Cooperative Spectrum Sensing with Slepian-Wolf Coded Cooperations

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Abstract— **A new Slepian-Wolf coded cooperation scheme is proposed for a cognitive radio network with two secondary users (SUs) performing cooperative spectrum sensing through a fusion center (FC). The SUs sense the spectrum by measuring the energy statistics of the received signals. The measured energy statistics are quantized with a Lloyd-Max quantizer at the SUs and forwarded to the FC, which then performs soft combining over the quantized information. This is different from most previous works that forward hard decisions based on local sensing results at the SUs. Due to the wireless nature of the channel, signals transmitted by one SU to the FC will also be observed by the other SU, which can cooperate with the transmitting SU by relaying the observed signals to the FC. In recognition of the strong correlation between the signals observed at the FC and the relay SU, a new asymmetric Slepian-Wolf code is employed at the relay SU to reduce the amount of cooperation information, thus to improve the cooperation efficiency. In addition, we propose to unequally allocate energy among the coded bits to compensate the energy loss due to the redundancy introduced by the coded cooperation, and this yields better performance compared to conventional equal energy coding schemes. Simulation results demonstrate that the proposed cooperative spectrum sensing scheme operating in practical fading channels can achieve a performance that is almost identical to the ideal case with soft combining performed over unquantized energy statistics transmitted through distortion-free channels.**

I. Introduction

Cognitive radio (CR) is emerging as one of the most promising techniques for efficient utilization of the precious spectrum resources [1]–[3]. In a CR network, secondary users (SUs) can coexist with primary users (PUs) by sensing the presence of PU signals and only transmitting at time-frequency holes with no PU activities. Therefore, Efficient and reliable spectrum sensing is critical to the proper operation of a CR network [4].

Energy detection is one of the most commonly used spectrum sensing methods given that it does not require the *a priori* knowledge of the PU and has a low complexity. The performance of the energy detection can be improved with the cooperative spectrum sensing, where multiple SUs can cooperate with each other by transmitting their local sensing results to a fusion center (FC) [5]–[9]. In most existing cooperative spectrum sensing schemes [5]–[7], the FC combines hard decisions from the SUs with an OR or majority data fusion rule. The hard combining is simple to implement, but the soft information in the energy statistics is lost due to the 1-bit hard decision at the SUs. A soft combining scheme that directly combines the analog energy statistics from the multiple SUs is proposed in [8], where it is assumed that the FC can have ideal distortion-free observations of the the analog energy statistics. Soft combining with practical channel is considered in [9], where the SUs forward soft analog information to the FC through an additive white Gaussian noise (AWGN) channel. The soft combining scheme outperforms the hard combining ones at the cost of significantly increased bandwidth requirement between the SUs and the FC.

In this paper, we propose a new cooperative spectrum sensing scheme with a practical coded cooperation for a CR network with two SUs and one FC. There are three main contributions of the proposed scheme. First, different from existing hard combining or the analog information-based soft combining schemes, the SUs will quantize the measured energy statistics with a Lloyd-Max quantizer, and forward the quantized information to the FC, which then performs soft combining over the quantized information. Second, the SUs forward the quantized information to the FC with a new Slepian-Wolf coded cooperation, where the two SUs transmit not only their own information but also relay each other's information through a coded cooperation. The Slepian-Wolf theorem states that two sources with correlated information can perform encoding separately and still achieve the same performance as the two sources are encoded jointly [10]. The signal transmitted by one SU will be observed by both the FC and the other SU, and this yields two strongly correlated signals at the FC and the receiving SU. The signal correlation can be exploited by an asymmetric Slepian-Wolf code, where the receiving SU can encode the signal from the transmitting SU and relay a compressed version of the signal to the FC. Such a coding scheme can significantly improve the cooperation efficiency by reducing the amount of relay information. Third, we propose to allocate unequal amount of energy among the coded bits to compensate the energy loss due to the redundancy introduced by the coded cooperation. Fading channels are used to model all the communication links in the network. Simulation results show that the proposed scheme can achieve almost the same performance as the analog information-based soft combining scheme with distortion-free SU-FC links.

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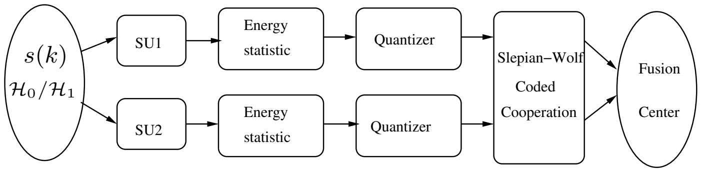

Fig. 1. System model of a cooperative spectrum sensing in cognitive radio networks

II. System Model

Consider a CR network with one PU and two SUs as shown in Fig. 1. Signals transmitted by the PU are received by the SUs. There are two hypotheses about the state of the PU: idle ($\mathcal{H}_0$) or busy ($\mathcal{H}_1$). Correspondingly, the signals observed by the n-th SU can be represented as

$$\begin{aligned} \mathcal{H}_0 : r_n(t) &= v_n(t), \quad n = 1, 2, \\ \mathcal{H}_1 : r_n(t) &= h_{pn}(t)s(t) + v_n(t), \quad n = 1, 2, \end{aligned} \tag{1}$$

where $s(t)$ is the band-limited signal from the PU with an one-sided bandwidth W, $v_n(t)$ is the additive white Gaussian noise (AWGN) with an one-sided power spectral density N_{nv}, $r_n(t)$ is the signal received by the n-th SU, and $h_{pn}(t)$ represents the fading coefficient between the PU and the n-th SU.

The SU performs energy measurement of the received signals during an interval of duration T. It is assumed that the state of the channel does not change within T. The n-th SU can obtain an energy statistic during the k-th detection interval by passing the received signal, $r_n(t)$, through a square law device and a finite time integrator, which yields

$$S_n(k) = \frac{1}{N_{0v}} \int_{(k-1)T}^{kT} |r_n(t)|^2 dt = \sum_{i=1}^{2u} \left(\frac{r_{ni}}{\sqrt{N_{0v}W}} \right)^2, \tag{2}$$

where $u = TW$ denotes the time bandwidth product, with W being the one-sided bandwidth of the signal, and $r_{ni} = r_n(\frac{i}{2W})$ is the received signal sample.

The energy statistic has the following distributions [12]

$$S_n(k) \sim \begin{cases} \chi^2_{2u}, & \mathcal{H}_0, \\ (1+\gamma_{sn})\chi^2_{2u}, & \mathcal{H}_1, \end{cases} \tag{3}$$

where χ^2_{2u} denotes the central chi-square distribution with $2u$-degree of freedom, $\gamma_{sn} = \frac{E_0}{N_{nv}}$ is the signal-to-noise ratio (SNR) at the SU, and $E_0 = \int_0^T |h_{pn}(t)s(t)|^2 dt$ is the signal energy.

Most existing cooperative sensing schemes make a hard decision of the PU's state at the SU by comparing $S_n(k)$ to a predefined threshold. The hard decision is then modulated and transmitted to the FC, which makes a final decision on the state of the PU by collecting hard decisions from all the SUs. Making binary decisions at the SU will lose the soft information contained in $S_n(k)$. The soft information can be used by the FC to further improve the sensing performance.

A soft combining scheme has been proposed in [8], which combines $S_n(k)$ from all the SUs, as

$$S(k) = \sum_{n=1}^{N} \frac{\gamma_{sn}}{1+\gamma_{sn}} S_n(k), \tag{4}$$

where γ_{sn} is the SNR of the signal observed by the n-th SU, and N is the number of SUs. The soft combining scheme assumes a distortion-free channel between the SUs and the FC, such that the FC can have ideal knowledge of the analog energy statistics, $S_n(k)$.

In practical systems, the SUs usually communicate with the FC through wireless links, which introduce fading and noise to the signals received by the FC. The fading and noise in the channel will cause significant distortions to the signals observed at the FC. Therefore, it is undesirable to directly transmit the analog information, $S_n(k)$, to the FC.

In order to take advantage of the soft combining in a system with practical channels between the SUs and the FC, we propose to quantize the energy statistics, $S_n(k)$, at the SUs, and then deliver the quantized digital information to the FC. A new Slepian-Wolf cooperation scheme is proposed in this paper for the efficient transmission and detection of the quantized energy statistics, and details are given in the next section. It will be shown with simulation that the proposed method with quantized information transmission in a wireless link can achieve a performance that is almost identical to a system with analog information transmitted in a distortion-free link.

The quantization of $S_n(k)$ is performed through a Lloyd-Max quantizer [11] at the SU. The construction of the Lloyd-Max quantizer requires the *a priori* knowledge of the distribution of $S_n(k)$. If the *a priori* probability of the state of the PU is known, then the average probability density function (pdf) of $S_n(k)$ can be expressed by

$$f_{S_n}(x) = P_0 f(x; 2u) + (1-P_0) \frac{1}{1+\gamma_{sn}} f\left(\frac{x}{1+\gamma_{sn}}; 2u \right), \tag{5}$$

where P_0 is the probability that the PU is idle, $f(x; 2u)$ is the pdf of a χ^2-distributed random variable (RV) with $2u$-degree of freedom. The pdf in (5) can then be used to formulate the Lloyd-Max quantizer.

The pdf in (5) requires the knowledge of the *a priori* probability P_0, which might not be readily available at the SU. Simulations indicate that quantizing with $f(x; 2u)$ lead to a performance that is very close to the optimum result obtained by using the true pdf $f_{S_n}(x)$. Therefore, the pdf $f(x; 2u)$ under the null hypothesis is used in this paper to quantize the signal.

Assume the number of the quantization levels is 2^m. The quantized information at the n-th SU can be represented by $Q[S_n(k)] = \mathbf{b}_n(k) = [b_{n1}(k), \cdots, b_{nm}(k)]^T \in \mathcal{B}^{m \times 1}$, where $Q[x]$ is the Lloyd-Max quantization operator, $\mathbf{a}^T$ is the transpose of the vector $\mathbf{a}$, and $\mathcal{B} = \{0, 1\}$. The FC obtains an estimate of the quantized information, $\hat{\mathbf{b}}_n(k)$. The quantized information recovered at the FC is converted back to the analog domain as $\hat{S}_n(k) = Q^{-1}[\hat{\mathbf{b}}_n(k)]$, which can then be used in (4) to obtain the soft combined energy statistic $\hat{S}(k)$.

The hard decision on the PU's state is obtained at the FC by comparing $\hat{S}(k)$ to a predefined threshold, $\mu(k)$. The PU is detected as busy if $\hat{S}(k) > \mu(k)$ and idle otherwise. Similar to [8], the threshold, $\mu(k)$, is calculated for a given probability of false alarm. The soft combining described in (4) maximizes the probability of detection under a fixed false alarm probability.

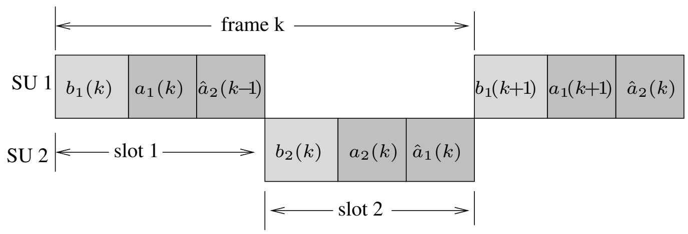

Fig. 2. The codewords of a practical Slepian-Wolf coded cooperation.

III. A New Slepian-Wolf Coded Cooperation for Spectrum Sensing

In this section, we present a new Slepian-Wolf coded cooperation scheme for the efficient and reliable delivery of the quantized information to the FC. The coded cooperation is developed by taking advantage of the wireless links between the SUs.

Due to the wireless nature of the channel and the relative proximity between the two SUs, signals transmitted by one SU to the FC will also be observed by the other SU. Without loss of generality, consider the case that SU n transmits a modulated codeword, $\mathbf{x}_n$, to the FC. The signal is also observed by SU $m \neq n$, which gets an estimate of the signal as $\hat{\mathbf{x}}_n$. The signals, $\mathbf{x}_n$ and $\hat{\mathbf{x}}_n$ are usually not identical due to the distortions of the wireless channel between the two SUs. However, they are strongly correlated. Motivated by this fact, we propose to perform coded cooperation between the two SUs by applying an asymmetric Slepian-Wolf code at the SU m. SU m can cooperate with SU n by including a compressed version of $\hat{\mathbf{x}}_n$ in its own signal to the FC. Such a scheme will reduce the amount of information that needs to be delivered to the FC and still achieve a diversity gain due to the cooperation. It should be noted that the Slepian-Wolf theorem is non-constructive, *i.e.*, it only states the existence of the coding scheme, but does not specify how the coding should be performed. In this paper, we propose a practical Slepian-Wolf cooperation scheme by employing linear block codes on the SUs. The details of the encoding, transmission, and decoding processes are given as follows.

A. Encoding

The encoding scheme is illustrated in Fig. 2 for a system with two SUs. The two SUs transmit to the FC through time division multiple access (TDMA), where each frame of a duration T is divided into two slots with a duration of $\frac{T}{2}$ each. The SU n transmits at the n-th slot of the frame, with $n = 1, 2$. The codewords formed by SUs 1 and 2 at the k-th frame can be represented, respectively, as

$$\mathbf{c}_1(k) = [\mathbf{b}_1^T(k), \mathbf{a}_1^T(k), \hat{\mathbf{a}}_2^T(k-1)]^T, \quad (6a)$$

$$\mathbf{c}_2(k) = [\mathbf{b}_2^T(k), \mathbf{a}_2^T(k), \hat{\mathbf{a}}_1^T(k)]^T. \quad (6b)$$

In the equations above, $\mathbf{b}_n(k) \in \mathcal{B}^{m\times 1}$ is the quantized energy statistic at the n-th SU, $\mathbf{a}_n(k) = \mathbf{P}\cdot\mathbf{b}_n(k) \in \mathcal{B}^{p\times 1}$ is the parity vector of $\mathbf{b}_n(k)$, with $\mathbf{P} \in \mathcal{B}^{p\times m}$ being a parity generation matrix of a linear block code with a coding rate $m/(p+m)$, and $\hat{\mathbf{a}}_n(k)$ is the cooperation information.

In the proposed Slepian-Wolf cooperation scheme, the cooperation information transmitted by node n is a distorted observation of the parity vector from node $m \neq n$ from the previous slot. As shown in Fig. 2, in the k-th frame, the cooperation information from SU 1 is the estimated parity vector, $\hat{\mathbf{a}}_2(k-1)$, transmitted by SU 2 at the second slot of the $(k-1)$-th frame, and the cooperation information from SU 2 is $\hat{\mathbf{a}}_1(k)$, an estimate of the parity vector transmitted by SU 1 at the first slot of the k-th frame. Even though node n has a distorted observation of the entire codeword from node m, it does not need to forward the entire codeword due to the strong correlation between the distorted codeword and the original information. In the proposed scheme, only the estimated parity bits are forwarded to the FC, and such a scheme reduces the number of bits required for cooperation.

The FC can perform decoding by combining the information from the two SUs. The information vector $\mathbf{b}_n(k)$ can be decoded by using the received signals $\mathbf{b}_n(k)$, $\mathbf{a}_n(k)$, and $\hat{\mathbf{a}}_n(k)$.

B. Transmission with Unequal Energy Allocation

The cooperation codeword, $\mathbf{c}_n(k)$, will be modulated and amplified before transmitting to the FC. Denote the modulated version of the information vector and parity vector as $\mathbf{s}_n(k) = M[\mathbf{b}_n(k)]$, $\mathbf{p}_n(k) = M[\mathbf{a}_n(k)]$, and $\hat{\mathbf{p}}_n(k) = M[\hat{\mathbf{a}}_n(k)]$, with $M[\mathbf{b}]$ representing the the binary phase shift keying (BPSK) modulation of the binary vector $\mathbf{b}$.

We propose to allocate different energy per bit to the information vector, $\mathbf{s}_n(k)$, and the parity vectors, $\mathbf{p}_n(k)$ and $\hat{\mathbf{p}}_n(k)$. The unequal energy allocation between the information and parity vectors is motivated by the fact that the FC has two distorted observations of the same parity vector due to the Slepian-Wolf cooperation, yet it receives only one copy of the information vector. Therefore, we can allocate less energy to the parity bits to account for the cooperative transmission. The codewords after modulation and energy allocation are

$$\mathbf{x}_1(k)=\left[\sqrt{E_s}\mathbf{s}_1^T(k), \sqrt{E_p}\mathbf{p}_1^T(k), \sqrt{E_p}\hat{\mathbf{p}}_2^T(k-1)\right]^T, \quad (7a)$$

$$\mathbf{x}_2(k)=\left[\sqrt{E_s}\mathbf{s}_2^T(k), \sqrt{E_p}\mathbf{p}_2^T(k), \sqrt{E_p}\hat{\mathbf{p}}_1^T(k)\right]^T, \quad (7b)$$

where E_s is the energy per information bit, $E_p = \delta E_s$ is the energy per parity bit, with $0 \leq \delta \leq 1$ being the energy allocation factor.

With the energy allocation scheme in (7), the effective uncoded energy per information bit can be calculated as

$$E_b = \frac{mE_s + 2pE_p}{m} = E_s\left(1 + \delta\frac{2p}{m}\right). \quad (8)$$

The energy allocation factor, δ, can be changed between 0 and 1 to adjust the energy allocation between the information and parity bits. When $\delta = 0$, the scheme degrades to a regular uncoded non-cooperative system.

The codeword, $\mathbf{x}_n(k)$, is transmitted to the FC through a wireless link, and the signal received from the n-th SU is

$$\mathbf{y}_n(k) = h_{nF}(k)\mathbf{x}_n(k) + \mathbf{z}_n(k), \quad (9)$$

where $h_{nF}(k)$ is the fading coefficient between the n-th SU and the FC, $\mathbf{z}_n(k)$ is the AWGN with a single-sided power spectral density N_{0z}. The received signal vector at the FC can be expressed as $\mathbf{y}_n(k) = [\mathbf{y}_{bn}^T(k), \mathbf{y}_{an}^T(k), \mathbf{y}_{\hat{a}n}^T(k_n)]^T$, where $\mathbf{y}_{bn}(k)$, $\mathbf{y}_{an}(k)$, $\mathbf{y}_{\hat{a}n}(k_n)$ are the received signal vectors corresponding to the coded sequence $\mathbf{b}_n(k)$, $\mathbf{a}_n(k)$, and $\hat{\mathbf{a}}_n(k_n)$, respectively, with $k_1 = k-1$ and $k_2 = k$.

C. Decoding

The FC recovers the quantized information vector, $\mathbf{b}_n(k)$, by decoding over two consecutive slots. The vector $\mathbf{b}_1(k)$ is decoded by using the received information corresponding to $\mathbf{b}_1(k)$, $\mathbf{a}_1(k)$, and $\hat{\mathbf{a}}_1(k)$ from the two slots in the k-th frame. The vector $\mathbf{b}_2(k)$ is decoded by using the received information corresponding to $\mathbf{b}_2(k)$, $\mathbf{a}_2(k)$, and $\hat{\mathbf{a}}_2(k)$, which are from the second slot of frame k and the first slot of frame $k+1$.

The decoding is performed at the FC with a modified message passing algorithm for graph-based codes.

For the received signals corresponding to the information vector, $\mathbf{b}_n(k)$, and the parity vector, $\mathbf{a}_n(k)$, the log-likelihood ratio (LLR) calculated from the channel observations is

$$\boldsymbol{\lambda}_{bn}(k) = -2\frac{\sqrt{E_s}\Re[\mathbf{y}_{bn}(k)h_{nF}^*]}{N_{0z}}, \quad (10)$$

$$\boldsymbol{\lambda}_{an}(k) = -2\frac{\sqrt{E_p}\Re[\mathbf{y}_{an}(k)h_{nF}^*]}{N_{0z}}, \quad (11)$$

where $\Re[x]$ is the real part operator, and a^* denotes the complex conjugate of a .

The LLR of the parity vector, $\mathbf{a}_n(k)$, can also be calculated from the cooperation information received from SU $m \neq n$, $\mathbf{y}_m(k_m)$, where $k_1 = k-1$ and $k_2 = k$. The LLR calculation of the cooperation information needs to take into consideration of the distortion introduced by the channel between the two SUs. If the bit error rate of the channel between the two SUs is ϵ, then the LLR of $\mathbf{a}_n(k)$ based on $\mathbf{y}_{\hat{a}m}(k_m)$ can be calculated as

$$\hat{\boldsymbol{\lambda}}_{an}(k) = \ln \frac{\epsilon + (1-\epsilon)\exp\left[-2\frac{\sqrt{E_p}\Re[\mathbf{y}_{\hat{a}m}(k_m)h_{mF}^*]}{N_{0z}}\right]}{(1-\epsilon) + \epsilon\exp\left[-2\frac{\sqrt{E_p}\Re[\mathbf{y}_{\hat{a}m}(k_m)h_{mF}^*]}{N_{0z}}\right]}, \quad (12)$$

The LLRs of $\mathbf{a}_n(k)$ from both the direct transmission and the cooperative transmission can be combined to obtain an enhanced parity LLR vector, as

$$\tilde{\boldsymbol{\lambda}}_{an}(k) = \boldsymbol{\lambda}_{an}(k) + \hat{\boldsymbol{\lambda}}_{an}(k). \quad (13)$$

The initial LLR vector of the linear block code can then be written as $\boldsymbol{\lambda}_n(k) = [\boldsymbol{\lambda}_{bn}^T(k), \tilde{\boldsymbol{\lambda}}_{an}^T(k)]^T \in \mathcal{R}^{(m+p)\times 1}$. The iterative message passing algorithm [13] can be applied by combining the initial LLR vector, $\boldsymbol{\lambda}_n(k)$, and the Tanner graph formulated from the parity check matrix, $\mathbf{H} = [\mathbf{P}, \mathbf{I}_p] \in \mathcal{B}^{p\times(m+p)}$. Details of the iterative message passing algorithm can be found in [13].

The iterative message passing decoding algorithm will be terminated when the syndrome of the codeword becomes 0. The decoded information vector is denoted as $\hat{\mathbf{b}}_n(k)$, which is then converted back to the analog domain as $\hat{S}_n(k) = Q^{-1}[\hat{\mathbf{b}}_n(k)]$ and used in the soft combining operation described in (4).

IV. Simulation Results

Simulation results are presented in this section to demonstrate the performance of the proposed cooperative sensing schemes. In the simulation, the time-bandwidth product is $\mu = 3$. The probability of detection is maximized at a fixed false alarm probability of 0.05.

We first study the impact of energy statistic quantization on the detection probability in Fig. 3. The probability P_d is shown as a function of γ_s, the SNR of PU-SU links. Error-free communications between the SUs and the FC are assumed in this example to highlight the impacts of quantization, and the effects of channel distortions between the SU-FC links will be considered later. The traditional one-bit hard decision at the SU is also shown for comparison. The simulation results indicate that the soft combining with quantized energy statistics outperforms the traditional hard decision except the 1-bit quantization case. A 4-bit quantization of the energy statistic can achieve exactly the same performance as combining the analog information without quantization. This demonstrates the effectiveness of the Lloyd-max quantizer for the soft combining. Therefore, the 4-bits quantizer is used for the remaining examples.

The next example is used to verify the proposed Slepian-Wolf cooperation with unequal energy allocation. Fig. 4 shows the bit error rate (BER) of various system configurations as a function of E_b/N_0 of the SU-FC links. The BER curves of the uncoded systems and the linear block code without cooperation are also shown in the figure for comparison. The (7, 4) Hamming code is used as the linear block code for both the cooperative and coded non-cooperative systems. Rayleigh fading channel is assumed for both the SU-SU link and the SU-FC links.

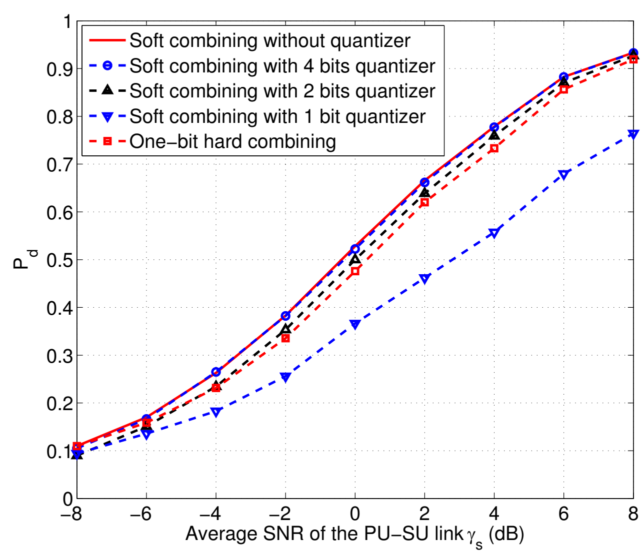

Fig. 3. Impacts of quantization on the performance of soft combining (ideal SU-FC links).

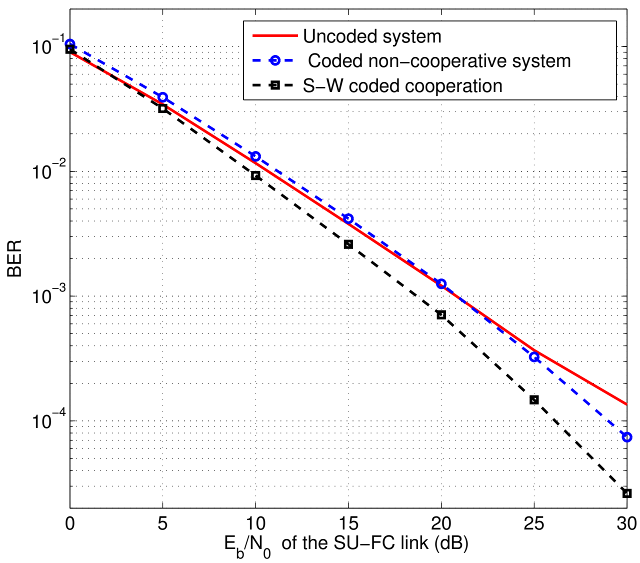

Fig. 4. Comparison of the Slepian-Wolf coded cooperation with other transmission schemes.

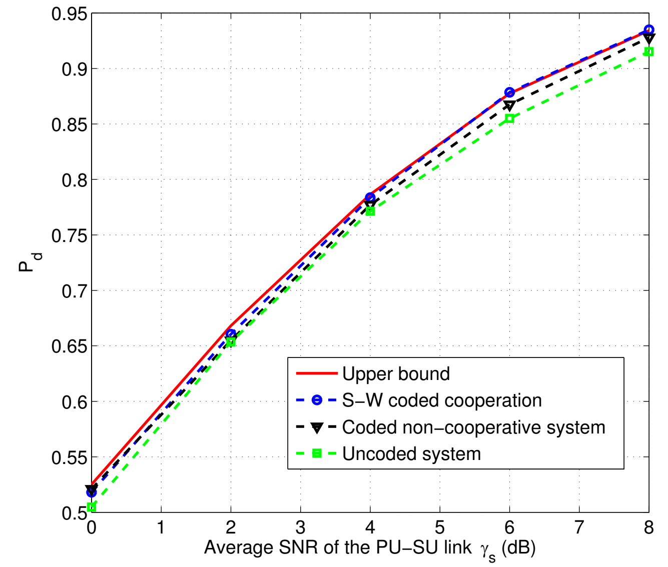

Fig. 5. Probability of detection with various cooperative spectrum sensing schemes (E_b/N_0 of the SU-FC link is 10 dB).

The SNR between the two SUs is 0 dB, which corresponds to an error probability of $\epsilon = 0.08$ for the cooperative link. The energy allocation factor is $\delta = 2/9$. The performance of the coded non-cooperative system is slightly worse than the uncoded system when $E_b/N_0 < 25$ dB because the coding gain is not enough to compensate the energy loss due to the parity bits, and the coding gain is only obvious after $E_b/N_0 \geq 25$ dB. The Slepian-Wolf cooperation with unequal energy allocation has a superior performance than both the uncoded system and the coded non-cooperative system for all the E_b/N_0 considered. It outperforms the coded non-cooperative system by 2.5 dB at BER = 10^{-4}.

Fig. 5 shows the detection probability at the FC as a function of γ_s, the SNR of the PU-SU link. The E_b/N_0 between the SU-FC link is fixed at 10 dB. The rest of the simulation parameters are the same as in Fig. 4. The upper bound shown in the figure is obtained by performing soft combining over unquantized, distortion-free energy statistics. As expected, the proposed Slepian-Wolf cooperation with unequal energy allocation outperforms both the uncoded system and the coded non-cooperative system. The performance of the proposed scheme achieves the upper bound for γ_s>4 dB.

V. Conclusion

A new Slepian-Wolf coded cooperation scheme with unequal energy allocation among the coded bits was proposed for a cooperative cognitive radio network. The energy statistics measured at the SUs were quantized with a Lloyd-Max quantizer, and then forwarded to the FC by utilizing the SU-SU link as a cooperation channel. The newly proposed unequal energy allocation among the coded bits can compensate the energy loss due to parity bits introduced by the coded cooperation. A soft combining scheme was employed at the FC to improve the detection probability by combining an estimate of the quantized energy statistics. Simulation results demonstrated that the proposed scheme in practical system configurations with fading and noise in the SU-FC links can achieve a performance that is almost identical to the ideal soft combining with distortion-free SU-FC links and no quantization. The scheme is proposed for a CR network with two SUs, but can be easily extended to networks with more than two SUs by grouping two SUs together for cooperation.

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