Medium Access Control Signaling for Reliable Spectrum Agile Radios

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***Abstract*—We address the problem of collaborative sensing in cognitive radios. In a cognitive radio network, all the nodes may sense the spectrum simultaneously. They should then exchange their sensing results in order to improve the reliability of the detection. This exchange of information has to be done efficiently to improve on the bandwidth efficiency of the network. We propose a medium access control (MAC) signaling protocol and study its performance behavior. For the case of a single-band channel, we present a thorough analysis of the proposed protocol and use the results to pick the protocol parameters that minimizes the signaling time for a given probability of detection. Analysis of the proposed protocol for multiband channels is solved by introducing a matrix formulation of the proposed protocol that allows its evaluation numerically.**

I. Introduction

A typical Cognitive Radio (CR) network [1] consists of secondary users (SUs) that should coexist with primary users (PUs) of a shared *broadband* spectrum. PUs have a priority access to the spectrum over SUs. The SU network should be designed to aggregate more of the available bandwidth subject to minimum interference with the PUs. The hidden terminal problem [2], also, should be solved to minimize the interference. For this purpose, the SU nodes should collaboratively sense the spectrum and decide which part of the spectrum is available to them. Collaborative sensing involves signaling through a *narrow-band* dedicated control channel (DCC). The DCC is a leased non-cognitive channel to control signalling between SUs. This is a small price to pay for achieving ultra-reliable data communication in a factory environment, for which we propose this system. In the factory environment PUs can be prior communication devices used for monitoring or control, or even they could be interferers within the range of our radios. Hence, we assume a fixed signaling channel.

Although signaling overhead plays a major role in cognitive radio networks, so far very limited studies have been performed in this area. To overcome the hidden node problem, Wiess et al [3] have proposed a *boosting protocol* where all the nodes in the network broadcast strong signals (i.e., shout) over the bands where they have observed PU activities thus reducing the need for a DCC. They argue, if boosting is done over short period of time and only for newly allocated subbands, it incurs insignificant interference to PUs and thus may be acceptable. However, in many situations this violates noninterference requirements of PU network. The robust method proposed in the same paper for broadcasting phase adds an extra 10% signaling overhead for achieving a desired reliability. Transform domain communication system and conventional contention scheme is proposed in [4] for access signaling of a network with a basestation. Visotsky, et al [5] analyze the probabilistic approach for collaborative detection under soft and hard information combining strategies. None of these works however considers the joint problem of detection and signaling to compute the overhead associated with spectrum exchange mechanism. Su and Zhang [6] study an analytical model of cognitive radio MAC with two types of channel sensing. The access mechanism, however, requires strong synchronization on mini-slot time scale. In [7], it is proposed that to minimize the interference with PUs a DCC should be used for signaling. The signaling overhead is then studied through computer simulations. The use of a DCC have also been brought up in [8]–[11]. An interesting outcome of the presence of unreliable SUs in cooperative sensing is discussed in [9].

In this paper, also, we consider a SU network in which a DCC is used for exchange of sensing information, i.e., for collaborative sensing. We consider a three-phase *cognitive cycle* consisting of a *sensing period*, a *collaborative signaling period*, and a *data transmission period*; see Fig. 1. During the sensing period, the broadband channel is divided into a number of subchannels and each SU senses these subchannels using a Filterbank [12], [13]. The signaling period is used to implement the collaborative sensing. Those SUs who have detected the PU activities will send broadcast messages (BMs) to other SUs to improve the detection results for the whole network. The BMs are transmitted randomly in synchronized time slots, i.e., in a random access slotted ALOHA, [2]. We assume a single hop network, meaning any broadcast by an SU in the network will be heard by all other nodes. For a BM to be successful only one SU has to broadcast. For instance, in Fig. 1, SU_0 and SU_1 have successful BMs in the second and last time slots, respectively. In the last phase, the data transmission begins over the available subchannels. The interference requirements of the PU network imposes restriction on the length of the cognitive cycle. We thus assume a fixed length for the cognitive cycle, and note that to maximize the bandwidth efficiency of the SU network, the sensing and signaling periods should be minimized. The sensing period depends on the width of the sensed band and the number of subchannels in it. Since for a given network these are predetermined, the sensing period is fixed. Thus,

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to maximize the bandwidth efficiency of the network, it is exceedingly important to design efficient MAC protocols that minimize the signaling time/overhead.

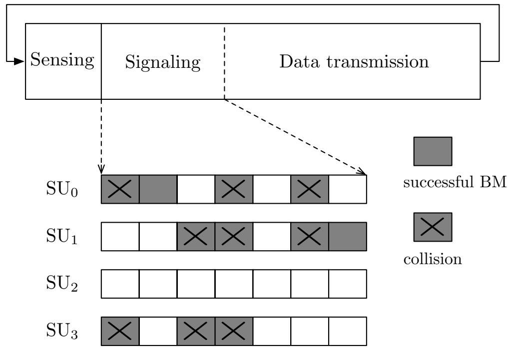

Fig. 1: The three phase cognitive cycle and the underlying signaling protocol.

For the signaling period, we propose a multiple access control (MAC) protocol. For the case where the data transmission channel consists of a single-band, we present a thorough analysis of the proposed protocol and discuss how one may adjust the protocol parameters to minimize the length of the signaling period subject to a desirable detection probability. We also develop a numerical procedure for analysis and optimization of the multiband case.

II. Problem definition

For simplicity of formulation, we only examine the case where all the SUs are in a close proximity to each other, (i.e., are in a single cell). Therefore, a successful transmission can be heard by all nodes, resulting in an upper-bound for detection probability in a realistic environment. Further, we assume the SUs are synchronized to use a DCC and since SUs are provided with wideband front-ends of a software defined radio [12], the overhead of switching between signaling and data communication is negligible.

Given a MAC protocol, our goal is to minimize the length of the signaling period subject to the constraint that each SU achieves a high detection probability by the end of the signaling period. We assume that the signaling period is time-slotted, and each BM is transmitted over the span of one time slot. At each time slot an SU can either transmit a BM or listen to the channel. We assume a τ-persistent ALOHA for BM transmission. this means that at each time slot, each SU sends a BM with probability τ, independent of other SUs. We also assume that after the sensing period, at time slot 0 each SU has detected each active PU band with probability q, independently of other SUs and other PU bands.

Assuming that there are M active PU bands, for an SU network of size N, let $P_D(n, N, M)$ denotes the probability that an arbitrary SU detects all the M PUs by the end of time slot n. Here, we have $P_D(0, N, M) = q^M$ which is the local detection probability right after the sensing period. We note that $P_D(n, N, M)$ is a non-decreasing function of n because as n increases, it is likely that an SU will receive broadcast messages from other SUs which will improve the detection probability. To minimize the length of the signaling period while maintaining a certain detection probability, we need to find the smallest n such that $P_D(n, N, M) \geq \gamma$, where $0 < \gamma < 1$ is a pre-set probability that is close to 1.

III. Single-band signaling protocol

Single-band signalling refers to the case where there is only one active PU band, viz., $M = 1$. We thus need to evaluate $P_D(n, N) = P_D(n, N, 1)$.

A. Definitions

Let us consider an arbitrary SU, say, SU_k. We define the following events for an N user SU network:

$$\begin{aligned} D_{n,N} &= \{\text{SU}_k \text{ detects PU no later than time } n\} \\ S_{n,N} &= \{\text{A successful BM received no later than time } n\} \\ \bar{S}_{n,N} &= \{\text{The first successful BM received at time } n\} \\ L_{d,N} &= \{d \text{ SUs detect PU at time } 0\} \\ C_{j,d} &= \{j \text{ out of } d \text{ SUs transmit at slot } 1\}. \end{aligned}$$

We also note that the following equations hold - $P(X)$ denotes the probability of the event X:

$$P(D_{n,N}) = P_D(n, N) \tag{1}$$

$$P(D_{0,N}) = P_D(0, N) = q \tag{2}$$

$$P(C_{jd}|\, L_{d,N}) = \binom{d}{j} \tau^j (1-\tau)^{d-j} \tag{3}$$

$$P(L_{d,N}) = \binom{N}{d} q^d (1-q)^{N-d} \tag{4}$$

$$P(S_{n,N}) = \sum_{i=1}^{n} P\big(\bar{S}_{i,N}\big) \tag{5}$$

B. The proposed protocol: τ-persistent slotted ALOHA

We let each SU transmit continuously with a probability of τ in successive time slots unless it received a successful BM. In this way, without using an acknowledgment (ACK) mechanism, most of the SU nodes stop transmitting early in the signalling period. In any case, signalling must stop after a preset$n = n_{opt}$ time slots. Also, to optimize the protocol, assuming a single-SU single-PU band detection probability q, one has to find τ that maximizes the probability of detection of PU for the whole network for $n \leq n_{opt}$.

We also recall that contention based carrier sense multiple access (CSMA) MAC layers with backoff scheme show a simple random access behavior in their steady state regimes [14], [15]. This behavior is analogous to τ-persistent slotted ALOHA in which the nodes broadcast with constant probability of τ in each time slot. The probability τ can be determined by knowing the traffic intensity and the choices over network parameters [15]. Therefore, the protocol that is proposed here and its analytical outcomes will be applicable to the more sophisticated protocols such as IEEE802.11 CSMA with backoff scheme.

If only one SU sends a BM, then due to the single-cell assumption, we assume that this BM will successfully reach

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every SU in the network, thus, the whole network becomes aware that the PU band in occupied. If two SUs or more attempt to send BMs during a time slot, this results in a collision, thus, we say the broadcast is unsuccessful. Since we do not consider any ACK mechanism in this protocol, once a SU sends a BM, it does not know whether it resulted in a successful transmission, or a failure (collision). Thus, the process of broadcasting continues for a predetermined number of time slots, $n - n_{opt}$, that we wish to minimize.

Let X^c denote the complement of event X and note that

$$\begin{aligned} P_D(n,N) &= P(D_{n,N}) \\ &= P(D_{0,N})P(D_{n,N}|D_{0,N}) + P(D^c_{0,N})P(D_{n,N}|D^c_{0,N}) \\ &= q \times 1 + (1-q)P(D_{n,N}|D^c_{0,N}) \\ &= q + (1-q)P\big(S_{n,N}\big|\, D^c_{0,N}\big) \\ &= q + (1-q)P(S_{n,N-1}). \end{aligned} \quad (6)$$

The last line follows because conditioned upon $D^c_{0,N}$, SU_k simply listens to the DCC and does not contribute to collaborative sensing, i.e., the time slot during which a BM is successfully sent has nothing to do with SU. This effectively reduces the size of the SU network to $N-1$. Next, we compute $P\big(\bar{S}_{n,N}\big)$, then $P(S_{n,N})$ from (5), and $P_D(n,N)$ from (6).

Applying the total probability law, $P\big(\bar{S}_{n,N}\big)$ may be expanded as

$$P\big(\bar{S}_{n,N}\big) = \sum_{d=1}^{N} P(L_{d,N})P\big(\bar{S}_{n,N}\big|\, L_{d,N}\big) \quad (7)$$

Note that in (7) we have automatically excluded the case of $d = 0$, because at least one local detection is needed for sending BMs. Among d SUs which have detected PU locally, we expand (7) based on the number of SUs that transmit in the time slot 1. For $n = 1$, we obtain

$$P\big(\bar{S}_{1,N}\big|\, L_{d,N}\big) = \binom{d}{1}\tau(1-\tau)^{d-1} = d \times \tau(1-\tau)^{d-1} \quad (8)$$

For $n > 1$, we get

$$\begin{aligned} P\big(\bar{S}_{n,N}\big|\, L_{d,N}\big) &= \sum_{j=0}^{d} P\big(\bar{S}_{n,N}\big|\, C_{jd}, L_{d,N}\big)P\big(C_{jd}\big|\, L_{d,N}\big) \\ &= P\big(\bar{S}_{n,N}\big|\, C_{1,d}, L_{d,N}\big)P\big(C_{1,d}\big|\, L_{d,N}\big) \\ &\quad + \sum_{j=0, j\neq 1}^{d} P\big(\bar{S}_{n,N}\big|\, C_{jd}, L_{d,N}\big)P\big(C_{jd}\big|\, L_{d,N}\big) \\ &= 0 \times P(C_{1,d}|L_{d,N}) \\ &\quad + \sum_{j=0, j\neq 1}^{d} P\big(\bar{S}_{n-1,N}\big|\, L_{d,N}\big)P\big(C_{jd}\big|\, L_{d,N}\big) \\ &= \sum_{j=0, j\neq 1}^{d} P\big(\bar{S}_{n-1,N}\big|\, L_{d,N}\big)P\big(C_{jd}\big|\, L_{d,N}\big) \\ &= P\big(\bar{S}_{n-1,N}\big|\, L_{d,N}\big) \sum_{j=0, j\neq 1}^{d} P\big(C_{jd}\big|\, L_{d,N}\big) \\ &= P\big(\bar{S}_{n-1,N}\big|\, L_{d,N}\big)\Big(1 - d \times \tau(1-\tau)^{d-1}\Big) \\ &= d \times \tau(1-\tau)^{d-1}\Big(1 - d \times \tau(1-\tau)^{d-1}\Big)^{n-1} \end{aligned} \quad (9)$$

where the third line follows since if only one BM was sent in the time slot 1 by SU_k (k being arbitrary) it would be a successful BM. In that case, all other SU nodes would stop broadcasting in subsequent slots, and the event $\bar{S}_{n,N}$ for $n > 1$ never occurs. If the number of BMs sent in the time slot 1 is not equal to one, all of the SUs are responsible for the transmission of a successful BM in the next $n - 1$ time slots. The last line of the (9) is obtained by recursive substitution for $P\big(\bar{S}_{n-1,N}\big|\, L_{d,N}\big)$ and using (8) at the end. It is also worth noting that for $n = 1$, (9) reduces to (8), thus, (9) is valid for any $n \geq 1$.

Finally, substituting (4) and (9) in (7), the result in (5), and using (6), we obtain

$$\begin{aligned} P_D(n,N) \,=\, q + (1-q)\sum_{i=1}^{n}\sum_{d=1}^{N-1}\binom{N-1}{d} q^d (1-q)^{N-d-1} \\ \times d \times \tau(1-\tau)^{d-1}\Big(1 - d \times \tau(1-\tau)^{d-1}\Big)^{i-1} \end{aligned} \quad (10)$$

To minimize the signaling period, using (10), for each τ, we can find the smallest n, denoted by $n_{\mathrm{opt}}(\tau)$, for which $P_D(n_{\mathrm{opt}}(\tau), N) \geq \gamma$. This gives us $n_{\mathrm{opt}}(\tau)$ which can then be used to find the optimum value of τ that minimizes n.

IV. Multiband Signaling Protocol Extension

A direct extension of the above analytical results to the case of multiband turns out to be a difficult problem. We thus approach the problem differently. We propose a matrix formulation of the problem that allows us to find the desired probabilities numerically through a simple procedure. The proposed method is also expected to pave the way for an analytical analysis in future. This study is underway.

We define a scheduling matrix for BMs. The scheduling matrix is a probability matrix which changes/evolves over time. In a multiband collaborative sensing, all SUs need to detect all of M PUs for successful detection. Each node continues broadcasting the entire set of locally detected PUs with probability τ in each BM time slot (τ-persistent slotted ALOHA), until hearing **enough** (i.e., one or greater) BMs containing more PUs than its local detection result. This is different from the case of single-band ($M = 1$), where detection is fulfilled when **one** BM has been successful.

A. Single-band case

For simplicity, we first present the case for single-band channel. Extension of the formulation to the multiband case then becomes straightforward. We refer to single-band channel as PU_0. Assuming that there is a total of T time slots, we define the scheduling matrix $\mathbf{S} = \{s_{ij}\}$ so that $0 \leq i < T$ denotes the time slot and $0 \leq j < N$ is the SU node number. $\mathbf{S}$ is a binary matrix defined as

$$s_{ij} = \begin{cases} 1 & \text{if } \mathrm{SU}_j \text{ should report } \mathrm{PU}_0 \text{ at slot } i \\ 0 & \text{otherwise.} \end{cases} \quad (11)$$

Moreover, as discussed below, $\mathbf{S}$ is an evolving matrix whose elements are updated at the end of each time slot. We also

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define the binary local detection vector $\mathbf{v}$ of PU_0 by N collaborative SUs with the elements of

$$v_j = \begin{cases} 1 & \text{if } SU_j \text{ detects } PU_0 \\ 0 & \text{otherwise.} \end{cases}$$

When $v_j = 1$ a BM is broadcasted by SU_j at time i if $s_{ij} = 1$ (i.e., if the transmission is scheduled for time i).

The scheduling matrix $\mathbf{S}$ is initialized as follows. It first filled with zeros and then for any j that has $v_j = 1$, the elements of the jth column of $\mathbf{S}$ filled with ones with probability of τ. This may be formulated as

$$\forall i, j,\ s_{ij}^{(0)} = \begin{cases} v_j & \text{with probability of } \tau \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

where the superscript 0 indicates the initial state of $\mathbf{S}$. Similarly, for $l > 0$, at the end of the time slot l, $\mathbf{S}$ is updated to $\mathbf{S}^{(l)}$ with the elements of $s_{ij}^{(l)}$ that are updated as follows. If at the time slot l a successful BM has been sent by SU_n, i.e., when at the lth row of $\mathbf{S}^{(l)}$ only $s_{l,n} = 1$, the ones in the succeeding row of $\mathbf{S}$ are set equal to zero (indicating that no more BM will be transmitted), except those in the nth column. Mathematically, this is expressed as

$$\begin{cases} \text{if } s_{ln}^{(l)} = 1 \text{ and } \forall j \neq n, s_{lj}^{(l)} = 0, \\ \text{then } \forall i > l \text{ and } j \neq n,\ s_{ij}^{(l+1)} = s_{ij}^{(l)} \widetilde{v_j} \end{cases} \quad (13)$$

Example: To clarify the above formulations, consider the case where

$$\mathbf{S}^{(0)} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 1 \end{bmatrix} \quad \text{and} \quad \mathbf{v} = \begin{bmatrix} 1 & 0 & 1 \end{bmatrix}.$$

Here, $T = 5$ and $N = 3$. Looking at detection vector $\mathbf{v}$, only SU_0 and SU_2 have detected PU_0. At time $l = 0$, SU_2 is scheduled for broadcasting at the time slots 1, 2 and 4, while SU_0 should broadcast at the time slots 1, 3 and 4. We may also note that all elements in column 1 of $\mathbf{S}$ are zero. This follows because SU_1 has not detected PU_0.

Looking back at $\mathbf{S}$, the BMs sent at the time slot 1 collide and the condition in (13) is not satisfied, hence, $\mathbf{S}^{(1)} = \mathbf{S}^{(0)}$. On the other hand, the BM sent by PU_2 at time slot 2 is a successful one. Hence, $\mathbf{S}$ is updated to

$$\mathbf{S}^{(2)} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Beyond the time slot 2, only SU_2 may broadcast, as other nodes have received a successful BM.

B. Simulation of multiband case

In the multiband case, one scheduling matrix is allocated to each PU band. In other words, a third dimension - the PU band dimension of size M - is added to $\mathbf{S}$. Accordingly, one may think of $\mathbf{S}$ having M slices each of size $T \times N$. Each slice/scheduling matrix is updated independently of the others in similar way to the single-band case when a successful BM, signaling the occupancy of the associated PU band, is transmitted. The sensing is considered as complete/fulfilled when all slices in $\mathbf{S}$ reach a state similar to $\mathbf{S}^{(2)}$ in the above example.

V. Numerical Results

In this section, we present a few numerical results to (i) corroborate the accuracy of (10) by simulating the proposed protocol according to the matrix formulation in Section IV; (ii) to numerically evaluate the performance of the proposed protocol in multiband channels. All simulations are done in a Monte Carlo fashion for more than 10000 runs, to achieve a standard deviation of less than 1%.

Fig. 2 shows the probability of detection for a network of size $N = 10$. In this figure, the analytical solution (10) is compared with simulation results generated following the matrix formulation presented in the previous section. As seen, the theoretical and simulation results match perfectly.

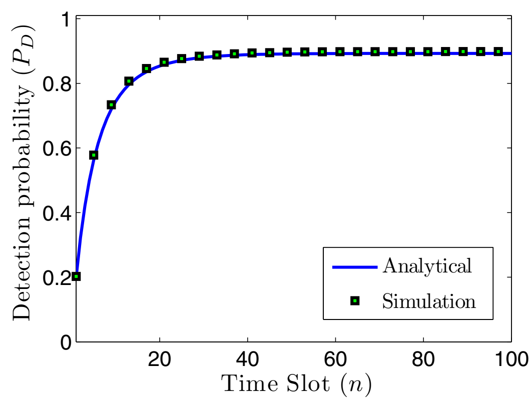

Fig. 2: Comparison of the analytical formula (10) and simulation results for simulation set up $N = 10$, $q = 0.2$, $\tau = 0.1$. The simulation is averaged after 10000 runs.

Fig. 3 illustrates how n_{opt} is changed with different network sizes, N, local detection probability, q, and broadcast probability, τ. It is also seen in this figure that for a given local detection probability, there exists a $0 < \tau_{opt} < 1$ that minimizes n_{opt}. When q is too small (e.g. $q < 0.26$) no n_{opt} exists. The choice of τ_{opt} (as an engineering decision) is relatively relaxed for large enough q (as seen in Fig. 3a) and for small enough network size (as seen in Fig. 3b). To elaborate, based on Fig. 3, for a detection confidence threshold $\gamma = 0.95$, having a network of size $N \leq 10$, and practical local detection of $q \geq 0.46$, any value of τ in the range 0.15 to 0.4 achieves $n \approx n_{opt} = 10$. Looking at the Fig. 3b one observes that for small τ having more SUs sense the spectrum (i.e. larger N) helps in collaborative detection, but the trend is reversed as τ increases and more BMs collide during signalling.

Fig. 4 shows the dependence of n_{opt} for a multiband case of $M = 5$ with different values of q and τ. The choice of optimal τ is more critical in this case. An upper bound for multiband is $n_{opt}(M) = M \times n_{opt}(1)$. This is confirmed by comparing Figs. 3a and 4 for the case of $q = 0.46$.

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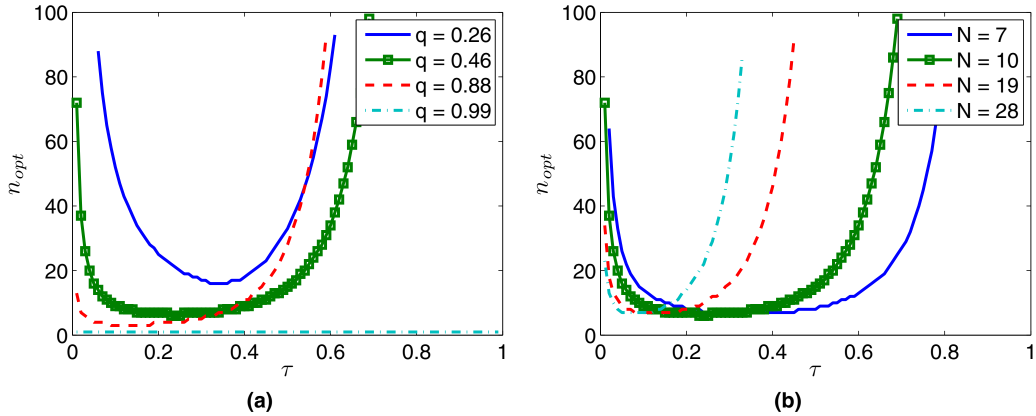

Fig. 3: The optimum number of time slots $n = n_{opt}$ as a function of broadcast probability τ, local detection probability q and network size N with $\gamma = 0.95$ confidence threshold: (a) shows n_{opt} for $N = 10$ over $0 \le \tau \le 1$ as q varies; (b) shows n_{opt} for $q = 0.46$ over $0 \le \tau \le 1$ as N takes different values. The case where $N = 10$ and $q = 0.46$ is presented in both figures as a reference.

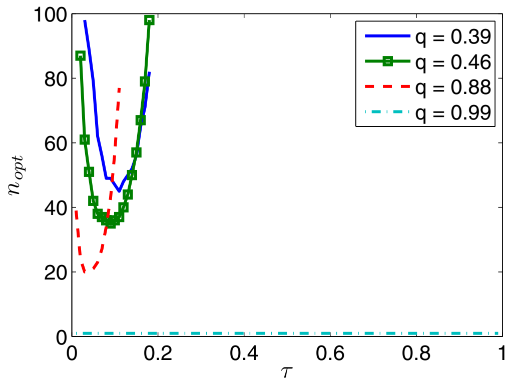

Fig. 4: Multiband simulation result for n_{opt} as a function of τ and q with $\gamma = 0.95$ for $M = 5$ and $N = 10$. The simulation is averaged after 10000 runs.

VI. Conclusions and Future Work

In this paper, we proposed a basic MAC protocol for collaborative sensing in cognitive radio networks. For a single-band channel, we derived a closed form solutions for the probability of detection. Using these results, we analyzed the effect of local detection probability and SU network size on the number of time slots required for achieving a desired detection probability. This analysis allowed us to pick the right network parameters for minimizing the signaling overhead and thus increasing its bandwidth efficiency. A matrix formulation, that easily scales to multiband channels was then developed. This formulation was applied to the networks with multiband channels for their optimization. More research to extend our analytical results of single-band case to multibands is underway. In the new formulation we rely on a generic distribution model for detection probability, which makes the modeling more realistic. Improvements to the proposed signaling protocol to relax on the range of τ that results in the n_{opt} is also desirable. Multiband results show that for large N the effect of collision requires incorporation of channel sequencing to increase performance.

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