SPECTRUM OPPORTUNITY AND INTERFERENCE CONSTRAINT IN OPPORTUNISTIC SPECTRUM ACCESS

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ABSTRACT

In this paper, we study two important concepts in opportunistic spectrum access: spectrum opportunity and interference constraint. We aim to provide a certain level of rigor to these seemingly intuitive terms central to opportunistic spectrum access. Their implications in spectrum opportunity detection and transmission power control of secondary users are discussed.

Index Terms: Opportunistic spectrum access, spectrum opportunity, interference constraint, spectrum opportunity detection, power control.

1. INTRODUCTION

The proliferation of a wide range of wireless devices and their applications has resulted in an overly crowded radio spectrum; almost all usable frequencies have already been occupied. This makes one pessimistic about the feasibility of integrating emerging wireless services such as large-scale sensor networks into the existing communication infrastructure.

Are we truly approaching the capacity of the radio spectrum? Actual spectrum usage measurements obtained by the FCC's Spectrum Policy Task Force [1] tell a different story: at any given time and location, much of the prized spectrum lies idle. This paradox indicates that spectrum shortage results from the spectrum management policy rather than the physical scarcity of usable frequencies. Analogous to idle slots in a static TDMA system with bursty traffic, idle frequency bands are inevitable under the current static spectrum allotment policy that grants exclusive use to licensees.

The underutilization of spectrum has stimulated a flurry of exciting activities in the engineering, economics, and regulation communities in searching for dynamic spectrum management policies. One approach to dynamic spectrum access is *spectrum overlay*, which was first envisioned by Mitola in 1999 under the term "spectrum pooling" [2] and then investigated by the DARPA XG program under the term "opportunistic spectrum access" [3]. The idea is to exploit instantaneous spectrum availability by opening the licensed spectrum to secondary users (for example, sensor networks). This would allow secondary users to identify available spectrum resources and communicate non-intrusively by limiting interference to primary users. In a broader context, this hierarchical access structure can also be employed to support different levels of Quality-of-Service (QoS) for licensees or users in unlicensed frequency bands.

Two concepts are fundamental to opportunistic spectrum access (OSA): spectrum opportunity and interference constraint. In the existing work, these two concepts are often understood at an intuitive level. Specifically, a channel in the spectrum is an opportunity if no signal from primary users is heard (listen before talk), and the interference constraint specifies the maximum interference power level. In this paper, we show that the above understanding of spectrum opportunity and interference constraint is insufficient. We aim to provide a certain level of rigor to these seemingly intuitive concepts. In particular, we address the following questions.

≤ When can a channel in the spectrum be considered as an opportunity? When detecting an opportunity, what should a secondary user look for? Can spectrum opportunity detection be carried out solely at secondary transmitters without involving their intended receivers?

≤ What are the minimal parameters that an interference constraint should specify? How does an interference constraint translate to the level of protection that it offers to primary users? How does interference constraint affect the transmission power control of secondary users?

To illustrate the basic idea, we often resort to the following example of OSA networks. The basic ideas presented in this paper, however, apply to general OSA networks.

An Example OSA Network We consider a spectrum consisting of N channels. Here we use the term "channel" broadly. A channel can be a frequency band with certain bandwidth, a

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collection of spreading codes in a CDMA network, or a set of tones in an OFDM system. We assume that interference across channels is negligible. Thus, a secondary user transmitting over an available channel does not interfere with primary users using other channels.

These N channels are allocated to a network of primary users. For ease of presentation, we assume that the primary system uses a synchronous slot structure, although the basic ideas apply more generally. Overlayed with this primary network is an ad hoc secondary network where users seek spectrum opportunities in these N channels. In each slot, a secondary user may choose a set of channels to sense and a set of channels to access based on the imperfect sensing outcomes.

2. SPECTRUM OPPORTUNITY AND INTERFERENCE CONSTRAINT: DEFINITIONS AND IMPLICATIONS

In this section, we provide definitions of spectrum opportunity and interference constraint.

2.1. Spectrum Opportunity

Intuitively, a channel can be considered as an opportunity if it is not currently used by primary users. In a network with geographically distributed primary transmitters and receivers, however, the concept of spectrum opportunity is more involved than it at first may appear.

With the help of Figure 1, we identify conditions for a channel to be considered as an opportunity. Consider a pair of secondary users where A is the transmitter and B its intended receiver. A channel is an opportunity to A and B if they can communicate successfully over this channel while limiting the interference to primary users below a prescribed level determined by the regulatory policy. This means that receiver B will *not be affected* by primary transmitters and transmitter A will *not interfere with* primary receivers.

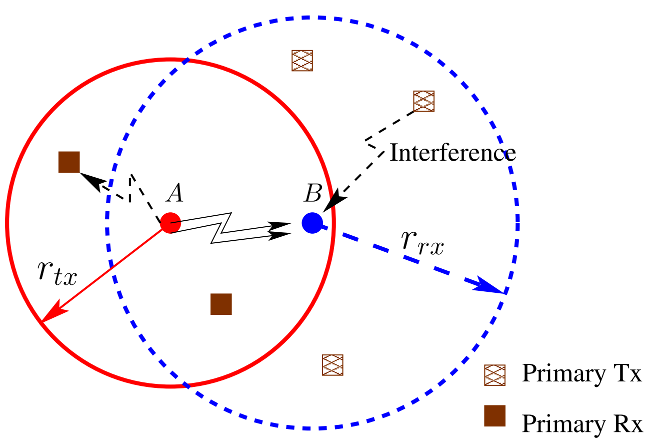

Fig. 1. Definition of spectrum opportunity.

To illustrate the above conditions, we consider monotonic and uniform signal attenuation and omnidirectional antennas. In this case, a channel is an opportunity to A and B if no primary users within a distance of r_{tx} from A are receiving and no primary users within a distance of r_{rx} from B are transmitting over this channel (see Figure 1). Clearly, r_{tx} is determined by the secondary users' transmission power and the maximum allowable interference to primary users, while r_{rx} is determined by the primary users' transmission power and the secondary users' interference tolerance. They are generally different.

We make the following remarks regarding the above definition of spectrum opportunity.

- $\leq$ Spectrum opportunity is a local concept defined with respect to a particular pair of secondary users. It depends on the location of not only the secondary transmitter but also the secondary receiver. For multicast and broadcast, spectrum opportunity is open for interpretation, and results in networking tradeoffs.
- $\leq$ Spectrum opportunity is determined by the communication activities of primary users rather than that of secondary users. Failed communications caused by collisions among secondary users do not disqualify a channel from being an opportunity.
- $\leq$ The definition of spectrum opportunity depends on the interference constraint through r_{tx} (see Section 2.2).

2.2. Interference Constraint

How to impose interference constraints is a complex regulatory issue. Restrictive constraints may marginalize the potential gain of OSA while loose constraints may affect the compatibility with legacy systems.

Generally speaking, an interference constraint should implicitly or explicitly specify at least two parameters: the maximum interference power level ζ perceived by an active primary receiver and how often, parameterized by ζ, the interference level at an active primary receiver may exceed ζ. The first parameter, ζ, can be considered as specifying the noise floor of primary users; interference below ζ does not affect primary users while interference above ζ results in a collision. It is thus inherent to the definition of spectrum opportunity (through r_{tx} in Figure 1) and determines the transmission power of secondary users as discussed in Section 4.

The second parameter, ζ, can be defined in different ways. It can be the maximum number of collisions that may occur during a given time window or the maximum probability of collision. In this paper, we take the latter definition. Given that errors in spectrum opportunity detection are inevitable, a positive value of ζ is necessary for secondary users to ever be able to exploit an opportunity. As shown in [4], ζ determines a secondary transmitter's access decision based on imperfect spectrum opportunity detection.

A cautionary aspect of collision probability is the probability space over which it is defined. Collision probabilities defined with respect to different probability space have different implications and offer different levels of protection to primary users. Consider the example OSA network given in Section 1. Should the maximum collision probability ζ be imposed on each channel and each slot or on the collision probability averaged over channels and/or a a long period of time? The former offers a specific level of protection to primary users no matter when and over which channel they transmit, while the protection given by the latter can be unpredictable when primary users have bursty arrivals of short messages, and the protection varies for different primary users depending on their traffic statistics.

A more subtle difference is whether collision probability is defined as a joint or conditional probability. Consider a particular channel i and a particular slot t. Let $S_i(t) \in \{0, 1\}$ denote whether channel i in slot t is an opportunity and $\Phi_i(t) \in \{0, 1\}$ a secondary user's decision of whether to access. Note that $\Phi_i(t)$ is a random variable depending on the potentially erroneous outcome of the spectrum opportunity detector and the transmission probability chosen by the secondary user based on the detection outcome. We can then define collision probability as either the joint probability given by

$$\Pr[\Phi_i(t) = 1, S_i(t) = 0]$$

or the conditional probability

$$\Pr[\Phi_i(t) = 1 \mid S_i(t) = 0].$$

The former includes the traffic statistic of primary users, specifically, $\Pr[S_i(t) = 0]$, into the interference constraint. As a consequence, the same constraint ζ on the collision probability offers a different level of protection to primary users with light traffic from those with heavy traffic.

While an interference constraint specified by $\{\zeta, \zeta\}$ should be imposed on the aggregated transmission activities of all secondary users, each secondary user needs to know the node-level constraint in order to choose transmission power and make access decisions (see Section 4 and [4, 5]). The translation from a network-level interference constraint to a node-level one depends on the geolocation and traffic of secondary users as well as the signal attenuation model in wireless fading environments. This problem is currently under investigation.

3. SPECTRUM OPPORTUNITY DETECTION

In this section, we study the implication of the spectrum opportunity definition given in Section 2.1 on the spectrum opportunity detection.

From the definition of spectrum opportunity illustrated in Figure 1, it is clear that in a general network setting, spectrum opportunity detection needs to be performed jointly by the secondary transmitter and receiver. It thus has both signal processing and networking aspects.

Consider the OSA network example given in Section 1. At the beginning of each slot, a pair of communicating secondary users need to determine whether a chosen channel is an opportunity in this slot. Ignore for now the contention among secondary users. One approach to opportunity detection is as follows [6]. The transmitter first detects the receiving activities of primary users in its neighborhood (see Figure 1). If the channel is available (no primary receivers nearby), it transmits a short request-to-send (RTS) message to the receiver. The receiver, upon successfully receiving the RTS, knows that the channel is also available at the receiver side (no primary transmitters nearby since RTS has been successfully received) and replies with a clear-to-send (CTS) message. A successful exchange of RTS-CTS completes opportunity detection and is followed by data transmission.

What remains to be solved is the detection of the receiving activities of primary users by the secondary transmitter. Without assuming cooperation from primary users, primary receivers are much harder to detect than primary transmitters. For the application of secondary wireless services operating in the TV bands, Wild and Ramchandran [7] proposed to exploit the local oscillator leakage power emitted by the RF front end of TV receivers to detect the presence of primary receivers. The difficulty of this approach lies in its short detection range and long detection time to achieve accuracy.

Another approach is to transform the problem of detecting primary receivers to detecting primary transmitters. Let R_p denote the transmission range of primary users, *i.e.,* primary receivers are within R_p distance to their transmitters. A secondary transmitter can thus determine that a channel is available if no primary transmitters are detected within a distance of $R_p + r_{tx}$ as illustrated in Figure 2. This approach is, however, is conservative that may lead to overlooked opportunities. As shown in Figure 2, the transmission activities of primary nodes X and Y may prevent A from accessing an opportunity even though the intended receivers of X and Y are outside the interfering range r_{tx} of A. Note that by adjusting the detection range with $R_p + r_{tx}$ being the most conservative, we reach tradeoffs between the throughput of secondary users and interference to primary users.

This approach reduces spectrum opportunity detection to a classic signal processing problem. As discussed in [8], based on the secondary user's knowledge of the signal characteristics of primary users, three traditional signal detection techniques can be employed: matched filter, energy detector (radiometer), and cyclostationary feature detector.

4. TRANSMISSION POWER CONTROL

Transmission power control of secondary users is a complex issue. To illustrate the basic parameters that affect power control, we ignore shadowing and fading and focus on a single

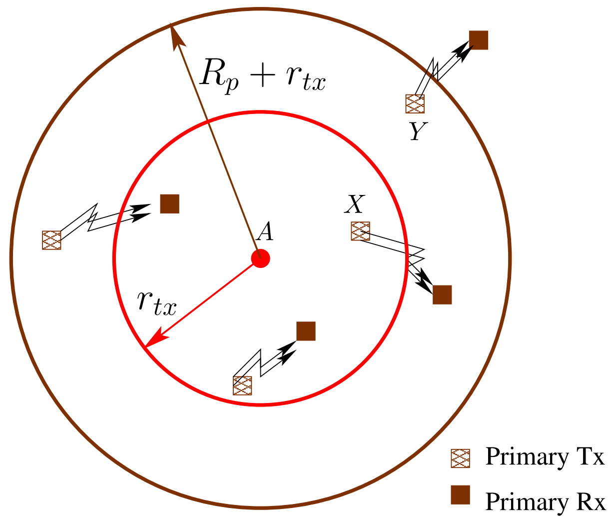

Fig. 2. Spectrum opportunity detection.

secondary user. Consider first that the secondary transmitter A is able to detect the presence of primary receivers within a distance of d (see Figure 1 with r_{tx} replaced by d). The transmission power P_{tx} of A should ensure that the signal strength at d away from A is below the maximum allowable interference level ζ. This leads to

$$P_{tx} \leq \zeta d^{\alpha},$$

where ζ is the path attenuation factor. The above equation indicates how the maximum transmission power of a secondary user depends on the detection range d of its spectrum detector, the prescribed maximum interference level ζ, and the path loss factor ζ.

When the secondary user can only detect the presence of primary transmitters within a distance of d (see Figure 2 with $R_p + r_{tx} = d$), we have,

$$P_{tx} \leq \zeta(d \leq R_p)^{\alpha},$$

where R_p is the transmission range of primary users. In other words, power control for secondary users should also take into account the transmission power of primary users. When we consider shadowing, fading, and interference aggregation due to simultaneous transmissions from multiple secondary users, a probabilistic model is necessary to address power control in OSA networks. We are currently studying this problem.

5. CONCLUSION

In this paper, we have addressed the definitions and implications of two fundamental concepts in opportunistic spectrum access: spectrum opportunity and interference constraint. We have shown that whether a channel is an opportunity to a pair of secondary users depends on the communication activities of primary users in the neighborhood of both the secondary transmitter and the secondary receiver. As a consequence, spectrum opportunities need to be identified jointly by secondary transmitters and receivers, and the listen-before-talk approach leads to overlooked spectrum opportunities even with perfect signal detectors. We have also identified the minimal set of parameters that an interference constraint should specify and the basic parameters that affect the transmission power control of secondary users.

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