth generation (5G) cellular wireless network is treated as a promising solution for high traffic volume demands spurred by the proliferation and penetration of wireless services [1]. 5G wireless networks are expected to be a mixture of network tiers of different sizes, transmission powers, backhaul connections, and radio access technologies accessed by unprecedented numbers of intelligent and heterogeneous wireless devices. How to guarantee the system capacity under various circumstances will be a key research challenge in multi-tier and heterogeneous 5G networks.

According to Shannon theory, channel capacity C, bandwidth B, and received signal-to-noise ratio (SNR) have a relationship of $C = B\log_2(1 + SNR)$. For the devices in 5G networks, it is easy to note that the increment of energy at transceivers can increase both bandwidth (by detecting more available channels) and SNR (by enhancing the transmission power), which will lead to improvement of channel capacity. Meanwhile, the network capacity of 5G networks can be improved by increasing the transmission power of a base station, which can increase the communication coverage. Hence, energy and spectrum resources are two vital factors influencing 5G networks' capacity.

For a conventional wireless communication system, recent research activities have been devoted to energy efficiency improvement, including energy saving hardware and devices, energy-efficient communication techniques, the design of energy-aware network architectures and protocols, energy-friendly software and applications, and renewable energy sources. Recently, interest has risen greatly with regard to wireless networks with renewable energy sources, such as thermal, vibration, solar, acoustic, wind, and even ambient radio power, which are used to reduce energy costs or potentially harmful effects on the environment caused by CO_2 emissions [2].

Along with energy efficiency, another key design objective in wireless networks is to maximize spectral efficiency. The explosive increase of wireless devices and applications poses a serious problem and a compelling need for numerous radio spectra. On the contrary, a recent report published by the Federal Communication Commission (FCC) reveals that most of the licensed spectra are rarely utilized continuously across time and space [3]. In order to address spectrum scarcity and underutilization, cognitive radio (CR) technology has been proposed to effectively utilize the spectrum [4]. In a CR network, the CR users/devices are allowed to opportunistically operate in the frequency bands originally allocated to the primary users/devices when these bands are not occupied by primary users. Secondary users are capable of sensing unused bands and adjusting transmission parameters accordingly, which makes CR an excellent candidate technology for improving spectral efficiency [5].

However, the existing network architectures and technologies have treated spectrum harvesting and energy harvesting as two separate cases in conventional wireless systems. In this article, we first motivate the design of an integrated energy and spectrum harvesting paradigm for 5G wireless systems. Then we present the integrated energy- and spectrum-harvesting-driven 5G architecture and model. After that, based on the proposed architecture, we provide several integrated spec-

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trum and energy control mechanisms for typical 5G systems, including device-to-device (D2D) networks, small cell networks (picocell and femtocell), and macrocell networks. Next, considering a heterogeneous 5G network, we propose a new medium access control (MAC) protocol, which attracts cooperative sensing participants with heterogeneous sensing and energy harvesting abilities. Illustrative results demonstrate that the proposed protocol can obtain significant energy and spectral efficiency for 5G wireless networks.

The remainder of this article is organized as follows. In the following section, we first identify the motivations for exploiting energy and spectrum harvesting for 5G wireless networks. Then the spectrum and energy harvesting 5G architecture and model are presented. The integrated spectrum and energy control mechanisms for typical 5G systems are described following that. Then we propose an energy-harvesting-based cooperative sensing MAC protocol. The illustrative results demonstrate the significant aggregate throughput and energy saving of the proposed protocol. The conclusion and future work are presented in the final section.

Motivation of Using Energy and Spectrum Harvesting in 5G Networks

Energy-Efficient Communication

One of the main challenges in 5G wireless networks is to improve the energy efficiency of battery-equipped wireless devices. In 5G networks, energy saving is extremely important for optimizing devices' operation, and ultimately prolonging the lifetime of the devices and networks. Energy harvesting technology is an appealing solution that can harvest energy from environmental energy sources (e.g., solar and wind energy) and even from ambient radio signals (i.e., RF energy harvesting) with reasonable efficiency over small distances. Due to the reconfigurability of a CR device, the specific circuit for harvesting energy is easily equipped in a conventional receiver that is designed for information transfer only. Also, a combination of different energy harvesting technologies can be utilized in energy harvesting CR assisted 5G wireless networks.

Prioritized Spectrum Access

The notions of both traffic-based and tier-based priorities will exist in 5G multi-tier networks. Traffic-based priority arises from different requirements of the users (e.g., reliability and latency requirements, energy constraints), whereas tier-based priority is for users belonging to different network tiers. By leveraging the software reconfigurability of CR technology, users are able to rapidly switch among different wireless modes, satisfy different service requirements, and fit in different network tiers.

Interference Management

There is increasingly intensive interference in 5G multi-tier networks due to heterogeneity and dense deployment of wireless devices, coverage and traffic load imbalance due to varying transmit powers of different base stations in the downlink, public or private access restrictions in different tiers that lead to diverse interference levels, and so on. The performance of 5G networks may be seriously degraded due to intra-tier and inter-tier interference. By employing the environmental sensing ability of energy harvesting CR, users in 5G networks are able to persistently detect the spectrum usage situation and ongoing transmissions of other users or networks. Hence, energy harvesting CR assisted 5G devices/networks can potentially reduce or even avoid interference caused by other devices/networks.

Data Rate and Latency

For dense urban areas, 5G wireless networks are envisioned to enable a data rate of 300 and 60 Mb/s in downlink and uplink, respectively, in 95 percent of locations and time [1]. The end-to-end latencies are expected to be on the order of 2–5 ms. One of the most revolutionary applications of energy harvesting CR is to address the spectrum scarcity issue in 5G wireless communications. Therefore, providing efficient spectrum utilization is one of the primary reasons for applying spectrum harvesting in 5G networks. In addition, energy harvesting CR also provides sufficient energy by harvesting energy from an ambient environment to improve data rate while decreasing transmission latency.

Energy and Spectrum Harvesting Driven 5G Architecture and Model

Network Architecture

The main components of an energy and spectrum harvesting driven 5G system (Fig. 1) include energy harvesting CR devices, picocell networks, femtocell networks, and a macrocell network. All devices and networks in the proposed architecture are equipped with an energy harvesting CR module which gives the devices and networks the ability of energy harvesting and spectrum sensing. Generally, the devices and networks are allowed to use the unlicensed channels and also to access the licensed channels in an opportunistic way, without causing interference to the licensed users. With spectrum and energy harvesting abilities, the main components of a 5G system are explained in detail as follows.

Energy harvesting CR devices communicate with others by periodically sensing and accessing the available licensed channels. Meanwhile, an energy harvesting CR device equipped with an energy harvester is able to convert ambient energy into electricity.

D2D networks are an underlaying network with sensing ability. D2D networks not only use the spectrum resources provided by a base station (BS), but also use the available licensed spectrum discovered by distributed sensing.

Picocell networks consist of a BS and energy harvesting CR devices. This network is operated and managed by the network operator. The picocell BS manages the spectrum and energy harvesting within its coverage in a centralized manner.

Femtocell networks are installed, powered, and connected by the end users with less active remote management. The network includes a femtocell access point (AP) and energy harvesting CR based end users that are semi-autonomous, sensing from their immediate environment to find the best spectrum channels and radio parameters to use. The femtocell AP harvests energy from renewable sources, and controls the spectrum and energy usage of all users.

Macrocell networks consist of a BS with an energy and spectrum harvesting (E&SH) controller. The E&SH controller is able to collect the spectrum and energy information from the devices, low-level networks, and energy sources; hence, it can jointly manage the harvesting and usage of both spectrum and energy in the entire macrocell network.

Multi-Tier Energy Harvesting Model

D2D Networks — Energy can be harvested from ambient radio signals (i.e., RF energy harvesting) with reasonable efficiency over small distances. The harvested energy may be used for D2D communication or communication within a small cell. Considering the D2D network with CR technology, [6] proposed a method for a D2D network where devices

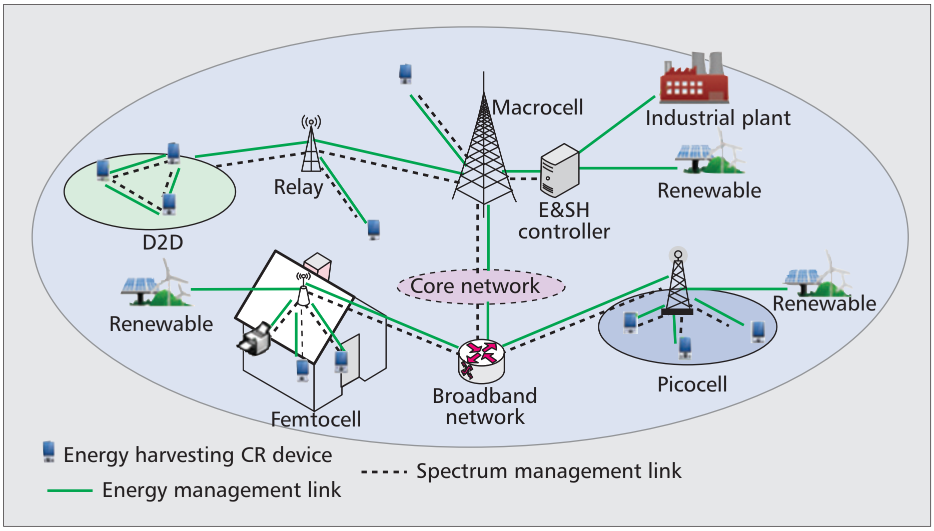

Figure 1. Energy harvesting cognitive radio architecture.

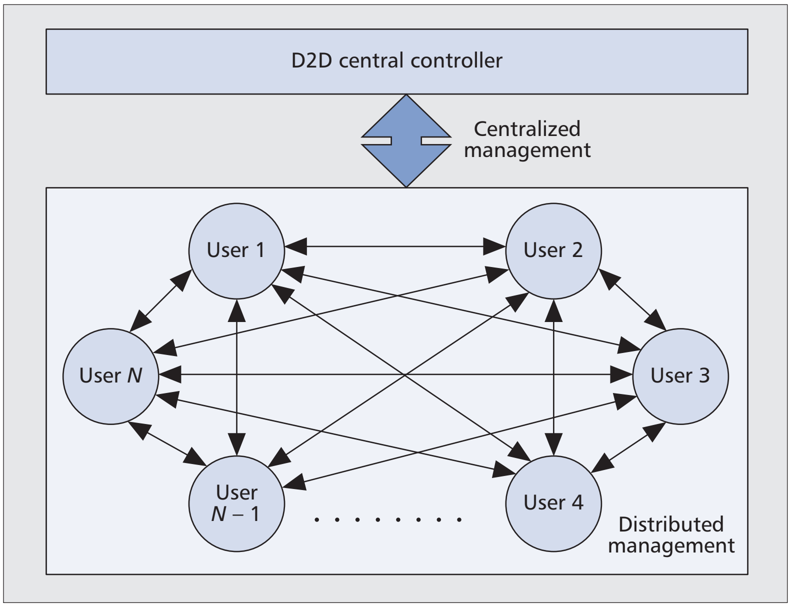

Figure 2. A centralized/distributed energy and spectrum management strategy for a D2D network.

from a secondary network, either harvesting energy from transmissions by nearby transmitters from a primary network, or transmit information if the primary transmitters are sufficiently far away. Secondary networks store harvested energy in rechargeable batteries with finite capacity and use all available energy for subsequent transmission when the batteries are fully charged. In this model, each primary transmitter is centered at a guard zone and a harvesting zone that are disks with given radii. The secondary transmitter harvests energy if it lies in the harvesting zone, transmits fixed power signals if it is outside all guard zones or else idles.

Small Cell Networks: Picocell and Femtocell Networks — Energy harvesting from ambient radio signals may not satisfy the energy requirement of an entire network. An appealing method is to harvest energy from environmental energy sources (e.g., solar and wind energy). The harvested energy is first stored in batteries, and the networks consume the stored energy. The energy arrival process is modeled as an independent and identically distributed sequence of random variables.

To improve both energy efficiency and spectral efficiency of renewable energy-harvesting CR networks, some joint spectrum and energy management mechanisms are needed. In [7], the detection threshold is adjusted for the CR device under the energy causality constraint and collision constraint. Increasing the detection threshold results in frequent spectrum access and increases the probability of accessing the occupied spectrum. This can in turn lead to a large waste of transmission energy. Decreasing the detection threshold reduces unnecessary energy waste and the probability of accessing the occupied spectrum, but may prevent the secondary transmitter from transmitting data even when the spectrum is idle. Accounting for both the energy causality and collision constraints, the proposed mechanism optimizes the detection threshold to maximize the expected total throughput.

Macrocell Network — Due to the potentially low efficiency of energy harvesting from ambient radio signals, a combination of different energy harvesting technologies may be required for macrocell communications. Renewable energy is a solution. However, while typical renewable energy sources offer a cheaper and cleaner energy supply, they also introduce supply uncertainty due to the volatility of their generation [2]. It is therefore important to include a complementary technology [8] or provide a mixture of traditional power to mitigate or cancel the volatility.

Cross-Tier Cooperative Sensing Model

To address the spectral efficiency and interference issues among different network tiers, cross-tier cooperative sensing is important. It can help devices or small cells know the environmental situation in a cell, and also the system information of other cells and tiers.

Cooperative Sensing in One Cell — In the one-cell case, CR devices sense channels at the same time. Synchronization among cooperative CR devices is usually achieved in an infrastructure-based architecture. For instance, in a CR-based picocell network, the CR picocell BS manages the network and serves as a fusion center. Upon receiving a request for spectrum sensing, the BS will send out a scheduling instruction to the cooperative CR devices. The cooperative CR devices could cooperatively sense the licensed spectrum in the picocell. After cooperative sensing, the participating devices send the sensing result to the CR picocell BS for a final decision.

Cooperative Sensing in Multiple Cells — For the multi-cell case, diverse CR devices from different networks may be involved in cooperative sensing. The cooperative devices' sensing moments and locations are different as well as their sensing abilities. When the cooperative sensing procedure is triggered, the fusion center sends out a sensing instruction to the cooperative CR devices. The cooperative CR devices will attach the sensing information with a specific tag indicating the sensing moments and sensing locations, and send it back to the fusion center to make a final decision.

For the multi-cell case, heterogeneous sensing exploits both spatial and temporal diversities. The combination of sensing information in the fusion center plays an important role in cooperative sensing. For example, the probability of channel availability varies as time goes on and location changes. Based on this observation, we introduce weight parameters to show the importance of sensing information. If the timing and location of the obtained sensing information are close to the targeted timing or location, the associated sensing information has higher importance and is assigned larger weight. Therefore, cooperative sensing is able to exploit the temporal and spatial diversities of channel availability.

To fit the heterogeneous topology of 5G networks, cooperative sensing could operate in a centralized or decentralized manner. Decentralized cooperative sensing operates as follows. A CR device invites some of its neighboring CR devices to organize a local cooperation team. Each team member serves as a volunteer to help the others detect the targeted channels. A cooperative device only helps the others in its idle time; hence, the overhead during sensing cooperation is low. The decentralized cooperative sensing scheme can be utilized in D2D networks or small cell networks where low-battery devices need to find available spectrum without communicating with a BS/AP.

Joint Energy and Spectrum Management for a Multi-Tier 5G System

D2D Networks

For a D2D network, the energy and spectrum harvesting module is deployed inside the D2D central controller connected to all D2D devices. The D2D central controller with energy and spectrum harvesting module can run a distributed algorithm to find the optimal energy and spectrum harvesting control strategy for each device. The optimization objective is to maximize the throughput of the system with minimum energy consumption. As shown in Fig. 2, with a game-theoretic analysis, a simple energy cost method can provide incentive for users to cooperate. The overall system performance is improved. Meanwhile, the energy consumption of each user stays low. In other words, through an appropriate energy cost incentive, the Nash equilibrium of the energy consumption game among the participating users who share the same energy and spectrum source is the optimal solution of a system-wide optimization problem.

Small Cell Networks: Picocell and Femtocell Networks

In small cell networks, simultaneous access of numerous devices is a big challenge for spectrum and energy harvesting, as shown in Fig. 3. The BS/AP in a small cell network is responsible for controlling the massive access and energy harvesting of each device. There are several massive access management methods can be utilized, among them contention-based random access (RA), reservation-based access, and hybrid access schemes.

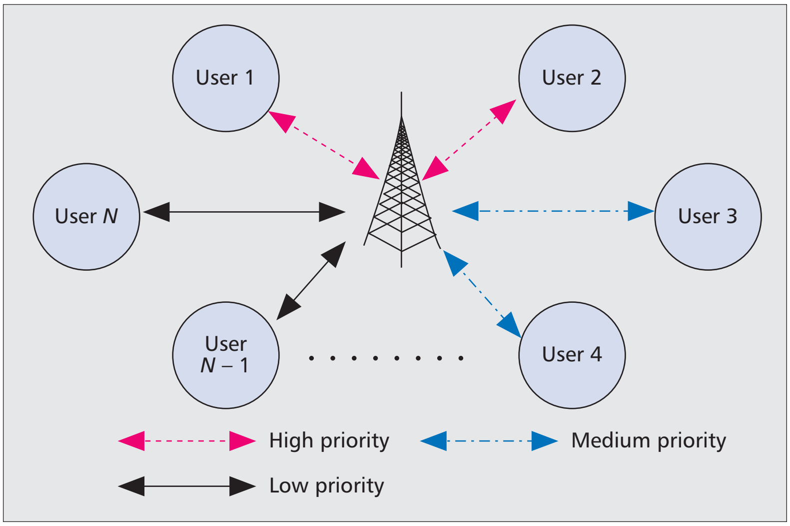

Figure 3. An energy and spectrum management strategy for a small cell/macrocell network.

Contention-Based Random Access Scheme — In an RA scheme, all of the devices randomly contend for transmission opportunities. A device that wins the contention can access the channel for transmission. The contention-based RA scheme is popular due to its simplicity, flexibility, and low overhead. Devices can dynamically join or leave the network without extra operations. However, transmission collisions are eminent when huge numbers of machine-to-machine (M2M) devices try to communicate with the BS all at once [9].

Reservation Based Scheme — Reservation-based schemes such as time-division multiple access (TDMA) can solve the problem seen in the RA scheme. TDMA is well known as a collision-free access scheme where the transmission time is divided into slots, and each device transmits data only during its own time slots. The main defect of TDMA is the low transmission slot usage if only a small portion of devices have data to transmit [10].

Hybrid Access Scheme — The hybrid access scheme is designed to combine the best features of both the reservation-based and contention-based schemes while offsetting their weaknesses. One example of using the hybrid access scheme is in a picocell network deployed in an office. The hybrid access scheme can adapt to the level of contention in the network. In a low contention scenario (at night), it behaves like the RA scheme. In a high contention scenario (daytime), it behaves like TDMA. We can propose a way to use hybrid access to support video streaming over home networks. Such a scheme can adapt to different bandwidth conditions depending on demands.

Marocell Networks

In this article, we propose dynamic spectrum and energy management for a prioritized macrocell network where different users and devices may have different spectrum and energy requirements, as shown in Fig. 3. Note that the users usually possess private utility functions, application requirements, and distinct channel conditions on different spectrum channels. We use a priority virtual queue interface that determines the required spectrum and energy information exchanges of various users. Based on the exchanged information, the interface

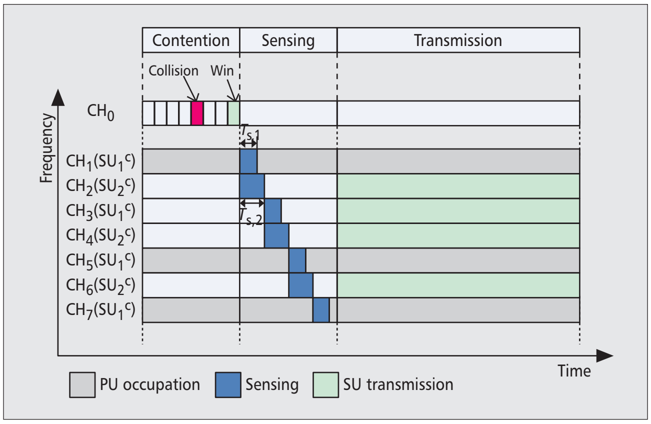

Figure 4. Proposed MAC protocol operation phases.

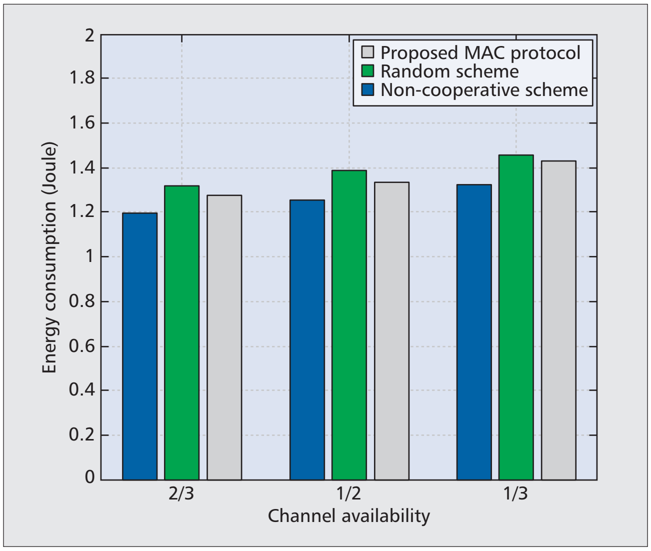

Figure 5. The comparison of energy consumption in terms of channel availability.

evaluates the spectrum and energy using priority queuing analysis that considers the wireless environment, traffic characteristics, and the competing users' behaviors. Based on the expected utility evaluation from the interface, we propose a dynamic strategy learning algorithm deployed at each device and BS. Such an algorithm exploits the expected energy and adapts the spectrum selection strategies to maximize the macrocell network's performance. Note that a frequency channel can be shared by several users in a same tier network. A user can also select multiple frequency channels to access over a multi-tier network. The learning algorithm addresses how multiple users find available channels and harvest energy over the macrocell network.

Energy-Harvesting-Based Cooperative Sensing MAC Protocol

Cooperative sensing has been studied as a promising alternative to improve sensing performance at both the physical and MAC levels. To guarantee efficient discovery of spectrum opportunities, efficient energy harvesting is required in cooperative sensing for CR networks [11]. Many studies are devoted to designing energy-efficient cooperative sensing strategies for battery equipped secondary users (SUs) and CR networks. However, few of them consider two crucial issues that may arise in the cooperative sensing of an energy harvesting CR network: how many SUs should be selected to participate in cooperative sensing and energy harvesting, and how much energy should be consumed by cooperative sensing.

Our Proposed MAC Protocol

In this article, we propose a cooperative sensing MAC protocol for an energy harvesting CR network in which SUs can be selected to perform cooperative sensing for improved sensing performance. In cooperative sensing, the SUs deployed with an energy harvesting module will continually sense the licensed channels until an available channel (the channel is not occupied by a PU) is discovered or their residual energy exceeds a predetermined threshold. Moreover, we consider energy harvesting heterogeneity, which is defined as different abilities to receive energy from the environment for different SUs. In addition, different SUs may have distinct sensing abilities. The specifications of the proposed MAC protocol are shown in Fig. 4. The whole timeframe of the proposed MAC protocol's operation is divided into three phases: contention, sensing, and transmission.

In the contention phase, when an SU has data to transmit, it first listens to the control channel. If no packet exchange is heard, the SU exchanges messages with the intended receiver to reserve the control channel.

In the sensing phase, the SU broadcasts SENSE-REQUEST messages to require cooperative sensing and waits for other SUs to reply with SENSE-JOIN messages containing their energy information. When the timer expires, the SU calculates the optimal number of cooperative SUs, and the energy amount can be consumed by each SU in sensing. Next, the SU starts cooperative sensing. Once all channels are sensed, the SU exchanges messages with all cooperative SUs for the list of available channels.

In the transmission phase, the SU conducts data transmission on the discovered channels.

Throughput Performance

The cooperative sensing has an inherent trade-off between the achievable throughput and the sensing overhead. It is clear that more SUs participate in cooperative sensing, more available channels can be found, and higher throughput can be obtained. Unfortunately, larger energy consumption will be incurred by the cooperative SUs which may suffer the energy shortage for their own sensing and transmission. Hence, the number of the cooperative SUs and the energy consumed in cooperative sensing are two crucial design parameters to balance the trade-off between the achievable throughput $\mathcal{V}(t)$ and the sensing overhead $\mathcal{O}(t)$.

The difference between the achievable throughput and the sensing overhead indicates the aggregate throughput of the CR network. Let Q denote the number of the licensed channels. Let $e_{s,i}(t)$ denote the sensing energy consumed by the ith SU at time slot t. We formulate an optimization problem to balance the achieved throughput and the sensing overhead as follows

$$\begin{aligned} \max_{\substack{U,\, e_{s,i},\\ i=1,2,\cdots,U}} \quad & \lim_{\mathbb{T}\to\infty} \frac{1}{\mathbb{T}} \sum_{t=1}^{\mathbb{T}} [\mathcal{V}(t) - \mathcal{O}(t)] \\ s.t. \quad & Ne_{s,i}(t) \le E_{r,i}(t) - E_{thd,i}, \\ & E_{r,i}(t+1) = \min\left\{E_{r,i}(t) + e_a(t) - Ne_{s,i}(t), E_c\right\}, \\ & i = 1,2,\cdots,U, \quad t = 1,2,\cdots,\mathbb{T}, \end{aligned} \tag{1}$$

where $N = \lceil Q/U \rceil$ denotes the number of cooperative sensing rounds, $E_{r,i}(t)$ is the residual energy at the ith SU at time slot t, $E_{thd,i}$ is the energy threshold for the ith SU, and E_c is the capacity of the rechargeable battery of an SU. $\{e_a(t), t = 1, 2, \ldots\}$ is the harvesting energy for each SU at time slot t, which is modeled as an independent and identically distributed sequence of random variables with mean $\mathbb{E}[e_a(t)] = \overline{E}_a$.

Illustrative Results

In this subsection, our major objective is to compare the performance of the proposed MAC protocol with the non-cooperative sensing and random cooperative sensing schemes. In the non-cooperative scheme, each SU has to monitor a set of licensed channels sequentially by itself. In the random cooperative sensing scheme, each SU randomly chooses one of the licensed channels for sensing without considering careful choice of cooperative SUs as well as the amount of sensing energy. In the simulation, 30 SUs and 10 licensed channels are considered. The channel bandwidth is 1 MHz. The length of a frame is 1 s. The sensing power and transmit power of an SU are 110 mW and 210 mW, respectively. In addition, $E_{thd,i} = 0.1$ J and $E_c = 1$ J.

Figure 5 shows the comparison of the energy consumption among the proposed MAC protocol, random scheme, and non-cooperative scheme. It is noted that the proposed MAC protocol is able to consume less energy than the random scheme. This is because the proposed MAC protocol only allows the optimal number of SUs to join the cooperative sensing. Meanwhile, the sensing energy consumed by each cooperative SU is carefully determined. Hence, the energy consumption during the sensing phase can be greatly reduced. In addition, the proposed protocol consumes more energy than the non-cooperative scheme. That is, in the proposed protocol, cooperative sensing needs sensing help from other SUs, which leads to extra energy consumption. However, this energy consumption can lead to higher throughput, as shown in Fig. 6.

Figure 6 shows the aggregate throughput comparison among our proposed MAC protocol, the random scheme, and the non-cooperative scheme. The comparison indicates that the proposed MAC protocol is able to achieve much higher throughput than the non-cooperative and random schemes. This can be explained as follows. During the sensing period, the proposed MAC protocol is able to search for and find more available channels than can the non-cooperative scheme. The random scheme uses all of the SUs to perform cooperative sensing, which increases the sensing overhead and leads to lower throughput. On the other hand, the proposed MAC protocol introduces the optimal number of cooperative SUs to guarantee that the overall cooperative sensing overhead will be restricted, which further results in higher throughput. As a consequence, the proposed MAC protocol is able to achieve higher throughput with lower sensing overhead.

As shown in simulation results, the proposed MAC protocol can achieve better network performance than other classical schemes, especially for 5G networks. This is because the main characteristic of 5G networks is the ability to provide all possible applications using only one universal device, and satisfying the resource (i.e., spectrum, energy) requirements over multi-tier networks in an optimal way. The proposed MAC protocol, deployed in CR-based energy harvesting networks with machine learning capabilities, collects information of spectrum and energy resources, intelligently determines current operating settings, and controls the operation of all devices to gain optimal network performance. Hence, the machine learning capability of CR benefits 5G networks.

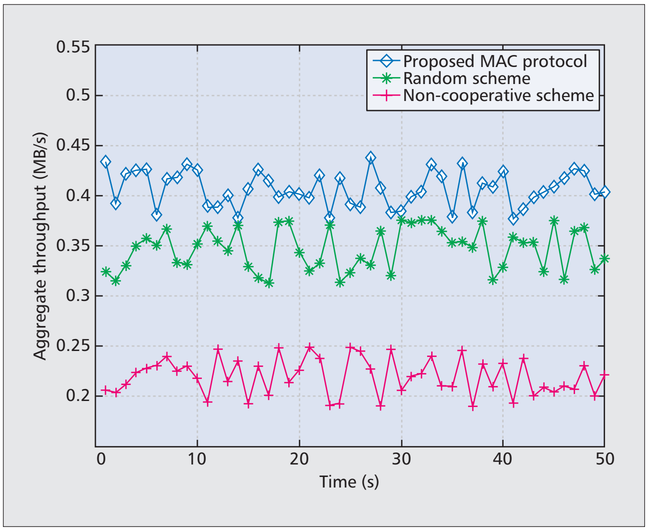

Figure 6. Aggregate throughput comparison where channel availability is 2/3.

Conclusion

In this article, we describe the design of an integrated energy and spectrum harvesting framework to improve energy and spectral efficiency for 5G wireless systems. We first propose the promotion of integrated energy and spectrum harvesting to confront various challenges in a 5G system, including latency, prioritized spectrum access, interference management, and energy-efficient communications. Then we introduce the integrated energy and spectrum harvesting 5G architecture, and present models of sensing and energy harvesting for different tiers in 5G networks. We show the integrated energy and spectrum control scheme for typical 5G systems: D2D networks, small cell (picocell and femtocell) networks, and macrocell networks. Finally, we propose an energy-harvesting-based cooperative sensing MAC protocol that can easily be used in a CR-assisted 5G wireless network, which is shown to significantly improve throughput and save energy.

In the future, we plan to extend our work in several directions. Our model system can be extended to the mobility scenario where the spectrum and power supply may be influenced by ambient noise over different wireless environments. In that case, new mechanisms and algorithms should be studied to cover the unstable and intermittent characteristics of spectrum and energy resources. In addition, cooperation among different tiers will be a key requirement to mitigate interference in 5G networks. Hence, we intend to design an efficient method of cooperation among multiple tiers in 5G networks.

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References

[1] Metis, "Scenarios, Requirements and KPIs for 5G Mobile and Wireless System," ICT-317669 METIS project, May 2013.
[2] Y. L. Lee *et al.*, "Recent Advances in Radio Resource Management for Heterogeneous LTE/LTE-A Networks," *IEEE Commun. Surveys & Tutorials*, vol. 16, no. 4, June, 2014, pp. 2142–80.

[3] Y. M. Atwa *et al.*,"Optimal Renewable Resources Mix for Distribution System Energy Loss Minimization," *IEEE Trans. Power Sys.*, vol. 25, no. 1, Feb. 2010, pp. 360–70.
[4] FCC, "Second Memorandum Opinion and Order," ET Docket No. 10174, Sept. 2010.
[5] R. Yu *et al.*, "Cognitive Radio Based Hierarchical Communications Infrastructure for Smart Grid," *IEEE Network*, vol. 25, no. 5, Sept./Oct. 2011, pp. 6–14.
[6] S. Lee, K. Huang, and R. Zhang, "Cognitive Energy Harvesting and Transmission from a Network Perspective," *IEEE Int'l. Conf. Commun. Sys.*, 21–23 Nov., 2012, Singapore, pp. 225–29.
[7] S. Park, H. Kim, and D. Hong, "Cognitive Radio Networks with Energy Harvesting," *IEEE Trans. Wireless Commun.*, vol. 12, no. 3, Mar. 2013, pp. 1386–97.
[8] S. Huang *et al.*, "Quantifying System-Level Benefits from Distributed Solar and Energy Storage," *J. Energy Eng.*, vol. 138, no. 2, June, 2012, pp. 33–42.
[9] A. Vinel *et al.*, "Capacity Analysis of Reservation-Based Random Access for Broadband Wireless Access Networks," *IEEE JSAC*, vol. 27, no. 2, Feb. 2009, pp. 172–81.
[10] M. Hasan, E. Hossain, and D. Niyato, "Random Access for Machine-to-Machine Communication in LTE-Advanced Networks: Issues and Approaches," *IEEE Commun. Mag.*, vol. 51, no. 6, April 2013, pp. 86–93.
[11] R. Deng *et al.*, "Energy-Efficient Cooperative Spectrum Sensing by Optimal Scheduling in Sensor-Aided Cognitive Radio Networks," *IEEE Trans. Vehic. Tech.*, vol. 61, no. 2, Feb. 2012, pp. 716–25.

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