Feedback-based access and power control for distributed multiuser cognitive networks

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***Abstract*—Cognitive radio networks enable secondary users to utilize spare bandwidth of primary users by limiting their interference. Moving beyond the traditional listen-before-talk paradigm, we propose a cognitive access methodology that exploits the feedback channel in two-way primary communication links for better spectrum utility and protection of primary users against secondary interference. We let secondary users dynamically control access and power based on primary ACK/NACK messages. We develop an optimal access policy applicable to multiple secondary user pairs. We also devise a distributed power control policy for multiple secondary users to maximize their individual throughput without significant cumulative interference to the primary link. Our distributed access and power control schemes can effectively provide good SU performance and primary protection without requiring central coordination.**

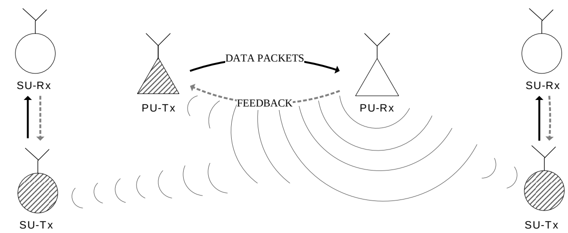

Fig. 1. System model.

I. Introduction

Cognitive Radio networks (CRNs) have generated much research interest in recent years as a promising technology for improving the current static spectrum utilization and for enabling new wireless services [1], [2]. Traditional works on cognitive radio have largely focused on the listen-before-talk (LBT) methodology (e.g., [5], [6], [7]). Although recent FCC reports [1][2] showed that LBT does not degrade TV receiver quality, LBT based schemes still suffers several drawbacks: the need to handle the SNR-wall issue [8]; the hidden receiving node problem; the failure to fully exploit the excess system capacity of interference-resistant PU networks.

In this paper, we propose CRNs to exploit the inherent feedback information and, more generally, data link control (DLC) information present in many wireless systems such as HSDPA [3] and WiMAX [4]. Such DLC information can be used to quantify the impact of the secondary access on the primary system.

There exist several related works. In [11] and [12] the authors proposed two distributed algorithms that perform power control. The authors of [13] formulated a joint power/rate allocation with max-min fairness criterion as an optimization problem. In [14], a distributed algorithm for CRNs to maximize data rates over multiple user communication sessions is devised. In [9], the SUs estimate the gain of the interference channel transmitting probing signals that change transmission power of the PU in response. In [10], a wideband OFDM cognitive radio dynamically changes its subcarrier usage based on the reactive behaviors of the narrow-band PU devices.

In our work we explicitly use the available feedback information that is pervasive in many "two-way" communication systems to facilitate the SU spectrum usage. This approach offers several advantages over the traditional LBT by providing (a) a more efficient spectrum utilization; (b) a way of implementing distributed multiple SU access while protecting the PU links; and (c) a means of improving PU/SU co-existence and interaction. To generalize, additional DLC information can be incorporated into the proposed schemes to improve the cognition of the CR devices and thus achieve highly efficient and harmless secondary spectrum access in CRNs.

II. System Model

The following standard notations will be used throughout the paper: $\mathbb{E}$ denotes the expectation operation, and $(x)^+$ is defined as $(x)^+ = \max\{0, x\}$.

The system model is shown in Figure 1. The "two-way" primary communication system consists of two channels: a forward channel from the PU-Tx to the PU-Rx, and a reverse ("answer") channel in the opposite direction. On the forward channel, the PU-Tx sends data packets to the PU-Rx. On the reverse channel, the PU-Rx sends back ACK/NACK packets to indicate whether or not the data packet reception was successful.

The SU objective is to opportunistically access the forward channel bandwidth. We assume that the "cognitive" SU-Tx can overhear and decode the ACK/NACK packets on the reverse channel, and exploit this feedback message to control its spectrum access. Since the PUs have higher priority in spectrum access, the interference from the SUs to the PU-Rx should be kept insignificant. By listening to the ACK/NACK

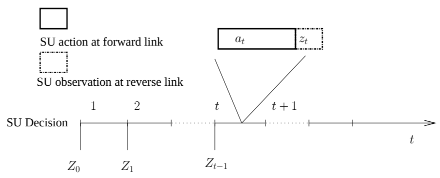

Fig. 2. Illustration of SU access decision.

packets, the SU can learn about its interference effect on the PU-Rx, and adjust its transmission strategy (access policy or transmit power) accordingly. This approach can mitigate the hidden receiver problem in the LBT approach since the SU activities adapt to the interference perceived by the PU-Rx directly, rather than only listening to the presence of PU-Tx transmission.

We assume that the PU transmission on the forward link is always active. Depending on the locations of the SU-Tx and the PU-Rx, the SU transmission may or may not harm the PU-Rx. Generally, when the PU-Rx is far away from the SU-Tx and close to the PU-Tx, the interference from the SU-Tx is negligible at the PU-Rx. In this case, the SU-Tx can transmit over the primary channel if its power/access is controlled appropriately. We assume that both PU and SU transmissions are slotted with the same slot duration and that the SU access is synchronized with the PU. This can be achieved by letting the SU listen to the broadcast control message common to many "two-way" communication links. We also assume that the feedback information from the PU-Rx to the PU-Tx has negligible delay when arriving at the SU.

Let Z_t denotes the observation outcome at the SU-Tx on ACK/NACK at the end of slot t:

$$Z_t = \begin{cases} 0, & \text{if an ACK is received at time } t \\ 1, & \text{if a NACK is received at time } t. \end{cases} \tag{1}$$

We denote the probability of having a NACK on the PU links at slot t as ζ_t. As illustrated in Fig. 2, based on the observation history of the ACK/NACK messages, the SU decides its access/power dynamically at the beginning of slot t. The SU can then learn its impact on the PU during slot t from the ACK/NACK information transmitted on the reverse channel, which marks the successful/failed reception of the PU data packet. Our objective is to determine the SU access and power control policies that achieve the best trade-off between the two conflicting goals of protecting PU communications versus maximizing SU capacity on the forward link. The results can also be generalized to the opportunistic spectrum access on the reverse channel.

III. Adaptive SU access control on PU ACK/NACK information

In this section, we consider the design of an optimal SU access control policy in which the SU-Tx decides whether or not to transmit based on the observation of ACK/NACK message on the reverse channel. We assume that all SU-Tx's transmit with the same fixed transmit power.

We define two states for the PU forward link as perceived by a given secondary user: an "error-resistant" (low interference) and an "error-prone" (high interference) state. This is because the channel between the PU-Tx and PU-Rx may experience impairment other than the SU transmission in question. Moreover, the two channel states can be used to approximate the effect of multiple uncoordinated SU transmissions. The "error-resistant" state accounts for the case in which no other SU-Tx interferes with the PU-Rx, whereas the "error-prone" state denotes the case in which there exist interfering sources. If the chosen SU-Tx does not transmit during the "error-resistant" state, then the PU-Rx packet error rate is Q_0, whereas the packet error rate during the "error-prone" state is Q_1. On the other hand, if the SU-Tx transmits during the "error-resistant" state, the packet error rate is approximately Q_1, and during the "error-prone"state the packet error rate is Q_2. Clearly, it is sensible to have $Q_0 < Q_1 < Q_2$. Moreover, their values mirror the signal to interference and noise ratio (SINR) levels at the PU-Rx under the different situations. We assume that the SU-Tx does not know exactly which state the forward channel is in, but it has the knowledge of $Q_0, Q_1,$ and Q_2 from experience and measurement.

Here, we consider the SU access control with infinite decision horizon. The SU decision state at time slot t is the probability that the PU forward link is in the error-resistant state, which is denoted by $q_t \in [0, 1]$.

The actions that the SU-Tx can take at time slot t are:

$$a_t = \begin{cases} 1 & \text{“transmit”} \\ 0 & \text{“stay idle”} \end{cases} \tag{2}$$

Depending on the access decision the SU-Tx make, we have the probability of receiving an NACK at slot t as:

$$\lambda(a_t) = \begin{cases} q_t Q_1 + (1 - q_t) Q_2, & \text{if } a_t = 1; \\ q_t Q_0 + (1 - q_t) Q_1, & \text{if } a_t = 0. \end{cases} \tag{3}$$

At the end of each time slot, SU-Tx updates its state according to the Bayesian rule. The update is based on whether a NACK or an ACK is received and whether the SU's action is to transmit or to be idle. When no ACK/NACK feedback is received, the state is unchanged as

$$q_{t+1} = q_t. \tag{4}$$

The probability of correctly detecting (overhearing) an ACK/NACK feedback packet from the PU-Rx is $\eta \in [0, 1]$.

The immediate reward is a function of the state and the action at time t, which is defined as:

$$r(q_t, a_t) = \begin{cases} R_s - C\zeta_t & \text{if } a_t = 1; \\ 0 & \text{if } a_t = 0. \end{cases} \tag{5}$$

Here, R_s is a constant gain that accounts for the channel access and C is a constant penalty that accounts for the event of receiving a NACK.

The goal of the SU-Tx is to maximize its total expected discounted reward:

$$V(x) = \max_{\pi}\{\mathbb{E}_{\pi}[\sum_{t=t_0}^{+\infty}\alpha^{t-t_0}r(q_t,a_t)|q_{t_0}=x]\}, \qquad (6)$$

where t_0 is the initial decision stage, and $q_{t_0} = x$ is the initial state. Note that $V(x)$ has the same form for any $t_0 < \infty$.

It can be proven that, $V(x)$ is a monotonically increasing and convex function of $x \in [0, 1]$. By virtue of these properties, the optimal access policy is a threshold policy. Specifically, the SU-Tx will transmit according to the following policy

$$a_t = \begin{cases} 1 \text{ if } q_t \geq \bar{q} \\ 0 \text{ if } q_t < \bar{q}, \end{cases} \qquad (7)$$

where $\bar{q}$ is the threshold to be computed numerically.

IV. Adaptive SU power control

In this section, we propose an adaptive power control scheme for a SU to maximize its transmit throughput while keeping its negative impact on the PU-Rx (in terms of additional NACKs) under control. The control parameter for the SU is its transmit power on the forward link. We develop an optimal power control policy for a single pair of secondary users by assuming perfect reception of the ACK/NACK packets from the PU-Rx. We then extend the policy to multiple secondary user pairs with imperfect ACK/NACK receptions.

To illustrate the design principle of the adaptive power control policy based on the ACK/NACK reception from the primary feedback channel, we consider scenarios in which the primary system does not perform any power control. We assume that the statistics of the interference channel gain from the SU-Tx to the PU-Rx does not change during the time interval of interest $(0, T]$. The action of the SU-Tx is the transmit power P_t at each time slot t. We impose a maximum power limit $\bar{P}$ on the SU-Tx such that $P_t \in [0, \bar{P}]$. The immediate reward for the SU pair with action $P_t = P$ at time slot t is the supported data rate on the forward link, given as $\gamma(P) = \log(1 + GP)$, where the constant G is the effective SNR for the SU-Rx.

For the PU-Rx, the transmission of the SU-Tx on the forward link degrades its channel quality and signal reception. The larger the SU transmit power, the higher the NACK rate perceived by the PU pair. We denote this interaction between the SU power P_t and PU NACK rate ζ_t by a function $\zeta_t = f_e(P_t)$, which is an monotonically increasing function.

Assuming perfect ACK/NACK observation, the SU-Tx maintains a record on the total number of NACK X_t received at the beginning of slot $t + 1$. We have the transition probabilities of X_t as:

$$\begin{aligned} &\Pr[X_{t+1} = k|X_t = k] = 1 - \zeta_{t+1}, \\ &\Pr[X_{t+1} = k+1|X_t = k] = \zeta_{t+1}, \end{aligned} \qquad (8)$$

where $\zeta_{t+1} = f_e(P_{t+1})$. Based on the value of X_t, the SU can infer the interference impact of its past transmission to the PU-Rx, and make timely adjustment on its transmit power.

To limit the SU interference on the PU traffic, we introduce a terminal cost that penalize the SU based on the total number of NACKs caused during the entire access period. We denote this terminal cost by $f_c(x_T)$, which should be chosen such that the NACK rate at the PU-Rx is under control.

The SU power control policy π specifies a sequence of functions that map the state space $\{X_t\}$ to the action space $[0, \bar{P}]$. Suppose that the number of NACK packets observed at the SU-Tx until time slot t is $X_{t-1} = x$. Let $V_t(\pi, x)$ be the total net-reward of the SU when there are $T - t + 1$ slots left until terminating slot T under a given power control policy π. We then have

$$V_t(\pi, x) = \mathbb{E}_{\pi}\left[\sum_{k=t}^{T}\gamma(P_k) - f_c(X_T)|X_{t-1} = x\right], \qquad (9)$$

where the expectation is taken over random variables $X_t, \cdots, X_T$ for a given policy π. The objective is to find a power control policy $\bar{\pi}$ that has the maximum expected total net-reward during the entire access period, i.e.,

$$\bar{\pi} = \arg\max_{\pi} \quad V_0(\pi, 0). \qquad (10)$$

Here, we use the fact that at the beginning of the SU access, the number of NACKs is fixed as $X_0 = 0$. In what follows, for notation simplicity, we use $V_t(x)$ instead of $V_t(\bar{\pi}, x)$ to represent the reward-to-go at time slot t achieved by the optimal policy.

According to the Bellman optimality equation, we have the following iterative relation on $V_t(x)$:

$$\begin{aligned} V_t(x) = \max_{P_t\in[0,\bar{P}]} \big\{ &\log_2(1 + GP_t) + f_e(P_t)V_{t+1}(x + 1) \\ &+(1 - f_e(P_t))V_{t+1}(x)\big\}; \end{aligned} \qquad (11)$$

and $V_{T+1}(x) = -f_c(x)$. Backward induction can be used to obtain the optimal power control policy $\bar{\pi}$.

There are often only finite number of power levels for the SU-Tx to choose from in practical systems. In such cases, by evaluating the right-hand-side of (11) at the known power levels, we can obtain the optimal transmit power for each slot as the one with smallest cost using backward induction. If the SU transmit power has continuous value, we can exploit the properties of the functions $f_e(\cdot)$ and $f_c(\cdot)$ (e.g., convexity) to derive the structure for the optimal policy.

The calculation of the optimal power control policy can be performed offline. Note that the maximum number of NACK packets during time interval $(0, T]$ is T, the resulting policy can be stored in a table of size[1] $T \times (T + 1)$, and the SU-Tx performs a table lookup operation at each slot according to the number of NACKs observed.

In practical systems, due to the potential errors of the ACK/NACK detection, the SU-Tx does not know the exact number of PU packets it has lost. To tackle this problem, we use the NACK probability ζ_t instead of Z_t to update the value of X_t in case the SU cannot decode the ACK/NACK packet

[1] Note that since $X_t \leq t$, the actual size of the table can be made much smaller.

at time slot t. The value of ζ_t can be estimated based on the number of correctly received ACK/NACK packets so far. The value of X_t is rounded to the nearest integer and used to look up the transmit power in the pre-calculated table.

V. Simulation results

We now test the performance of the proposed feedback-based access and power control schemes. The locations of the PU pair and SU pairs used in the simulations are shown in Fig. 3. The distances between the PU-Tx (SU-Tx) and the PU-Rx are denoted by d_a and d, respectively; while the communication range of the SU pair is denoted by δ.

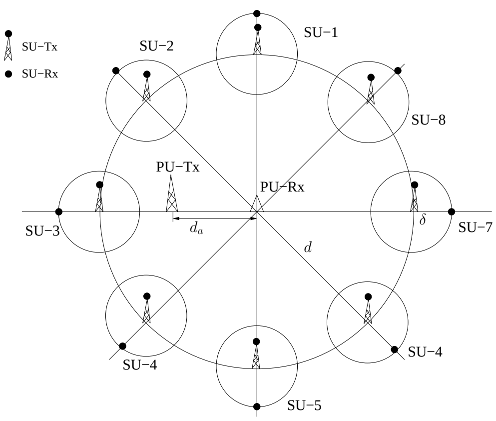

Fig. 3. Location of PUs and SUs.

A. Adaptive access control

In the adaptive access control policy, the SU-Tx estimates the effect of its transmission on the PU-Rx through the feedback packets that are sent on the reverse link. We use the NACK rate, i.e., the average number of the NACK packets sent by the PU-Rx in time, to illustrate the performance of our distributed algorithm in protecting the primary communication link. We assume all channels to be AWGN.

In an AWGN channel, the probability of packet error in the "error-resistant" state Q_0 is:

$$Q_0 = 1 - (1 - \mathrm{BER}_0)^{N_b}. \quad (12)$$

Here BER_0 is the bit-error-rate of the "error-resistant" channel when the SU-Tx does not transmit and N_b is the number of bits in a PU packet. The BER is a function of the Gaussian distribution and is modulation-dependent. Similar expression applies to probabilities Q_1 and Q_2, with bit-error-rate BER_1 and BER_2, respectively.

In our simulations, we define Q_0, Q_1 and Q_2 by considering the SINR at PU-Rx due to 0, 1, and 2 interferers, respectively. We use the resulting values to obtain the threshold $\bar{q}$ which characterizes the secondary transmission policy. Note that the actual packet error rate at the PU-Rx has been calculated at every time slot according to the effective number of secondary transmitters.

We consider the application of our proposed threshold access strategy to the case of multiple secondary users. With respect to the SU distribution of Fig. 3, we consider the special cases of 8 secondary SU-Tx and 2 secondary SU-Tx randomly selected from among the 8. In our simulation, we let $Q_0 = 10^{-4}, Q_1 = 0.0112$, and $Q_2 = 0.1020$. Figure 4 shows the resulting NACK rates of the three cases with one SU, two SUs, and eight SUs, respectively. The x-axis is time (in slots). The initial state of the secondary transmitters (q_{t_0}) is randomly chosen over $[0, 1]$. For 2 and 8 SU-Tx's, the NACK rates approach 1%. For 1 SU-Tx, the NACK rate is more sensitive to the primary channel model. In our test, the resulting single SU-Tx NACK rate converges to approximately 2% when the primary channel model is set to be in the "error-resistant" state with probability of 0.8.

TABLE I
SU performance.

number of SUs	1	2	8
per SU throughput	0.6393	0.4752	0.1390
variance	0	$9.4 \cdot 10^{-4}$	$3.7 \cdot 10^{-4}$

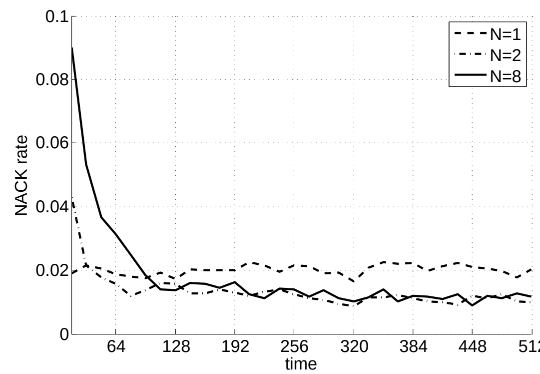

Fig. 4. NACK rate in case of 1,2, and 8 secondary pairs

Table I compares the per SU throughput. The per SU throughput is defined as the number of times a SU-Tx accesses the primary channel out of the total simulation time. Since the total channel capacity is limited, the throughput per SU declines as the number of SU-Tx increases. Nevertheless, because of spatial reuse, the aggregated SU throughput increases. The protocol also results in good fairness because all the SU-Tx's obtain very close values of throughput as shown by the low variance of the per SU throughput in Table I.

In summary, the throughput result and the NACK rate in Fig. 4 show that the distributed primary channel access protocol for cognitive radios successfully protects the primary quality of transmission by keeping the NACK rate low. At the same time, it achieves fairness for multiple secondary transmitters whose individual throughput shows little difference from user to user.

B. Adaptive power control

Next, we present simulation results for the proposed adaptive power control policy.

In the simulation, we assume the number of power levels supported by the SU-Tx as finite. Specifically, we allow the

TABLE II
SIMULATION RESULTS WITH MULTIPLE SUS

	d	NACK (%)	Individual SU Throughput
SU-1,5	500	1.41	0.068/0.068
SU-1,5	1500	2.09	4.95/4.95
SU-1,3,5,7	500	1.52	0.04/0.00/0.04/0.45
SU-1,3,5,7	1500	2.52	4.77/0.44/4.77/6.01
SU-1˜8	500	1.67	0.02/0.00/0.00/0.00/0.02/0.19/0.36/0.19
SU-1˜8	1500	3.32	4.48/2.51/0.26/2.51/4.48/5.41/5.69/5.41

SU-Tx to choose transmit power uniformly from the interval $[-50\text{dBm}, 50\text{dBm}]$ with 1dBm resolution. The time horizon T is set to 100. The penalty function used here is $f_c(k) = T\cdot[(k-f_e(0)T)^+]^2$. To determine the function $f_e(P_t)$ and the probability of successful ACK/NACK reception (i.e., η) at the SU-Tx, we consider both the path loss and Rayleigh fading effects in the channel model. We assume that the path loss factor is 4, and the fading on different channels is independent. The transmit power of the PU-Tx on the forward channel and the PU-Rx on the reverse channel are set to be 50dBm. In addition, we set $d_a =$1000m and $\delta =$100m.

Note that we assume a packet to be correctly decoded only if the average SNR at the receiver side is higher than a certain threshold. We therefore calculated the values of $f_e(P_t)$ and η according to this model. We also assumed that the channel statistics do not change over time and that the function $f_e(P_t)$ and the value of η are the same for all time slots. We test the cases with multiple SU pairs with their locations shown in Fig. 3. SU pairs are uniformly distributed around the PU-Rx. Hence, the ACK/NACK reception probability is the same at each SU-Tx, though the ACK/NACK observation is assumed to be independent among different SU-Tx's. Each SU independently performs the power control algorithm based on its estimated number of the NACK packets. The individual throughput of each SU pair and the accumulated NACK at the PU are summarized in Table II. From the results, we can observe that due to the accumulated interference from multiple SU-Tx's, the NACK rate increases with the number of SUs, albeit at a slow rate. Additionally, since the interference power from the PU-Tx differs from one SU-Rx to another, the individual SU throughput differs significantly for the power control algorithm. Indeed, the SU throughput increases with the distance from the PU-Rx to the SU-Tx by keeping the NACK rate low.

In summary, the simulation results show that exploiting the inherent feedback information of the primary systems makes it possible for SUs to control the interference level at the PU-Rx in a distributed fashion.

VI. CONCLUSION

In this work, we present a new framework for distributed cognitive radio access and power control through utilizing the primary feedback information. We explore this novel idea of cognition to allow the secondary users adapt their access based on the primary DLC information that they overhear. We derive an optimal channel access policy and an optimal power control policy for cognitive radios. We show that the proposed schemes leads to negligible additional packet loss for the PU link while enabling SUs to achieve good spectral utilization in a distributed manner. Both access and power control schemes offer stable PU packet protection regardless of the number of secondary users. Although, we limited our discussion to exploiting the ACK/NACK message of the "two-way" primary communication systems, the more general utilization of other DLC information for cognitive access is currently under investigation.

REFERENCES

[1] FCC, "Spectrum Policy Task Force Report,", Nov. 2002.

[2] FCC, "Office of engineering and technology releases TV white space phase II test report," http://www.fcc.gov/oet/projects/tvbanddevice/Welcome.html, Nov. 2008.

[3] *3GPP Technical Specification Group Radio Access Network Physical layer procedures (FDD) (Release 5)*, 3rd Generation Partnership Project Std. S25.214 V5.11.0, 2005.

[4] *Air Interface for Fixed Broadband Wireless Access Systems*, IEEE Std. 802.16-2004, 2004.

[5] Y. Chen, Q. Zhao, and A. Swami, "Joint design and separation principle for opportunistic spectrum access in the presence of sensing errors," *IEEE Transactions on Information Theory*, vol. 54, no. 5, pp. 2053–2071, 2008.

[6] S. Geirhofer, L. Tong, and B. Sadler, "Cognitive medium access: Constraining interference based on experimental models," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 95–105, Jan. 2008.

[7] Y.-C. Liang, Y. Zeng, E. Peh, and A. T. Hoang, "Sensing-throughput tradeoff for cognitive radio networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 4, pp. 1326–1337, April 2008.

[8] R. Tandra and A. Sahai, "SNR walls for signal detection," *IEEE Journal on Selected Topics in Signal Processing*, pp. 4 – 17, 2008.

[9] R. Zhang and Y. C. Liang, "Exploiting hidden power feedbacks in cognitive radio networks," *Poster Session, the 3rd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, 2008.

[10] H. Rahul, N. Kushman, D. Katabi, C. Sodini, and F. Edalat, "Learning to share: narrowband-friendly wideband networks," *SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 4, pp. 147–158, 2008.

[11] J. Huang, R. Berry, and M. Honig, "Distributed interference compensation for wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 5, pp. 1074–1084, May 2006.

[12] S. Srinivasa and S. Jafar, "Soft sensing and optimal power control for cognitive radio," *IEEE Global Telecommunications Conference (GLOBECOM)*, pp. 1380–1384, Nov. 2007.

[13] L. Le and E. Hossain, "Qos-aware spectrum sharing in cognitive wireless networks," *IEEE Global Telecommunications Conference (GLOBECOM)*, pp. 3563–3567, Nov. 2007.

[14] Y. Shi and Y. Hou, "A distributed optimization algorithm for multihop cognitive radio networks," *The 27th Conference on Computer Communications. IEEE INFOCOM 2008*, pp. 1292–1300, April 2008.