The Impact of Reporting MAC on Cooperative Spectrum Sensing in Multiband Cognitive Networks

Xia Li, Marina Petrova, Petri Mähönen
Institute for Networked Systems, RWTH Aachen University, Germany
Email:{xia, mpe, pma}@inets.rwth-aachen.de

***Abstract*—Cooperative spectrum sensing generally consists of two consecutive stages: sensing and reporting, where sensors measure channels at the sensing stage and then use a multiple access protocol to report their local measurement results which we call the reporting MAC protocol. In this paper, we examine the impact of reporting MAC protocols on centralized cooperative sensing in multiband cognitive networks. Specifically, we study the applicability of TDMA and IEEE 802.11 CSMA/CA protocols for cooperative spectrum sensing reporting. A general mathematical model has been developed to quantify the achievable bandwidth utilization within a secondary system, which takes into account different combinations of sensor assignment strategies, reporting MAC, fusion rules, and regulatory constraints. The model allows the cross-layer optimization on the PHY and MAC layers of cooperative detection. The results show that the reporting control signaling can dominate the sensing overhead and result in significant capacity loss in some scenarios, which emphasizes the importance of using an efficient reporting MAC in cooperative sensing.**

I. Introduction

With the advent of cognitive radio technology, opportunistic Dynamic Spectrum Access (DSA) has been considered as a promising approach to mitigate the spectrum under-utilization problem and meet the increasing demand for wireless bandwidth. Spectrum sensing is one of the core techniques involved in DSA that enables secondary users to detect the absence or presence of licensed transmissions over primary bands and hence opportunistically exploit the vacant spectrum segments. It is well known that the sensing result from one single user is often not reliable enough to adequately protect primary services. Cooperative spectrum sensing has thus been introduced to exploit spatial diversity in wireless channels to combat the adverse effects of a single sensor.

The cooperative sensing generally consists of two consecutive stages: sensing and reporting, which are respectively implemented at the PHY and MAC layers. The PHY layer sensing concentrates on techniques to accurately detect the existence of primary user signals. In cooperation each secondary user is assigned a number of channels for measurements, and all the users share the observation results for jointly making a decision according to certain fusion rule. Important design issues associated with the sensing include sensor assignment over multiple bands, measurement time of each channel, sensing technique (e.g., energy or feature based detection) and fusion rule. On the other hand, the MAC layer schedules the frequency of spectrum sensing, and adopts a multiple access protocol to transmit measurement results of multiple sensors.

These two stages are tightly interrelated with each other and affect the design parameters of a cooperative spectrum sensing strategy. One typical example of such a parameter is the number of secondary sensors. Cooperative schemes require multiple collaborating sensors to perform channel measurements for better protecting the primary users. Correspondingly, the larger the number of sensors involved, the less the measurement time required for each sensor and thereby the more the exploitable spectrum opportunities within a secondary system. Nevertheless, a large number of sensors comes at the cost of high communication overhead of reporting measurements during information combining, which could significantly reduce the spectrum opportunities for secondary usage. As a result, it is necessary to select an appropriate number of sensors, which takes the cross-layer interaction into design consideration.

There is a rich literature on cooperative spectrum sensing. In [1] and [2], a sensing-throughput tradeoff problem is formulated to find the optimal PHY layer channel measurement time and fusion rule settings. The authors in [3]–[5] investigate the number of collaborating users under correlated shadowing. A survey of existing cognitive MAC protocols can be found in [6]–[8]. However, most of cooperative solutions have ignored or greatly simplified the multiple access protocols for reporting local measurements. When it comes to the reporting process, almost all the studies assume an ideal sequential time-slotted based reporting mechanism. The literature on reporting MAC for cognitive radio networks is rather limited at this time. There have been two recent studies towards proposing reporting MAC protocols for cognitive networks in [9] and [10]. They have developed time-slotted based solutions for distributed cooperative detection where in each slot the secondary sensors use contention based mechanisms to broadcast local measurement to each other.

In this paper, we examine the impact of reporting MAC protocols on centralized cooperative spectrum sensing in multiband cognitive networks. In centralized schemes, cooperating sensors report their observations to a fusion center over a shared media through multiple access protocols. Specifically, we select TDMA and IEEE 802.11 CSMA/CA multiple access mechanisms, and study their applicability as reporting MAC protocols in cooperative detection. To evaluate the cooperative sensing under cross-layer framework, a mathematical model has been developed to quantify the achievable spectrum usage within the secondary system under regulatory constraints. We

978-1-4673-5939-9/13/$31.00 ©2013 IEEE

have thoroughly analyzed multiple access behaviors of sensors. A novel analytical model for the CSMA/CA MAC has been developed and is different from the conventional approach used in the literature such as [11] where the MAC protocol is used to serve data networks with long haul traffic. Our analysis is unique in that in the reporting MAC each sensor transmits only one packet. The developed model is comprehensive enough to be used for the cross layer parameter design in cooperative spectrum sensing. The results show the reporting overhead can not be negligible especially with less efficient CSMA/CA MAC protocols in a low bandwidth context.

The rest of the paper is organized as follows. Section II describes the general model and assumptions used in our study. In Section III, we analyze the sensing and reporting phases. In Section IV, we conduct the numerical results analysis with conclusion given in Section V.

II. System Model Preliminaries and Problem Formulation

A. System Model Preliminaries

We consider a multiband cognitive radio network consisting of M licensed channels indexed from 1 to M, and one Common Control Channel (CCC) dedicated to fusion process of multiple secondary users. In our work, we do not address the problem of how a CCC is selected and set up. We assume the CCC temporally or permanently exists on either licensed or unlicensed bands and is always available for all secondary users of the entire network. We consider N number of cooperative secondary sensors are distributed over M channels, and send their observations to a fusion center which does not do measurement. Each sensor has a single half-duplex transceiver.

The centralized cooperative spectrum sensing requires all the secondary sensors to measure the channels simultaneously and report their observations quickly over a short period of time to ensure detection precision. For this purpose, a quiet period T_q is usually defined where all the secondaries in the cognitive networks stop transmitting on the M licensed channels and implement cooperative spectrum sensing. The quiet period consists of two phases: sensing and reporting. The sensors measure one or a number of channels during the sensing phase T_s and report their observations to the fusion center through CCC in the reporting phase T_r. In this study, we only consider the scenarios where spectrum sensing and reporting are performed in a time division manner with perfect synchronization among sensors. The reporting phase is started only when all the sensors finish their channel measurements, i.e., $i.e., T_q = T_s + T_r$. In our another work [12], we have also investigated the overlapped sensing and reporting phases ($T_q < T_s + T_r$) due to different sensing load of each sensor.

It is evident that a long quiet period could result in significant inefficiency of licensed bandwidth utilization within the secondary system especially when there are a large number of licensed channels, since all the M primary channels cannot be utilized by secondaries during the T_q.

B. Problem Formulation

The most common approach to evaluate a cooperative spectrum sensing scheme is to quantify the achievable throughput for a secondary system under the regulatory constraint that the target performance in the primary system is not violated. Considering a periodic sensing strategy where the sensing operation is performed every T period of time, the usable bandwidth in a secondary system is determined by $T - T_q$. In our system, the achievable normalized throughput of the secondary system can be expressed as:

$$\eta = \frac{T - T_q}{T} \cdot \frac{1}{M} \sum_{i=1}^{M} P_i(H_0)(1 - P_{fi}) \tag{1}$$

where $P_i(H_0)$ is the probability that there is no primary transmission on the ith channel, and P_{fi} is the false alarm probability of the ith channel. It should be noted that (1) is a simplified expression of achievable secondary bandwidth utilization. We have ignored the transmissions of secondary users during mis-detection, which could also contribute to the throughput if they are not corrupted by the ongoing primary signals. Since numerous spectrum measurement campaigns have shown that the actual licensed spectrum is severely underutilized in vast temporal and geographic dimensions (say less then 30%), we suppose that (1) dominates the achievable throughput within a secondary system and ignore the other aspects in our model.

We start from a base scenario and assume that $P(H_0)$ of each channel is identical for the sake of simplicity. Mathematically, the problem can be formulated as an optimization problem as follows:

$$\max \eta = \max_{T_q, P_F} \frac{T - T_q}{T}(1 - \frac{1}{M} \sum_{i=1}^{M} P_{fi}), \tag{2}$$

$$\text{s.t.} \quad \min_{i \in [1,M]} \{P_{di}\} \le P_d^*, \tag{3}$$

$$\text{or s.t.} \quad \frac{1}{M} \sum_{i=1}^{M} P_{di} \le P_d^*, \tag{4}$$

where P_{di} is the detection probability of the ith channel and P_d^* is the target detection probability with which the primary system is defined as being sufficiently protected. Two types of protection constraints are defined for a multiband primary system as indicated by (3) and (4) where the protection limits of a primary system are defined from single and average points of view, respectively. These two constraints can be considered either jointly or separately. Note that P_d^* in (3) and (4) can be different.

By observing (2)-(4), our target is transformed to derive the quantities of P_χ and T_q, where P_χ stands for the average detection ('χ' is 'D') or false alarm ('χ' is 'F') probabilities over M channels. These quantities depend on the sensing and reporting activities during the quiet period. The derivation of them can allow us to optimize the cross-layer cooperative parameters such as sensing time, sensing distributions, MAC operation parameters, number of sensors and number of sensed channels, etc.

III. Sensing and Reporting Analysis

In this section, we analyze the sensing and reporting phases which satisfy $T_q = T_r + T_s$. In T_s, N sensors are distributed over M channels. Each sensor select one or a number of channels to do channel measurements. In T_r, all the sensors transmit their sensing results through the shared media via multiple access schemes such as TDMA and CSMA/CA.

A. Sensing Phase T_s

Each sensor has to determine which channels should be sensed among the M channels. As random selection could result in missed detection of some channels, we consider static assignment of sensing into multiple channels. Assume N sensors are evenly distributed on M channels. Each sensor is assigned a fixed number of channels m and senses these channels in a sequential order. The number of sensors allocated per channel is kept the same and the number of measurements per channel is then given by $\frac{Nm}{M}$, on average. For simplicity, we assume $\frac{Nm}{M}$ is an integer. The detection performance of each channel is identical, and we have:

$$P_\chi = \frac{1}{M}\sum_{i=1}^{M} P_{\kappa i}(\frac{Nm}{M}) = P_\kappa(\frac{Nm}{M}), \quad Nm \geq M \tag{5}$$

where P_κ stand for the detection ('κ' is 'd') and false alarm ('κ' is 'f') probabilities.

The sensing duration T_s is given by:

$$T_s = \min(m, M)(\tau_s + t_{sw}), \tag{6}$$

where t_{sw} is the channel switching time, and τ_s is the amount of time employed for the primary signal collection on one channel by each sensor. We assume τ_s of each sensor is identical and is a fixed value. The values of T_s and τ_s should be as short as possible in order to maximize the exploitation of the detected opportunity.

B. Reporting Phase T_r

The length of reporting phase T_r mainly depends on two aspects: the amount of data sent by sensors and the transmission strategies of the local observations. The former is determined by the data fusion rules used and the number of reporting sensors. In this subsection, we develop general analytical models for TDMA and CSMA/CA based multiple access schemes, which can incorporate various PHY layer sensing and fusion techniques, and hence allow us to identify proper number of sensors in cooperative spectrum sensing.

1) **TDMA**: TDMA is a static multiple access scheme for which one time slice is designated to each sensor, and hence provides a clear guarantee on the completion time of data collection. Therefore, T_r is expressed as:

$$T_r = Nt_{data}, \tag{7}$$

where t_{data} is one time slot taken to transmit the data from one sensor to the fusion center. Note that here we do not consider the guard interval between two time slots.

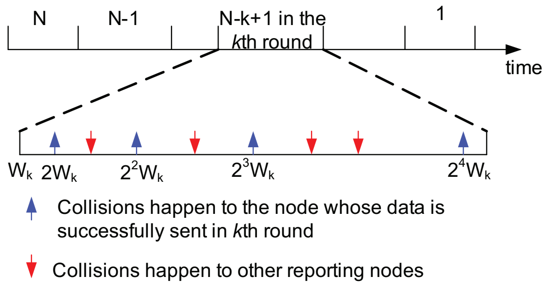

Fig. 1. An illustration of contention cycles. Each contention cycle has different collision probability due to different number of competing nodes.

Although conceptually simple and effective, TDMA faces several technical challenges in cognitive networks, which makes it difficult for a single design to fit in all deployment scenarios. A well-known challenge imposed to TDMA access is to require extremely tight synchronization among all the transmitters, since each sensor transmits only one small or medium sized data packet to the fusion center. In addition, when there is a significant fluctuation in the number or locations of reporting sensors (e.g., due to mobility), a slot assignment algorithm may necessarily be frequently implemented to identify appropriate sensors and schedule the transmission order, which could significantly increase complexity and overhead. This contradicts the proposition that the length of T_r should be kept as short as possible in order to maximize the exploitation of the detected opportunity.

2) **CSMA/CA**: We study the IEEE 802.11 MAC protocol with Distributed Coordination Function (DCF) due to its widespread deployment in reality. We consider two basic working modes of 802.11: DATA-ACK two-way and RTS-CTS-DATA-ACK four-way handshaking mechanisms. The reporting period T_r is largely dependent on the number of collisions, and can be derived as follows.

Two-way :

$$T_r = t_{bo} + (N + \aleph_c)(t_{difs} + t_{data} + t_{ack} + t_{sifs}), \tag{8}$$

Four-way :

$$T_r = t_{bo} + \aleph_c(t_{difs} + t_{rts} + t_{cts} + t_{sifs}) + N(t_{difs} + t_{rts} + t_{cts} + t_{data} + t_{ack} + 2t_{sifs}), \tag{9}$$

where $\aleph_c$ is the total number of collisions with which the packets need to be retransmitted; t_{rts}, t_{cts}, t_{data}, t_{ack}, t_{sifs} and t_{difs} are the transmission durations of RTS packet, CTS packet, DATA packet, ACK packet, SIFS and DIFS respectively; and t_{bo} is the time spent on backoff counting by all the sensors. As a matter of fact, t_{bo} is equal to the total backoff time experienced by the last reporting node, since the backoff processes of all the nodes take place concurrently.

To derive $\aleph_c$ and t_{bo}, we begin by estimating the collision probability and contention window evolution experienced by sensors. It should be noted that in cooperative spectrum sensing each secondary sensor has only one data packet to send. As soon as the measurement data is successfully sent to the fusion center, the sensor quits the contention. As shown in Fig. 1, let the interval between two successful consecutive transmissions be one round of contention. The number of reporting sensors in the first round is N. It decreases by one in each succeeding round. Correspondingly, the collision probability and number of collisions in each round are reduced as the number of reporting nodes decreases.

It is evident that the last successfully sent packet goes through $N-1$ rounds of contentions with different collision probability in each round. We are interested in modeling the process experienced by the last node. However, explicit formulation for the evolution of collision probability and contention window in each contention round as illustrated in Fig. 1 is fairly complicated and difficult to handle. We adopt a simplified approach to estimate all the backoff activities and collisions seen by the last node. We use the average value for a variable wherever possible.

Let W stand for the initial contention window of each node. The backoff window of each node is then uniformly distributed over $[1, W]$ with the average value of $W/2$; for simplicity, we use $W/2$ instead of $(W+1)/2$. If a node fails to send its data, its contention window size is doubled. This doubling continues in the case of each collision until the contention window reaches its maximum limit W_{max}. As a result, the contention window before the ith collision is $W_i^c = min(2^{i-1}W, W_{max}), i \geq 1$. From average point of view, the probability that a node attempts to transmit in an arbitrary slot before the ith collision is determined by its average backoff window $W_i^c/2$ and given by $2/W_i^c$ [11]. If one node begins transmission, the probability that other nodes do not transmit in the same slot is $(1-2/W_i^c)^{n_i-1}$, where n_i denotes the average number of contending nodes during the ith collision. The collision probability p_i is then expressed as:

$$p_i = 1 - (1 - \frac{2}{W_i^c})^{n_i-1}, \quad i \geq 1. \tag{10}$$

During the ith collision, $n_i(1-p_i)$ number of nodes transmit successfully and quit from the reporting stage. The rest $n_i p_i$ number of nodes suffer from the collision and continue accessing the shared channel with a larger contention window size. Therefore, the number of contending nodes in the $(i+1)$th contention becomes $n_{i+1} = n_i p_i$. n_i is given by:

$$n_i = \begin{cases} N & \text{if } i = 1 \\ n_{i-1}p_{i-1} & \text{if } i > 1. \end{cases} \tag{11}$$

Replacing p_{i-1} in (11) using (10), the number of contending nodes n_i can be expressed as a function whose parameters are n_{i-1} and W_{i-1}^c. Mathematically this is a recursive equation. Reverting back to the first collision, n_i becomes a function of initial window size W, the total number of reporting nodes N and the collision number i, and hence can be easily solved.

As the number of collisions i increases, the number of contending nodes n_i during each collision decreases and can eventually reach a positive value n_{i_L} no more than one after certain number of collisions i_L. This node can be thought of as the last reporting node. It experiences the $i_L - 1$th and i_Lth collisions with the probabilities $1 - n_{i_L}$ and n_{i_L} respectively. The total average backoff window of the last reporting node is then approximated by:

$$W_{bo} = n_{i_L} \sum_{i=1}^{i_L} \frac{W_i^c}{2} + (1 - n_{i_L}) \sum_{i=1}^{i_L-1} \frac{W_i^c}{2} \tag{12}$$

Hence, we solve t_{bo} in (8) and (9) as follows:

$$t_{bo} = W_{bo} t_{slot}. \tag{13}$$

It should be noted that in (11), the total number of colliding nodes does not mean the same number of collisions. A collision is attributed to more than one node having the same backoff window. We compute the probability that k nodes among n_i nodes select the same window slot as:

$$P_{col}(k) = \binom{n_i}{k} (\frac{1}{W_i^c})^k (1 - \frac{1}{W_i^c})^{n_i-k}, \tag{14}$$

where n_i is assumed to be an integer. The collision probability due to k nodes among n_i nodes is then given by:

$$Pr(k) = \frac{P_{col}(k)}{1 - P_{col}(0) - P_{col}(1)}, \quad k \geq 2, \tag{15}$$

where the denominator is a normalization term. Therefore, the total number of collisions $\aleph_c$ in (8) and (9) is given by:

$$\aleph_c = \sum_{i=1}^{i, n_i > 1} \aleph_c(i) = \sum_{i=1}^{i, n_i > 1} \sum_{k=2}^{n_{i+1}} n_{i+1} Pr(k), \tag{16}$$

where $\aleph_c(i)$ denotes the average number of collisions at the ith average collision.

IV. Numerical Results

This section presents the numerical results to assess the performance of cooperative spectrum sensing with reporting MAC considered and validate the developed analytical models. We have studied a variety of network setups with the number of channels M ranging from 1 to 10. We only present the case of $M = 6$ due to the same results observed. Note that for all results presented in this section, the simulation results agree very well with the analytical models. To make the graphs clear, we only present the analytical results.

A. Parameter Settings

For the sake of simplicity, we only consider the energy detection and an equal weight data fusion rule in the numerical evaluation. However, this does not exclude our model from being used for other detection and data fusion techniques. We consider the hypotheses of one channel sampling as:

$$H_0 : y = \mu \tag{17}$$

$$H_1 : y = s + \mu \tag{18}$$

Assume both the noise μ and the primary signal s are Gaussian, i.i.d distributed random processes and independent

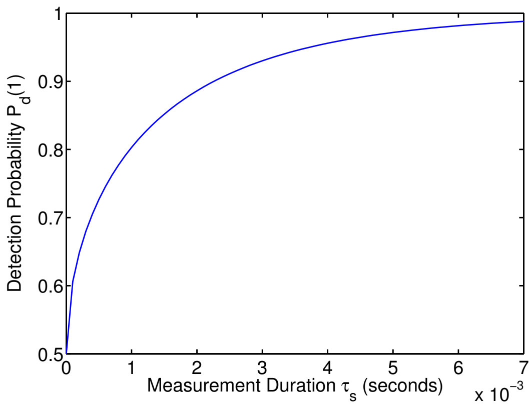

Fig. 2. The relationship between detection probability $P_d(1)$ and spectrum measurement duration τ_s.

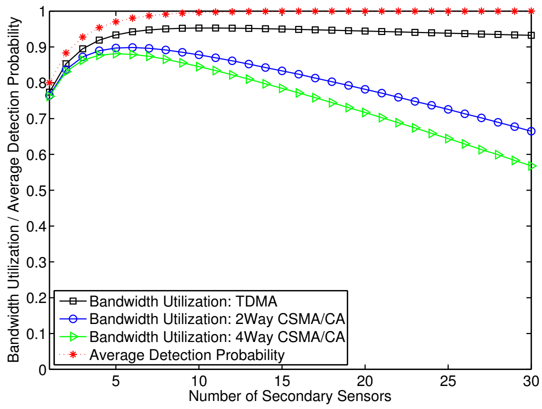

Fig. 3. A comparison of three multiple access schemes, $m = 6$, $Pd(1) = 0.8$.

of each other. For the measurement of the ith channel by n_i number of sensors, we use the test statistic:

$$T(y) = \frac{1}{n_i \tau_s f_s} \sum_{k=1}^{n_i} \sum_{j=1}^{\tau_s f_s} |y_k(j)|^2, \tag{19}$$

where f_s is the sampling rate and $\tau_s f_s$ is the number of samples. For a large number of samples, according to central limit theorem, $T(y)$ can be approximated by Gaussian distributions [1], the detection and false alarm probabilities of n_i cooperating sensors can be given by:

$$P_f(n_i) = Q\left((\frac{\epsilon}{\sigma_\mu^2} - 1) \sqrt{\frac{n_i \tau_s f_s}{2}} \right), \tag{20}$$

$$P_d(n_i) = Q\left((\frac{\epsilon}{(\gamma+1)\sigma_\mu^2} - 1) \sqrt{\frac{n_i \tau_s f_s}{2}} \right), \tag{21}$$

where $Q(\cdot)$ is the complementary distribution function of a standard Gaussian variable and is given by $\frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt$; σ_μ^2 is the variance of μ; γ denotes the received signal-to-noise (SNR) ratio of the primary signal measured at the secondary receiver under the hypothesis H_1; ϵ is the detection threshold.

The sensing sampling rate is assumed to be f_s = 6MHz. We set the target values of $P_d^*(1) = 0.9$ and $P_f^*(1) = 0.1$ with $\gamma = -15$dB, and derive a fixed value of $\frac{\epsilon}{\sigma^2}$ which is further used in (20) and (21) to compute the $P_d(n_i)$ and $P_f(n_i)$ later in this section. Given the fixed $\frac{\epsilon}{\sigma^2}$, the relationship between the detection probability of one user over one channel and the spectrum measurement duration τ_s is given in Fig. 2.

Channel switching time could take from 40 μs to 150 μs theoretically according to the settling time of VCO (Voltage Controlled Oscillator) for IEEE 802.11 [13]. In this study, we use 80 μs of channel switching time to assess the performance of cooperative spectrum sensing. The sensing period T is set to 200 milliseconds. Assume that the measurement data size of each sensor is independent of the measured number of channels and is 128 bytes. We adopt IEEE 802.11a as the MAC protocol with 6Mbps. Note that the minimum contention window W_{min} is set to 32 instead of the original value of 16 in order to avoid unnecessary collisions, since the number of nodes N in our study ranges from 1 to 30.

B. Results

In Fig. 3, we study and compare the three reporting MAC protocols. It can be seen that for all the three protocols there exists an optimal number of sensors with which the achievable secondary bandwidth utilization can be maximized under the imposed constraint of the average detection probability depicted by the red-dotted line. Obviously, TDMA can provide an ideal upper bound, and the two-way handshaking mechanism behaves better than the four-way case due to less transmission overhead. Note that here we study only the error-free CCC. The results will be different for the error-prone CCC since the four-way working mechanism was originally proposed to overcome the hidden terminal and transmission problems of radio links. In addition, it is observed that, given a regulatory requirement of 95% detection probability, around 9% and 11 $\sim$ 13% of the potential capacity are lost for TDMA and CSMA/CA respectively due to the sensing and reporting overhead. Of this overhead, 58% (TDMA) and 77 $\sim$ 80% (CSMA/CA) are attributed to control signaling and the rest to sensing. One can increase the CCC transmission rate or the sensing period to minimize the overhead. However, the former is not always feasible. A long sensing period may increase the danger of missed detection of primary system activities. Therefore, it is necessary to use an efficient reporting MAC in cooperative sensing.

The single detection probability is set to $P_d(1) = 0.8$ in Fig. 3 where the corresponding channel measurement time τ_s approximates 1 ms. Further in Fig. 4, we explore the relationship between the achievable bandwidth utilization and the single detection capability. It can be seen that the achievable bandwidth increases with the growth of single detection probability $P_d(1)$ when the number of secondary sensors N is small, and then decreases with the growth of $P_d(1)$ as N becomes large, even though a higher $P_d(1)$ has led to better average detection performance. This secondary throughput reduction is due to the increased measurement time

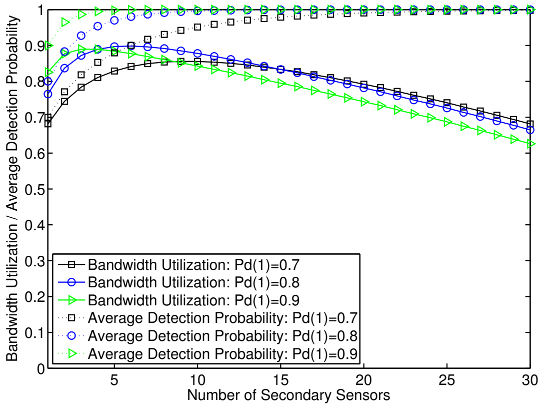

Fig. 4. A study on the impact of single detection capability, two-way access, $m = 6$.

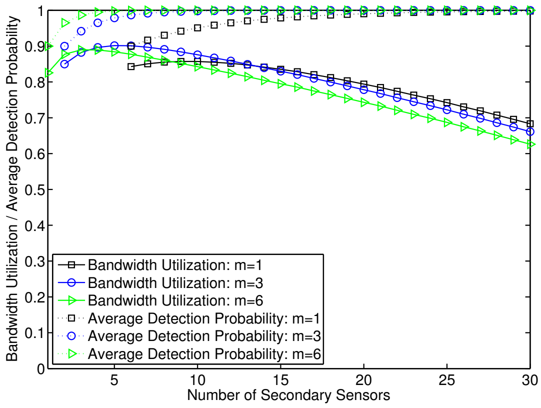

Fig. 5. A study on the impact of m, two-way access, $Pd(1) = 0.9$.

τ_s, which causes the value of T_s to become a dominant factor in (2) as N becomes large. Moreover, it is also observed that a good detection probability of each secondary user does not always lead to an optimal throughput capacity for the secondary system. For example, in the figure, given a target average detection probability of 0.95, the achievable bandwidth for $P_d(1) = 0.9$ ($\tau_s \approx 2$ ms) is maximized when $N = 3$. However, a better utilization can be reached just through simply adjusting the number of sensors to $N = 5$ with a reduced $P_d(1) = 0.8$ ($\tau_s \approx 1$ ms). In general, the adjustment of the number of sensors is much preferable in many deployment scenarios, since the good detection precision of a single sensor is sometimes hard to achieve due to the harsh radio transmission environment even though the hardware capability is there.

Fig. 5 shows the impact of number of channels measured by each sensor on the achievable secondary bandwidth utilization and average detection probability. Similar to Fig. 4, a larger value of m can lead to better detection performance, but at the cost of increased T_s, which then degrade the secondary exploitable bandwidth as N becomes large. The best secondary throughput performance is obtained when the conditions $N = 5$ and $m = 3$ are satisfied. This result, combined with previous findings, suggests the importance of a comprehensive cross-layer design for cooperative spectrum sensing strategies.

V. Conclusions

We have carried out an analytical study to assess centralized cooperative spectrum sensing over multiband cognitive networks by jointly taking into account a number of factors across the PHY and MAC layers, including regulatory constraints, sensor assignment, reporting MAC and fusion rules. Our model defines two types of constraints where the primary system is protected in terms of each single channel or the average performance of all channels. In addition, we have investigated the detailed transmission behaviors of TDMA and IEEE 802.11 MAC protocols, and developed a novel analytical model for 802.11 MAC due to the unique property of the reporting MAC in cooperative sensing. Our model can incorporate various PHY layer sensing and fusion techniques, and allows us to optimize the cross-layer cooperative parameters including sensing time, number of sensors and MAC layer operation parameters.

Acknowledgment

We acknowledge a partial financial support from European Union through EU FP7 project INFSO-ICT-248303 QUASAR. We also thank the support from DFG through UMIC research center.

References

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

[2] E. C. Y. Peh, Y.-C. Liang, and Y. L. Guan, "Optimization of cooperative sensing in cognitive radio networks: A sensing-throughput tradeoff view," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 9, pp. 5294–5299, 2009.

[3] E. Visotsky, S. Kuffner, and R. Peterson, "On collaborative detection of TV transmissions in support of dynamic spectrum sensing," in *IEEE DySPAN*, November 2005, pp. 338–345.

[4] A. Ghasemi and E. Sousa, "Asymptotic performance of collaborative spectrum sensing under correlated log-normal shadowing," *IEEE Communication Letter*, vol. 11, no. 1, pp. 34–36, Jan. 2007.

[5] Y. Chen, "Analysis of user selection in collaborative spectrum sensing with correlated shadowing," *Wireless Communications and Mobile Computing*, Feb. 2011.

[6] C. Cormio and K. R. Chowdhury, "A survey on MAC protocols for cognitive radio networks," *Ad Hoc Netw.*, vol. 7, pp. 1315–1329, September 2009.

[7] T. Vamsi Krishna and A. Das, "A survey on MAC protocols in OSA networks," *Comput. Netw.*, vol. 53, pp. 1377–1394, June 2009.

[8] A. D. Domenico, E. C. Strinati, and M. D. Benedetto, "A survey on MAC strategies for cognitive radio networks," *Communications Surveys & Tutorials, IEEE*, pp. 1–24, December 2010.

[9] J. Park, J. Hwang, and S.-L. Kim, "An efficient contention-based reporting protocol for collaborative spectrum sensing," *CogArt*, 2011.

[10] R.-R. Chen, K. H. Teo, and B. Farhang-Boroujeny, "Random access protocols for collaborative spectrum sensing in multi-band cognitive radio networks," *IEEE Journal of Selected Topics in Signal Processing*, vol. 5, no. 1, pp. 124–136, 2011.

[11] Y. C. Tay and K. C. Chua, "A capacity analysis for the IEEE 802.11 MAC protocol." *Wireless Networks*, vol. 7, no. 2, pp. 159–171, 2001.

[12] X. Li, M. Petrova, and P. Mähönen, "FCSS: CSMA/CA based fast cooperative spectrum sensing over multiband cognitive networks," in *IEEE PIMRC*, Sept. 2012.

[13] P. Bahl, R. Chandra, and J. Dunagan, "SSCH: slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks," in *MobiCom*, 2004, pp. 216–230.