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Performance-traffic tradeoff in eigenvalue fusion and decision fusion for spectrum sensing of OFDMA signals under errors in the reporting channel

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Abstract The eigenvalue (EV) fusion technique was recently proposed for detecting idle subchannels of OFDMA signals in centralized cooperative spectrum sensing for cognitive radio (CR). It has been shown that the technique outperforms the conventional decision fusion, in spite of the larger volume of data reported to the fusion center. It has been conjectured, though, that bit errors in the reporting channel could be more disastrous to the data carrying CR decisions than to the data carrying EVs. In this paper we investigate this conjecture and conclude that it is partially true: CR decisions can be more sensitive to channel errors, but the amount of redundancy inserted to protect the decisions does not always lead to a larger number of bits compared to the EV fusion. Then, performance and traffic in the reporting channel must be traded when deciding upon the fusion scheme to be adopted. We also suggest a modified version of the original EV fusion and show that it can achieve approximately the same performance of the original one, with a significant reduction in the reporting channel traffic.

Keywords Cognitive radio · Eigenvalue fusion · Eigenvalue spectrum sensing · Wideband spectrum sensing · Orthogonal frequency division multiple access

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1 Introduction

The increased demand for wireless communication services and the adoption of a fixed spectral allocation policy have resulted in spectral congestion and scarcity, thus representing a huge problem for the deployment of new systems and services. With the advent of the cognitive radio (CR) concept [1], 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. It is the task of monitoring the frequency spectrum, seeking for idle portions (also called 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 [2]. Then, the importance of research on spectrum sensing techniques is undeniable, as exemplified by the recent announcement made by the IEEE about the creation of the IEEE 802.22 Spectrum Occupancy Sensing (SOS) Study Group [3]. 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". Recently, cognitive capabilities have also been proposed to be used in wireless sensors networks in order to overcome the limitations imposed to the deployment of such networks [4].

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) [5]. The main reason for choosing OFDM is that it has some advantages in delivering high speed data, when compared with single-carrier systems, especially in multipath, frequency-selective fading channels [5]. Moreover, combined with the subcarrier nulling flexibility of OFDM signals, OFDM-based cognitive radios can opportunistically reuse non-contiguous underutilized spectrum bands. This is particularly favorable to the recently-proposed generalized frequency division multiplexing (GFDM), which is arising as a candidate to be used in the fifth generation (5G) of wireless communication systems [6].

Since OFDM-like systems are being adopted and will continue to be adopted as the schemes of choice in broadband wireless communication systems, it is important for CR networks to sense OFDM-like signals. This represents the main motivation of the present work.

1.1 Related work and contributions

Several spectrum sensing techniques have been proposed so far, and can be casted as narrowband or 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 [7]. For wideband sensing, recent studies point to three major techniques: energy detection [8], wavelet-based detection [9] and compressed (or compressive) sensing detection [10,11]. Eigenvalue-based detection [12] is one of the most recent and promising technique for spectrum sensing. Likewise energy detection, eigenvalue detection can be applied to narrowband and to wideband signals.

Cooperative spectrum sensing, also known as collaborative spectrum sensing, is a possible solution for problems experienced by cognitive networks that use non-cooperative sensing. Among such problems are the receiver uncertainty, the multipath fading and the correlated shadowing [2]. Cooperative spectrum sensing can be centralized, distributed or relay-assisted [2]. In the centralized approach, data collected by each cooperating CR (e.g., samples of the received signal) are sent to a fusion center (FC) through a dedicated reporting 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. This operation is called decision fusion, in which the final decision about the channel state is made from 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; 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 [13]. 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. This new fusion scheme was applied to variants of four test statistics for binary hypothesis test, namely [12]: 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 has been shown in [13] that the eigenvalue (EV) fusion (or EV combining) can outperform schemes based on decision fusion and sample fusion. Moreover, EV fusion produces lower data traffic when compared with the sample fusion. The lowest amount of traffic is an intrinsic characteristic of the decision fusion strategies. All of these conclusions, however, did not take into account that the reporting channel can cause errors in the information to be combined.

A conjecture in [13] states that bit errors in the reporting channel can be more disastrous to the data representing CR decisions than to the data representing eigenvalues. These bit errors 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 traffic in the reporting channel. Motivated by this conjecture, in [14] we have reported preliminary results comparing the volume of reporting channel traffic of the EV fusion scheme and of conventional decision fusion schemes in the context of the spectrum sensing of OFDMA subchannels under reporting channel errors.

This paper is a thorough extension of [14]. Here we also consider the problem of sensing the spectrum of OFDMA sub-channels under reporting channel errors. Comparisons between the performances of the EV fusion and the decision fusion schemes are made, also focusing on the reporting channel traffic, but in a more detailed and unified manner than in [14]. Specifically, here we add new results considering the MMED, the MED and the ED to the results for the GLRT reported in [14]. We also suggest a modified version of the original EV combining rule and show that the modified rule can achieve approximately the same performance of the original one, but with a significant reduction in the reporting channel traffic. A bunch of new results considering this modified combining rule are also provided. A tradeoff analysis between performance and reporting channel traffic is also included for the modified EV combining. We end-up concluding that CR decisions can be indeed more sensitive to channel errors, but the amount of redundancy inserted to protect the decisions does not always lead to a larger number of bits compared to the eigenvalue fusion. Then, performance and traffic in the reporting channel must be traded when deciding upon the fusion scheme to be adopted. A number of publications have already addressed, theoretically and by simulation, the influence of reporting channel errors in the performance of the spectrum sensing; see for example [15,16] and references therein. To the best of our knowledge, however, no tradeoff analysis similar to the one presented here has been made yet, considering a recently proposed eigenvalue combining rule and the presence of channel coding. Moreover, it is in order to recall that a lot of material is already available in the literature as far as the traditional decision fusion schemes AND, OR and majority voting are concerned. No similar material is available for the analysis of the eigenvalue combining rule proposed in [13].

The results and conclusions reported in this paper rely mainly on computer simulations. For this reason, whenever possible, we have validated some simulation results against known ones so that new results become reliable. An intrinsic difficulty arises when dealing with analytical investigations related to eigenvalue-based detection, mainly because these investigations heavily rely on the random matrix theory. This is further complicated here, since the test statistics are new ones and empirically proposed based on known eigenvalue-based test statistics, adapted to the joint spectrum sensing of multiple subcarriers of OFDMA signals. The seek for analytical results, if possible, is then an opportunity for further research.

The remaining of this paper is organized as follows: in Sect. 2, the operation of the eigenvalue fusion and the decision fusion for detecting idle OFDMA subchannels is reviewed. Section 3 is concerned with the system model for performance assessment. Extensive numerical results are provided in Sects. 4 and 5, where the analysis of the tradeoff between performance and reporting channel traffic is summarized. Section 6 presents a comparison analysis considering the data storage and computational complexity taking into account three approaches: the eigenvalue fusion and its modified version, and the decision fusion. Finally, Sect. 7 concludes the paper.

2 Eigenvalue fusion and decision fusion methods for detecting idle OFDMA subchannels

Aiming at making this paper self-contained, in this section we provide some background material based on [13].

The 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 S subchannels. Thereby, $K = K'/S$ subcarriers will form a subchannel indexed by s, $s = 1, 2, \ldots, S$. It is assumed that each of the m single-sensor 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 ith CR and sth subchannel will be formed according to

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

where $Y_{k,j}^{(i)}(s)$ is the jth sample collected by the ith CR in the kth subcarrier pertaining to the sth 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

$$\mathbf{R}_s^{(i)} = \frac{1}{N}\mathbf{A}_s^{(i)}\mathbf{A}_s^{(i)\dagger}, \tag{2}$$

where † stands for complex conjugate and transpose.

Different uses of (2) are made depending on the fusion scheme adopted by the cooperative spectrum sensing technique, as described in the following subsections. Independent of the scheme adopted, increasing the dimension of the sample matrix will bring improvement in the sensing performance due to a better estimation of the sample covariance matrix, at the expense of an increased complexity due to an increased number of samples to be processed, and an increase in the sensing time.

2.1 Eigenvalue fusion for OFDMA signals

The mKS eigenvalues estimated from the sample covariance matrices in (2) are sent to the FC. The test statistics for the sth OFDMA subchannel are computed at the FC according to the following expressions [13]:

$$T_{\mathrm{GLRT},s} = \frac{SK\sum_{i=1}^{m}\lambda_{1,s,i}}{\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{i=1}^{m}\lambda_{k,s,i}}, \tag{3}$$

$$T_{\mathrm{MED},s} = \frac{\sum_{i=1}^{m}\lambda_{1,s,i}}{m\sigma^2}, \tag{4}$$

$$T_{\mathrm{MMED},s} = \frac{S\sum_{i=1}^{m}\lambda_{1,s,i}}{\sum_{s=1}^{S}\sum_{i=1}^{m}\lambda_{K,s,i}}, \tag{5}$$

$$T_{\mathrm{ED},s} = \frac{\sum_{k=1}^{K}\sum_{i=1}^{m}\lambda_{k,s,i}}{Km\sigma^2}, \tag{6}$$

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

2.2 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 S sample covariance matrices, K eigenvalues are estimated in each cognitive radio and ordered as $\{\lambda_{1,s} \geq \lambda_{2,s} \geq \cdots \geq \lambda_{K,s}\}$. The occupation of the sth subchannel is determined in each CR by comparing the decision threshold with any of the test statistics [13]:

$$T_{\mathrm{GLRT},s} = \frac{SK\lambda_{1,s}}{\sum_{k=1}^{K}\sum_{s=1}^{S}\lambda_{k,s}}, \tag{7}$$

$$T_{\mathrm{MED},s} = \frac{\lambda_{1,s}}{\sigma^2}, \tag{8}$$

$$T_{\mathrm{MMED},s} = \frac{S\lambda_{1,s}}{\sum_{s=1}^{S}\lambda_{K,s}}, \tag{9}$$

$$T_{\mathrm{ED},s} = \frac{\sum_{k=1}^{K}\lambda_{k,s}}{K\sigma^2}. \tag{10}$$

The mS 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.

3 System model

In order to analyze the influence of the errors in the transmissions from the CRs to the FC (which we call the reporting channel errors), the decision of each CR in the decision fusion operation, for the GLRT, the MMED, the MED and the ED, is 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 are estimated via majority decoding and the estimated decisions are combined according to the desired rule (AND, OR or MAJ voting) for subsequent final decision.

In the case of the eigenvalue combining, we have considered two approaches:

Approach 1 The eigenvalues computed by each CR are converted into a digital data with b_1 bits of resolution using uniform (linear) quantization, and then sent to the FC through a BSC channel. Received bits are converted into analog quantities representing the corrupted eigenvalues, and EV combining is made according to (3)–(6) to form the desired test statistic.

Approach 2 The eigenvalues computed by the ith CR are locally combined using floating-point operations, forming partial test statistics for the sth subchannel, as follows:

$$T_{\mathrm{GLRT},s,i} = \frac{SK\lambda_{1,s,i}}{\sum_{k=1}^{K}\sum_{s=1}^{S}\lambda_{k,s,i}}, \tag{11}$$

$$T_{\mathrm{MED},s,i} = \frac{\lambda_{1,s,i}}{m\sigma^2}, \tag{12}$$

$$T_{\mathrm{MMED},s,i} = \frac{S\lambda_{1,s,i}}{\sum_{s=1}^{S}\lambda_{K,s,i}}, \tag{13}$$

$$T_{\mathrm{ED},s,i} = \frac{\sum_{k=1}^{K}\lambda_{k,s,i}}{Km\sigma^2}. \tag{14}$$

These partial test statistics are converted into digital data with b_2 bits of resolution using uniform quantization, and then sent to the FC through a BSC channel. Received bits are converted into analog quantities that are added (on the index i) to yield the final test statistics. Notice that, for the GLRT and the MMED, the final test statistics will differ from the original ones, even if infinite quantization is applied. For this reason we name this approach as a *modified* EV *combining*, shortly MEV combining (or MEV fusion). By adopting MEV combining, the volume of data in the reporting channel is potentially reduced if compared

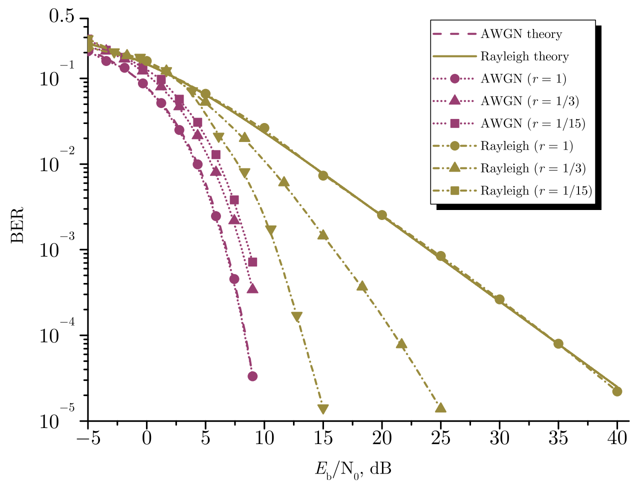

Fig. 1 Performance of the coherently-detected BPSK modulation with repetition code in the pure AWGN channel and in the Rayleigh fading channel

with EV combining, since b_2 bits per subchannel must be sent to the FC by each CR, against $b_1 K$ bits per subchannel in the EV combining rule. It would be possible to maintain the equivalence between the first and second approaches in what concerns the GLRT and the MMED, if the numerators and denominators of (11) and (13) are separately sent to the FC and combined before division; this would increase the number of bits sent to the FC from b_2 to $2b_2$.

The **Approach 1** is the same considered in [14] for the GLRT, and here it is further assessed with the MMED, the MED and the ED. The **Approach 2** is new and is a modified version of the **Approach 1**. It is assessed here also for the GLRT, the MMED, the MED and the ED.

Without loss of generality, the BSC model has been adopted because it correctly models the modulation-channel-demodulation chain in a flexible and modulation-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, thus providing large diversity gains. Moreover, by using a repetition code the coding rate and, thus, the diversity gain can be easily configured. This leads to flexibility in terms of the amount of redundancy inserted for a given target performance, which is particularly suitable for the investigation at hand.

For illustration purpose only, Fig. 1 shows theoretical (solid lines) and simulated (lines plus symbols) bit error rate (BER) results against the ratio between the average energy per information bit and the noise power spectral density (E_b/N_0) for the pure AWGN channel and for the fully-interleaved slow and flat Rayleigh fading channel plus AWGN. Binary phase-shift keying (BPSK) modulation with coherent detection is assumed in both cases. Notice that repetition encoding is trivial, i.e., it does not produce coding gain [17]. Indeed, in the pure AWGN channel the BER of the coded system increases as the coding rate reduces, a result that is well-known from the channel coding theory [18]. Notice, however, that large diversity gains can be achieved in the fading channel, and that the BER of the coded system is reduced, in a diminishing-return fashion, with the reduction in the coding rate, which is characteristic of diversity schemes [17]. For example, Fig. 1 shows that a diversity gain around 15 dB is achieved with a short $r = 1/3$ repetition code at BER $= 10^{-5}$; a longer $r = 1/15$ code produces a diversity gain around 25 dB at the same BER. In this illustration we have applied hard decision on the BPSK symbols and majority decoding of the repetition-coded block of length n. It is known that, if soft-decision with maximum ratio combining is applied to the detector output, in the limit of $n \to \infty$ the performance of the repetition-coded system over the Rayleigh fading channel tends to the performance of the uncoded system over the pure AWGN channel.

4 Numerical results for Approach 1: all eigenvalues sent to the FC

Following [13], here we also consider a primary network with $S = 4$ subchannels. The number of cooperating CRs is $m = 6$. An OFDMA channel has $K' = 20$ subcarriers. The subchannels are created by forming $S = 4$ sets with $K = K'/S = 5$ subcarriers randomly selected. We also consider unitary primary signal power and a signal-to-noise ratio SNR $= -10$ dB. The small SNR regime was chosen to represent a more degrading, yet realistic situation from the perspective of the spectrum sensing performance. For instance, the IEEE 802.22 standard requires that the presence of digital TV transmissions must be sensed with a probability of detection of 0.9 with a receiver sensitivity of -114 dBm, which may be translated into a very low SNR level. The wireless channel between the primary transmitter and secondary receivers (CRs) is modeled as a 20-path slow frequency-selective Rayleigh fading channel whose frequency response is kept constant during a sensing period, being varied independently from one sensing period to another. The second moment of the channel gains are 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 is $N = 60$. Other parameter values could be used as well, but the reason for choosing the above ones is that we were able to validate some simulation results against the same theoretical results used as references in [13]. Additionally, we were also able to validate our simulations by reproducing some results from [13].

We first 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. Then, 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.

The ROC (receiver operating characteristic) 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 from 5000 Monte Carlo simulation 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 in **Approach 1**, and the partial test statistics in **Approach 2** were quantized with $b_1 = b_2 = 4$ bits. This value was chosen as the minimum resolution that maintained the performance practically unchanged when compared to the maximum resolution (floating-point operation). This value is consistent with the required number of quantization bits reported in [19]. The simulation code was implemented in MATLAB according to the models and test statistics described in Sects. 2 and 3.

4.1 Results without channel coding in Approach 1

Figure 2 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 reporting channel error probability, which is denoted by P_{e}. Firstly, one can notice that the EV fusion scheme outperforms all other fusion rules when the channel is error-free ($P_{\mathrm{e}} = 0$), a result that is in agreement with [13]. 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, 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. At a first glimpse, it seems that the EV fusion is more sensitive to channel errors than the decision fusion with MAJ voting. However, it must be emphasized that in low values of P_{e}, the superiority of the EV fusion is maintained.

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 [15,16]. For instance, taking into account the OR rule, $P_{\mathrm{fa}} \geq 1 - (1 - P_{\mathrm{e}})^m$ and this bound

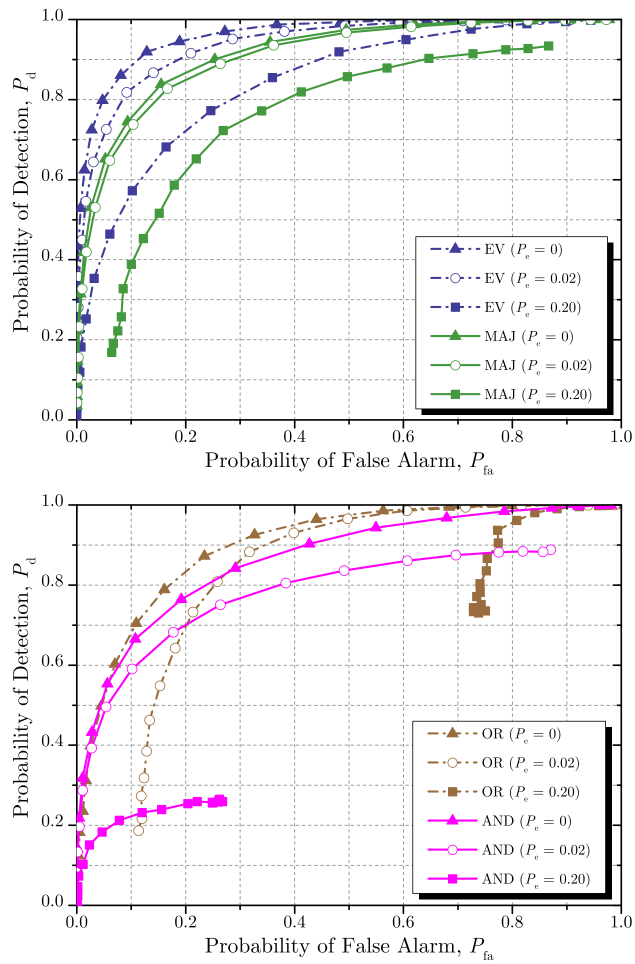

Fig. 2 ROCs using the GLRT without coding for different values of the channel error probability in Approach 1, for the EV, the MAJ, the OR and the AND decision fusion rules. (re-simulated performances corresponding to [14, Fig. 1], ©IEEE)

does not depend on the SNR [16]. A careful observation of Fig. 2 (bottom) confirms that the minimum P_{fa} is around 0.11 if it is considered the OR rule with $P_{\mathrm{e}} = 0.02$. This is consistent with [16]. As P_{e} increases, the bounding effect is more pronounced in the cases of OR and AND decision fusion rules than with MAJ voting. In what follows, similarly to what we have done for the GLRT, we address the remaining detection techniques, i.e., MMED, MED and ED. We use the same system parameters adopted for the GLRT. Figures 3, 4, and 5 show ROC curves for the EV fusion and the decision fusion schemes, respectively for the MMED, the MED and the ED. In terms of ranking with $P_{\mathrm{e}} = 0$, the EV fusion continues to be the best, followed by the decision fusions with MAJ, OR and AND, except for the ED, a case in which the performances of the MAJ and the OR combining are approximately the same. As far as the detection techniques are concerned, the best performance is achieved with the ED, followed by the MED, the GLRT and the MMED. All theses results are

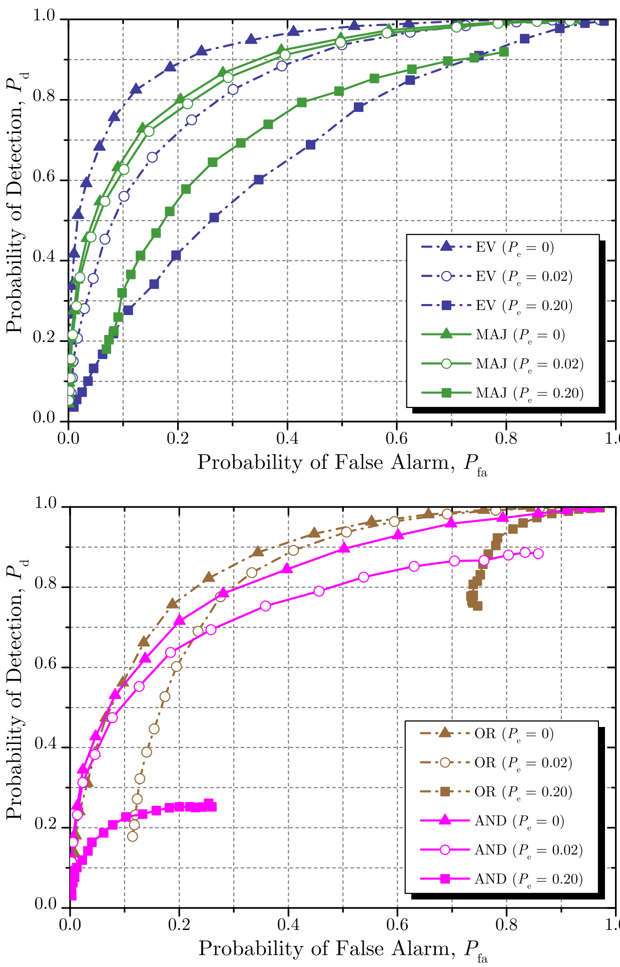

Fig. 3 ROCs using the MMED without coding for different values of the channel error probability in Approach 1, for the EV, the MAJ, the OR and the AND decision fusion rules

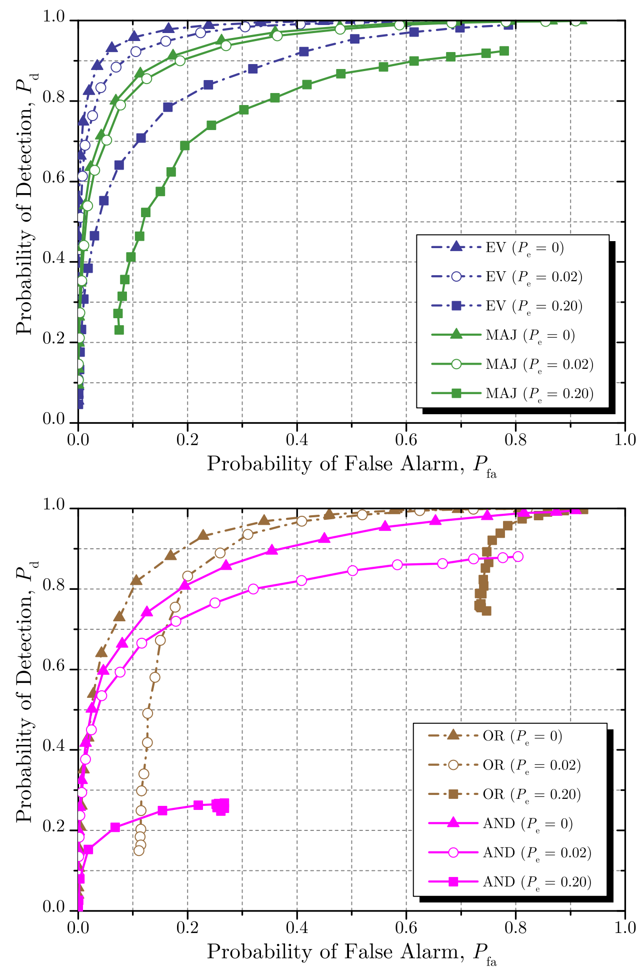

Fig. 4 ROCs using the MED without coding for different values of the channel error probability in Approach 1, for the EV, the MAJ, the OR and the AND decision fusion rules

in agreement with those in [13]. In terms of the sensitivity to channel errors, the decision fusion with MAJ voting beats the remaining ones, but beats the EV fusion only at lower values of P_e. However, as in the case of the GLRT, in spite of being more sensitive, the superiority of the EV fusion can be maintained at low P_e. The bounding effect in the decision fusion schemes also appear in the MMED, the MED and the ED. This effect becomes more pronounced as the channel error probability increases, with a clear advantage of the MAJ rule over the OR and the AND rules.

From Figs. 2, 3, 4, and 5 we can check part of the conjecture stated in [13]. 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. We must recall that these conclusions apply to the **Approach 1**, in which all eigenvalues are sent to the FC. The **Approach 2**, in which partial test statistics are formed at the CRs, will be addressed in Sect. 5.

4.2 Results with channel coding in Approach 1

In order to assess the tradeoff between the spectrum sensing performance and the reporting channel traffic, we have adopted the following procedure: the reporting channel error probability is increased until the performance of the EV fusion rule approximates the performance of a given decision fusion rule in the error-free scenario, without channel coding. Obviously, a performance degradation of the considered decision fusion rule is expected. Then, the channel encoding is enabled for the decision fusion and the coding rate is progressively decreased (the redundancy is progressively increased) until the performance of the coded decision fusion reaches as close as possible to the performance of the uncoded EV fusion. The necessary amount of bits sent to the FC is then compared, along with the resulting ROC curves.

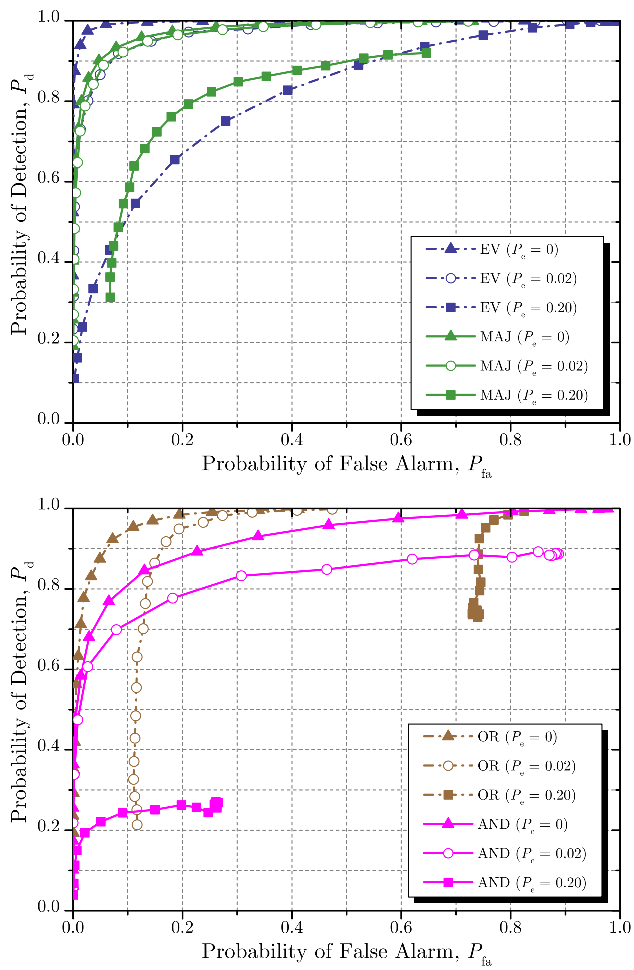

Fig. 5 ROCs using the ED without coding for different values of the channel error probability in Approach 1, for the EV, the MAJ, the OR and the AND decision fusion rules

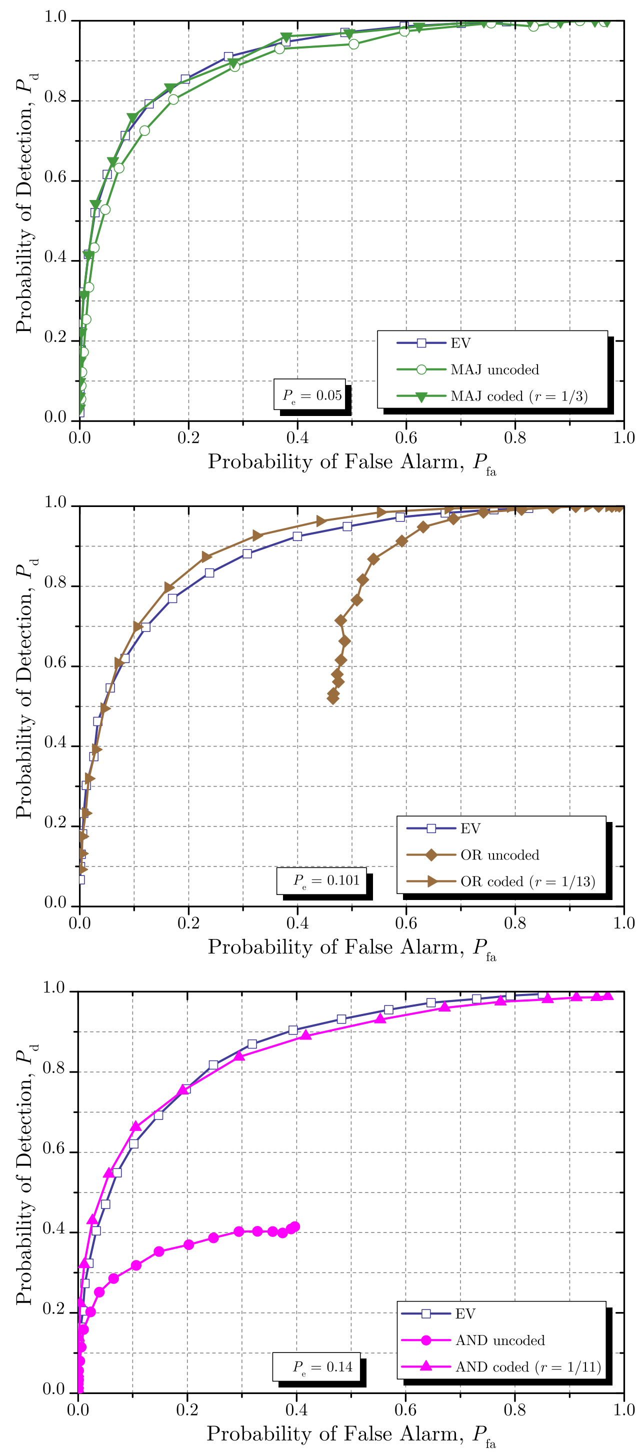

Fig. 6 ROCs for the EV fusion and the decision fusions MAJ, OR and AND, using the GLRT with and without channel coding in Approach 1. (re-simulated performances corresponding to [14, Figs. 2, 3 and 4], ©IEEE)

Figure 6 was constructed according to the procedure just described and depicts ROC curves using the GLRT for the EV fusion and for the decision fusion rules with MAJ, OR and AND combining. The corresponding values of P_e that equates the performances of the EV fusion and the uncoded decision fusion in the error-free situation are also shown. One can observe that the MAJ voting rule has produced the best result among the decision combining rules. For the same performance of the EV combining, the MAJ rule needs only 3 bits to represent each CR decision per subchannel, against 13 bits and 11 bits for the OR and the AND rules, respectively.

The same procedure was adopted to assess the performances of the MMED, the MED and the ED, for which the results are respectively presented in Figs. 7, 8 and 9. A comment is in order about the MMED performance with MAJ decision fusion, shown in Fig. 7: Notice that, differently from the ROC curves for the other detection techniques, here only two curves are shown, instead of three. This is because the performance of the EV combining has reached the performance of the MMED with MAJ voting at $P_e = 0.0075$ before the performance of the MAJ rule had even moved

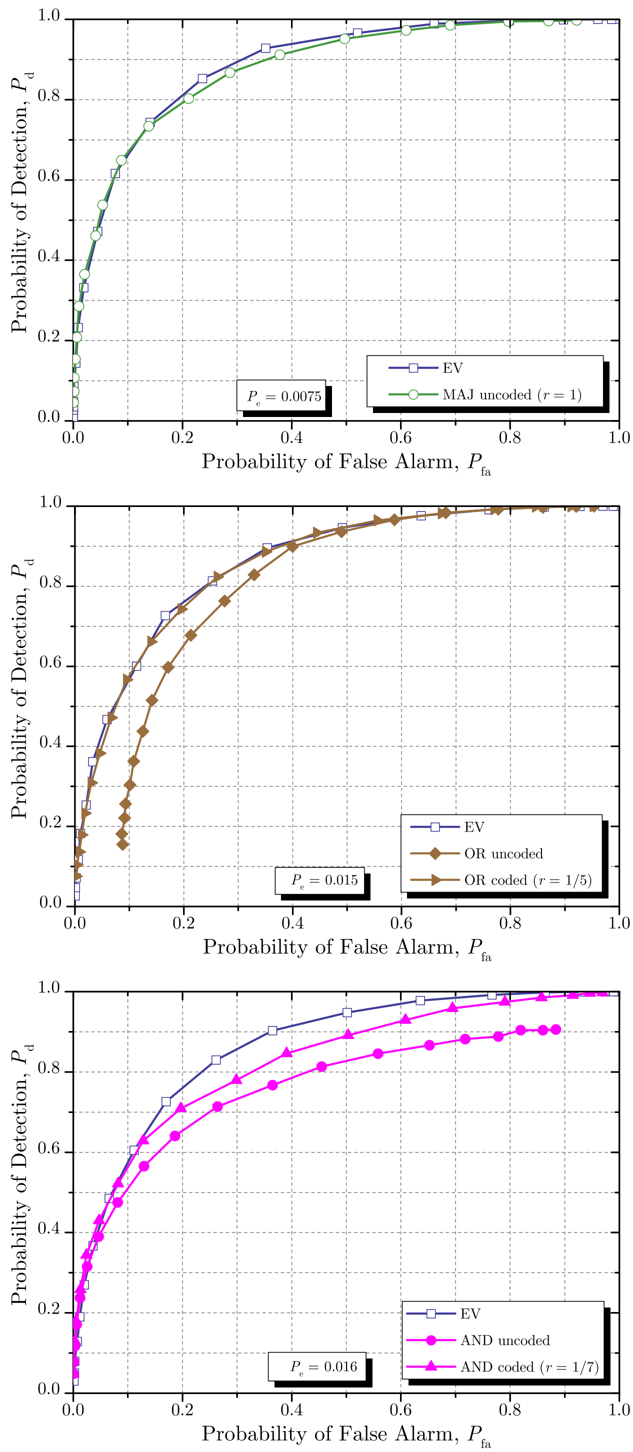

Fig. 7 ROCs for the EV fusion and the decision fusions MAJ, OR and AND, using the MMED with and without channel coding in Approach 1

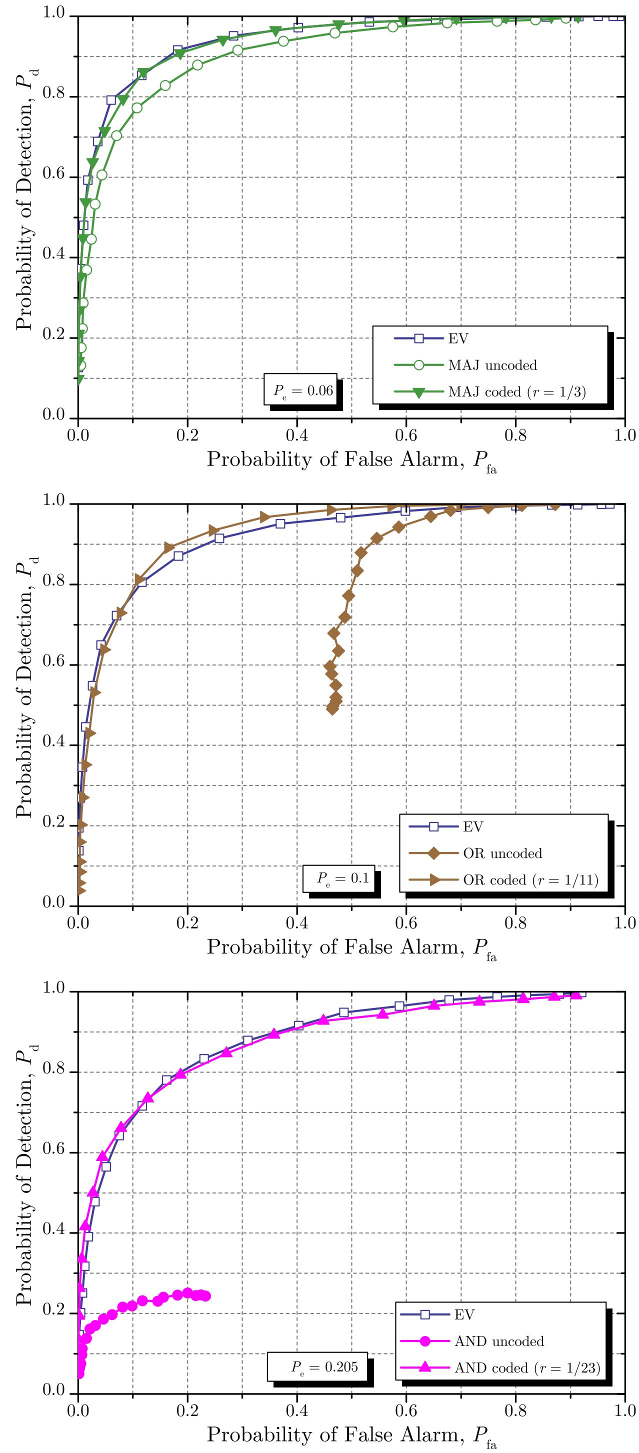

Fig. 8 ROCs for the EV fusion and the decision fusions MAJ, OR and AND, using the MED with and without channel coding in Approach 1

slightly, meaning that no redundancy was necessary to the MAJ decision fusion with MMED.

Table 1 summarizes the channel error probabilities and the coding rates, $(P_e; r)$, for each sensing technique, considering the MAJ, the OR and the AND decision fusion rules. Recall that we are referring to the **Approach 1**, in which all eigenvalues are sent to the FC in the EV combining rule. The **Approach 2**, which forms partial test statistics at the CRs, will be addressed in the next section.

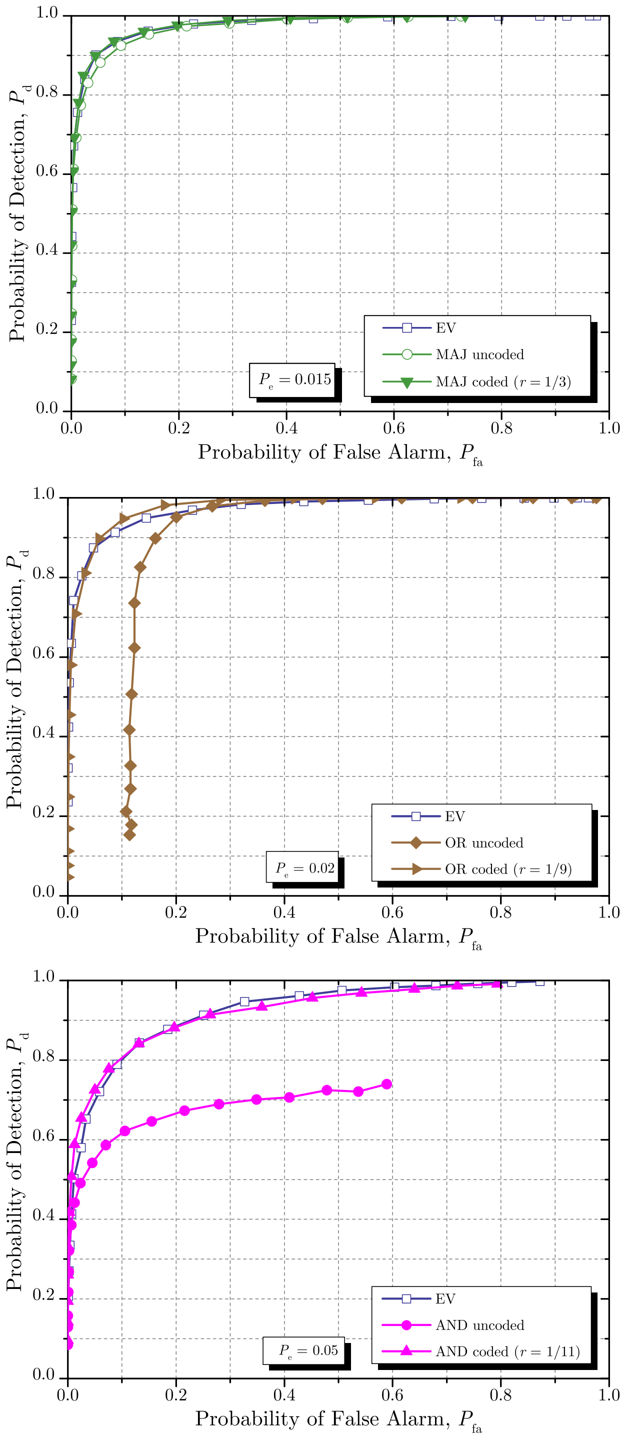

Fig. 9 ROCs for the EV fusion and the decision fusions MAJ, OR and AND, using the ED with and without channel coding in Approach 1

4.3 Tradeoff between performance and reporting channel traffic under Approach 1

For all fusion schemes, the number of bits sent to the FC is proportional to the number of sensed OFDMA subchannels,

Table 1 The error probability and the coding rate, $(P_e; r)$, for each sensing technique under Approach 1. (from [14], ©IEEE)

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)

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 (which is equal to the number of eigenvalues) and the number of bits used to quantize each eigenvalue, i.e., it is a number proportional to $Kb_1 = 5 \times 4 = 20$ 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 1, in the case of the MAJ rule this number is proportional to 1 for the MMED and to 3 for the 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.

Under the **Approach 1**, we conclude that, in spite of being more sensitive to channel errors than the EV combining in the regime of high probability of channel error, the coded decision fusion schemes can be the preferred choices in terms of the number of bits sent to the FC. There is one exception involving the AND rule with MED, a case in which this number is slightly larger (23 for the AND/MED against 20 for the EV fusion). The superiority of the MAJ rule is apparent, mainly for the MMED.

5 Numerical results for Approach 2: modified eigenvalue combining

The results presented in this section were obtained assuming the same set of parameters considered for the **Approach 1**, as described at the beginning of Sect. 4. Aiming at transmitting the smallest number of bits over the reporting channel, the numerators and denominators of (11) and (13) were not separately sent to the FC and combined before division. Instead, divisions have been performed at each CR and the 4-bit results were sent to the FC for subsequent conversion to analog quantities and combination (please, refer to the description of the **Approach 2** in Sect. 3 to recover further details). For the error-free reporting channel, this choice has

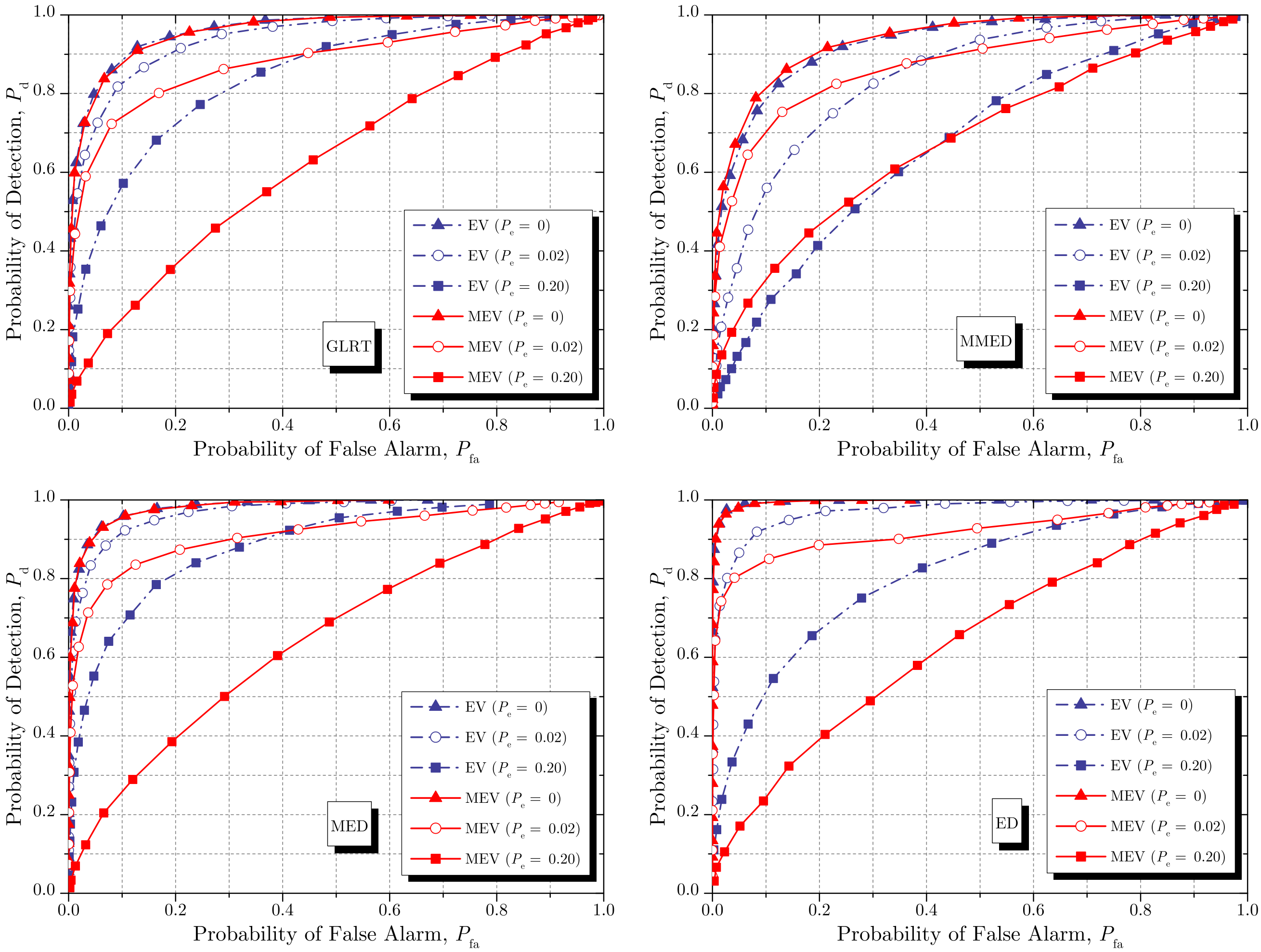

Fig. 10 ROCs using the GLRT, the MMED, the MED and the ED, without channel coding for different values of the channel error probability in Approaches 1 (EV) and 2 (MEV)

caused practically no change in performance. Surprisingly, it has produced a small, but noticeable improvement for $P_e \neq 0$ (please, refer to the description of the **Approach 2** in Section 3).

5.1 Results without channel coding in Approach 2

Figure 10 presents the results concerning the sensitivity to channel errors in the eigenvalue (EV) and modified eigenvalue (MEV) combining considered in the **Approach 1** (EV) and **Approach 2** (MEV) for the GLRT, the MMED, the MED and the ED. The results considering the **Approach 1** were already provided in Sect. 4, but are repeated here in order to facilitate comparisons. Results for the decision fusion rules are not given here, since they are not affected by the choice of the eigenvalue combining approach. From this figure it is clear that the EV and the MEV combining produce almost the same performance in the error-free channel. Nevertheless, the performance of the MEV combining drops more with an increase in the channel error probability, a behavior that is more pronounced at higher values of P_e. In terms of ranking we still have the ED as the best detection technique, followed by the MED, the GLRT and the MMED. One must recall that the superiority of the ED and MED comes at the expense of having to know the noise variance. Moreover, it is interesting to notice that, in the case of the MMED, the MEV combining outperforms the EV combining at small values of P_{fa}. We conjecture that this behavior resulted from an improvement on the statistical power of the MMED from its original version in **Approach 1** to the one considered in **Approach 2**. Such improvement is possible, since the original test statistic (9) has been empirically developed, bringing some margin for the improvement attained with the **Approach 2** via the partial test statistic (13). The remaining of the test statistics did not unveil any improvement when adopting the combining of the partial test statistics, which is an indication that their original statistical powers are high already.

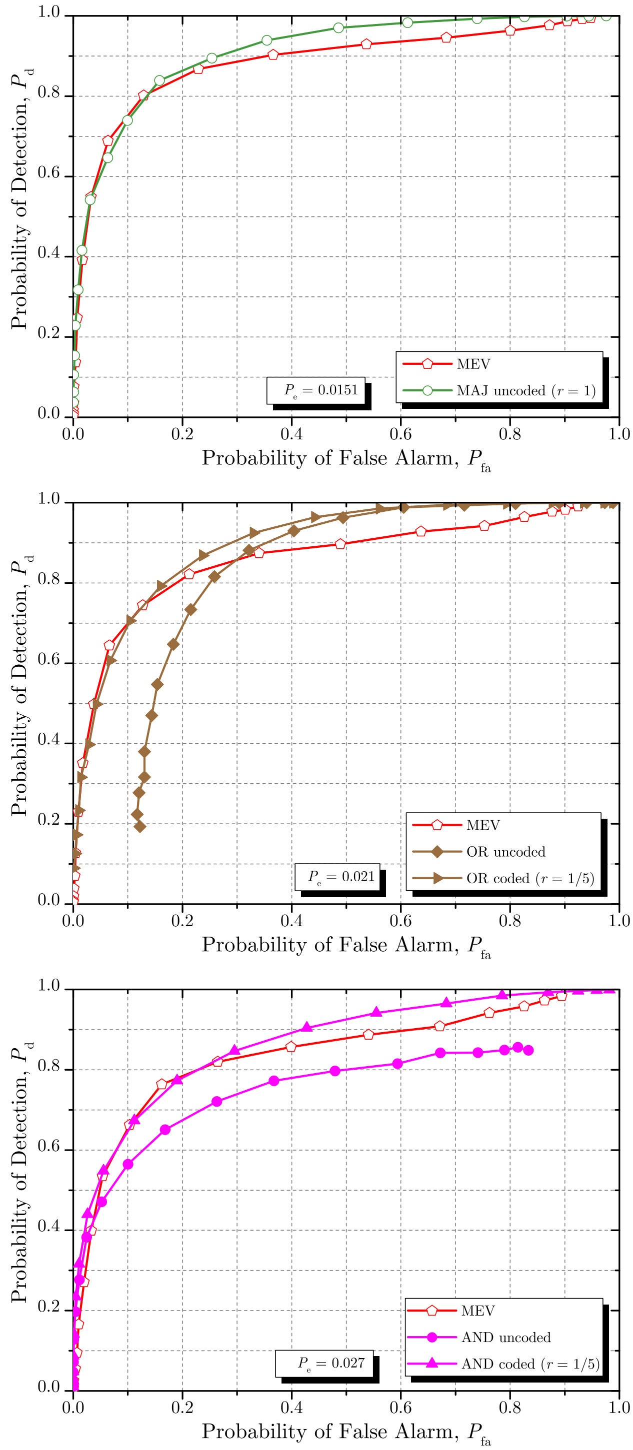

Fig. 11 ROCs for the MEV fusion and the decision fusions MAJ, OR and AND, using the GLRT with and without channel coding in Approach 2

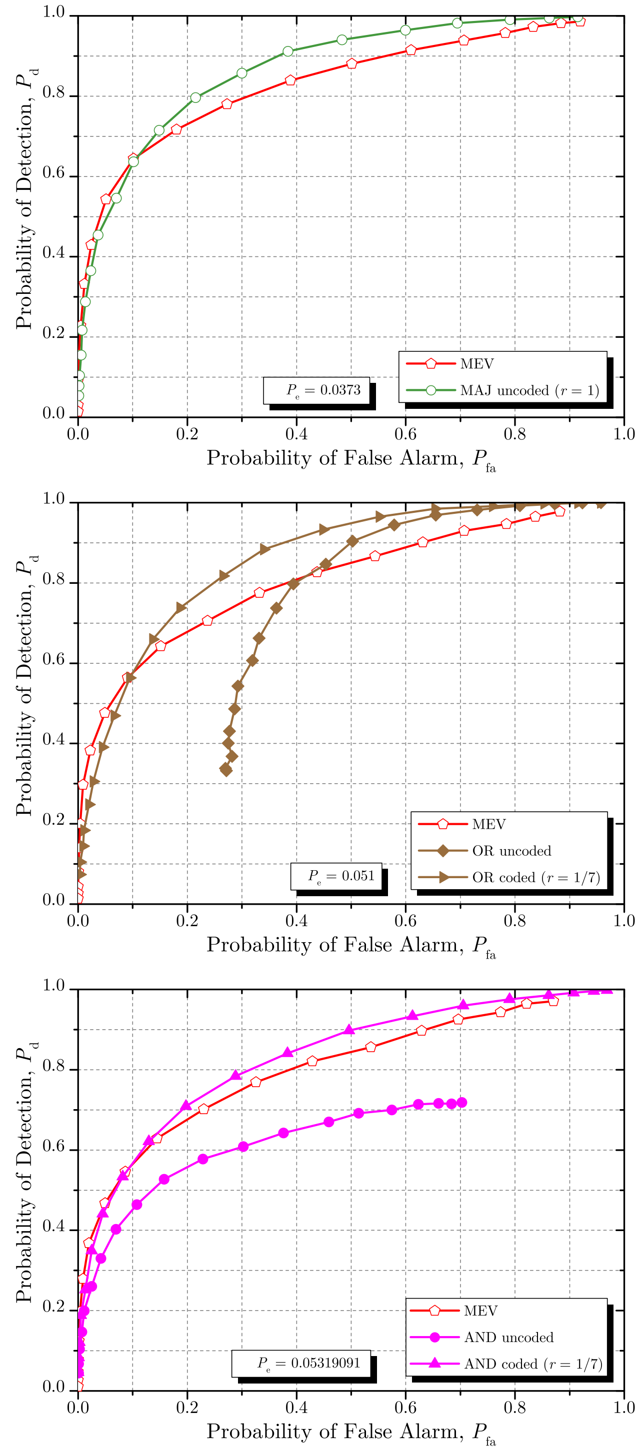

Fig. 12 ROCs for the MEV fusion and the decision fusions MAJ, OR and AND, using the MMED with and without channel coding in Approach 2

5.2 Results with channel coding in Approach 2

In this section we have adopted a slightly modified version of the procedure described at the beginning of Sect. 4.2 to assess the system performance with channel coding: as before, the P_e is increased until the performance of the MEV fusion rule approximates the performance of a given decision fusion rule in the case of $P_e = 0$, without channel coding. Then, the

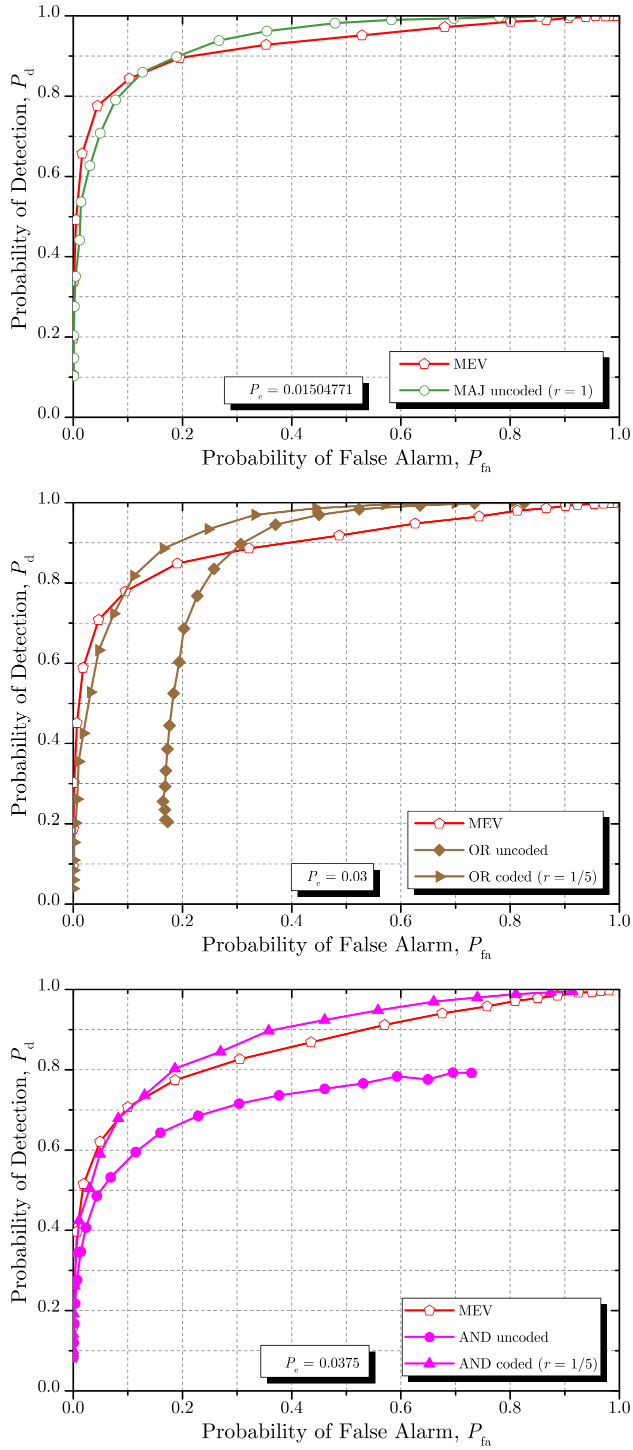

Fig. 13 ROCs for the MEV fusion and the decision fusions MAJ, OR and AND, using the MED with and without channel coding in Approach 2

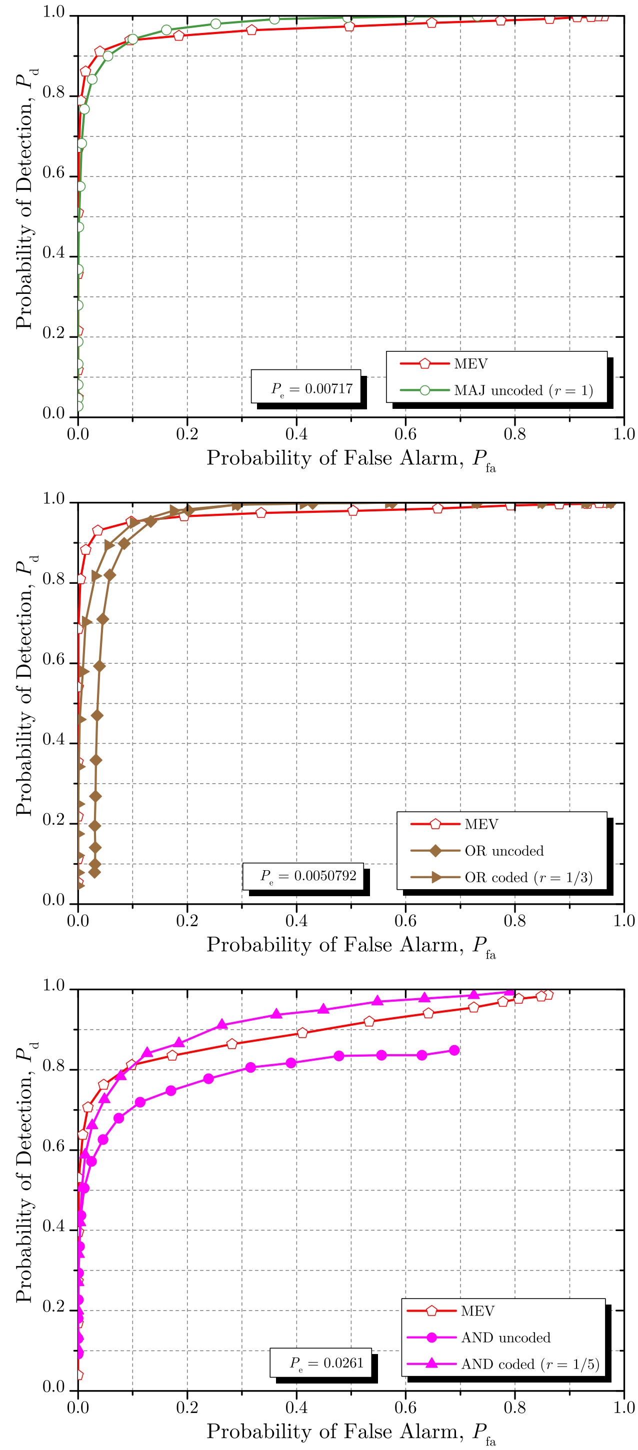

Fig. 14 ROCs for the MEV fusion and the decision fusions MAJ, OR and AND, using the ED with and without channel coding in Approach 2

channel encoding is enabled for the decision fusion and the coding rate is progressively decreased until the performance of the coded decision fusion reaches the performance of the uncoded MEV combining. However, as it will be noticed from the results henceforth, we were not able to approximately equate the P_d of the MEV and the given decision fusion for the entire range of P_{fa}, since a crossing point in performance was observed. Then, we have searched for approximately the same P_d of the coded decision fusion and

Table 2 The error probability and the coding rate, $(P_e; r)$, for each sensing technique under Approach 2

Technique	MAJ	OR	AND
GLRT	(0.0151; 1)	(0.0210; 1/5)	(0.0270; 1/5)
MMED	(0.0373; 1)	(0.0510; 1/7)	(0.0532; 1/7)
MED	(0.0150; 1)	(0.0300; 1/5)	(0.0375; 1/5)
ED	(0.0072; 1)	(0.0051; 1/3)	(0.0261; 1/5)

the uncoded MEV for $P_{fa} = 0.1$, that is, we have searched for situations in which the crossing point of P_d occurs at $P_{fa} \cong 0.1$.

Figure 11 was constructed according to the procedure just described and depicts ROC curves using the GLRT for the MEV fusion and for decision fusion rules with MAJ, OR and AND combining. The corresponding values of P_e that equates the performances (crossing points of P_d occurring at $P_{fa} \cong 0.1$) of the MEV fusion and the uncoded decision fusion in the error-free situation are also shown. One can observe that the MAJ voting rule has produced the best result among the decision combining rules. For the same performance of the MEV combining, the MAJ rule did not need any redundancy, whereas 5 bits were needed to represent each CR decision per subchannel for the OR and the AND rules.

The same procedure was adopted to assess the performances of the MMED, the MED and the ED, for which the results are presented respectively in Figs. 12, 13 and 14.

Table 2 summarizes the channel error probabilities and the coding rates, $(P_e; r)$, for each sensing technique, considering the MAJ, the OR and the AND decision fusion rules. Recall that we are referring to the **Approach 2** in which partial test statistics are formed at the CRs and then are digitized and sent to the FC where final test statistics are computed.

5.3 Tradeoff between performance and reporting channel traffic under Approach 2

Likewise in the **Approach 1**, in the **Approach 2** the number of bits sent to the FC is proportional to the number of sensed OFDMA subchannels, which means that this constant can be eliminated from the tradeoff analysis. Differently from the EV combining, in the MEV combining the number of bits sent to the FC is only proportional to the number of bits used to quantize each partial test statistic, i.e., it is a number proportional to $b_2 = 4$ bits per CR (recall that the partial test statistics were not coded). For the decision fusion schemes, the situation from the **Approach 1** is repeated: 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 2, in the case of the MAJ rule this number is proportional to 1 for the MMED, the GLRT, the MED and the ED. Considering the OR rule, this number is proportional to 5, 7, 5 and 3, 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 5, 7, 5 and 5, respectively for the GLRT, the MMED, the MED and the ED.

When the EV fusion (**Approach 1**) was compared with the decision fusion schemes, we concluded that the decisions can be more sensitive than digitized eigenvalues in the regime of high probability of channel error, but coded decisions can be the preferred choice in terms of reporting channel traffic, with a clear advantage of the decision fusion with majority voting. Now, with **Approach 2** we have a different picture. First, when observing the results in Figs. 2, 3, 4 and 5 with those in Fig. 10, we can notice that the MEV combining has become more sensitive to channel errors than the EV combining in some cases. As a consequence, we are not anymore able to make a simple judgement in what concerns the sensitivities of the decision fusion schemes and the MEV combining. Nevertheless, from Table 2 we can see that for channel error probabilities around 0.05 or less, the decision fusion with majority voting is still the preferred choice, since it does not need to be coded to produce the same performance of the MEV fusion. In this case, the number of bits sent to the FC in the MEV will be 4 times larger for all the detection techniques. The OR and the AND decision fusion schemes will need more bits than the MEV combining for all but one (the ED) detection technique.

6 Storage and computational complexity analysis

In order to provide an analysis involving the CRs' and the FC's data storage and computational complexity taking into account the EV fusion, the MEV fusion and the decision fusion, we have considered the simulation parameters used in Sects. 4 and 5. So we have a system containing a total of $K' = 20$ available OFDMA subcarriers and $S = 4$ sensed subchannels. These subchannels are formed with sets of $K = K'/S = 5$ subcarriers each. With $N = 60$, a matrix of order $K \times N = 5 \times 60$, containing the sample values collected by the ith CR, in the sth subchannel, is obtained from (1). Consequently, $S = 4$ covariance matrices of order $K \times K = 5 \times 5$ are computed via (2).

Related to the data storage, in all the three cases the number of samples collected by each CR is $KN = 300$ samples per subchannel, resulting in a total amount of data of $SKN = 1200$ samples. After that, a total of $SK = 20$ eigenvalues are locally computed and, according to the chosen fusion scheme, i.e., the EV fusion (**Approach 1**), the MEV fusion (**Approach 2**) and the decision fusion, the resulting data is sent to the FC through the reporting channel.

Considering the **Approach 1**, the EV fusion, where all eigenvalues are sent to the FC, with $S = 4$ OFDMA subchannels, $b_1 = 4$ bits of quantization and $m = 6$ cooperating CRs, the total of eigenvalues sent to the FC is equal to $SKm = 120$, then the FC receives a total of $SKb_1m = 480$ data bits. In the **Approach 2**, the MEV fusion, a partial test statistic is previously computed by each CR for the sth subchannel before the K eigenvalues are sent to the FC. In this case the number of bits sent to the FC is then reduced by a factor of $K = 5$. Therefore, being $b_2 = 4$ bits of quantization, the FC receives a total of $Sb_2m = 96$ data bits. In the decision fusion approach, the CRs just need to send their local decisions about the occupation state of each sensed subchannel. Then, for the decision fusion scheme, the FC receives a total of $Sm = 24$ data bits, a considerable reduction compared to the EV fusion approach. A smaller data traffic volume is an intrinsic characteristic of the decision fusion schemes. These numerical results show that the EV fusion is the technique that sends the larger volume of data traffic through the reporting channel, followed by the MEV fusion and the decision fusion scheme, respectively.

Generically speaking, for the EV fusion SKb_1m data bits are transmitted to the FC. For the MEV fusion, the number of bits sent to the FC is Sb_2m, a reduction of $SKb_1m/Sb_2m = K$ bits compared to the EV fusion, with $b_1 = b_2$. For the decision fusion, Sm data bits are transmitted to the FC. In this case, the amount of bits sent to the FC is reduced by a factor of $SKb_1m/Sm = Kb_1$ and $Sb_2m/Sm = b_2$ in comparison to the EV fusion and the MEV fusion, respectively.

Now, in what concerns the devices' computational complexity, the FC needs to process $SKm = 120$ eigenvalues in the EV fusion approach. For the MEV fusion, the FC's computational complexity is smaller, since it has to process a number K times smaller of analog quantities than in the EV fusion, resulting in Sm analog quantities, with $b_1 = b_2$. For the decision fusion scheme, the FC's computational complexity is reduced even more, since the FC needs just to process the received local CRs' decisions.

According to the presented analysis, one can notice that the computational complexity of the CRs increases as the amount of data traffic sent to the FC is reduced. In the worst case, for the decision fusion scheme, SKm eigenvalues are combined before transmission. For the case of the MEV fusion, and comparing to the decision fusion, the computational complexity is reduced $SKm/SK = m$ times, since now just SK eigenvalues are combined by the CRs before transmission. Finally, the smaller CRs' complexity is achieved in the EV fusion approach, since in this case the CRs do not need to combine any eigenvalue, which means that all the computed eigenvalues are sent to the FC for combination.

It is clear that the volume of data traffic in the reporting channel and the computational complexity can vary a lot depending on the adopted fusion scheme. In numbers, the data traffic is reduced $Kb_1 = 20$ times when comparing the decision fusion with the EV fusion. On the other hand, the CRs have to combine all the eigenvalues. However, when the comparison is about the MEV fusion and the decision fusion, the data traffic is reduced just $b_2 = 4$ times and the computational complexity is $m = 6$ times smaller than when the EV fusion is applied. Concluding, the proposed MEV fusion reveals to be a good choice for the spectrum sensing, since it can significantly reduces both the CRs' computational complexity, when compared with the decision fusion case, and the amount of data traffic in the reporting channel, when compared with the EV fusion.

7 Conclusions and directions for new research

In this paper we have seen that CR decisions in the decision fusion can be more sensitive to the reporting channel errors than digitized eigenvalues in the eigenvalue and modified eigenvalue fusion approaches. However, the amount of redundancy inserted to protect the decisions so as to equate the performances of the fusion schemes does not always lead to a larger amount of data in the decision fusion. Specifically, with the MED detection at the CRs and the decision fusion rule AND at the FC, the amount of data is larger than in the case of the eigenvalue fusion under the **Approach 1** (EV combining). Considering the **Approach 2** (MEV combining) a different situation is observed: firstly, the sensitivity to channel errors of the MEV has increased, meaning that the larger sensitivity of the decision fusion schemes is not anymore evidenced. Additionally, all the detection rules with majority voting has achieved a smaller amount of data traffic when compared with the MEV. In the cases of the OR and the AND decision fusion, the amount of traffic has been larger than in the case of the MEV. Then, for all cases previously considered 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.

If only the EV and the MEV are compared, we can conclude that if the channel error probability is not too high, the modified eigenvalue combining is the preferred choice, since it leads to approximately the same performance of the original eigenvalue combining, but using a significantly smaller number of bits in the reporting channel.

It is worth mentioning that, due to the use of the OFDMA subchannel sensing approach, other channel coding schemes could be adopted. In this case, an (n, k) block code could be applied to encode the decisions upon all subchannels in a given CR, with the message block length equating the number of subchannels, i.e., $k = S$. The restriction of $k = S$ does not need to be followed if bits other than those representing decisions or partial test statistics are to be sent to the FC. A different way of analyzing the performance-traffic tradeoff could also be adopted: channel coding is inserted in the EV/MEV with rate $1/n_{\text{EV}}$, keeping the channel coding in the decision fusion with rate $1/n_{\mathrm{OR}}$, $1/n_{\mathrm{AND}}$, $1/n_{\mathrm{MAJ}}$ and finding n_{EV}, $n_{\mathrm{OR,AND,MAJ}}$ and P_{e} such that the performance of EV/MEV equates the performance of the given decision fusion. This new analysis would be particularly useful, and can unveil completely different conclusions, if the reporting channel error probability is assumed to be high. This is indeed an interesting opportunity for future work.

Other opportunities for future work are the analysis of a weighted EV/MEV combining, the assumption of different noise variances at the CR inputs and the adaptation of the eigenvalue combining approaches to the implementation-oriented CR model suggested in [19].

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References

1. Mitola, J, I. I. I., & Maguire, G. Q, Jr. (1999). Cognitive radio: Making software radios more personal. *IEEE Personal Communications*, *6*, 13–18.
2. Akyildiz, I. F., Lo, B. F., & Balakrishnan, R. (2011). Cooperative spectrum sensing in cognitive radio networks: A survey. *Physics Communications*, *4*, 40–62.
3. The IEEE Standards Assossiation. (2014). New IEEE 802.22 study group to consider standardization of SOS technology for optimizing usage of radio spectrum for wireless broadband services. http://www.ieee802.org/22/
4. Joshi, G. P., Nam, S. Y., & Kim, S. W. (2013). Cognitive radio wireless sensor networks: Applications challenges and research trends. *Sensors*, *13*(9), 11196–11228.
5. Yang, S. C. (2010). *OFDMA system analysis and design*. London: Artech House.
6. Michailow, N., Datta, R., Krone, S., Lentmaier, M., & Fettweis, G. (2012). Generalized Frequency division multiplexing: A flexible multi-carrier modulation scheme for 5th generation cellular networks. In *Proceedings of the German microwave conference* (*GeMiC'12*), Ilmenau, Germany, March 12–14.
7. Yucek, T., & Arslan, H. (2009). A survey of spectrum sensing algorithms for cognitive radio applications. *IEEE Communications Surveys and Tutorials*, *11*, 116–130.
8. Quan, Z., Cui, S., Sayed, A. H., & Poor, H. V. (2009). Optimal multiband joint detection for spectrum sensing in cognitive radio networks. *IEEE Transactions on Signal Processing*, *57*, 1128–1140.
9. Tian, Z., & Giannakis, G. B. (2006). A wavelet approach to wideband spectrum sensing for cognitive radios. In *Proceedings of 1st international conference on the cognitive radio oriented wireless networks and communications*. pp. 1–5, Mykonos Island, June 8–10.
10. Qiu, R., Guo, N., Li, H., Wu, Z., Chakravarthy, V., Song, Y., et al. (2009). A unified multi-functional dynamic spectrum access framework: Tutorial, theory and multi-GHz wideband testbed. *Sensors*, *9*, 6530–6603.
11. Wang, Y., & Zhang, G. (2014). Compressed wideband spectrum sensing based on discrete cosine transform. *The Scientific World Journal*. doi:10.1155/2014/464895
12. Nadler, B., Penna, F., & Garello, R. (2011). Performance of eigenvalue-based signal detectors with known and unknown noise level. In *Proceedings of 2011 IEEE international conference on the communications*, (*ICC*). pp. 1–5, Kyoto, June 5–9.
13. Guimarães, D. A., da Silva, C. R. N., & de Souza, R. A. A. (2013). Cooperative spectrum sensing using eigenvalue fusion for OFDMA and other wideband signals. *Journal of Sensor and Actuator Networks*, *2*(1), 1–24.
14. Guimarães, D. A., Costa, L. S., & de Souza, R. A. A. (2014). Comparison between eigenvalue fusion and decision fusion for spectrum sensing of OFDMA signals under errors in the control channel. In *Proceeding of the international telecommunications symposium* (*ITS*). pp. 17–20, São Paulo, Brazil.
15. Chaudhari, S., Lunden, J., & Koivunen, V. (2013). BEP walls for collaborative spectrumsensing. In *Proceeding of the IEEE international conference acoustics, speech and signal processing* (*ICASSP*). pp. 2984–2987.
16. Letaief, K. B., & Zhang, W. (2009). Signal interception: Cooperative communications for cognitive radio networks. *Proceedings of the IEEE*, *97–5*, 878–893.
17. Proakis, J. G. (1995). *Digital communications*. New York: McGraw-Hill.
18. Feher, K. (1995). *Wireless digital communications: Modulation and spread spectrum applications*. Upper Saddle River, NJ: Prentice-Hall PTR.
19. Guimarães, D. A., & de Souza, R. A. A. (2012). Implementation-oriented model for centralized data-fusion cooperative spectrum sensing. *IEEE Communications Letters*, *16*, 1804–1807.

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