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Energy/bandwidth-Saving Cooperative Spectrum Sensing for Two-hop WRAN

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Abstract

A two-hop wireless regional area network (WRAN) providing monitoring services operating in Television White Space (TVWS), i.e., IEEE P802.22b, may employ a great number of subscriber customer-premises equipments (S-CPEs) possibly without mains power supply, leading to requirement of cost-effective and power-saving design. This paper proposes a framework of cooperative spectrum sensing (CSS) and an energy/bandwidth saving CSS scheme to P802.22b. In each round of sensing, S-CPEs with SNRs lower than a predefined threshold are excluded from reporting sensing results. Numerical results show that the fused missed-detection probability and false alarm probability could remain meeting sensing requirements, and the overall fused error probability changes very little. With 10 S-CPEs, it is possible to save more than 40% of the energy/bandwidth on a Rayleigh channel. The principle proposed can apply to other advanced sensing technologies capable of detecting primary signals with low average SNR.

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1. Introduction

With the explosive growth of broadband wireless users and services, the current spectrum for wireless communications becomes more and more congested. Fortunately, to explore Television White Space (TVWS) – the unused TV channels at certain time in certain geographic area – may alleviate the problem. IEEE 802.22 is one of the current efforts to utilize TVWS for services in regional area. The 802.22 working group has developed IEEE Std 802.22-2011 for regional broadband services and now is working on IEEE P802.22b for regional monitoring and metering, etc [1, 2].

Unlike 802.22-2011 that employs cellular network topology, P802.22b incorporates two-hop relay by which a great number (e.g., tens to hundreds) of subscriber customer-premises equipments (S-CPEs) may connect to a relay CPE (R-CPE) and then a multi-hop base station (MR-BS). IEEE P802.22b S-CPEs require cost-effective and energy/bandwidth-saving designs due to the big volume and the fact that they may not be mains powered.

On the other hand, following regulatory requirement, periodic quiet periods (QPs) are reserved in P802.22b frames where an S-CPE can perform spectrum sensing to detect the presence of the primary users (PUs). The current P802.22b employs individual spectrum sensing technologies, of which some require high-capability processors and therefore lead to high-cost S-CPEs [1].

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For the goal of low-cost and simple design of S-CPEs, we propose cooperative spectrum sensing (CSS) for IEEE P802.22b. With CSS, many nodes sense the spectrum at same time and report individual result to a fusion center (FC). The FC compounds the received individual results and makes the final sensing decision. Compared to sensing by a single node, the sensing performance can be improved due to space diversity of the radio signal [7, 8]. It is therefore at each S-CPE, relatively lower sensing performance is required and then lower-cost processor can be used. In the proposed scheme, as shown in Fig. 1, a number of S-CPEs associated with a R-CPE perform CSS and report results to the R-CPE. The R-CPE acts as an FC and it reports the fused result to the MR-BS it associates with. If a fused result reported by a R-CPE is the presence of the PU, the MR-BS needs to request the R-CPE and the associated S-CPEs to stop transmissions immediately.

Moreover, in order to save energy and bandwidth for a P802.22b system that employs a great number of S-CPEs that may be powered by batteries, we propose only the S-CPEs with detected primary signal-to-noise ratio (SNR) higher than a threshold to report the sensing results to a R-CPE. An SNR threshold is stored at each S-CPEs for comparison to the detected SNR locally. Numerical results show that with the proposed partial reporting scheme, the energy/bandwidth can be saved while the sensing performance can be maintained. The saved energy/bandwidth increases with the number of S-CPEs. The principle of the proposal applies to other spectrum sensing technologies although energy detection is considered here for simplicity.

In the literatures [3]-[12], researches of energy/bandwidth-saving for CSS incorporating energy detection focus on two approaches: (1) to reduce energy for individual spectrum sensing; (2) to reduce energy for reporting individual sensing result to an FC. In [9], Chien *et al.* proposed a partial spectrum sensing technology to save energy for spectrum sensing. In [10], the spectrum sensors are divided into subsets and scheduled to cooperatively sense the spectrum in an optimized sequence so that the overall energy consumption is minimized. [3] and [4] demonstrated that the overall energy for CSS can be saved when only an optimal number of SUs participate CSS and each SU employs optimized sensing time. In [12], Zhang *et al.* studied the optimal fusion rule and optimized the number of SUs performing CSS. Compared to other proposals, the energy/bandwidth-saving scheme of this study requires no global comparison of the primary SNR thus extra energy and spectrum can be saved.

This paper is organized as follows. Following the introduction, we introduce P802.22b in section 2. Then we present the proposed cooperative scheme for P802.22b in section 3. CSS with energy/bandwidth-saving is proposed and analyzed in section 4. Numerical results are presented in section 5 and the paper is concluded by section 6.

2. IEEE P802.22b and Spectrum Sensing

There are various broadband services and monitoring applications in context of wireless regional area networks where 802.22-2011 device may not able to serve. The regional services include real-time and near real-time monitoring, emergency broadband services, remote medical diagnose, etc, where a great number of subscriber terminals with simpler design and lower cost are needed but are not supported by 802.22-2011. For this consideration, IEEE P802.22b is to amend IEEE Std 802.22-2011 by introducing new class CPEs, i.e., R-CPEs and S-CPEs. An S-CPE is of lower capability, for example, lower transmission power, lower antenna height, and lower-gain/cost amplifier, etc. Thus the effective communication distance for an S-CPE is not likely to be tens of kilometers, but is of 1 to 2 kilometers. A R-CPE is a 802.22-2011 CPE supporting advanced functions such as relay, multiple-input multiple out (MIMO) and channel bounding, etc. The supported communication distance of a R-CPE is of tens of kilometers. Correspondingly, an MR-BS supports advanced functions like relay, MIMO and channel bounding, etc. As shown in Fig. 1, in P802.22b, the data traffic between the S-CPEs and an MR-BS is relayed by the R-CPEs.

The general frame structure of P802.22b is shown in Fig. 2, where both downstream (DS) subframe and upstream (US) subframe are divided into access zone and relay zone. As shown in the figure, a contention window in both access and relay zone of a US subframe is allocated for ranging, bandwidth request,

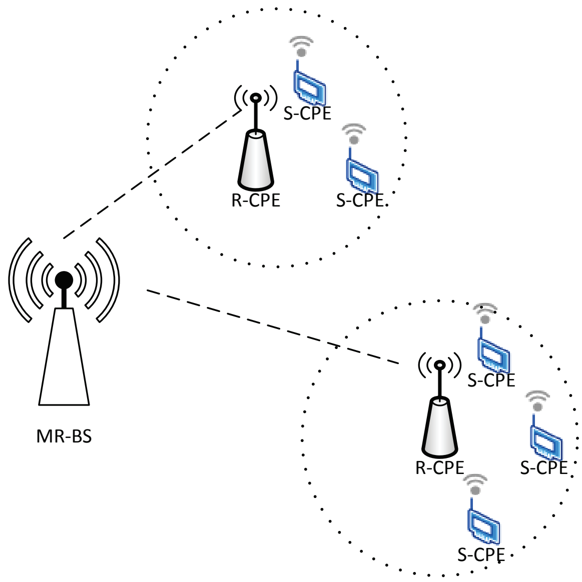

Figure 1. IEEE P802.22b network structure.

and urgent coexistence situation (UCS) notification. A UCS Notification window can be scheduled in this time period for urgent reporting detection of primary transmissions.

Following 802.22-2011, periodic Quiet Periods (QPs) are scheduled along the frames for incumbent detection by spectrum sensing in P802.22b. It has been designed that across a P802.22b network, QPs at all stations are synchronized. In a P802.22b system, a fraction of the S-CPEs/R-CPEs can be instructed to sense the spectrum and if the presence of PUs are detected, it needs to be reported to an MR-BS as soon as possible.

In current P802.22b, an S-CPE has two possible ways to report the detected results. For an S-CPE with upstream bandwidth allocation, it sets the UCS flag in the generic MAC header for reporting to a MR-BS. For an S-CPE without upstream bandwidth allocation, it needs to report in the UCS Notification window using contention or code-division multiplexing access (CDMA).

3. Cooperative Spectrum Sensing for P802.22b

3.1. Proposal of CSS

The big volume of S-CPEs under a R-CPE imposes requirement of simplicity and low-cost design for an S-CPE. To meet this requirement, we propose CSS framework for P802.22b. It is well known that by CSS, the overall sensing performance can be improved and then the requirement of individual sensing performance can be relaxed. Therefore, an S-CPE may employ a simpler and low-cost sensing component thus the total cost can be saved.

With the proposed CSS, under a R-CPE, a number of S-CPEs are instructed to sense the spectrum cooperatively. After a QP during which spectrum sensing is performed, an S-CPE reports to a R-CPE if the presence of PU is detected at its location. If an S-CPE has upstream bandwidth, it reports by setting the UCS flag of the generic MAC header, otherwise, it reports the PU presence in the UCS notification window. The

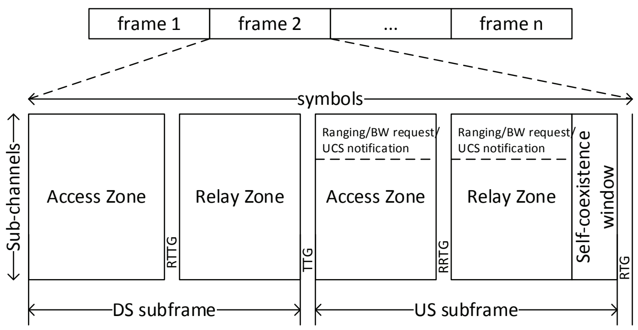

Figure 2. IEEE P802.22b general frame structure.

R-CPE acts as a fusion center and it reports to an MR-BS if the fused result is PU transmission is present. For simplicity, energy detection and OR-fusion rule are assumed. The energy/bandwidth-saving CSS proposed in this study is not limited to energy detection. If other advanced spectrum sensing method is applied at all S-CPEs, it is also possible to apply the CSS scheme proposed for P802.22b here.

3.2. System Model and Assumptions

Referring to the network structure shown in Fig. 1, it assumes that under a R-CPE, N S-CPEs are instructed to sense spectrum during any QP. Among the N S-CPEs, $g \cdot N$ S-CPEs have been allocated upstream bandwidth, and $(1-g) \cdot N$ S-CPEs have no upstream bandwidth, where $0 \le g \le 1$. If an S-CPE detects the presence of PU during a QP, then it reports the detected result to the R-CPE immediately, otherwise it does not report. As required by P802.22b [1], if a R-CPE receives a report from an S-CPE, then it assumes that the S-CPE has detected the presence of PU, otherwise it assumes that the S-CPE has detected no presence of PU.

For presentation simplicity, the S-CPEs with upstream bandwidth are called Group-1 S-CPEs and the S-CPEs without upstream bandwidth are called Group-2 S-CPEs, since their reporting mechanisms are different. For Group-1 S-CPEs, it assumes that all S-CPEs can report successfully as they have upstream bandwidth. For Group-2 S-CPEs, contention/CDMA reporting method is used and in case there are two or more S-CPEs to report, an S-CPE may fail to report due to conflicts. Clearly, when more Group-2 S-CPEs report in an UCS Notification window, the success probability will be lower. It is difficult to precisely describe the relationship between the success reporting probability and the number of the reporting S-CPEs mathematically due to the complexity. In this study, we assume the success reporting probability is substantially modeled by following equation

$$p_t(X) = \begin{cases} 1, & X = 1, \\ e^{-X}, & X = 2, 3, \ldots \end{cases}, \tag{1}$$

where X is the number of Group-2 S-CPEs reporting in same UCS Notification window.

If a Group-2 S-CPE detects the presence of PU but it fails in reporting, then based on the P802.22b reporting mechanism, a R-CPE shall assume that S-CPE has not detected the presence of PU.

We assume that the detected instantaneous signal-to-noise ratio (SNR) of the primary signal at each S-CPE varies with time due to channel fading, and the averaged SNR $\bar{\gamma}$ at all S-CPEs under a R-CPE are equal since the path loss exponent of the P802.22b scenarios is general low and the distance between the S-CPEs of a local cell is in range of 1 to 2 kilometers, which is generally much shorter than the distance to a primary transmitter (usually a TV tower).

Let p_d and p_f stand for the local detection probability and false alarm probability at an S-CPE, respectively. For fading channel, p_d and p_f are averaged over the primary SNR.

High detection probability and low false alarm probability are required by P802.22b for effective protection of PUs and utilization of TVWS, respectively. Without loss of generality, for the proposed CSS scheme to P802.22b, we propose that at a R-CPE, the fused detection probability Q_d should be higher than 90% and the fused false alarm probability Q_f should be lower than 10%. The fused missed-detection probability, i.e., Q_m (=1-Q_d) therefore should be less than 10%.

3.3. Fused Miss-detection Probability

The fused missed-detection probability at a R-CPE is given by $Q_m = Q_{m_1} \cdot Q_{m_2}$, where Q_{m_1} is fused missed-detection probability of the Group-1 S-CPEs and Q_{m_2} is fused missed-detection probability of the Group-2 S-CPEs.

Let H_1 stands for the assumption that PUs are present during sensing, and H_0 stands for the counterpart, i.e., no PU is present.

With assumption of H_1, we have

$$Q_{m_1} = (1 - p_d)^{gN}, \tag{2}$$

and

$$Q_{m_2} = (1 - p_d)^{(1-g)N} + \sum_{K=2}^{(1-g)N} \left\{ \binom{(1-g)N}{K} \times \{p_d [1 - p_t(K)]\}^K (1 - p_d)^{[(1-g)N-K]} \right\}, \tag{3}$$

where K is the number of Group-2 S-CPEs detected H_1. In Eq. (3), the first term corresponds to scenario when none of the Group-2 S-CPEs has detected the presence of the primary signal, for the second term, there are K Group-2 S-CPEs have detected PU signal, however, none of them succeeded to report to the R-CPE due to conflicts. Note K is in range of $[2, (1-g)N]$. When only one S-CPE detects PU signal, it can report to a R-CPE successfully since there is no competitors.

3.4. Fused False Alarm Probability

The fused false alarm probability at a R-CPE is given by $Q_f = 1 - \left(1 - Q_{f_1}\right) \cdot \left(1 - Q_{f_2}\right)$, where Q_{f_1} is fused false alarm probability of the Group-1 S-CPEs and Q_{f_2} is fused false alarm probability of the Group-2 S-CPEs.

With assumption of H_0, we have

$$Q_{f_1} = 1 - \left(1 - p_f\right)^{gN}, \tag{4}$$

and

$$Q_{f_2} = 1 - \left(1 - p_f\right)^{(1-g)N} - \sum_{L=2}^{(1-g)N} \left\{ \binom{(1-g)N}{L} \times \left\{p_f [1 - p_t(L)]\right\}^L \left(1 - p_f\right)^{(1-g)N-L} \right\}, \tag{5}$$

where L is the number of Group-2 S-CPEs detected H_1 (false alarm). In Eq. (5), the second term corresponds to none of the Group-2 S-CPEs falsely detects the presence of the primary signal (false alarm). And for the third term, there are L Group-2 S-CPEs have detected the primary signal falsely, however, all of them failed to report due to conflicts. Note that if only one Group-2 S-CPE detects the primary signal falsely, i.e., $L = 1$, then it can report to a R-CPE successfully since no competitor.

3.5. Fused Error Probability

The fused error probability at a R-CPE is given by

$$Q_e = P_1 Q_m + P_0 Q_f, \tag{6}$$

where P_1 is the probability of H_1 and P_0 is probability of H_0. Clearly, when Q_m $(= 1 - Q_d)$ and Q_f is lower than 10%, Q_e should be less than 10%.

4. Energy/Bandwidth-saving CSS for P802.22b

The main mechanism of the proposed energy/bandwidth-saving CSS for P802.22b is to exclude the S-CPEs with ignorable contribution to the sensing performance from reporting their sensing results. By this way, power can be saved and conflicts in reporting sensing results to R-CPEs can be reduced.

4.1. Energy Detection

With spectrum sensing method of energy detection, an S-CPE collects energy during sensing window and the collected energy is compared to a predefined energy threshold. If the collected energy is bigger, it decides H_1, otherwise, it decides H_0. The local false alarm probability and missed-detection probability are given, respectively, by [13]

$$p_{f,i} = \Pr\{E_i > \lambda_i | H_0\} = \Gamma(u, \lambda_i/2)/\Gamma(u), \tag{7}$$

$$p_{d,i} = \Pr\{E_i > \lambda_i | H_1\} = Q_u\left(\sqrt{2\gamma_i}, \sqrt{\lambda_i}\right), \tag{8}$$

where E_i, λ_i, and γ_i are the collected energy, the energy threshold, and the detected instantaneous SNR at the ith S-CPE, respectively; u is the sensing time-bandwidth product and is assumed an integer for simplicity. $\Gamma(\cdot)$ and $\Gamma(u, x)$ are the complete and incomplete gamma function, respectively; $Q_u(a, x)$ is the generalized Marcum Q-function.

We assume that all S-CPEs have same energy threshold, i.e., $\lambda_i = \lambda$, then all S-CPEs have equal false

$$Q^*_{m_2} = \sum_{I=0}^{(1-g)N} \begin{pmatrix} (1-g)N \\ I \end{pmatrix} (p_d \hat{p})^I (1-p_d)^{[(1-g)N-I]} + \sum_{M=2}^{(1-g)N} \begin{pmatrix} (1-g)N \\ M \end{pmatrix} \{p_d (1-\hat{p}) [1-p_t(M)]\}^M \left\{ \sum_{I=0}^{(1-g)N-M} \begin{pmatrix} (1-g)N-M \\ I \end{pmatrix} (p_d \hat{p})^I (1-p_d)^{[(1-g)N-M-I]} \right\}, \quad (9)$$

$$Q^*_{f_2} = 1 - \sum_{J=0}^{(1-g)N} \begin{pmatrix} (1-g)N \\ J \end{pmatrix} \left(p_f \hat{p}\right)^J \left(1-p_f\right)^{[(1-g)N-J]} - \sum_{L=2}^{(1-g)N} \begin{pmatrix} (1-g)N \\ L \end{pmatrix} \left\{p_f (1-\hat{p}) [1-p_t(L)]\right\}^L \left\{ \sum_{J=0}^{(1-g)N-L} \begin{pmatrix} (1-g)N-L \\ J \end{pmatrix} \left(p_f \hat{p}\right)^J \left(1-p_f\right)^{[(1-g)N-L-J]} \right\}. \quad (10)$$

alarm probability, i.e., p_f. For fading channel, the averaged detection probability, i.e., p_d is given by $p_d = \int_0^\infty Q_u\left(\sqrt{2x}, \sqrt{\lambda}\right) f_\gamma(x)\,dx$, where $f_\gamma(\cdot)$ is probability density function of the primary SNR (γ).

4.2. Proposed Energy/Bandwidth-saving CSS

Since at each round of spectrum sensing, the detection probability $p_{d,i}$ is increasing function of the instantaneous primary SNR, it is possible to exclude S-CPEs that have relatively low instantaneous SNR from reporting their results to a R-CPE, in condition that the deteriorated fused detection probability still meets the sensing requirement. Estimation of SNR at a receiver has been reported in [14, 15]. By excluding such S-CPEs to report results if they detect H_1, it also helps to reduce the fused false alarm probability and increase the success reporting probability. By doing so, energy consumption and bandwidth can be saved in a P802.22b system.

We propose to set a SNR threshold γ_T, and if a Group-2 S-CPE detects an instantaneous SNR smaller than γ_T, in this round of sensing, it does not report to a R-CPE even it has detected H_1. By this way, the S-CPEs that are excluded from reporting their results can save energy and bandwidth consumption in this round of spectrum sensing. However, this is not so meaningful to Group-1 S-CPEs since they have been granted bandwith and will be likely to transmit packages, no matter they set the 1-bit UCS flag in the generic MAC header to report the detection of PU signal or not.

In other studies, it is found that optimal CSS performance can be achieved if only letting nodes with high-enough SNRs report results for final fusion [4]. However, to select the nodes with 'high-enough SNRs', global comparison is needed. The scheme proposed in this section requires only local comparison to γ_T and no global comparison is needed thus it may save more energy and bandwidth.

Let $\hat{p} = \int_0^{\gamma_T} f_\gamma(x)dx$ stands for the probability that a detected instantaneous SNR is less than the SNR threshold, then the fused missed-detection probability of Group-2 S-CPEs and fused false alarm probability of Group-2 S-CPEs at a R-CPE are given by Eq. (9) and Eq. (10), respectively. In Eq. (9), I is the number of the Group-2 S-CPEs without upstream bandwidth having detected H_1 (under assumption of PU transmission) but the detected SNRs are less than γ_T so that the S-CPEs haven't reported the results to a R-CPE. M is the number of the Group-2 S-CPEs without upper bandwith having detected H_1 (under assumption of PU transmission) and the detected SNRs are higher than γ_T but all failed in reporting the results to a R-CPE due to competition and then the PU transmission is missed. Similarly, in Eq. (10), J is the number of Group-2 S-CPEs without upper bandwidth having falsely detected PU transmission (under assumption of NO PU transmission) but the detected SNRs are less than γ_T so that the S-CPEs haven't reported the results to a R-CPE. And L is the number of Group-2 S-CPEs without upper bandwidth having detected H_1 (under assumption of NO PU transmission) and the detected SNRs are higher than γ_T but all failed in reporting the results to a R-CPE due to competition therefore the PU transmission is not falsely detected.

With the proposed energy/bandwidth-saving CSS, the fused missed-detection probability and false alarm probability at a R-CPE are given by $Q^*_m = Q_{m_1} \cdot Q^*_{m_2}$ and $Q^*_f = 1 - \left(1 - Q_{f_1}\right) \cdot \left(1 - Q^*_{f_2}\right)$, respectively. The error probability at a R-CPE becomes $Q^*_e = P_1 Q^*_m + P_0 Q^*_f$.

Setting a high SNR threshold allows more energy saved, however, it leads to higher Q^*_m. Following the requirement of P802.22b system, Q^*_m and Q^*_f should be less than 10%, then γ^*_T can be found by solving following equation numerically

$$\gamma^*_T = \arg_{\gamma_T} \max\left(Q^*_m, Q^*_f\right), \qquad Q^*_m \leq 0.1, \; Q^*_f \leq 0.1. \quad (11)$$

The maximum overall normalized saved energy/bandwidth is then given by $(1-g)\,\hat{p}^*$, where $\hat{p}^* = \int_0^{\gamma^*_T} f_\gamma(x)dx$.

4.3. Number of Group-2 Reporting S-CPEs

With the proposed energy/bandwidth-saving CSS, in case a Group-2 S-CPE having detected PU transmission during a QP, only when its detected instantaneous SNR is higher than a predefined SNR threshold it reports the sensing result to a R-CPE. Therefore, usually only part Group-2 S-CPEs report sensing results. Based on above analysis, the probability that there are S Group-2 S-CPEs reporting sensing results under assumptions with and without PU transmission are given by Eq. (12) and Eq. (13), respectively, and the overall probability is given by Eq. (14), where $0 \le S \le N$.

$$\Pr(X = S|H_1) = \binom{(1-g)N}{S} \{p_d(1-\hat{p})\}^S \times \left\{ \sum_{0}^{(1-g)N-S} \binom{(1-g)N-S}{K} (p_d\hat{p})^K (1-p_d)^{(1-g)N-S-K} \right\} \tag{12}$$

$$\Pr(X = S|H_0) = \binom{(1-g)N}{S} \left\{p_f(1-\hat{p})\right\}^S \times \left\{ \sum_{0}^{(1-g)N-S} \binom{(1-g)N-S}{L} \left(p_f\hat{p}\right)^L \left(1-p_f\right)^{(1-g)N-S-L} \right\} \tag{13}$$

$$\Pr(X = S) = P_1 \cdot \Pr(X = S|H_1) + P_0 \cdot \Pr(X = S|H_0). \tag{14}$$

5. Numerical results

Figure 3 and Figure 4 show the overall probability of S Group-2 S-CPEs reporting sensing results to a R-CPE as function of SNR threshold (γ_T) with parameter g of 0.2 and 0.6, respectively. $g = 0.2$ (or 0.6) means that there are 20% (or 60%) of the S-CPEs participating sensing have been allocated upstream bandwidth. A higher g means more Group-1 S-CPEs and less Group-2 S-CPEs. Rayleigh fading channel with an average SNR ($\bar{\gamma}$) of 10 dB is assumed, and the channel is assumed being occupied by the primary users over 80% of the time, i.e., $P_1 = 0.8$ and $P_0 = 0.2$. u is set to 10. At each S-CPE, the energy threshold λ is set to a value with which the fused error probability is minimized. As shown in the two figures, in most cases, only a small part (zero, one or two) of Group-2 S-CPEs report sensing results, indicating most of Group-2 S-CPEs usually keep silent, especially when there is a larger SNR threshold or a higher g.

Figure 5 shows the normalized saved energy/bandwidth as function of the SNR threshold when the energy/bandwidth-saving scheme is applied. g is set to 0.2, 0.4 and 0.6, and $P_1 = 0.8$ and $P_0 = 0.2$.

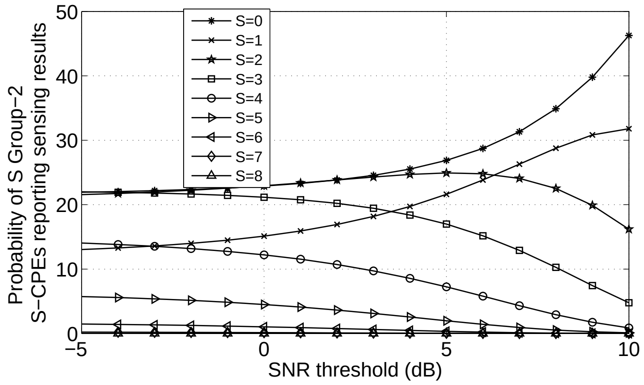

Figure 3. The probability of S Group-2 S-CPEs reporting sensing results as function of the SNR threshold (γ_T) (dB). Rayleigh fading channel with $\bar{\gamma}$ of 10 dB, $N = 10$, $g = 0.2$.

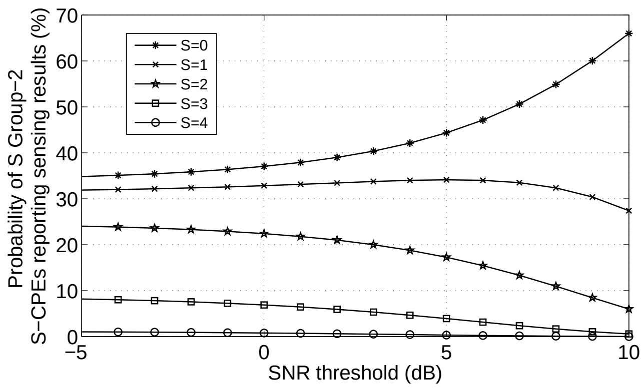

Figure 4. The probability of S Group-2 S-CPEs reporting sensing results as function of the SNR threshold (γ_T) (dB). Rayleigh fading channel with $\bar{\gamma}$ of 10 dB, $N = 10$, $g = 0.6$.

Rayleigh fading channel with average SNR of 10 dB is assumed. It can be seen that the saved energy/bandwidth increases rapidly with the SNR threshold. In case of $g = 0.2$, when γ_T equals to 8.5 dB, more than 40% of energy/bandwidth can be saved, while for γ_T above 10 dB, more than 50% of energy/bandwidth can be saved. For a higher g (0.4 or 0.6) less energy/bandwidth is saved owning to that more Group-1 S-CPEs will report sensing results if detecting PU transmission, no matter the detected instantaneous SNR is higher or lower than the SNR threshold.

Figure 6 and Figure 7 show the fused miss-detection probability (Q_m and Q_m^*) and the fused false alarm probability (Q_f and Q_f^*) at a R-CPE as function of the threshold of SNR (γ_T) with parameter g of 0.2 and 0.6, respectively. Other parameters setting are same as above while N is set to 10 and 20 for comparison. As shown in the figures, Q_m and Q_f keep unchange with γ_T since all Group-2 S-CPEs detecting H_1 need to report when the proposed energy/bandwidth saving CSS is not

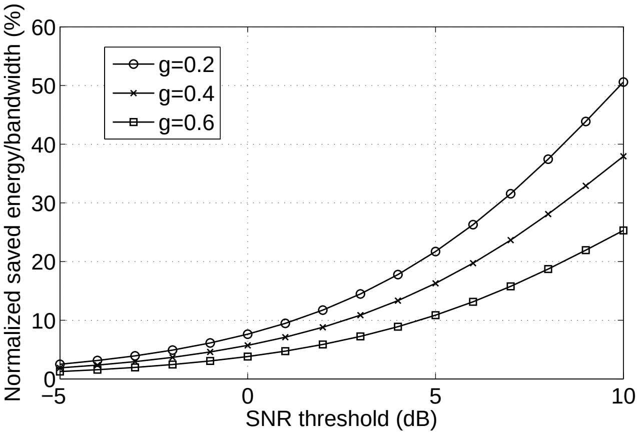

Figure 5. Normalized saved energy/bandwidth as function of the instantaneous SNR threshold. Rayleigh fading channel with $\bar{\gamma}$ of 10 dB, $N = 10$.

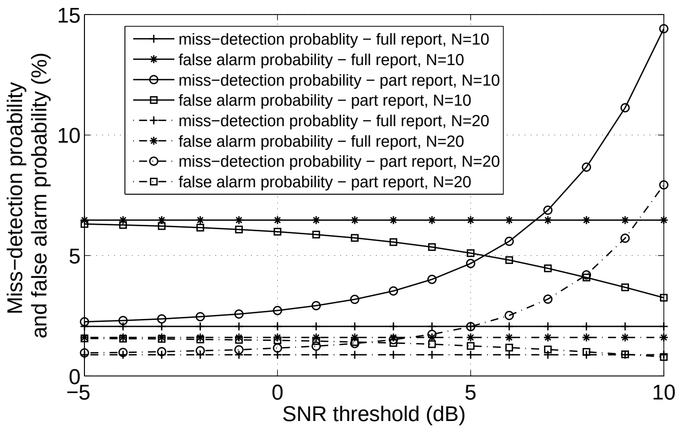

Figure 6. Fused miss-detection probability and fused false alarm probability at a R-CPE as function of the SNR threshold. Rayleigh fading channel with $\bar{\gamma}$ of 10dB. ($g = 0.2$)

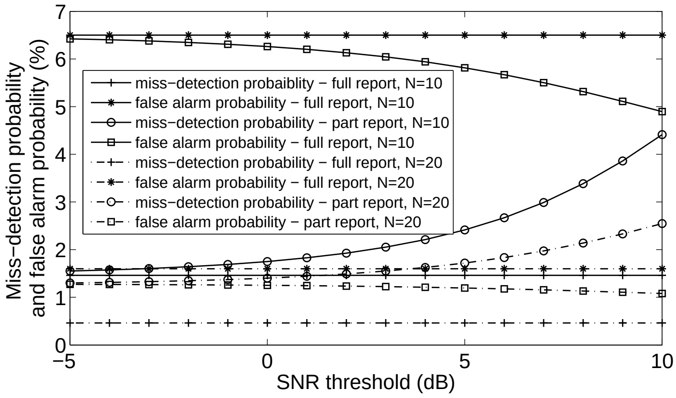

Figure 7. Fused miss-detection probability and fused false alarm probability at a R-CPE as function of the SNR threshold. Rayleigh fading channel with $\bar{\gamma}$ of 10dB. ($g = 0.6$)

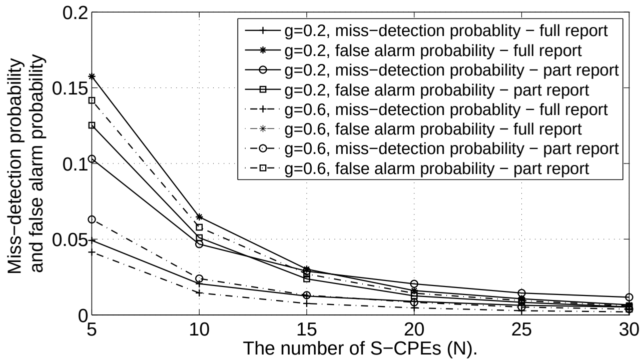

Figure 8. Fused miss-detection probability and fused false alarm probability at a R-CPE as function of the number of S-CPEs. Rayleigh fading channel with $\bar{\gamma}$ of 10 dB, γ_T=5 dB.

applied. As observed, the fused false alarm probability after enery/bandwidth-saving CSS is applied (Q_f^*) decreases with the SNR threshold (γ_T) since less Group-2 S-CPEs detecting H_1 report sensing results to a R-CPE, while the fused miss-detection probability increases with the SNR threshold because of the same reason. Comparison between $N = 10$ and $N = 20$ indicates that the proposed enery/bandwidth-saving CSS follows the usual rule of OR cooperative sensing that with more sensing S-CPEs, better sensing performance, i.e., lower Q_m^* and Q_f^*, can be achieved. In case of $g = 0.2$, for $N = 10$, when the SNR threshold γ_T is higher than 8.5 dB, Q_m^* becomes higher than 10%, meaning that the allowed maximum SNR threshold (γ_T^*) for $N = 10$ is about 8.5 dB. For $N = 20$, γ_T^* is higher than 10 dB. When $g = 0.6$, better performance can be achieved for both Q_m^* and Q_f^* indicating that more Group-1 S-CPEs leads to better sensing performance.

Figure 8 shows the fused miss-detection probability (Q_m and Q_m^*) and the fused false alarm probability (Q_f and Q_f^*) at a R-CPE as function of the number of the S-CPEs (N). Clearly, when the number of the S-CPEs increases, the spectrum sensing performance becomes better. When N equals to 10, Q_m, Q_m^*, Q_f and Q_f^* are all lower than 10%, meaning that the CSS approach meets the requirement of 802.22 system in both cases with and without applying the energy/bandwidth-saving scheme. $\gamma_T = 5$ dB leads to saving about 22% energy/bandwidth. Figure 9 shows the fused overall error probability (P_e and P_e^*) as function of the S-CPE number. From Figure 8, when the energy/bandwidth-saving SCC scheme is applied for a given N, the false alarm probability becomes lower and the miss-detection probability becomes higher, as result, the fused error probability changes very little (see Figure 9).

Figure 10 shows the maximum allowed SNR threshold (γ_T^*) as function of the average SNR ($\bar{\gamma}$). Condition of finding γ_T^* is $max\{Q_m^*, Q_f^*\} \leq 10\%$ as

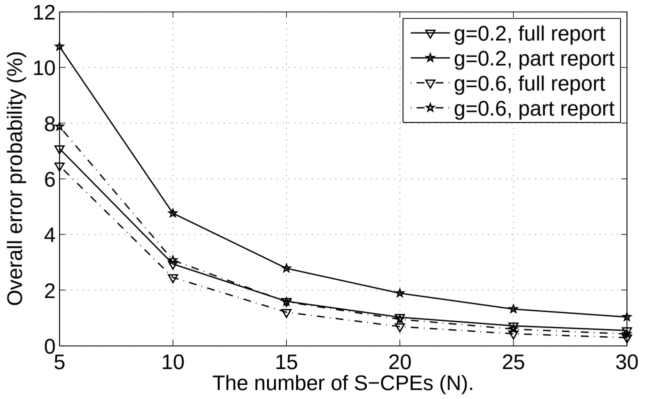

Figure 9. Fused overall error probability at a R-CPE as function of the number of S-CPEs. Rayleigh fading channel with $\bar{\gamma}$ of 10 dB, γ_T=5 dB.

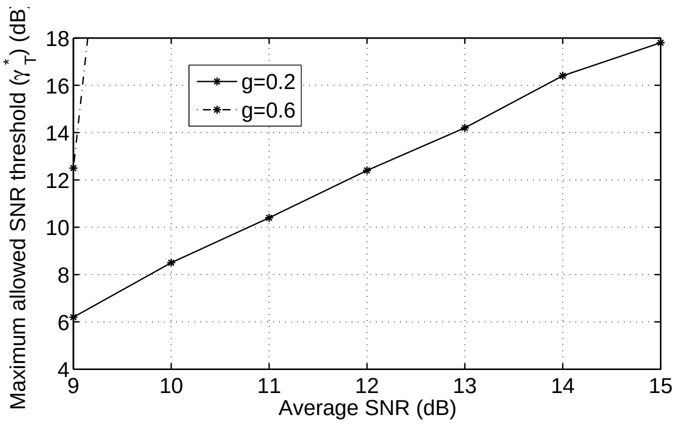

Figure 10. Maximum allowed SNR threshold (γ_T^*) as function of the average SNR ($\bar{\gamma}$). Rayleigh fading channel, $N = 10$.

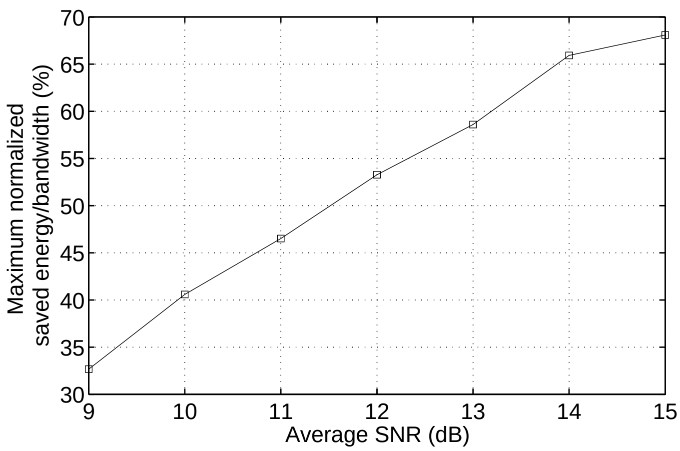

Figure 11. Maximum normalized saved energy/bandwidth as function of the average SNR ($\bar{\gamma}$). Rayleigh fading channel, $N = 10$, $g = 0.2$.

required by P802.22b. It is observed that for a Rayleigh fading channel with higher average SNR, higher γ_T^* is allowed meaning more energy/bandwidth can be saved. This is confirmed by Figure 11 which shows the maximum normalized saved energy/bandwidth as function of the average SNR ($\bar{\gamma}$). When $\bar{\gamma} = 15$, γ_T^* can be set as 18 dB and about 68% energy/bandwidth can be saved for $g = 0.2$. Fog $g = 0.6$, i.e., 60% of S-CPEs are Group-1 S-CPEs with upstream bandwidth, in most cases ($\bar{\gamma} > 9$ dB), the Group-1 S-CPEs can meet spectrum sensing requirement of $max\{Q_m^*, Q_f^*\} \leq 10\%$, therefore, it may require no Group-2 S-CPEs to participate spectrum sensing, indicating that for a channel with good SNR and high g, all Group-2 S-CPEs may not sense spectrum so more energy can be saved.

6. Discussion and Conclusion

Due to the performance limitation of energy detection in complex condition, the assumed average SNR is relatively high. The required SNR for target performance could be decreased by applying other advanced sensing technologies, for example, feature detection used in [16, 17] can detect PU signal with low SNR of around -20 dB.

In conclusion, IEEE P802.22b engages two-hop network structure which each R-CPE connecting with an MR-BS and a great number of S-CPEs requiring low-cost and power/bandwidth-saving designs; in this study an energy/bandwidth saving CSS scheme is proposed for P802.22b to meet the design requirement of the S-CPEs while still maintain the sensing performance. With the proposed scheme, when an S-CPE without upstream bandwidth detects the presence of PU, it reports to a R-CPE only if the detected SNR is above a pre-defined SNR threshold. Numerical results show that with the proposed CSS, the fused miss-detection probability becomes higher and the fused false alarm probability becomes lower, while the overall error probability changes very little. It is possible to save more than 40% to 50% energy/bandwidth when 10 or 20 S-CPEs are instructed to sense a fading channel. Although energy detection is considered in this study for simplicity in analysis, the proposed principle may be applied to other sensing technologies with higher performance.

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