Energy-Efficient Reporting Scheme for Cooperative Spectrum Sensing

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Abstract—Cooperative spectrum sensing (CSS) has been proposed in order to improve the reliability of the spectrum occupancy decision in cognitive radio networks. There are two well-known schemes for cooperation among cognitive users (CUs), soft scheme (SS) and hard scheme (HS). In SS the exact local sensing result is reported to a Fusion Center (FC), usually by quantizing it with a large number of bits. In contrast, only one bit is used in HS to convey the local sensing result to the FC. The difference in the number of reported bits results in high accuracy in SS and low energy consumption in HS. In this paper, we propose a novel scheme that gets benefits from both schemes, where the proposed scheme uses only one bit, as in HS, and provides high accuracy, almost as in SS. In the proposed scheme, each CU reports only one bit on a time slot related to its actual sensing results. At the FC, the arrival time of a single bit represents the sensing result of the reporting CU. Simulation results show that our proposal outperforms both HS and SS in terms of detection accuracy and energy efficiency.

I. INTRODUCTION

Cognitive Radio (CR) has been proposed as a new technology able to overcome spectrum underutilization [1]. In CR, the unused portions of the spectrum, also known as spectrum holes, can be exploited by unlicensed users. These unlicensed users, also called Cognitive Users (CUs), should have the ability to detect the activity of the licensed users. Hence, the spectrum needs to be sensed by the CUs before commencing the exploitation of spectrum holes [2].

The spectrum sensing process implies extra energy consumption with respect to the typical wireless transmissions. Moreover, Cooperative Spectrum Sensing (CSS), where the CUs send their local results to a central entity called Fusion Center (FC), further increases the energy consumption even though CSS improves the reliability of the sensing process by mitigating the effects of multipath fading and shadowing [3], [4].

Several works have presented solutions for the high energy consumption problem in CSS, and these works can be classified into four main directions: reducing the number of CUs [5], [6], reducing the amount of reported information to the FC [7], reducing the number of sensed channels [8], and optimizing the parameters of CSS [9], [10], [11]. The contributions of this paper are considered in the direction of reducing the amount of reported information.

Two main schemes have been proposed for reporting the local sensing results to the FC, Soft Scheme (SS) and Hard Scheme (HS). In SS, after performing local sensing by all CUs, each CU quantizes its sensing result by a number of bits and sends it to the FC. The number of bits should be large enough to ignore the resulting quantization noise. In contrast, a single bit is used to convey the sensing result in HS. Obviously, more accurate results will be available at the FC if SS is employed. However, CUs may suffer from high energy and time resources consumed in SS. On the other hand, reduced energy and time resources are required in HS but in price of less accuracy in the reported results. Many studies have tackled the comparison between these two schemes [12], [13], [14], [15], [12] shows that there is a performance gain in using SS even in the presence of reporting channel errors. In [13] the gain of SS over the HS is set lower than a fraction of a dB, while [14] demonstrates that the performance of both schemes will nearly converge under low SNR values when the ratio between the number of sensing users in HS and SS schemes equals 1.6. On the opposite, a comparison based on limited time resources has shown that HS is better than SS in most critical cases in [15].

In this paper, we present a novel reporting scheme that gets benefits from both HS and SS. In the proposed scheme, each CU reports only a single bit to the FC, as in HS, and, at the same time, provides accurate results to the FC, almost as in SS. The idea is based on splitting the reporting period to several time slots, and mapping these slots to specific intervals on the range of the local sensing result. Each CU (after obtaining the sensing result) will report a single bit on the time slot that is corresponding to the actual sensed value. At the FC, whenever a bit is received, the sensing result can be extracted by de-mapping the time slot on which the bit is received to the corresponding sensing result. However, according to this proposal, there is probability that more than a CU report on the same time slot, and hence, their reports will collide and appear as one report to the FC. Also, the division of the reporting period and spectrum sensing intervals affects the overall performance of the proposed scheme. These effects are intensively investigated in this paper. The performance of the proposed scheme is compared to the SS and HS, where simulation results show that our proposal outperforms both scheme in terms of detection accuracy and energy efficiency.

The rest of this paper is organized as follows, Section II describes the system model. In Section III the proposed scheme is presented along with its mathematical framework, followed by a discussion in performance optimization in Section IV. Simulation results are presented in section V, and conclusions are drawn in Section VI.

II. SYSTEM MODEL

In cognitive radio networks (CRN), a set of cognitive users (CUs) attempts to exploit the unused portions of a spectrum. However, this should be performed with minimum interference to the licensed users of the spectrum. Therefore, CUs should sense the spectrum in order to identify its status. The probability that the spectrum is not being used by a licensed user is denoted by $P_0$. The optimal method for spectrum sensing is energy detection method especially when no prior information is available [13]. In the energy detection method, each CU collects a number of energy samples from the target spectrum for $T_s$ sec.
As CSS implies, the final decision about spectrum status is made cooperatively, which requires all local sensing results to be reported to the FC. Upon receiving the results from CUs, the FC will process these results, and apply a specific fusion rule in order to obtain the final decision. The reliability of the final decision is measured by two main indicators, the detection probability \( P_D \) and the false-alarm probability \( P_F \). \( P_D \) is the probability of identifying a used channel as used, while \( P_F \) is the probability of identifying an unused channel as used.

Based on the final decision, only if the spectrum is identified as unused, a CU will be scheduled for data transmission in the rest of the frame.

The time frame \( T \) of the cognitive transmission is divided into three phases, sensing phase \( T_s \) where local sensing is performed by each CU, reporting phase \( T_R \) where local results are reported to the FC, and data transmission phase \( T_D \) where one of the CUs is scheduled for data transmission. The total energy consumption by the whole network includes the energy consumed during the three phases. Notice that the energy consumption during sensing and reporting phases always exists, while the transmit energy exists only if the spectrum was identified as unused, i.e., if the spectrum is identified as used, no data transmission will occur and hence no transmit energy will be consumed. The probability of identifying the spectrum as unused, denoted as \( P_{\text{unused}} \), is given as follows:

\[
P_{\text{unused}} = P_0(1 - P_F) + P_1(1 - P_D) \tag{1}
\]

where \( P_1 = 1 - P_0 \). Hence, the average total energy consumption by the whole CRN is given as follows

\[
E_T = E_S + E_R + P_{\text{unused}}E_D \tag{2}
\]

where \( E_S \), \( E_R \) and \( E_D \) are the consumed energy during sensing, reporting and transmission, respectively.

The average achievable throughput is the average successfully delivered amount of data. Success in data transmission occurs only if the spectrum is unused and correctly identified. The average achievable throughput is expressed as follows

\[
T_h = P_0(1 - P_F)DT_t \tag{3}
\]

where \( D \) is the transmission data rate.

Using (2) and (3), we can define the energy efficiency as the ratio of the achievable throughput to the average energy consumption, as follows:

\[
\mu = \frac{T_h}{E_T} \tag{4}
\]

Notice that the energy efficiency, achievable throughput, and the total energy consumption depend on the detection accuracy of the CSS represented by \( P_D \) and \( P_F \), as appears in (2), (3) and (4). Thus, since \( P_F \) and \( P_D \) mainly depend on the accuracy of the reported results provided to the FC, the report scheme will hugely influence the overall performance of the CRN.

III. THE PROPOSED REPORTING SCHEME

The two well-known report schemes, HS and SS, have been intensively investigated in the literature. In HS, the sensing results are conveyed in only one bit, also known as binary local decision, and reported to the FC, while in SS the sensing result is quantized and reported by multiple bits. The number of bits is selected to be large enough to avoid significant quantization noise. It is obvious that HS consumes less energy in results’ reporting than SS due to the difference in the number of reported bits. On the other hand, conveying sensing results in only one bit leads to poor accuracy, and hence, lower detection performance than SS.

Motivated by this, we propose a novel reporting scheme that is able to consume an amount of energy as in HS while achieving a detection accuracy almost as in SS. In this proposal, the reporting phase \( T_R \) is split into \( L \) time slots \( \{t_1, t_2, ..., t_L\} \). Likewise, the possible range of the sensing result, which is represented by the average of the collected energy samples, is divided into \( L \) intervals using \( L + 1 \) thresholds \( \{\gamma_1, \gamma_2, ..., \gamma_{L+1}\} \). Each interval is represented by a unique level \( v_i \). Upon ending the local sensing and computing the samples’ average \( A_i \) at each CU, if \( A_i \) is within the \( l^{th} \) interval, i.e., \( \gamma_l \leq A_i < \gamma_{l+1} \), then, one bit will be reported to the FC on the \( l^{th} \) time slot. At the FC, whenever a bit is received on the \( l^{th} \) time slot, the FC will consider the samples’ average of the reporting CUs equal to \( v_l \). Fig. 1 shows the mapping between the time slots and the samples’ average.

\[\begin{align*}
\gamma_{l=0} & \quad \gamma_1 & \quad \gamma_2 & \quad \gamma_3 & \quad \gamma_4 & \quad \gamma_{L=100} \\
T_5 & \quad \cdots & \quad T_R = L \cdot t & \quad T_D
\end{align*}\]

**Fig. 1.** Description of the quantization intervals used at the CU-end, frame division at the FC-end, and the mapping between them in the proposed scheme.

In formulas, a CU that has obtained a samples’ average \( A_i \) will report one bit on the time slot \( (l(i)) \) given by

\[
l(i)(\gamma_l \leq A_i < \gamma_{l+1}) = t_l \tag{5}
\]

At the FC, the recovered samples’ average \( \hat{A}_i \) of a CU whose reported bit has been received at the FC on the \( l^{th} \) time slot is expressed as follows

\[
\hat{A}_i(l(i) = t_l) = v_l \tag{6}
\]

Following this proposal, each CU reports only one bit to the FC so that the energy consumed in reporting is equal to the HS. On the other hand, the resulting detection accuracy is affected by several factors, the thresholds \( \gamma \)’s, the recovered values \( v \)’s, and the number of levels \( L \). In the following we discuss each one of them.

A. Quantizer Design

The process of representing the samples averages in discrete levels is considered as a scalar quantization process [16]. Thus, the selection of the thresholds \( \gamma \)’s and the representing values \( v \)’s follow the typical problem of quantization design. The
optimal $\gamma$’s and $v$’s that minimize the squared-error distortion could not be formulated in analytical forms, and they are obtained using an iterative algorithm [17]. Therefore, in this work we consider an maximum-entropy quantization process in order to reduce complexity and smooth the following analysis [18]. According to the maximum-entropy quantization, the thresholds are selected so that the probability that the sensed valued lies in an interval is equal probable for all intervals, as follows

$$Pr(v_l \leq A_i < v_{l+1}) = \frac{1}{L} \quad \text{for } l = 1, ..., L \quad (7)$$

where the notation $Pr(\cdot)$ refers to the probability of an event. (7) can be rewritten using the cumulative distribution function of the samples’ average ($F_A$) as follows

$$F_A(v_{l+1}) - F_A(v_l) = \frac{1}{L} \quad \text{for } l = 1, ..., L \quad (8)$$

The optimal level $v$ for each interval has been found to be the centroid (the conditional expected mean) of the corresponding interval [17]. Therefore, the representing level of any interval can be given as

$$v_l = \int_{v_l}^{v_{l+1}} f_A(x) \cdot dx \quad \text{for } l = 1, ..., L \quad (9)$$

which can be simplified as follows

$$v_l = L \int_{v_l}^{v_{l+1}} f_A(x) \cdot dx \quad \text{for } l = 1, ..., L \quad (10)$$

where $f_A$ is the probability density function of $A$.

### B. Reports Collision

Due to the absence of results exchange among CUs, there is a probability that two or more CUs report their bits on the same time slot. This implies that the sent reports on the same time slot will collide, and hence, the FC will be unable to recognize if the received signal from one or more CUs. Therefore, the FC will deal with them as one CU. Obviously, these collisions affect directly the achievable performance and the detection accuracy since the number of participating CUs in making the final decision will be lower than the total available CUs.

If we denote the number of reporting CUs in the $l^{th}$ time slot by $n_l$, then the probability of $n_l$ is expressed as follows

$$Pr(n_l = i) = \sum_{i=0}^{N} \binom{N}{i} \left( \frac{1}{L} \right)^i \left( 1 - \frac{1}{L} \right)^{N-i} \quad (11)$$

Notice that (11) is identical for all time slots because of the equal probable levels. Accordingly, the average number of reporting CUs in any time slot can be given as:

$$\bar{n} = \frac{N}{L} \quad (12)$$

It is worthy to mention that the average number of reporting CUs decreases as the number of levels increases. However, the increase in number of levels requires more time resources for the reporting process.

### IV. Performance Optimization

The proposed scheme for reporting the local results to the FC reduces the energy consumption in CSS. On the other hand, the achievable detection accuracy depends on the number of used quantization levels (time slots), where an increase in the number of levels improves the detection accuracy. However, increasing the number of time slots reserves more time resources for CSS ($T_D$), which, in turn, affects the time dedicated for transmission ($T_D$) since the total frame length $T$ is fixed. Such decrease on $T_D$ results into two contrasting effects on the achievable energy efficiency. First, shorter $T_D$ results in lower throughput, as indicated in (3), which consequently, degrades the achievable energy efficiency. Second, lower $T_D$ decreases the total energy consumption during data transmission, as appears in (2), and hence, energy efficiency is improved.

The number of the time slots should be optimized so that the achievable energy efficiency is maximized. To this goal, the resulting detection probability and false-alarm probabilities should be computed based on the proposed scheme. Both probabilities depend on the number of CUs ($N$) and the number of time slots ($L$). However, due to the possible collision among different CUs, the number of successfully received reports could be less than the total number of sent reports. If we denote the number of successfully received reports by $x$ ($1 \leq x \leq N$)*, then the probability of $x$ is expressed as follows

$$Pr(x = i) = \frac{L!}{L^n} \left( \frac{N}{L} \right)^i \sum_{k=1}^{K_i} \frac{S_k}{\prod_{j=1}^{K_i} d_{kj}!} \quad (13)$$

where $d_{kj}$ ($j = 1, 2, ..., i$ and $k = 1, 2, ..., K_i$) is the $j^{th}$ element in the set $D_k$ that contains $i$ non-zero elements whose sum is $N$, i.e., $\left( \sum_{j=1}^{i} d_{kj} = N, \ d_{kj} \neq 0 \right)$, $K$ is the number of possible sets that satisfy $D$, and $S_k$ is the number of different combinations of the set $D_k$. For example, consider $L = 10$ and $N = 6$ and we want to compute the probability that only two reports are received successfully, i.e., $Pr(x = 2)$. In other words, we compute the probability that 6 CU report on 2 time slots. In this case, 3 different sets can satisfy the condition of $D$, which are $D_1 = \{5, 1\}$, $D_2 = \{4, 2\}$ and $D_3 = \{3, 3\}$, and the number of the different combinations of each one is $S_1 = 2$, $S_2 = 2$ and $S_3 = 1$, respectively. Now, by substituting these values in (13), $Pr(x = 2)$ can be easily computed.

At the FC, if $i$ CUs have reported on the same time slot, their reports will collide, and be considered as only one report. The final decision is made by comparing the sum of the received reports to a predefined threshold. Thus, the average achievable detection probability and false-alarm probability are given respectively as follows:

$$\bar{P}_D(L, N) = \sum_{i=1}^{N} P_r(x = i) P_D(i) \quad (14)$$

$$\bar{P}_F(L, N) = \sum_{i=1}^{N} P_r(x = i) P_F(i) \quad (15)$$

where $P_D(i)$ and $P_F(i)$ are respectively the detection probability and false-alarm probability when $i$ CUs are involved.

*Notice that if more than one report are sent on the same time slot, one of them will be consider as received successfully.
Now, let us investigate energy consumption and throughput. Following the proposed scheme, (2) can be rewritten as follows:

\[ E_T = \rho_s T_s + \rho_r N t + P_{\text{unused}} \rho_t (T - T_s - Lt) \]  \hspace{1cm} (16)

where \( \rho_s, \rho_r \) and \( \rho_t \) are the consumed power during sensing, reporting and transmission, respectively. Notice that the energy consumption during sensing and reporting is dependent of \( L \), while the transmit energy is directly affected by increasing \( L \). This effect is related to the change on \( P_{\text{unused}} \) and the decrease in transmission time.

Regarding the throughput, (3) can be rewritten as follows:

\[ Th = P_0 (1 - P_F) D (T - T_s - Lt) \]  \hspace{1cm} (17)

Likewise, the throughput will be affected here also by increasing \( L \) due to the decrease in \( P_F \) and the decrease in the transmission time.

From (16) and (17), we can say that the achievable energy efficiency is influenced by \( L \), and hence, \( L \) should be optimized so that the energy efficiency is maximized.

V. SIMULATION RESULTS

A CRN of \( N \) CUs is considered. The sensing channel is assumed to be additive Gaussian noise channel with an average signal to noise ratio equals \( SNR = -10 \log(B!) \). The proposed scheme is compared to the two classical schemes, Soft Scheme and Hard Scheme, in terms of the detection accuracy and energy efficiency. The common simulation parameters among the three schemes are shown in Table I. In SS, the sensing results are reported using 8 bits, where the resulting quantization noise is ignored.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_0 )</td>
<td>0.5</td>
<td>( T_s )</td>
<td>0.1 MHz</td>
</tr>
<tr>
<td>( t )</td>
<td>20 ( \mu s )</td>
<td>( \rho_r )</td>
<td>1 W</td>
</tr>
<tr>
<td>( \rho_t )</td>
<td>1 W</td>
<td>( \rho_s )</td>
<td>0.1W</td>
</tr>
<tr>
<td>( T )</td>
<td>50 ms</td>
<td>( I_s )</td>
<td>1 ms</td>
</tr>
<tr>
<td>( SNR )</td>
<td>(-10 \log B!)</td>
<td>( H )</td>
<td>200Kbps</td>
</tr>
</tbody>
</table>

Fig. 2 shows the missed-detection probability versus the false alarm probability for the proposed scheme (\( L = 10 \)) and both HS and SS. It is clear that at a fixed false alarm probability, our proposal can achieve lower missed detection probability than the HS. This is due to the more accurate results provided by our proposal. On the other hand, the SS still attains lower missed detection than the proposed scheme, due to the perfect accuracy in the reported sensing results. It is obvious that the number of levels (\( L \)) has an important role in the detection performance since increasing the number of levels improves the accuracy in the reported information. In Fig 3, the detection probability is plotted versus the number of levels at a fixed false-alarm probability (\( P_F = 0.1 \)). Clearly, the detection probability increases as the number of levels increases. The proposed scheme outperforms the HS with a small number of levels, while the achievable detection probability by the SS represents the maximum detection probability that can be attained by the proposed scheme. However, for \( L \geq 12 \), the difference in detection probability can be ignored between our proposal and the SS.

\[ ^1 \text{All derived equations are applicable to any other fading model that could be considered.} \]

The previous two figures show that the detection accuracy of the proposed scheme depends on the number of levels (time slots). However, in view of the limited time resources, increasing the number of time slots affects the energy consumption, achievable throughput and energy efficiency. This is due to increasing the number of time slots that are dedicated for reports reception, which reduces the time spent in data transmission. Hence, energy consumption, throughput and energy efficiency will be affected. Also, since energy efficiency is affected by detection performance that mainly depends on \( L \). Fig. 4 depicts the energy efficiency versus the false alarm probability for the proposed scheme (at \( L = 20 \)) compared to the SS and the HS. Our proposal can achieve higher energy efficiency than the other two schemes for most of the range of \( P_F \).
The energy efficiency versus the false alarm probability for the three schemes.

Fig. 4. The energy efficiency versus the false alarm probability for the three schemes. \((N = 10)\).

The achievable energy efficiency by the proposed scheme using the optimal \(L\) is shown in Fig. 5 versus the number of sensing users \(N\). The proposed scheme achieves higher energy efficiency than the other schemes due to the low energy consumption and the high accuracy in the reported results. The proposed scheme outperforms the other two schemes over the whole range of the number of CUs.

Fig. 5. The energy efficiency versus versus the number of available users \(N\) for the three schemes. The optimal number of levels is used in the proposed scheme. \((P_F = 0.1)\)

VI. CONCLUSIONS

A novel energy-efficient reporting scheme for spectrum sensing results is presented in this work. The proposed scheme gets benefits from both SS and HS, where each CU reports only a single bit on a time slot related to its actual sensing result. At the FC, the sensing result is extracted based on the arrival time. Extended discussion and simulation results have demonstrated the superiority of the proposed scheme in terms of achievable energy efficiency over both HS and SS.

REFERENCES