Comparison Between Eigenvalue Fusion and Decision Fusion for Spectrum Sensing of OFDMA Signals Under Errors in the Control Channel

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***Abstract*—Recently, an eigenvalue fusion approach for detecting idle subchannels of OFDMA signals in the context of centralized cooperative spectrum sensing for cognitive radio (CR) was proposed. Four detection techniques were analyzed, and it was concluded that the eigenvalue fusion outperforms the decision fusion scheme, in spite of the larger volume of data sent to the fusion center (FC) in the eigenvalue fusion. Nevertheless, it was conjectured that bit errors in the reporting channel could be more disastrous to the data representing CR decisions than to the data carrying eigenvalues, masking a potential advantage of the eigenvalue combining also in terms of the volume of data sent to the FC. In this paper we investigate this conjecture and conclude that it is partially true: CR decisions are indeed more sensitive to channel errors, but the amount of redundancy inserted to protect the decisions so as to equate the performances of the two fusion schemes does not always leads to a larger number of bits in the decision fusion. Then, one needs to trade performance and amount of data in the reporting channel to decide upon which fusion scheme must be adopted, in a case by case analysis.**

I. INTRODUCTION

Due to the increased demand for wireless communication services and the adoption of a fixed spectral allocation policy, spectral congestion and scarcity have become a huge problem. With the advent of the cognitive radio (CR) concept, spectrum sensing and opportunistic dynamic access to idle bands have arisen to contribute partially in solving such a problem.

Combined or not with some spectrum occupation database, spectrum sensing is a fundamental task performed by a CR. As the name suggests, it is the task of monitoring the frequency spectrum, seeking for idle portions (spectrum holes or whitespaces) for subsequent opportunistic occupation. CRs with spectrum sensing capability have to identify whitespaces efficiently and avoid harmful interference to primary users by either switching to an unoccupied band or keeping the interference below a maximum acceptable level [1]. Then, the importance of studies involving spectrum sensing techniques is undeniable and, now, even more pronounced since that, recently, actually this year, the IEEE announced the creation of the IEEE 802.22 Spectrum Occupancy Sensing (SOS) Study Group [2]. As stated by the chair of the working group, "standardization could lead to the more efficient use of spectrum, especially in places where the information about the primary users is difficult to find". Yet, "individual and collaborative spectrum sensing is one of the tools to complement the information contained in databases to create an accurate spectrum occupancy survey, which would combine information from multiple sensors along with local terrain information to predict the spectrum occupancy patterns" [2].

The majority of the third generation (3G) broadband systems are based on direct sequence spread spectrum (DSSS), such as Evolution Data Optimized (EVDO) or High Speed Packet Access (HSPA). Fourth generation (4G) systems, however, mostly adopt multicarrier transmission techniques, such as orthogonal frequency division multiplexing (OFDM), combined with or without its access counterpart, the orthogonal frequency division multiple access (OFDMA) [3]. The main reason for choosing OFDM is that it has some advantages in delivering high speed data, especially in a multipath, frequency selective fading channel [3]. Moreover, combined with the subcarrier nulling flexibility of OFDM signals, OFDM-based cognitive radios can opportunistically reuse non-contiguous underutilized spectrum bands. Since OFDM-like systems are being adopted and will continue to be adopted as the schemes of choice in broadband communication systems, it is important for CR networks to sense OFDM-like signals.

A. Related Works and Contributions

Several spectrum sensing techniques have been proposed so far, which can be classified as narrowband and wideband according to the bandwidth of the spectrum sensed. Narrowband sensing techniques are limited to detect the presence of primary signals in a single band, whereas wideband techniques aim at jointly or sequentially monitoring multiple bands. In what concerns narrowband sensing, energy detection, matched filter detection and cyclostationary feature detection are widely discussed in the literature [4]. For wideband sensing, recent studies point to three major techniques: energy detection [5], wavelet-based detection [6] and compressed (or compressive) sensing detection [7]. Eigenvalue-based detection [8] are one of the most recent and promising techniques for spectrum sensing. Likewise energy detection, eigenvalue detection can be applied to narrowband and to wideband signals.

Cooperative spectrum sensing is a possible solution for problems experienced by cognitive networks that use non-cooperative spectrum sensing. Among such problems are the receiver uncertainty, the multipath fading and the correlated shadowing [1]. Cooperative spectrum sensing can be centralized, distributed or relay-assisted [1]. In centralized cooperative sensing, data collected by each cooperating CR (e.g., samples from the received signal) is sent to a fusion center (FC) through a dedicated control channel. This process is called data fusion. After the data is processed, the FC decides upon the occupation state of the channel. Centralized cooperative spectrum sensing can be executed as well from the decisions about the channel occupancy state made by each cooperating CR individually. This operation is called decision fusion, where the final decision about the channel state is accomplished on the CR decisions through binary operations such as AND, OR and majority (MAJ) voting. In both centralized schemes, the final decision is informed back to the CRs through the control channel. The access algorithm adopted by the secondary network then takes place.

A new approach for the detection of OFDMA and other wideband signals in the context of centralized, data fusion cooperative spectrum sensing was proposed in [9]. The approach is based on the eigenvalues of the received signal covariance matrix whose samples are in the frequency domain. Soft combining of the eigenvalues at the FC was the main novelty. It was applied to variants of four test statistics for binary hypothesis test, namely [8]: the eigenvalue-based generalized likelihood ratio test (GLRT), the maximum-minimum eigenvalue detection (MMED), also known as eigenvalue ratio detection (ERD), the maximum eigenvalue detection (MED), also known as Roy's largest root test (RLRT), and the energy detection (ED). It was shown in [9] that the eigenvalue (EV) fusion can outperform schemes based on decision fusion and sample fusion. Moreover, it produces lower data traffic when compared with the sample fusion. The lowest amount of traffic is an intrinsic characteristic of the decision fusion strategies.

This paper reports a performance comparison between the EV combining scheme proposed in [9] and the decision fusion scheme in the context of the spectrum sensing of OFDMA subchannels under reporting channel errors. This comparison was motivated by a conjecture in [9] stating that bit errors in the control channel could be more disastrous to the data representing CR decisions than to the data representing eigenvalues. This would demand increased protection of the decisions, eventually reducing the difference in the volume of traffic between the decision fusion and the EV fusion, making the later the preferred choice both in terms of performance and amount of data traffic.

Several publications have addressed, theoretically and via simulation, the influence of reporting channel errors in cooperative spectrum sensing, under a variety of circumstances and scenarios; see [10], [11] and references therein. To the best of our knowledge, however, no comparison similar to the one presented here has been made yet, what we credit to the short time since the publication of [9].

II. EIGENVALUE FUSION AND DECISION FUSION METHODS FOR DETECTING IDLE OFDMA SUBCHANNELS

OFDMA is a multiple access technique that allocates to a given user a set or multiple sets of subcarriers, allowing for simultaneous access to the overall band by several users. A set of frequencies is called a subchannel. A subchannel can be formed according to two methods: adjacent subcarrier method (ASM), which groups a set of contiguous subcarriers to form a subchannel, and diversity subcarrier method (DSM), in which non-contiguous subcarriers are chosen to form a subchannel. As a consequence, when any spectrum sensing scheme is applied to the detection of a primary OFDMA signal, it aims at detecting the signal at the subchannel level, i.e., it aims at detecting if a given subchannel is vacant or not.

Let a single OFDMA signal with K available subcarriers and P subchannels. Thereby, $K' = K/P$ subcarriers will form a subchannel indexed by s, $s = 1, 2, \ldots, P$. It is assumed that each of the m cooperating CRs knows the subcarrier allocation map for each subchannel (this information can be readily available from the primary network standard). A matrix of order $K' \times N$ with sample values at the i-th CR and s-th subchannel will be formed according to

$$\mathbf{A}_s^{(i)} = \begin{bmatrix} Y_{s,1}^{(i)}(1) & \cdots & Y_{s,1}^{(i)}(N) \\ \vdots & \ddots & \vdots \\ Y_{s,K'}^{(i)}(1) & \cdots & Y_{s,K'}^{(i)}(N) \end{bmatrix} \tag{1}$$

where N is the number of samples, $Y_{s,k'}^{(i)}(j)$ is the j-th sample collected by the i-th CR in the k'-th subcarrier pertaining to the s-th subchannel with $j = 1, 2, \ldots, N$, $i = 1, 2, \ldots, m$, and $k' = 1, 2, \ldots, K'$. From (1), the next step is to compute the corresponding sample covariance matrices, according to

$$\mathbf{R}_s^{(i)} = \mathbf{A}_s^{(i)} \mathbf{A}_s^{(i)\dagger} / N\,. \tag{2}$$

A. Eigenvalue Fusion for OFDMA Signals

From (2), $mK'P$ eigenvalues are estimated and sent to the FC. The test statistics for the s-th OFDMA subchannel are computed at the FC according to the following equations [9]:

$$T_{\mathrm{GLRT},s} = \frac{PK' \sum_{i=1}^{m} \lambda_{1,s,i}}{\sum_{j=1}^{K'} \sum_{z=1}^{P} \sum_{i=1}^{m} \lambda_{j,z,i}}, T_{\mathrm{MED},s} = \frac{\sum_{i=1}^{m} \lambda_{1,s,i}}{m\sigma^2},$$

$$T_{\mathrm{MMED},s} = \frac{P \sum_{i=1}^{m} \lambda_{1,s,i}}{\sum_{z=1}^{P} \sum_{i=1}^{m} \lambda_{K',z,i}}, T_{\mathrm{ED},s} = \frac{\sum_{j=1}^{K'} \sum_{i=1}^{m} \lambda_{j,s,i}}{K' m \sigma^2},$$

where $\{\lambda_{1,s,i} \geq \lambda_{2,s,i} \geq \cdots \lambda_{K',s,i}\}$ are the K' ordered eigenvalues associated with the s-th subchannel and i-th CR, and σ^2 is thermal noise variance at the input of each CR. The sensing process is then concluded by comparing the test statistics with a threshold pre-defined according to the desired performance of the sensing process. If a test statistic is greater than the threshold, the subchannel is deemed occupied; otherwise the subchannel is declared vacant.

B. Decision Fusion for OFDMA Signals

A matrix with sample values at each CR and for each subchannel will be formed according to (1), from where the corresponding sample covariance matrices are computed via (2). From each of the resulting P sample covariance matrices, K' eigenvalues are estimated in each CR and ordered as $\{\lambda_{1,s} \geq \lambda_{2,s} \geq \cdots \lambda_{K',s}\}$. The occupation of each subchannel is determined in each CR by comparing the decision threshold with any of the test statistics given by [9]:

$$T_{\text{GLRT},s} = \frac{PK'\lambda_{1,\,s}}{\sum_{j=1}^{K'}\sum_{z=1}^{P}\lambda_{j,z}}, T_{\text{MED},\,s} = \frac{\lambda_{1,s}}{\sigma^2},$$

$$T_{\text{MMED},s} = \frac{P\lambda_{1,\,s}}{\sum_{z=1}^{P}\lambda_{K',z}}, T_{\text{ED},\,s} = \frac{\sum_{j=1}^{K'}\lambda_{j,s}}{K'\sigma^2}.$$

The mP CR decisions are then sent to the FC for binary arithmetic combining (AND, OR or MAJ voting) and final decisions upon the occupancy of each subchannel.

III. SYSTEM MODEL

In order to analyze the influence of the reporting channel (from the CRs to the FC) errors in the system performance, the decision of each CR in the decision fusion operation, for the GLRT, the MMED, the MED and the ED, was encoded via a repetition code with configurable coding rate $r = 1/n$, odd n, and sent through a binary symmetric channel (BSC) with configurable crossover (error) probability. Corrupted repetition-coded decisions from the CRs were decoded by majority rule and the estimated decisions were combined according to the desired fusion rule (AND, OR or MAJ voting) for subsequent final decision. In the case of the EV fusion, the eigenvalues computed by each CR were converted into a digital data with b bits of resolution, and then sent to the FC through a BSC channel. Received bits were converted into analog quantities representing the corrupted eigenvalues, and EV combining was then performed using the GLRT, the MMED, the MED and the ED for subsequent final decision.

Without loss of generality, the BSC has been adopted because it can fairly model the modulation-channel-demodulation chain in a flexible and modulation/channel-independent way in terms of error probabilities. The repetition code, the simplest among the coding schemes, has been chosen because it is well known that it behaves like a diversity scheme in fading channels, providing large coding gains. Moreover, by using a repetition code, the coding rate and, thus, the error correction capability can be easily configured. This leads to flexibility in terms of the amount o redundancy inserted for a given target performance, which is particularly suitable for the investigation at hand.

IV. NUMERICAL RESULTS

We have considered a primary network with $P = 4$ subchannels. The number of cooperating CRs was $m = 6$. An OFDMA channel with $K = 20$ subcarriers was adopted. The subchannels were created by forming $P = 4$ sets with $K' = K/P = 5$ subcarriers randomly selected. We also considered unitary primary signal power and SNR $= -10$ dB. The wireless channel between the primary transmitter and secondary cognitive receivers (CRs) was modeled as a 20-path slow frequency-selective Rayleigh fading channel whose frequency response was kept constant during a sensing period, being varied independently from one sensing period to another. The second moment of the channel gains were normalized so as to keep the average received signal power equal to the average transmitted signal power. The number of samples collected in each subcarrier frequency was $N = 60$.

We have considered two scenarios for system simulation. In the first one we just compare the performances of the EV combining and the decision combining strategies using the GLRT, the MMED, the MED and the ED techniques, under different BSC error probabilities, without channel coding. In the second one we introduce the repetition encoding and investigate the necessary amount of redundancy enough for approximating the performances of a given decision fusion rule and the EV fusion, again for the GLRT, the MMED, the MED and the ED. In this second scenario it is possible to infer about the performance and volume of data traffic tradeoff.

The ROC curves presented hereafter were built from the average of the probability of false alarm, P_{fa}, and the probability of detection, P_{d}, in all subchannels of the OFDMA signal. The curves were obtained via Monte Carlo simulations, counting a minimum of 100 false alarm or detection events (which occurs first) or a maximum of 5000 runs. The primary radio signal activity in each subchannel was modeled as a Bernoulli random variable with 50% of the time in the ON state (for P_{d} computations) and 50% in the OFF state (for P_{fa} computations). The eigenvalues computed in each CR were quantized with $b = 4$ bits. This value of b was chosen as the minimum value that maintained the performance practically unchanged when compared to the maximum resolution (floating-point operation). Additionally, this value corroborates the results reported in [12]. The code was implemented in MATLAB according to the models and test statistics described throughout the paper.

It is clear that the amount of scenarios arising from the combinations of the system parameters and the detection techniques is very large. In what follows, due to the lack of space, some results were only presented for the GLRT. We attest, however, that when this occurs, very similar behaviors were observed for the MMED, the MED and the ED, and that all conclusions drawn from the GLRT also apply to the other ones.

A. Results Without Channel Coding

Figure 1 shows ROC curves for the EV fusion and the decision fusion using the GLRT for sensing OFDMA subchannels without channel coding, for different values of the channel error probability, denoted here by P_{e}. Firstly, one can notice that the EV fusion scheme outperforms all other fusion rules when the channel is error-free ($P_{\text{e}} = 0$), which is in agreement with [9]. In terms of ranking, the performance of the EV fusion is followed by the MAJ, OR and AND decision fusion. One can also observe the expected performance degradation for all fusion rules as P_e increases. Notice that, among the decision fusion schemes, the MAJ rule is less sensitive to the channel errors, followed by OR and AND, i.e., for a given false alarm probability the degradation in the detection probability for the MAJ rule with an increase in P_e is smaller than in the OR and AND cases.

For the decision fusion rules, it is clear that the false alarm probability and the detection probability are lower/upper bounded in some situations, which is in agreement with the theoretical results in [10], [11]. For instance, taking into account the OR rule, $P_\mathrm{fa} \geq 1 - (1 - P_\mathrm{e})^m$ and this bound does not depend on the SNR [11]. A careful observation of Figure 1 confirms that the P_fa is around 0.11 if it is considered the OR rule with $P_\mathrm{e} = 0.02$. This is consistent with [11]. As P_e increases, the bounding effect is more pronounced in the cases of OR and AND decision fusion rules than with MAJ voting.

From Figure 1 we can check part of the conjecture stated in [9]. Notice that the AND and OR fusion rules are indeed more sensitive to channel errors than the EV combining. The MAJ voting is less sensitive than the EV combining only in regimes of low P_e. For higher values of P_e, the bounding effect starts to show up even for the MAJ rule, which deems the EV combining the preferable choice.

B. Results With Channel Coding

In order to assess the performance versus reporting data traffic tradeoff, we have adopted the following procedure: the reporting channel error probability is increased until the performance of the EV fusion rule reaches the performance of a given decision fusion rule in the error-free scenario, without channel coding. Obviously, some performance degradation of the considered decision fusion rule is also expected. Then, the channel encoding is enabled for the decision fusion schemes and the coding rate is progressively decreased (the redundancy is progressively increased) until the performances of the EV fusion and the decision fusion rules are the approximately the same.

Figures 2-4 were constructed according to the procedure just described and depict ROCs using the GLRT for the EV fusion and the desired decision fusion rule, i.e., MAJ, OR, and AND, respectively. In this scenario, the MAJ voting rule has produced the best result among the decision combining rules. Notice that, for the same performance of the EV combining, it needs only 3 bits to represent each CR decision per sub-channel, against 13 bits and 11 bits for OR and AND rules, respectively. The same procedure was adopted to assess the performances of the MMED, the MED and the ED. To avoid graphing all results, Table I summarizes the channel error probabilities and the coding rates, $(P_\mathrm{e}; r)$, for each sensing technique, considering the MAJ, OR and AND decision fusion rules.

We now address the volume of data sent to the FC for each CR. For all fusion schemes, the number of bits sent to the FC is proportional to the number of sensed OFDMA subchannels, and then this constant can be eliminated from the tradeoff analysis. In the case of the EV fusion, the number of bits sent to the FC is proportional to the order of the covariance matrix and the number of bits used to quantize each eigenvalue, i.e., it is a number proportional to $K'b = 5 \times 4 = 20$ bits per CR (recall that the eigenvalues were not coded). For the decision fusion schemes, the number of bits sent to the FC by each CR is proportional to the repetition block code length, since each CR produces one bit per decision per OFDMA subchannel. According to Table I, in the case of the MAJ rule this number is proportional to 1 for the MMED and to 3 for GLRT, the MED and the ED. Considering the OR rule, this number is proportional to 13, 5, 11 and 9, respectively for the GLRT, the MMED, the MED and the ED. In the case of the AND rule, the number of bits is proportional to 11, 7, 23 and 11, respectively for the the GLRT, the MMED, the MED and the ED.

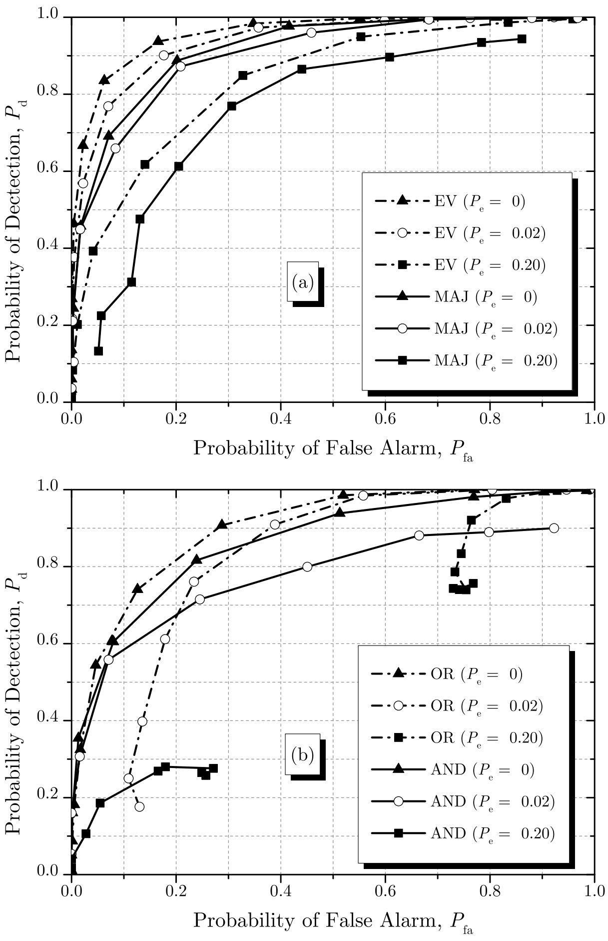

Fig. 1. ROCs using the GLRT without channel coding for different values of the channel error probability (a) for EV and MAJ decision fusion and (b) for AND and OR decision fusion

We conclude that, in spite of being more sensitive to channel errors, the coded decision fusion schemes can be the preferred choices in terms of the number of bits sent to the FC, except in one case with the AND rule, for which this number is slightly

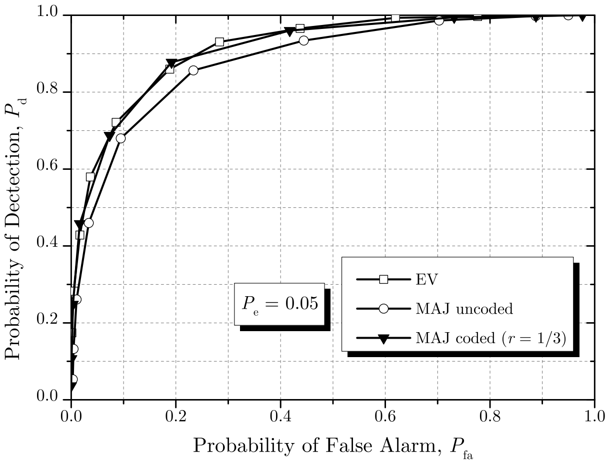

Fig. 2. ROCs for EV fusion and decision fusion MAJ using the GLRT with and without channel coding

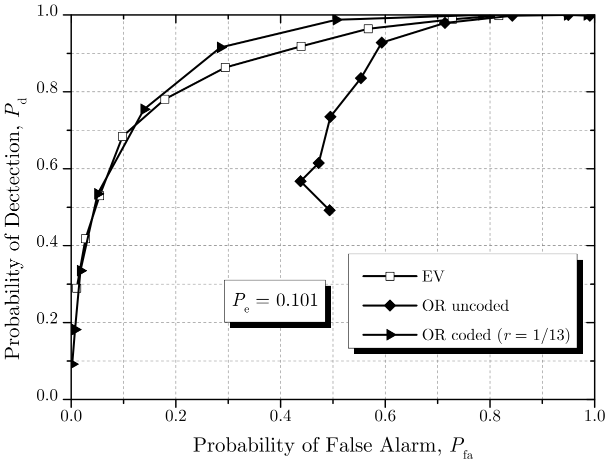

Fig. 3. ROCs for EV fusion and decision fusion OR using the GLRT with and without channel coding

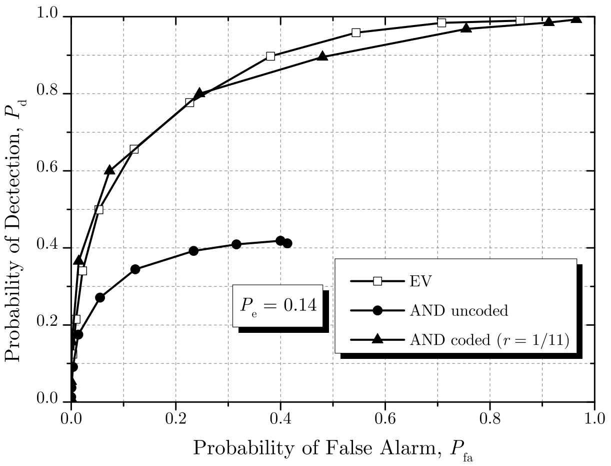

Fig. 4. ROCs for EV fusion and decision fusion AND using the GLRT with and without channel coding

TABLE I

THE ERROR PROBABILITY AND THE CODING RATE, $(P_e; r)$, FOR EACH SENSING TECHNIQUE.

Technique	MAJ	OR	AND
GLRT	$(0.0500; 1/3)$	$(0.1010; 1/13)$	$(0.1400; 1/11)$
MMED	$(0.0075; 1)$	$(0.0150; 1/5)$	$(0.0160; 1/7)$
MED	$(0.0600; 1/3)$	$(0.1000; 1/11)$	$(0.2050; 1/23)$
ED	$(0.0150; 1/3)$	$(0.0200; 1/9)$	$(0.0500; 1/11)$

larger. The superiority of the MAJ rule is apparent.

V. CONCLUSION

In this paper we have seen that CR decisions in the decision fusion approach are more sensitive to reporting channel errors than digitized eigenvalues in the EV fusion approach. However, the amount of redundancy inserted to protect de decisions so as to equate the performances of the two fusion schemes does not always lead to a larger amount of data in the decision fusion. Then, one needs to trade performance and amount of data in the reporting channel to decide upon which fusion scheme must be adopted, in a case by case analysis.

It is worth mentioning that, due to the use of the OFDMA subchannel sensing approach, other channel code schemes could increase even more the advantage of the decision fusion schemes over the EV one. In this case, an (n, k) block code cold be applied to encode the decisions upon all subchannels in a give CR, with the message block length equating the number of subchannels, i.e., $k = P$.

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