Cognitive Network Cooperation for Green Cellular Networks

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Abstract— Green networking is the method of incorporating energy efficient technologies for reducing the resource use as possible. Now a days, , there has been an increasing attention in green cellular networks for the sake of reducing the energy dissipated by communications and networking systems, including the base stations (BSs) and battery-powered user terminals (UTs). The joint employment of cognition and cooperation techniques can be invoked for improving the energy efficiency of cellular networks. To be clear, the cellular devices first have to identify the unused spectral bands (known as spectrum holes) using their spectrum sensing functionality. This idea is termed cognitive network cooperation, since different wireless access networks cognitively cooperate with cellular networks. It is shown that for a given number of information bits to be transmitted, the total energy consumed can be significantly lowered, when both cognition and cooperation are supported in cellular networks.

Key words: BS, UT, ED, FE, MAC

I. INTRODUCTION

The past few decades have witnessed an emerging growth in the improvement and implementation of ever more sophisticated wireless networks. The rapid growth in wireless communications has resulted in a significant increase of the energy consumption of both the service providers and mobile users. The image and video applications (e.g., video on demand, video games, etc.) rapidly drain the battery charge of mobile terminals. Specifically, the second- generation (2G) mobile devices have a relatively low power consumption of around 1-2 watts, while the third- generation (3G) terminals double this figure. The fourth- generation (4G) terminals are expected to have another twofold increase over the 3G devices' power consumption. If no action is taken to reduce the power consumption of mobile terminals, 4G terminals would be limited to operate only in certain places, or would even become restricted to locations, where power charging outlets are available, which is referred to as an ``energy trap". It is therefore extremely important to explore energy-efficient wireless communication technologies for reducing the energy consumption of both the base stations and of user terminals. The cognition and cooperation are considered to be the key enabling techniques adopted for green wireless communications.

Cooperation (also termed as cooperative communications) is also well recognized as an important research topic in wireless communications. Cooperative communications permits the distributed network nodes to help each other for enhancing their respective interests, which provides a new vision on wireless network optimization. Cooperative techniques are able to improve the transmission reliability with the aid of their spatial diversity gain and/or increasing the system throughput with the help of resource aggregation. Cooperative communication architectures have already been taken in different wireless networking standards, e.g., IEEE 802.16j and the long term evolution (LTE) advanced systems. In addition to improving the reliability and throughput, cooperative communications also presents potential energy savings in wireless networks. For example, in cellular networks, if a user lies at the edge of its associated cell (a so-called cell-edge user), typically a high transmit power is required to maintain the target quality-of-service (QoS) requirement in the uplink (UL), which would significantly drain the user's battery energy and may additionally cause severe co-channel interference as well. In this case, selecting an appropriate relay to assist the cell-edge user's data transmission is capable of effectively reducing its power consumption. For example, having a perfect-reconstruction decode-and-forward relay halfway between the BS and MS in the case of an inverse fourth-power law reduces the required power by 12dB, i.e., over an order of magnitude. Hence there is much practical interest to explore cooperative methods for energy savings in cellular networks, particularly for the cell-edge users.

To be specific, today's wireless terminals (e.g., smart phones) are provided with multiple network access interfaces, such as Bluetooth, Wi-Fi, and LTE, where the different wireless access networks involve different radio characteristics in terms of their coverage area and energy consumption. Thus both Bluetooth and Wi-Fi provide local area coverage at low energy consumption, whereas LTE offers a wider coverage, but unfortunately at the expense of a higher energy consumption. As different wireless networks complement each other, we have found the cooperation between multiple heterogeneous wireless networks (e.g., Bluetooth and LTE) in which may be referred to as network cooperation. More specifically, we have checked the use of Bluetooth to assist LTE transmissions for enhancing the energy efficiency of cellular communications. Given the specific target data rate and outage probability requirements, network cooperation has the potential of significantly reducing the total energy consumption of cellular transmissions, especially when the mobile stations (MSs) roam at the edge of a cell. However, no cognitive features were considered for network cooperation in leaving unused spectral bands that could otherwise be fully exploited for beneficial energy efficiency improvements. In this paper, motivated by these considerations, we address the integration of CR features into the above-mentioned network cooperation framework, which is termed to as cognitive network cooperation. In this method cellular devices are first allowed to identify spectrum holes through spectrum sensing. Then, network cooperation is invoked for efficiently exploiting the available spectrum holes for green communications.

II. SPECTRUM SENSING RELYING ON COGNITION

By recognizing and exploiting spectral holes the cellular communications can be made energy efficient while satisfying both the throughput and QoS requirements. There are two typical spectrum opportunities, namely the temporal and spatial spectrum opportunities. To be specific, if a spectral band is not occupied by licensed (or primary) users at a particular time, we can temporarily reuse it for unlicensed (or secondary) users .This is referred to as a temporal spectral opportunity. By contrast, if the licensed and unlicensed users are sufficiently far away from each other, so that no excessive interference will be imposed when they transmit over the same frequency band, the unlicensed users can fully reuse the licensed users' spectral band. This is referred to as a spatial spectral opportunity.

The various methods for signal detection which are considered for the identification of spectrum holes are energy detection(ED), matched filtering (MF), and feature extraction (FE). To be Specific, an energy detector accumulates the energy of the received signal over a given frequency band which is then compared to a predefined threshold to decide whether the spectral band is taken by licensed users or not. In general, if the accumulated energy is less than the predefined threshold, the observed spectrum band is considered as idle. Contrary, the band is regarded as being occupied by the licensed user. ED cannot differentiate the desired signal from both the interference and the noise; hence it is prone to missed detection or false alarm events. These events are triggered by the interference and noise. The MF based detector was introduced as an attractive means for counteracting this interference, which is considered as the optimal detector in additive white Gaussian noise (AWGN) environments. However, the MF requires some prior knowledge of the primary signal to be detected, which includes pulse shape, modulation type and so on. The feature extraction aided detector (e.g., cyclostationary FE) emerges as a promising sensing approach, which is capable of effectively distinguishing the primary signals from both the background noise and from the interference. This makes the FE detector robust to the background noise even in extremely low signal-to-noise ratio (SNR) conditions. FE detector provides this robustness only at the cost of a high computational complexity, since it requires an extra training process for extracting the desired signal features. Because of the higher computational complexity FE detector consumes more energy than the other two methods.

Both the three methods for signal detection typically work well in Gaussian noise environments, but their receiver operating characteristics (ROC) severely degrade in wireless fading scenarios. Specifically, if a deep fade is encountered, the desired signal received at an unlicensed user may become too weak to be detected by the ED, MF and FE detectors, thus causing degradation in performance. In order to combat the fading effects, cooperative spectrum sensing may be invoked by allowing multiple users to cooperate with each other in identifying spectrum holes, where the multiple users first scan the licensed spectrum bands and then inform their independent observations to a fusion center for the sake of forming a final decision regarding the idle or busy status of the scanned spectral bands. The cooperative spectrum sensing significantly outperforms the conventional non-cooperative approaches. This, however, comes at the cost of additional energy consumption, since the cooperative spectrum sensing consumes extra power on its reporting phase.

A geo-location incumbent database that stores and periodically updates the data of licensed spectral occupancy in any given geographical location is an design alternative for spectrum sensing. Thus unlicensed users can readily access the available unused spectrum by observing the incumbent database with their new geo-locations. This is an energy- efficient method, but results in a degraded ROC performance, since the spectrum hole is determined using a propagation model of the primary signal, which fails to reject real- world environments such as mountains, buildings, tunnels, and so on. As a remedy, we can combine the cooperative sensing and geo-location database, aiming for achieving a good tradeoff between the achievable performance and the energy savings.

III. EXPLOITING SPECTRUM HOLES

The benefits of cooperation in successfully exploiting the spectral access opportunities detected for the sake of energy conservation in green cellular networks. Fig.1shows a cellular network consisting of a BS and multiple UTs that support different types of wireless access interfaces, including both Bluetooth and Wi-Fi. Since the UTs (e.g., smart phones) are equipped with both Bluetooth and Wi-Fi, they are capable of forming a secondary network within the cellular network and use the secondary network for assisting cellular communications to achieve energy efficiency solutions, where the secondary network operates within the detected spectrum holes. It is pointed out that there are some standardization efforts in developing Wi-Fi over the unoccupied TV bands, which is known as the IEEE 802.11af. This means that coming generation Wi-Fi and Bluetooth interfaces would be expected to operate in a broader range of spectral bands (including the TV bands), rather than being limited to the industrial, scientific and medical (ISM) bands only. If no spectrum holes are recognized, the secondary network is deactivated and the UTs directly communicate with the BS within the cellular spectrum. By contrast, when a spectrum hole is detected with the aid of spectrum sensing, different wireless networks may be invoked for cooperating with classic cellular communications. This technique may thus be referred to as cognitive network cooperation, since the above-mentioned cognitive feature was exploited.

As shown in Fig. 1, when considering Wi-Fi as an example of the secondary network, the UTs first communicate with an access point (AP) through Wi-Fi links over the spectrum holes detected and then the AP exchanges data packets with the BS through cellular links over the cellular spectrum. In this way, the UTs can communicate with the BS relying on the AP for increasing the attainable energy efficiency of cellular communications. As an alternative, we can also adopt Bluetooth for assisting cellular communications between the UTs and the BS, as depicted in Fig.1.Without loss of generality, let us consider the cellular downlink transmissions from the BS to a pair of UTs, namely to U1 and U2.We first allow the BS to transmit its downlink data packets to U1 and U2, respectively, over the cellular spectrum. Due to the broadcast nature of the wireless medium, U1 (or U2) can overhear the transmissions from the BS to U2 (or U1). Then, if a spectrum hole is identified, U1 and U2 exchange their received signals through a two-way Bluetooth link over the spectrum hole detected. Therefore, the employment of Bluetooth over the spectrum holes provides spatial diversity for cellular communications and hence reduces the overall energy consumption under a specific target QoS requirement.

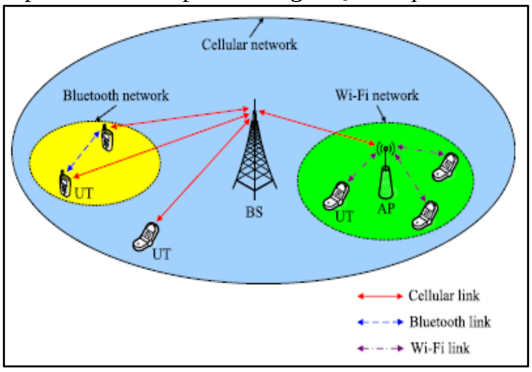

Fig. 1: A Heterogeneous Wireless Environment

Naturally, a similar network cooperation process may be applied in cellular uplink transmissions from the UTs to the BS. To be specific, given that a spectrum hole is identified, we first allow the spatially-distributed UTs to communicate through a secondary network over the detected spectrum hole for exchanging their uplink packets. Once the UTs obtained each other's data packets, they can cooperate (with the aid of space-time coding) for the sake of transmitting their packets to the BS over the cellular spectrum. It can be observed that a secondary network is employed for assisting the cellular communications in an opportunistic manner, provided that a spectrum hole has been detected. This technique is more sophisticated than the traditional cooperative regime operating in a homogeneous network environment. Explicitly, in the traditional cooperation, a UT is required to transmit its data packet to its cooperative partner, which then forwards the received data to the BS, both transmissions occurring over the same cellular spectrum. This halves the cellular spectrum efficiency, since two orthogonal channels are needed for completing the transmissions from a UT to the BS via its partner. By contrast, intelligent cognitive network cooperation allows a UT to transmit its data to its partner using a secondary network over the detected spectrum hole, instead of using the cellular spectrum. This saves cellular spectrum resources by leveraging the idle spectrum hole and thus has the potential of improving the energy-efficiency as compared to the traditional cooperation.

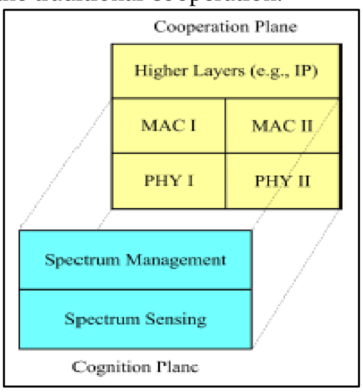

Fig. 2: Protocol Reference Model

In Fig.2, we portray the protocol reference model of the proposed cognitive network cooperation composed of two planes, namely the cognition plane and the cooperation plane. As shown in Fig.3.2. 2, the cognition plane incorporates both spectrum sensing and spectrum management functions. The spectrum sensing functions are invoked for identifying spectrum holes, which are then allocated to the different network entities by the spectrum management function. Fig. 2 also illustrates an example of the cooperation plane, where two sets of medium access control (MAC) and physical layer (PHY) protocols are considered, which are denoted in the figure by PHY I-MAC I and PHY II-MAC II, respectively. It may be observed that the two PHY-MAC pairs (i.e., PHY I-MAC I and PHY II-MAC II) share common higher layers, namely common network (NET) and application (APP) layers. As a benefit, the different network access interfaces can be coordinated and controlled with the aid of the upper-layer protocols. It is worth mentioning that contemporary cellular devices (e.g., smart phones) typically support multiple PHY-MAC protocols for the sake of cooperating with different wireless access networks, including the 3G, LTE, Wi-Fi, Bluetooth and other networks. In practice, the energy consumed by the upper-layer protocol management is non-negligible and should be taken into account for minimizing the overall network energy dissipation. Thus, it is of particular interest to investigate the optimization of the cooperation plane by jointly considering the PHY, MAC and upper-layer protocols. Additionally, it is important to address the time scale and synchronization issues, when different network access interfaces cooperate with each other.

IV. Conclusion

Quantitative benefits of combined cognition and cooperation in the context of green cellular networks are discussed, where the cellular devices are first allowed to identify spectrum holes with the aid of their cognitive functionality (e.g., spectrum sensing) and then to cooperate for efficiently exploiting the spectrum holes detected to achieve energy savings. Several spectrum hole identification approaches, including the low-complexity ED/MF based detection and FE detection are summarized. Their advantages network cooperation framework for the sake of the energy-efficient use of spectrum holes was introduced where both the Bluetooth and Wi-Fi networks were invoked for supporting and disadvantages in terms of their robustness to noise variance uncertainty as well as their computational complexity and energy efficiency are discussed.The cognitive cellular communications. For a given outage probability and data rate, the total energy dissipated by cellular communications is significantly reduced by exploiting the joint cognition and cooperation

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