FCSS: CSMA/CA based Fast Cooperative Spectrum Sensing over Multiband Cognitive Networks

Xia Li, Marina Petrova, Petri Mähönen
Institute for Networked Systems, RWTH Aachen University
Kackertstrasse 9, D-52072 Aachen, Germany
Email:{xia, mpe, pma}@inets.rwth-aachen.de

***Abstract*—The design of a cooperative spectrum sensing strategy has to take two aspects into consideration: from the physical layer perspective, a number of secondary users cooperatively measuring the channels to improve the detection performance, and from the MAC layer perspective, the users efficiently reporting their measurement results to a decision entity. Both operations are time critical and required for efficient spectrum opportunity exploitation by the secondary system. However, most of the existing cooperative solutions in the literature ignore the reporting process or over simplify it by assuming a perfect time-slotted multiple access. In this paper, we consider a CSMA/CA based reporting process. We show that fairness no longer plays a role in multiple access of the reporting process. Instead, fastness becomes the dominant measure of the MAC protocol. We propose a Fast Cooperative Spectrum Sensing (FCSS) scheme over multiband cognitive networks by exploiting concurrent occurrence of the spectrum sensing activities and the reporting process with an improved CSMA/CA based MAC protocol. The proposed scheme incorporates a joint static and random sensor assignment algorithm over multiple channels. A mathematical model has been developed for evaluating the performance of FCSS and serving as a basis to select appropriate parameters.**

I. INTRODUCTION

Dynamic spectrum access has emerged as a promising technology to solve the spectrum under-utilization problem by opportunistically utilizing the vacant portions of licensed spectrum. Geo-location database and spectrum sensing are recognized as two major approaches to the detection and exploration of spectrum holes in opportunistic spectrum access. For the former, the FCC's recent authorization on the implementation of geo-location databases for TV white spaces makes this technology viable in an increasing number of market niches. The DVB-T spectrum coverage is stable in spatial dimension and hence suitable for the database approach which requires less frequent database updates and checks. On the other hand, spectrum sensing can be thought of as an alternative or complementary method to the database. It is a technique for making prompt detections of time-varying spectrum availability of licensed channels. In this paper, we focus on cooperative spectrum sensing over multiband cognitive networks.

Cooperative spectrum sensing exploits spatial diversity in wireless channels to combat the adverse effects (such as shadowing and hidden nodes) confronted by sensing from a single site. Spectrum measurements from multiple secondaries located at various sites are combined to estimate the likelihood of channel availability. The cooperation requires all the sensors to carry out the spectrum sensing simultaneously over a short period of time and report their observations quickly after sensing in order to ensure an accurate and timely result. For this purpose, a quiet period is usually defined where all the secondaries in the cognitive network stop their transmission attempts on licensed channels and implement cooperative spectrum sensing. From the secondary system's perspective, a long quiet period could result in significant inefficiency in bandwidth utilization especially when there is a large number of licensed channels. Hence, there is a pressing need to design optimal sensing and reporting strategies for the quiet period, which should be kept as short as possible in order to maximize the exploitation of the detected spectrum opportunity under satisfied sensing reliability.

A number of strategies can be used to shorten the sensing and reporting time. The reduction of the sensing time can be done through either increasing the number of sensors or adopting advanced sensing techniques or powerful hardware. On the other hand, to minimize the reporting time, a Common Control Channel (CCC) is usually used for information combining. The fundamental approach is to allocate a large bandwidth to the CCC, which is, however, not always feasible. Some research has been carried out to enhance the CCC bandwidth utilization efficiency. One solution is to limit the traffic load through adjusting the number of reporting sensors or the size of local measurement data. In [1] and references therein, several schemes have been developed to censor and quantize the local measurement results. In [2], any sensor that has detected the existence of primary users signals in a common designated slot. The decision is made by summing up all power of the slot. Another solution class for efficient bandwidth utilization is to use efficient modulation and transmission protocols such as CDMA and TDMA. However, it is noted that almost all the studies on cooperative spectrum sensing have ignored the reporting process or greatly simplified it by assuming a perfect time-slotted based sequential access [3]–[5]. Although contention based multiple access is considered in [6] and [7], their proposals are time-slotted based schemes where in each slot the sensors contend to access the shared media. A drawback of the time-slotted access is that it requires tight time synchronization among all the users, since each user transmits only one small or medium sized data packet. In addition, when fluctuation in the number of reporting sensors is frequent (e.g., due to mobility), identifying proper number of time slots and scheduling the transmission order are extremely challenging.

In this paper, we consider a CSMA/CA based reporting process, and develop a novel cooperative strategy for multiband cognitive networks, which we call Fast Cooperative Spectrum Sensing (FCSS), by exploiting concurrent occurrence of distributed channel measurements and an improved CSMA/CS based multiple access protocol. We find out that, since each cooperating sensor has only one data packet to send, the main role of the reporting MAC protocol is different from traditional wireless MAC protocols which are employed to regulate and balance network resources among nodes. The fairness issue becomes trivial. The dominant measure for the reporting MAC protocol is how fast the local observations can be reliably transmitted to the fusion center. We propose a protocol enhancement to the IEEE 802.11 MAC protocol because of its widespread deployment. Our proposal is a simple modification of 802.11 MAC and shows non-negligible performance improvement. Moreover, to evaluate the FCSS scheme, we have developed a model to quantify the achievable spectrum usage within the secondary system under the constraint that the primary system is sufficiently protected. The model can be used to optimize selected network parameters of the FCSS strategy including the number of sensors and sensing distribution settings over multiple bands.

The rest of the paper is organized as follows. The proposed FCSS is detailed in Section II. In Section III, a mathematical model for determining the optimum sensing parameter settings of FCSS is developed. We then present numerical results in Section IV and conclude the paper with Section V.

II. Scheme Illustration

We consider a multiband cognitive radio network consisting of M licensed channels and one CCC dedicated to the fusion process of multiple secondary users. In this work, we do not address the problem of how a CCC is selected and set up. The CCC is assumed to temporally or permanently exist on either licensed or unlicensed bands and is always available for all secondary users of the entire network. Let N denote the number of cooperating sensors. Each secondary sensor has a single half-duplex transceiver. We outline the key design elements of our proposed FCSS as follows.

A. Concurrent Sensing and Reporting

A fundamental notion in our strategy is that FCSS exploits concurrent occurrence of sensing and reporting to shorten the quiet duration. Fig. 1 illustrates a quiet period T_q comprising the overlapped sensing phase T_s and reporting phase T_r. The overlapped duration is denoted by T_{sr}. All the sensors will firstly perform sensing during T_{sa} and then enter the reporting phase T_r during which part of the sensors conduct the channel measurement when the CCC is occupied. Note that the sensing phase T_s ends earlier than T_r because all the sensors become inactive during the transmission of the last reporting node. Obviously, $T_q < T_s + T_r$ in this case.

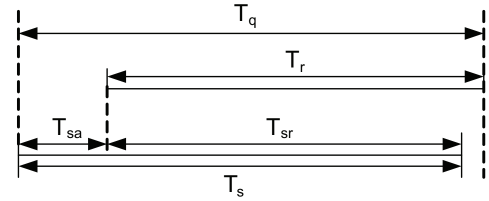

Fig. 1. A quiet period with overlapped sensing and reporting phases

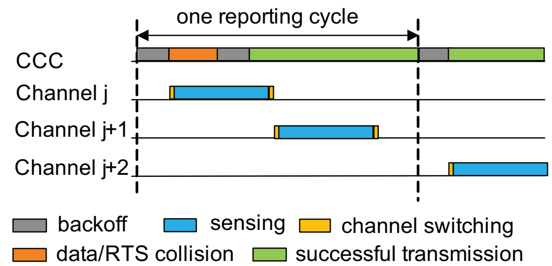

Fig. 2. An illustration of implementation details during T_{sr}. In the two-way handshake, the length of the collision box approximates that of the successful transmission box.

Fig. 2 depicts the implementation details for the overlapped duration T_{sr}. The reporting phase can be viewed as a cyclic process where one cycle is defined as the interval between the start of a new packet transmission attempt and the start of the next packet transmission attempt. For each cycle, when the CCC channel is sensed idle, all the reporting nodes compete to access the channel through random backoff in order to report their measurement results. When the CCC channel is sensed occupied, the reporting sensors proceed to measure the states of one or more licensed channels.

In the scheme, after completing the measurement of one channel, each sensor switches to the CCC channel again to check its availability instead of continuing to sense more number of channels. If the CCC is still detected busy, the sensor will jump to measure another licensed channel. This process is repeated until the CCC is found idle or the number of measurements within one cycle reaches its limit. The number of channels measured within one cycle is limited by the time spent on reporting one data packet and is given by:

$$m_k = \lfloor \frac{t_{dk}}{\tau_s + 2t_{sw}} \rfloor, \tag{1}$$

where the subscript k stands for the kth cycle; $\lfloor * \rfloor$ rounds the $*$ to the nearest integer no more than $*$; t_{dk} is the duration to transmit the kth data packet; τ_s is the amount of time employed for the primary signal collection on one channel by each sensor; and t_{sw} is the channel switching time.

The operation of switching to the CCC channel after every channel measurement comes at the cost of increased channel switching time, but in return for much lower computation complexity, and broader generality and applicability. Those who have completed reporting the data stop their sensing activities. With this approach, each sensor may observe different number of channels and make a report with varied sized data packets.

TABLE I
TRANSMISSION TIME FOR ONE MAC DATA FRAME
(DATA SIZE: 1-1024 BYTES)

Protocol	DATA-ACK	RTS-CTS-DATA-ACK
802.11a (6Mbps)	0.1 ms-1.6 ms	0.3 ms-1.9 ms
802.11b (1Mbps)	1 ms-10 ms	2 ms-11 ms

It should be noted that the value of m_k in (1) may be equal to zero, which implies a relatively fast reporting process. The secondary sensors need not to perform spectrum sensing during the reporting phase. The sensing phase T_s and reporting phase T_r are hence distinct and temporally separated. The reporting starts only when all the sensors finish their channel measurements. The rationale behind our FCSS strategy is that the CCC channel has a limited bandwidth, so that the reporting duration is long enough to allow some sensors to observe more channels simultaneously. The typical value of τ_s ranges in the order of tens of microseconds to tens of milliseconds depending on the hardware processing capabilities and the adopted sensing techniques such as energy or feature detections. Table I lists the approximate transmission time of one MAC data frame (data size from 1 to 1024 bytes) for the data rates of 1Mbps and 6Mbps in IEEE 802.11a and 802.11b. It is clear that 802.11b is favorable. In the real world, the CCC channel could be narrower with much lower data rates, which makes our proposal feasible.

B. Joint Static and Random Sensing Distributions

Each sensor has to determine which channels should be sensed among M channels. A joint static and random sensor assignment algorithm has been adopted in our scheme. As shown in Fig. 1, T_s is comprised of two parts: T_{sa} and T_{sr}. A static assignment rule is used in T_{sa}, in which all the sensors are evenly distributed on M channels. Each sensor is assigned the same fixed number of channels m_{sa} and senses these channels in a sequential order. During T_{sr}, without tuning into the CCC channel, one has no means to know which sensors have made reports and which channels the others have measured. This makes an equal assignment of measurements over all the channels infeasible. Hence, we employ the random channel selection algorithm where each sensor randomly select unmeasured channels to perform sensing. The number of measured channels by each sensor depends on the length of T_{sr} and how early one sensor can report its measured results. The later one sensor reports its observation, the more number of channels it could measure.

C. Enhanced MAC Protocol for Fast Reporting

We consider contention based MAC protocols for the reporting process. The traditional wireless CSMA/CA MAC protocols were originally designed to serve data networks with long haul traffic where each node has a queue of data to transmit. They use complex contention resolution mechanisms (e.g., exponential backoff) to avoid bandwidth loss due to transmission collisions and hence regulate the network resources among nodes to meet the throughput and fairness requirement. Such mechanisms usually incur high contention overhead. Different from the long-haul traffic network, each node in the data fusion process has to transmit only one data packet through a multiple access process. It does not matter whether one packet arrives earlier than the others or consumes more bandwidth. The fairness is no longer a desirable quality to be sought. Thus, a node experiencing collisions does not mean that it has to back off with a larger contention window and spare resources to maintain a fair usage. On the contrary, more attention should be paid to transmitting local measurements as fast as possible. In this paper, we propose an enhancement to IEEE 802.11 DCF MAC protocol, which, although being a simple modification to 802.11 MAC, significantly reduces the complexity of contention resolution algorithm and shortens the reporting duration T_r. The detailed implementation of our scheme is as follows.

As long as a sensor has a packet to send, it waits until the channel is sensed idle for a DIFS period denoted by t_{difs}. Let W denote the initial contention window of each node. As shown in Fig. 2, during the first cycle, all the sensors randomly select their backoff windows from $[1, W]$ after t_{difs} and compete to report their data. Once a transmission takes place, the others hearing the channel busy proceed to measure primary channels. In the case of a collision, the colliding sensors do not double their contention windows like IEEE 802.11. Instead, they continue to compete for the CCC at succeeding contentions with a certain contention window, W_c, which can be a reduced window of W or the same as W. The nodes failed in the succeeding contentions restore their contention windows to W and move to perform the measurement task on the primary channels. The reason not to increase the contention window in the case of collisions is that the number of colliding nodes (i.e., contending nodes in the succeeding contentions) is fairly small, which indicates a rather low probability of collisions in the succeeding contentions given a certain contention window W_c. We derive the number of colliding nodes in one collision and provide the proof as follows.

Proof: For N nodes contending to make reports, the probability that i nodes select the same backoff window follows a binomial distribution and is given by:

$$Pr(i) = \binom{N}{i}(\frac{1}{W})^i(1-\frac{1}{W})^{N-i}, \tag{2}$$

where $Pr(i)$ is a monotonically decreasing function of i for $i > 0$ and a monotonically increasing function of N. In the cases of 802.11a ($W = 16$) with $N = 16$, and 802.11b ($W = 32$) with $N = 32$, the probability that there are 4 contending nodes in one arbitrary slot is as low as ~ 0.01, which indicates that the number of colliding nodes in one collision is hardly greater than 4. ■

For such a small number of nodes, a relatively small value of W_c can be selected so that collisions hardly occur. We select $W_c = 16$ in our study. As a result, the contention overhead in FCSS can be significantly reduced.

III. Mathematical Model

This section presents a mathematical model for the proposed FCSS protocol. The methodology is similar to our previous work in [8]. The model takes into account sensing distribution algorithm, multiple access protocol, fusion rules and regulatory constraints, and yields the achievable throughput within the secondary system under the constraint that the primary system is sufficiently protected. It can be used to jointly optimize the network parameters of FCSS at the PHY and MAC layers.

A. Problem formulation

Considering a periodic sensing strategy where the sensing operation is performed every T period of time, the achievable normalized throughput of the secondary system can be expressed as:

$$\eta = \frac{T - T_q}{T} \cdot \frac{1}{M} \sum_{i=1}^{M} P_i(H_0)(1 - P_{fi}) \tag{3}$$

where $P_i(H_0)$ is the probability that the ith channel is free from primary transmissions, and P_{fi} is the false alarm probability of the ith channel. It should be noted that (3) is a simplified expression of achievable secondary throughput. In practice, the secondary users also transmit when a miss detection takes place, which contributes to the throughput if the transmissions are not corrupted by the ongoing primary signals. In our model, we suppose that (3) dominates the achievable throughput and ignore the other aspect, since numerous spectrum measurement campaigns have shown that the primary activity probability $P_i(H_1)$ is very small in reality (say less than 0.3), which is also a key factor in making the exploration of secondary usage economically feasible.

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

$$\max \zeta = \max \frac{T - T_q}{T}(1 - \frac{1}{M} \sum_{i=1}^{M} P_{fi}), \tag{4}$$

$$\text{subject to } \min_{i \in [1,M]} \{P_{di}\} \leq P_d^*, \tag{5}$$

$$\text{or subject to } \frac{1}{M} \sum_{i=1}^{M} P_{di} \leq P_d^*, \tag{6}$$

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. We have considered two types of protection constraints for a multiband primary system as indicated by (5) and (6) where the protection limits of multiple channels 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 (5) and (6) can be different.

By observing (4)-(6), 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. P_χ is a function of the number of cooperating sensors N, dependent on how the N number of sensors are assigned to measure M channels. T_q meets $T_q = T_{sa} + T_r$. We analyze the sensing and reporting phases, and derive these quantities in the following two subsections.

B. Reporting Phase T_r

Since the value of T_s depends significantly on the length of T_r, we first derive T_r. The length of reporting phase T_r mainly depends on two aspects: the amount of data sent by sensors and the MAC protocol used. The former is determined by the number of reporting sensors and data fusion rules. It is obvious that the hard decision fusion rule has the least T_r since each sensor makes local decisions and can use one or several bits to report the existence of primary transmissions. On the contrary, the soft fusion rule requires the sensors to send lengthy data to the fusion center which consumes more bandwidth at the cost of increased T_r.

We consider a transmission error-free CCC channel. As shown in Fig. 2, the reporting phase of the FCSS scheme can be modeled as a cyclical process in terms of each successfully reported data. The reporting duration T_r is then given by:

$$T_r = \sum_{k=1}^{N} T_{rk} + t_{bo}, \tag{7}$$

where T_{rk} is the duration of the kth reporting cycle without taking into account the backoff time in the first contention, and t_{bo} is the total time spent on backoff counting in the first contention of all the cycles. The time T_{rk} is given by:

$$T_{rk} = \begin{cases} t_{difs} + p_k t_{col} + t_{dk} & k < N, \\ t_{difs} + t_{dk} & k = N, \end{cases} \tag{8}$$

where p_k denotes the collision probability and is approximated by $1 - (1 - \frac{1}{W})^{N-k}$; t_{col} and t_{dk} are the durations for one collision and one successful data transmission respectively. We here make an assumption to ignore any collision in the second contention of each reporting cycle due to the small number of contending nodes derived in (2). We consider two operation modes of 802.11 DCF: DATA-ACK two-way and RTS-CTS-DATA-ACK four-way handshaking mechanisms. The collision and successful transmission durations t_{col} and t_{dk} are respectively given by:

Two-way :

$$t_{col} = \frac{W_c}{2} t_{slot} + t_{difs} + t_{data} + t_{ack} + t_{sifs}, \tag{9}$$

$$t_{dk} = t_{data} + t_{ack} + t_{sifs}. \tag{10}$$

Four-way :

$$t_{col} = \frac{W_c}{2} t_{slot} + t_{difs} + t_{rts} + t_{cts} + t_{sifs}, \tag{11}$$

$$t_{dk} = t_{rts} + t_{cts} + t_{data} + t_{ack} + 2t_{sifs}. \tag{12}$$

Note that t_{data} of each reporting cycle may vary since each sensor could measure a different number of channels.

The time 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. Then, t_{bo} can be approximated by:

$$t_{bo} = t_{slot}\frac{W}{2}(1 + p_1 + \cdots + p_i + \cdots), \tag{13}$$

where p_i stands for the probability that the last reporting node experiences the ith collision. Let x_i denote the number of contending nodes in the ith collision. The average backoff window during each collision is $\frac{W}{2}$. Collisions take place in one slot only when more than one node has active transmission in that slot. The probability p_i is derived as

$$p_i = 1 - (1 - \frac{2}{W})^{x_i - 1}, \tag{14}$$

where $x_i = x_{i-1}p_{i-1}$. The computation of p_i stops until $x_i < 1$. Reverting back to the first collision where $x_1 = N$, t_{bo} can be easily solved.

C. Sensing Phase T_s

As explained in section II-B, T_s consists of two phases: T_{sa} and T_{sr}, where static and random sensor assignment strategies are used respectively. The duration T_{sa} can be easily obtained by:

$$T_{sa} = m_{sa}\tau_s + m_{sa}t_{sw}. \tag{15}$$

The average detection performance P_χ depends on how the N number of sensors are assigned to measure M channels. In T_{sa}, the number of measurements occurred on each channel is identical and given by $\frac{Nm_{sa}}{M}$, on average. For simplicity, we assume $\frac{Nm_{sa}}{M}$ is an integer. In T_{sr}, the number of channels measured by each sensor could be different. Let $\mathbf{n} = \{n_1, n_2, \cdots, n_M\}$ denote the number of measurements over channels $1, 2, \cdots, M$ during T_s. Then $\mathbf{n}$ meets the condition:

$$\sum_{i=1}^{M} n_i = \min(MN, m_{sa}N + m_{sr}), \forall n_i \in [\frac{Nm_{sa}}{M}, N] \tag{16}$$

where m_{sr} stands for the total number of measurements over M channels during T_{sr}. It is dependent on how long T_r lasts, and is derived as:

$$m_{sr} = min\left(\sum_{k=1}^{N-1}(N-k)m_k, (M - m_{sa})N\right), \tag{17}$$

where m_k is given by (1).

The sensing distribution problem can be thought of as distributing a number of nodes $m_s = \sum_{i=1}^{M} n_i$ into M channels with equal probability $\frac{1}{M}$. Thus, the probability that channels $1, 2, \cdots, M$ get $n_1, n_2, \cdots, n_M$ number of measurements respectively, is given by a multinomial distribution:

$$\frac{m_s!}{n_1!n_2!\cdots n_M!}(\frac{1}{M})^{m_s}. \tag{18}$$

This probability should be normalized over the space defined by (16) to ensure a valid probability distribution between $[0, 1]$. Hence, the probability that channels $1, 2, \cdots, M$ get $n_1, n_2, \cdots, n_M$ number of measurements respectively, is given by:

$$f(\mathbf{n}) = \frac{\frac{(m_s)!}{n_1!n_2!\cdots n_M!}(\frac{1}{M})^{m_s}}{\sum_{\mathbf{n}} \frac{(m_s)!}{n_1!n_2!\cdots n_M!}(\frac{1}{M})^{m_s}} = \frac{\frac{1}{n_1!n_2!\cdots n_M!}}{\sum_{\mathbf{n}} \frac{1}{n_1!n_2!\cdots n_M!}}, \tag{19}$$

where the denominator is the sum of all combinations of $\mathbf{n}$ satisfying (16).

Based on (19), P_χ is expressed as:

$$P_\chi = \frac{1}{M}\sum_{\mathbf{n}}\left(f(\mathbf{n})\sum_{i=1}^{M} P_{\kappa i}(n_i)\right), \tag{20}$$

where $P_{\kappa i}$ stands for the detection ('κ' is 'd') or false alarm ('κ' is 'f') probabilities of the ith channel and is determined by the number of measurement n_i conducted on the channel.

Note that it is necessary to find an appropriate m_{sa} to maximum the detection accuracy and efficiency. In the case of $N << M$, which could imply a small m_{sr}, a relatively large value should be selected for m_{sa}. Otherwise, a small value of m_{sa} is set to ensure there is at least one measurement during T_{sa} in the case of a large N.

IV. Numerical Results

This section presents the numerical simulations that were done to assess the performance of our proposed FCSS scheme and validate the developed analytical model. We have studied a variety of network setups with M ranging from 1 to 10. We only present the case of $M = 6$ with the two-way handshaking mechanism due to the same results observed.

A. Parameter Settings

For the sake of simplicity, we only consider the energy detection in the numerical evaluation. We assume the secondary sensors are sparsely dispersed across one region and are in well selected locations which can minimize the correlated shadowing effects. Correspondingly, a simple cooperative fusion rule is used in our study by assuming an equal weighting of measurements from all the sensing sites. 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:

$$H_0 : y = \mu, \tag{21}$$

$$H_1 : y = s + \mu. \tag{22}$$

Assume both the noise μ and the primary signal s are Gaussian, i.i.d distributed random processes and independent of each other. For the measurement of the ith channel by n_i number of sensors, we use the test statistic:

$$T(y) = \frac{1}{n_i\tau_s f_s}\sum_{k=1}^{n_i}\sum_{j=1}^{\tau_s f_s}|y_k(j)|^2, \tag{23}$$

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

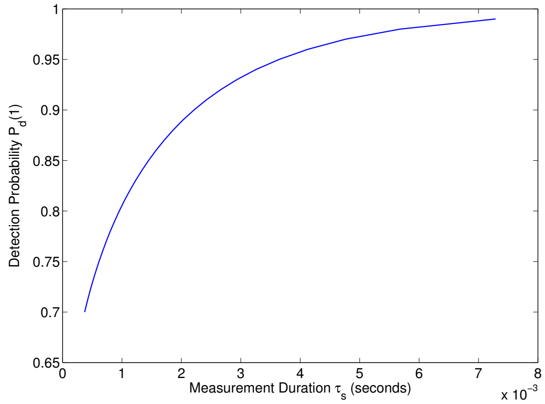

Fig. 3. The relationship between detection probability $P_d(1)$ and spectrum measurement duration τ_s.

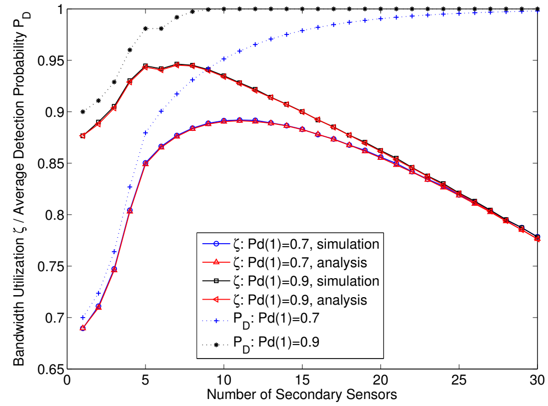

Fig. 4. A comparison of simulation and analytical results. The selection of m_{sa} meets the condition that each channel is sensed at least once during T_{sa}.

limit theorem, $T(y)$ can be approximated by Gaussian distributions [9], the detection and false alarm probabilities of n_i cooperating sensors can be given by:

$$P_f(n_i) = Q\left((\frac{\epsilon}{\sigma_\mu^2} - 1)\sqrt{\frac{n_i \tau_s f_s}{2}} \right),$$
$$P_d(n_i) = Q\left((\frac{\epsilon}{(\gamma+1)\sigma_\mu^2} - 1)\sqrt{\frac{n_i \tau_s f_s}{2}} \right), \quad (24)$$

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 $\gamma = -20$dB, and derive a fixed value of $\frac{\epsilon}{\sigma^2}$ which is further used in (24) 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. 3.

The channel switching time is set to 80 μs to assess the performance of cooperative spectrum sensing. The sensing period T is set to 1 second. Assume that the measurement data size of each sensor is independent of the measured number of channels and is 128 bytes. We adopt one of the most widely quoted analytical models of IEEE 802.11 MAC as given in Table II which gives the numerical values of the protocol parameters for 802.11b DSSS.

TABLE II
IEEE 802.11B DSSS MAC PROTOCOL PARAMETERS

Parameter	802.11b DSSS
W_{min}	32 slots
W_{max}	1024 slots
t_{slot}	20 μs
t_{sifs}	10 μs
t_{difs}	50 μs
ACK	14 bytes
RTS	20 bytes
CTS	14 bytes
PLCP header	192 μs
MAC header	34 bytes
PHY rates	1 Mbps

B. Results

In Fig. 4, we explore the relationship between the achievable secondary bandwidth utilization ζ and the number of secondary sensors N as well as the single detection capability $P_d(1)$. Note that for all results presented in this section, simulation results agree well with the developed model as shown in the figure. The figure depicts that, given certain detection capability of one sensor, there always exists one optimal number of secondary sensors which is, e.g., $N = 10$ and $N = 7$ for the cases of $P_d(1) = 0.7$ and $P_d(1) = 0.9$ respectively. The initial increase of ζ is due to the increased number of cooperating sensors which results in better average detection performance, i.e., $P_F = \frac{1}{M}\sum_{i=1}^{M} P_{fi}$ in (4). After ζ reaches its maximum value, it further decreases as N becomes large. This is because P_F tends to be similar along with the increase of N. Over many cooperating sensors may contain significant spatial redundancy and have a limited contribution to the spectrum detection performance. Hence, the reporting time T_r becomes the dominant factor in (4). This reason also explains why the discrepancy of ζ between $P_d(1) = 0.7$ and $P_d(1) = 0.9$ is large for a small number of cooperating sensors, and then decreases and almost disappears at a large value of N.

It should be noted that the selection of m_{sa} in Fig. 4 satisfies the condition that each channel is measured at least once during T_{sa}. As previously explained, there exists an optimal m_{sa} for each pair of (M, N) to maximize the achievable secondary bandwidth utilization ζ. Fig. 5 depicts the optimal value of m_{sa} given different number of collaborating sensors N. The optimal m_{sa} is equal to M in the case of $N = 1$, and then decreases until it converges to one as the number of sensors becomes large. This is because a large N stands for a long reporting duration T_{sr} which can accommodate more spectrum sensing activities. Hence the spectrum measurement activities during T_{sa} can be minimized. It is also observed

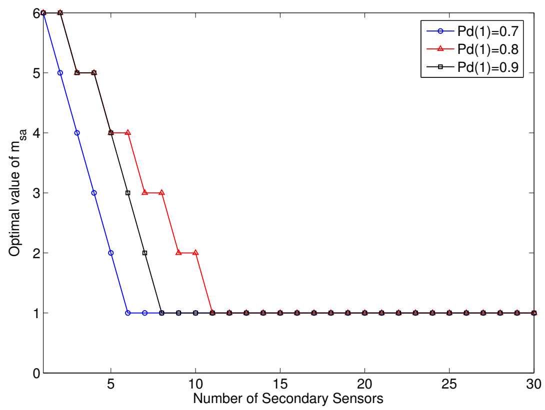

Fig. 5. Optimum selection of m_{sa}, $M = 6$

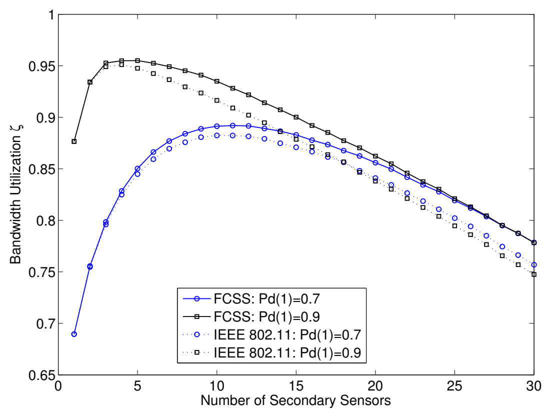

Fig. 6. A comparison between FCSS and the IEEE 802.11 scheme where the sensing and reporting phases are temporally separated.

in Fig. 5 that the optimal m_{sa} varies with the detection probability of a single sensor $P_d(1)$. This is because there exists a unique single measurement time τ_s for each $P_d(1)$ as shown in Fig. 3, which results in a different allowable number of measurements during T_{sr} as defined by (1).

Fig. 6 depicts a comparison of throughput performance between our proposed FCSS scheme and the IEEE 802.11 scheme where the sensing and reporting phases are not overlapped with each other. The achievable secondary bandwidth utilization ζ is maximized for each pair of (M, N) with the optimal m_{sa}, which is $m_{sa} = 6$ For IEEE 802.11. It is evident that the FCSS outperforms the IEEE 802.11 scheme, especially as the number of cooperating sensors increases. This is explained by the fact that larger number of sensors result in more collisions which prolong the contention time. The FCSS scheme is designed to alleviate the contention overhead through avoiding the exponential backoff of contention window as in 802.11. Note that we consider an error-free control channel in the study. If an error-prone channel is considered, the exponential backoff in IEEE 802.11 scheme will frequently occur and result in significant contention overhead. Thus FCSS will exhibit much superior performance.

V. Conclusions

In this paper, we propose a novel cooperative spectrum sensing scheme for multiband cognitive networks, which we call Fast Cooperative Spectrum Sensing (FCSS), aiming to minimize the total sensing and reporting time under guaranteed detection reliability. The scheme incorporates three key techniques: concurrent occurrence of the sensing and reporting phases, a joint static and random sensor assignment strategy, and an enhanced IEEE 802.11 MAC protocol for the reporting process. The reporting MAC protocol is a simple modification to the contention algorithm of IEEE 802.11, in which the contending nodes reduce or keep their contention window instead of doing exponential backoff in the case of collisions. A general mathematical framework that allows including various PHY layer sensing and fusion techniques has been developed to quantify the achievable bandwidth utilization within a secondary system. The accuracy of developed analytical model is corroborated by computer simulations. In this paper, we study only the error-free control channel and a simple energy detection based fusion rule with an equal weighting of measurements from all the secondary sensors. The investigation on error-prone channel and more realistic detection techniques (e.g., considering shadowing effects) could be part of the future work.

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