A multi-antenna framework for spectrum reuse based on primary-secondary cooperation

SHORT PAPER

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***Abstract*— This paper proposes a new framework for spectrum reuse. Existing architectures have centered on secondary users (cognitive radios) that can reliably sense primary users and opportunistically transmit, without directly interacting with the primary system. We present a paradigm in which the primary and secondary systems *cooperate*, to minimize interference to primary users and provide predictable access for secondary users. Because this architecture gives the primary system full control over spectrum sharing, it could be more favorable in the current economic and political environment. We illustrate a concrete instance of our framework by showing how secondary radios can reuse the entire uplink channel of a cellular network, with only modest changes to the primary infrastructure.**

I. Introduction

The current system of spectrum allocation has resulted in the vast under-utilization of frequency resources [1], [2]. While all bands below 3 GHz have been allocated [3], measurements of spectrum usage reveal significant spatial and temporal variations, including large "white spaces" of unused spectrum [4], [5]. In order to more effectively utilize scarce frequency resources, the FCC has issued a Notice of Proposed Rule Making [6], advancing Cognitive Radio (CR) technology as a candidate to implement negotiated or opportunistic spectrum sharing. These cognitive radios would be designed to operate in multiple frequency bands and dynamically adapt their transmission to their environment. Building practical cognitive radio systems is a significant technical challenge.

A system architecture designed to enable spectrum reuse must satisfy several requirements in order to be commercially viable. Most important, the amount of interference and service degradation experienced by the primary (legacy) system as a consequence of the presence of the secondary (cognitive radio) system must be kept below a tolerable level. It is crucial that the primary system have the ability to *control* and minimize the interference that it experiences. Also, the secondary system must be assured of consistent and *predictable* access to the spectrum, in order to provide a meaningful quality of service (QoS) to its users. Finally, deploying the system must be economically feasible. The cost of the new hardware required by both the primary and secondary systems must be acceptably small.

Most spectrum sharing research to date has focused on systems that opportunistically reuse frequency bands by detecting the presence and absence of primary systems [7], [8]. To prevent interference with the primary system, the secondary system must be able to accurately sense the presence of primary users, and then either suppress transmission or control its radiation pattern via beamforming when primary users are present. In this paradigm, the primary is not modified in any way when the secondary system is deployed, and in fact has no knowledge of the presence of secondary users.

There are a number of challenges associated with opportunistic spectrum sharing schemes. There are fundamental limitations to the detection of signals in low SNR environments [9]. Shadowing and deep channel fades will further degrade detector performance. Also, in many primary systems, for example television, the receivers are passive devices. Thus, the secondary will not receive any feedback, even implicitly, from the primary users. Monitoring interference created by the secondary system then requires explicit feedback from the network operator of the primary system, which contradicts the principle of opportunistic reuse. In addition, due to the time-varying nature of wireless channels and the fact that primary users enter and leave the system, the secondary must sense the spectrum continuously, which consumes significant resources.

In this paper we present a new paradigm for spectrum sharing, based on collaboration between the primary and secondary systems. We argue that a system architecture based on cooperation could exploit the *spatial domain* more effectively than an opportunistic architecture, and provide a higher QoS level to both systems. This architecture permits greater flexibility in the location and transmission range of the secondary system than an architecture based on spectrum sensing. The cooperative framework also provides the primary system with an economic incentive to enable spectrum reuse.

In Section II, we present a general framework for spectrum reuse that can be applied to a wide variety of systems. Then, in Section III, we give a detailed treatment of a specific application: the reuse of the uplink channel of a cellular network for both short and long range communication. Section

Omar Bakr's research is sponsored by a fellowship from King Abdullah University of Science and Technology.

IV applies these ideas to an OFDMA cellular system. While spectrum sharing is a rapidly evolving field with many open problems, we hope that this work provides the impetus for examining these questions from a new direction and offers some useful guidelines for designing and deploying practical systems.

II. Cooperative framework for spectrum reuse

We propose a new framework for spectrum reuse that is based on cooperation between the primary and secondary systems. In contrast to opportunistic schemes, the primary and secondary collaborate to control interference at primary users and guarantee spectrum access to the secondary system. In general, this cooperation will be implemented via feedback from the primary that informs the secondary when to transmit and how much interference is being generated. The channel used to convey this feedback to the secondary users, as well as the exact nature of the feedback, are application specific. They will depend on several factors, including the size and topology of both systems, the underlying physical layer of the primary, the required bandwidth and QoS for each system, and the degree to which the network operators will invest in hardware upgrades. In our framework, it is beneficial, but not essential, for the secondary users to also be members of the primary system, so called *dual citizens*, to facilitate cooperation and enhance the QoS for secondary users. In this work, we will focus on the dual citizen approach to spectrum reuse.

The fundamental technical tools that enable spectrum sharing in this framework are beamforming and beam nulling. The secondary transmitters will minimize interference to the primary system by adjusting their array patterns so that there are nulls in the directions of the primary receivers. If the secondary users have a sufficient number of antennas, they can further improve spectrum utilization by also beamforming in the direction of their intended receivers.

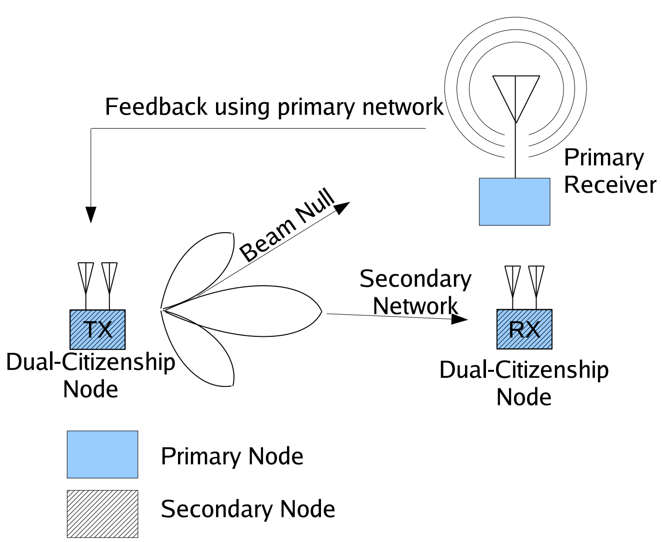

Fig. 1. Basic architecture for cooperative spectrum reuse

The basic elements of this general architecture are summarized in Figure 1. A secondary transmitter (employing multiple antennas) receives feedback from the primary receiver. This feedback assists the secondary in shaping its beam pattern, so that the power radiated in the direction of the primary receiver is effectively zero. In Section III, we demonstrate how this framework can be applied to the specific application of reusing the uplink frequency band of a cellular network.

Cooperation has a number of economic, technical, and policy advantages for both primary and secondary systems.

- In this model, there is no need for government regulation. Spectrum sharing is driven purely by economic forces. Without the necessity of complex and time-consuming government involvement, spectrum reuse systems can be deployed and adapted much more quickly.
- The primary system has *full control* at all times, giving it more protection against service degradations. This in turn gives the primary an economic incentive to accommodate secondary systems.
- The primary and secondary systems can be geographically co-located. There is no requirement on the minimum physical separation between the two networks.
- Explicit feedback from the primary system enables secondary users to reduce their interference more effectively than in an opportunistic paradigm.
- The additional hardware and complexity required in both systems are quite low.
- Because the scheme is based on existing, mature technologies, it can be deployed more quickly than proposed cognitive radio systems that rely on technical capabilities that have not yet been implemented and tested.

While the benefits of the cooperative framework are clear, a number of challenges also must be overcome before systems based on this paradigm are practical.

- Primary users must be active nodes that have the ability to announce their presence. While this initially appears to be a significant barrier, it may be less of a problem in the future as devices are increasingly connected to the internet via WiFi and bluetooth radios.
- For the secondary system to be practical and economically feasible, primary receivers must be relatively static and geographically sparse, e.g., cellular base stations, satellite base stations, or TV receivers.
- There are also open questions as to how to adapt this model to existing standards, such as WiMAX, that use technologies like MIMO and space-time coding. Spectrum reuse in systems where primary users have multiple antennas could benefit from collaborative and distributed beamforming techniques [10], [11].

In this framework, the secondary system could be either a separate entity or an extension of the primary. For example, the primary network operator could deploy its own secondary system to provide service upgrades to some users, without requiring that all primary users replace their hardware. However, there are other scenarios that might necessitate the deployment of the secondary as an independent system. For example, the operator of the secondary system may be able to use this architecture to aggregate bandwidth from several primary systems and provide services that any single primary is unable to offer[1].

III. Cellular uplink reuse

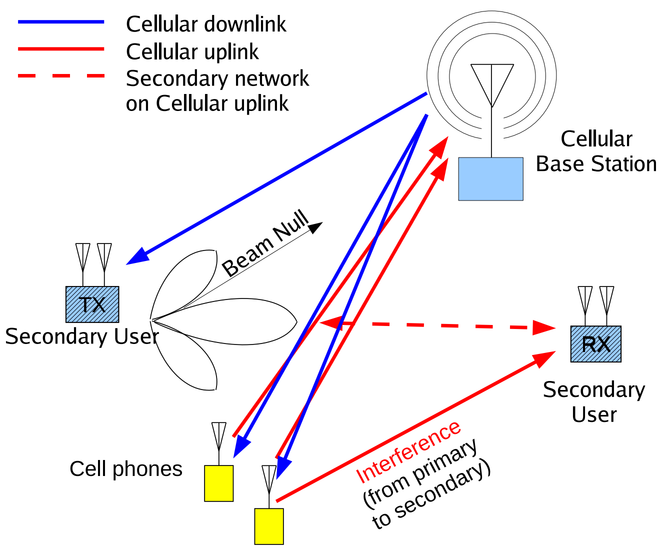

Fig. 2. Cooperative reuse of a cellular uplink channel

The uplink channel of a cellular communication system is a band that can be effectively reused by our proposed framework. This is because on the uplink, unlike the downlink, the primary receivers (base stations) are sparsely distributed and have static locations. In addition, base stations are more easily modified by the network operator than the mobile units.

The basic scenario is depicted in Figure 2. The multi-antenna secondary user connects to the base station as though it were a regular subscriber (a dual citizen), and is allocated channel resources (i.e., time slots, subcarriers, chip sequences, etc.) on both the uplink and the downlink. Once the connection is established, the secondary radio starts transmitting on its allocated channel of the uplink band. The goal of the secondary user is to choose a beamforming weight vector such that the signals from its antenna array cancel out at the base station. Such a weight vector can be efficiently computed by tracking the channel gains with an adaptive filter and using a minimum variance beamformer, as described in [12]. Once the secondary user has chosen a weight vector that results in sufficient signal rejection at the base station, it begins transmitting on the entire uplink band. However, the base station can inform the secondary user to stop transmitting on the entire uplink. Thus, the base station can suppress the secondary system if primary users experience service degradation.

In frequency division duplexing (FDD) systems, the secondary user requires explicit feedback from the base station (on the downlink) in order to learn the uplink channel response and compute an appropriate weight vector. On the other hand, in time division duplexing (TDD) systems, the secondary user can learn the channel responses of the uplink by directly estimating the downlink and using channel reciprocity. In the TDD case, the secondary user can transmit on the entire cellular band, but only in uplink time slots.

For a secondary system to be viable, not only does it have to avoid causing interference to the primary system, but it must also be able to suppress interference from the primary transmitters. In the cellular uplink application, the secondary receiver may experience interference caused by some of the primary transmitters (mobile phones) on the uplink. However, there are several reasons why primary interference should not excessively degrade the secondary system. Experimental measurements show that the spectrum usage on the uplink is much less than on the downlink [2]. Also, because the mobile units use a much lower transmit power than the base stations, their impact on the performance of the secondary receivers will be less significant. Furthermore, a secondary radio can use its multiple antennas when receiving to suppress large signal jammers, without the assistance of explicit feedback. Finally, in many cellular standards with universal frequency reuse (e.g. CDMA, OFDMA), the secondary receiver can take advantage of interference averaging [13], which employs coding to reliably communicate when a portion of the time-frequency slots are lost to interference.

IV. OFDMA cellular systems

As a concrete example of cellular uplink reuse, we will consider an OFDMA system, which is particularly well suited to this cooperative spectrum reuse framework. In general, higher bandwidth systems require more degrees of freedom to achieve good signal rejection over the entire spectrum[2]. The required complexity can be reduced by using OFDM, which divides a wideband channel into N parallel and orthogonal subchannels, which can be individually nulled. Each subchannel, referred to as a subcarrier, is much smaller than the coherence bandwidth. The subcarriers can be treated as single tap narrowband channels, which can be nulled with fewer antennas than wideband channels.

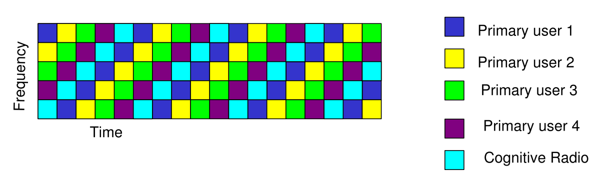

Fig. 3. Multiple access in OFDMA systems

Every subscriber is allocated a time-frequency hopping sequence by the base station on both the uplink and the downlink, as shown in Figure 3. In any given time slot

[1]Legal and economic reasons might prevent two primary systems from sharing bandwidth.

[2]In scattering environments with high delay spreads, the signal bandwidth can be much larger than the coherence bandwidth. In this case the channel response will be composed of multiple taps. The number of antennas required to null the entire band is proportional to the number of taps.

(OFDM symbol), different users transmit on different subcarriers, which implies that the hopping sequences allocated to different subscribers are orthogonal to one another. The hopping sequence is periodic, with period $d \leq N$ where d is usually chosen to be prime [13]. A single period is known as an OFDM block. Each hopping sequence contains d distinct subcarriers, which are usually spread out over the entire band in order to maximize the diversity. To reuse the uplink, the secondary proceeds as follows:

(1) The secondary user requests a hopping pattern from the cellular network and offers the network payment for the use of these resources. The network agrees to the terms and assigns the secondary user a time/frequency hopping pattern. At this point the secondary user is a member of both the primary and secondary systems (a dual citizen).
(2) The secondary radio transmits a pilot sequence on this pattern, and receives feedback from the base station[3].
(3) The secondary radio uses the feedback information to adaptively choose a set of antenna weights that nulls out its signal at the base station. The nulling process is done for each subcarrier individually.
(4) Once the SNR at the base station on all subcarriers falls below a fixed threshold, the secondary radio is permitted to reuse the entire uplink band for a fixed period of time. The secondary can reuse all N subcarriers, since the d subcarriers in its allocated hopping sequence are spread throughout the band.
(5) The secondary user continues to transmit a known sequence on its assigned hopping pattern, and receives regular feedback from the base station. The secondary can thus adapt its antenna weights as the channels vary in time.

Because the secondary is nulling each subcarrier individually, and the narrowband subcarriers experience flat fading [13], two antennas are sufficient. Note that in this scenario the secondary users will have to use OFDM to communicate with each other, as the nulling is done on a per subcarrier basis.

In practice, the secondary system can potentially interfere with multiple base stations, not only the base station with which it is registered. This is especially true in high density or sectorized cellular networks. The exact number of base stations depends on the density and network topology, as well as the desired coverage of the secondary system. The scheme described in this section can be used to null multiple base stations, if the secondary radio is assigned the same hopping sequence by each of them. This could be accomplished by having the primary system reserve a fixed sequence at all base stations for use by the secondary system. Alternatively, if the base stations assign the secondary different hopping sequences, the secondary can null all of the primary receivers via an iterative scheme, detailed in [12]. In both cases, the number of required antennas will also grow linearly with the number of base stations.

[3]The exact nature of the feedback depends on the specific beamforming algorithm in use. For example, the feedback might be the signal value at the receiver or the energy in the received signal.

V. Conclusion

This paper proposes a new framework for spectrum reuse that relies on collaboration between primary and secondary systems. Secondary radios, assisted by feedback from the primary system, use beam nulling to eliminate interference with the primary receivers. As a demonstrative example, we show how this paradigm can be used to allow secondary systems to reuse the uplink of an OFDMA cellular system. As this application shows, spectrum sharing can be accomplished with little hardware complexity in the secondary radios (as few as two antennas per radio) and little change to the primary infrastructure. Both factors are necessary to the success and future adoption of a system.

Furthermore, in addition to the low deployment and transition costs, this new paradigm presents advantages to both primary and secondary users. The primary system is in full control of how and when the spectrum is shared, and thus can provide guarantees on the service degradation experienced by its users. Cooperation also gives the secondary the benefit of more effective and predictable spectrum access than in opportunistic paradigms. Finally, in this framework spectrum sharing is driven by economic forces and does not require government regulation.

There are still a number of open questions which require further investigation. For example, the impact of various properties of primary systems (e.g. size, scale, topology, protocols, etc.) on the design of secondary systems and the cooperation framework must be analyzed. Similarly, practical beamforming and nulling algorithms for more complex applications must be developed. Our goal in this paper is to introduce the cooperation framework as a new direction in cognitive radio research and present guidelines for designing future systems.

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