Routing in Opportunistic Cognitive Radio Networks

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I. INTRODUCTION

A recent report by the FCC [1] challenges for the first time the common belief of spectrum scarcity by indicating that at any given time and in any geographic locality, less than 10% of the available spectrum is being utilized. To exploit underutilized portions of the spectrum (a.k.a, *white spaces*, *spectrum holes*, etc.), the report advocates the need for a new generation of smart, programmable radios that are capable of interference sensing, environment learning, and dynamic spectrum access. These so-called *cognitive radios* (CRs) have recently been the forefront of wireless communications research (see [2] for a survey). Originating from the concept of a *software defined radio*, CRs promise to provide reliable and programmable wireless communications as well as efficient (adaptive) sharing of the radio spectrum.

Numerous efforts have focused on defining the design guidelines and operating constraints of CR networks (CRNs). First, CR transmissions should not noticeably degrade the signal quality at primary radio (PR) receivers, which have priority in spectrum access. This can be achieved by adapting the transmission power of CR nodes. Second, a CR node should immediately interrupt its transmission whenever a neighboring PR activity is initiated. This requires frequent monitoring of the PR activities by CR nodes.

Much of the research on CRN protocols has dealt with the MAC and physical layers. Optimizing these two layers without consideration to the routing protocol (the network layer) can lead to sub-optimal solutions at best. For example, an optimized MAC protocol may provide the best channel/power/rate assignment for a particular link, but such an assignment can be quite inefficient when considering the end-to-end path of the flow.

We investigate a routing design for a multi-hop CRN that geographically coexists with several PR networks (PRNs). The problem at hand presents somewhat similarities with routing in multi-channel, multi-hop ad hoc and mesh networks, but with the added challenges of having to deal with simultaneous transmissions over multiple channels and with PR-to-CR interference. By definition, the operation of a CRN should be transparent to coexisting PRNs, so no feedback from or control over the PRNs can be expected. The need to interrupt CR transmissions whenever a PR activity is detected further complicates the routing design, which now has to aim at determining the most *stable* route. Route stability can be indirectly achieved by maximizing the likelihood of meeting the rate demand of the CR flow and by operating multiple parallel channels over a CR link. As part of our routing design, we introduce a novel routing metric that is based on a probabilistic definition of the available capacity over a channel. This definition relies on the probability distribution of the PR-to-CR interference at a given CR node over a given channel, which was shown in [3] to approximately follow a lognormal distribution. Our routing metric is used to determine the most probable path (MPP) to satisfy a given bandwidth demand D. The MPP is not guaranteed to satisfy the demand D, so an augmentation phase is used whereby “bottleneck” links are augmented with additional channels such that the resulting path meets the bandwidth demand D with a given probability (confidence level) δ. Our design is incorporated into a routing algorithm for CRNs.

II. PROTOCOL DESCRIPTION

A. Routing Metric

We consider an opportunistic CRN of N nodes that operates over a maximum of M orthogonal frequency bands (channels) of respective bandwidths $W_1, \dots, W_M$ (in Hz). Each band is licensed to a given PRN. The distribution of nodes in the ith PRN follows a 2D Poisson process of rate (node density) ρ_i. Each node in this PRN is active with probability α_i. Using this model, the authors in [3] derived the moment generating function for the total PR-to-CR interference at any CR receiver, and used it to design a MAC protocol that supports soft outage guarantees for PR communications. We use the same underlying setup to design our routing protocol. Let $P_{I,j}^{(i)}$ be the total PR-to-CR interference at CR node j over channel i, where $i = 1, \dots, M$ and $j = 1, \dots, N$. In [3], the authors showed that the distribution of $P_{I,j}^{(i)}$ is approximately lognormal, with mean and variance μ_i and σ_i (which depend on ρ_i and α_i). Consider a CR node j that receives data from CR node k over channel i. The maximum channel capacity $C_{kj}^{(i)}$ is given by Shannon’s Theorem:

$$C_{kj}^{(i)} = W_i \log_2 \left[1 + \frac{P_{r,j}^{(i)}}{N_0 + P_{I,j}^{(i)}} \right] \tag{1}$$

where N_0 is the power of the white Gaussian noise and $P_{r,j}^{(i)}$ is the power of the received signal. The value of $P_{r,j}^{(i)}$ was computed in [3] such that a certain outage probability (at the MAC layer) can be guaranteed for PR users. It depends on the PR parameters ρ_i and α_i, the maximum transmission range for a CR node, and the link margin of the PRNs.

For a given CR connection request of rate demand D (in bits/second), the probability that channel i can support this demand is given by:

$$l_{k,j}^{(i)} \overset{\text{def}}{=} \Pr[C_{kj}^{(i)} \geq D] = \Pr\left[P_{I,j}^{(i)} \leq \frac{P_{r,j}^{(i)}}{2^{D/W_i}-1} - N_0\right] \quad (2)$$

As stated earlier, we assume that $P_{I,j}^{(i)}$ follows a lognormal distribution, our analysis, however, is equally applicable to any distribution. The probability in (2) can be obtained for every channel of every link by calculating the CDF of the lognormal distribution of the PR-to-CR interference.

B. Estimating Capacity

A key contribution of our work is the way we estimate the available capacity of every channel. Our metric classifies channels based on the probability that their capacities is greater than D (equation (2)) without being able to determine the exact capacity. Therefore, a tool for estimating the capacity is needed. Because (1) gives the capacity distribution over a channel, it is possible to estimate the achievable capacity of a channel at a fixed probability δ, where $\delta < 1$. More precisely, for every channel i of every link (k, j), we calculate the capacity $X_{kj}^{(i)}$ that such a channel can support with probability δ (e.g., $\delta = 0.9$). This can be done by setting $\Pr[C_{kj}^{(i)} > X_{kj}^{(i)}] = \delta$, and solving for $X_{kj}^{(i)}$:

$$\Pr\left[W_i \log_2(1 + \frac{P_{r,j}^{(i)}}{N_0 + P_{I,j}^{(i)}}) > X_{kj}^{(i)}\right] = \delta \quad (3)$$

C. Path Selection Algorithm

We now propose a reactive source-based routing protocol for CRNs. As in many other studies, coordination between nodes is achieved through a low-bandwidth control channel. Our algorithm will be initiated by the source node whenever an application requests a route to a destination with a capacity demand D. Note here that all required information for this computation can be obtained from the control channel. The link probabilities on all channels are calculated based on the required demand with equation (2). Once all link weights calculated, the source runs a path selection algorithm to find a route to the destination. In our case for instance, we use a -log operation on the probability to obtain increasingly ordered link weights (*i.e* the smallest weight refers to the highest probability) then run a Dijkstra-like algorithm to find a path. We call the obtained result the most probable path since it has the highest probability of satisfying the application demand. The MPP can be considered as the most probabilistically stable path to the destination, however, it is not sure that the capacity it can carry satisfies the demand. Consequently, we add the capacities calculated as in equation (3) as a simple *indicator* of the achievable capacity over every link. If the calculated capacity is smaller than the demand, then the link is augmented with another frequency. In fact, the algorithm will look for the *next most probable* channel between nodes where the $X^{(i)}$ (plus the considered cognitive interference) is not larger than the demand along the already discovered single path; we call this mechanism the path augmentation. The algorithm terminates only if one of the following two states is reached: *i)* On every link of the most probable path, the total capacity (that is the sum of calculated available capacities on every channel) is greater than the demand. Thus the path is set and will be injected in the transmitted packets' header; *ii)* the total estimated capacity between two nodes on all channels (*i.e* after augmentation) does not satisfy the demand. In this case, the destination is declared unreachable and no path is available for that destination.

III. FIRST RESULTS

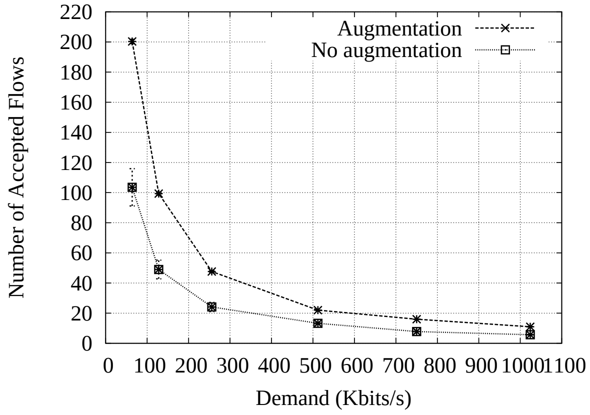

Fig. 1. The number of accepted connections for different D

We illustrate in Figure 1 a preliminary result about the gain that can be achieved by using the augmentation technique in terms of accepted connections. In a 20 nodes topology, we notice about 200% gains compared to the case where the augmentation is not used. In the latter case we stop accepting new demands when a most probable frequency cannot carry the whole demand. It is also important to note that when the demand is bigger, we clearly accept less connections and notice a decrease in the obtained gain. This is due the fact that splitting a *large* demand over multiple residual frequencies reduces the number of accepted connections compared to the case where D is small and can be easily divided over fewer frequencies.

REFERENCES

[1] FCC, "spectrum policy task force report," *ET docket no. 02-155, November*, 2002.

[2] I. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "Next generation dynamic spectrum access cognitive radio wireless networks: A survey," *Computer Networks Vol. 50, Issue 13, pp. 2127-2159*, 2006.

[3] H. Salameh, M. Krunz, and O. Younis, "Throughput-oriented MAC protocol for opportunistic cognitive radio networks with statistical performance guarantees," *Technical report, University of Arizona UA-ECE-2007-2*, 2007.