Collaborative Spectrum Sensing Scheme: Quantized Weighting with Censoring

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Abstract. Spectrum vacancies that stem from current non-usage of the spectrum band by legacy primary users can be detected using various spectrum sensing techniques. These techniques depend on the actual knowledge of the radio environment being inspected, i.e. signal characteristics, noise levels etc. The simplest and most common spectrum sensing technique is energy based detection that needs no a priori knowledge about the monitored spectrum, but may lead to imprecision when assessing the possible presence (or absence) of a primary user. Therefore, possible collaboration among the nodes performing the energy based spectrum sensing (in terms of sensing reports exchanges) improves the reliability and avoids the hidden terminal problem caused by the shadowing from large obstacles. This paper introduces a novel collaborative spectrum sensing scheme with light communication overhead called Quantized Weighting with Censoring (QWC). The scheme includes censoring of the unreliable sensing reports in some range of uncertainty and introduces weighting coefficients for different quantization levels. The performances of the QWC scheme are compared with the Majority Voting (MV) and Equal Gain Combining (EGC) schemes. The results show that the QWC scheme outperforms the well known EGC scheme.

Keywords: collaborative spectrum sensing, quantized decision combining, data fusion, and cognitive radio networks.

1 Introduction

Wireless technologies and services lately experience tremendous growth making the available spectrum a scarce resource. Traditionally, the problem of spectrum insufficiency in wireless networks is tackled by fostering additional spectrum portions. Recently, several measurement campaigns showed that the current spectrum is underutilized [1] as a result of the currently static spectrum access policies that allow only legacy licensed users (termed as primary users) to use the spectrum. However, allowing so called unlicensed users (i.e. non-legacy users, secondary users etc.) to use the vacancies of the licensed spectrum (when the primary users do not use it) leads to significant improvements in the overall spectrum usage. This opens the possibilities for *dynamic spectrum access* and *cognitive radio networks* as its enablers.

The cognitive radio networks cope with the problem of spectrum scarcity by introducing secondary cognitive users, which are able to sense the spectrum and

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detect temporary unused spectrum parts i.e. spectrum holes [2]. The secondary users communicate over the available spectrum holes left vacant by the primary users. The system of secondary (i.e. cognitive) users operates inconspicuously from the primary users. As a result, the secondary users must ensure reliable primary user detection by exploiting some spectrum sensing technique.

The simplest and most common spectrum sensing technique is *energy detection* [3]. It requires no a priori knowledge about the inspected spectrum. However, unexpected channel conditions may significantly degrade the performances since, due to fading or shadowing, a secondary user may infer absence of primary user even when it is present. The *collaborative spectrum sensing* overcomes this issue by using spectrum sensing data from more nodes in the final decision about the presence of the primary user (i.e. introduces a form of spatial diversity) [4, 5].

Collaborative spectrum sensing usually operates in two phases, i.e. *sensing* and *reporting*. In the sensing phase, each node senses the spectrum individually. In the reporting phase, the nodes report the sensing observations to common receiver/s (e.g. fusion centre/s) that reach the final decision about the presence of a primary user.

Collaborative spectrum sensing schemes can operate in various network topologies:

- centralized,
- decentralized and
- cluster based.

In *centralized* network structures, the nodes send the sensing observation to a common fusion centre that makes the final sensing decision and announces it to the nodes [6, 7]. In *decentralized* solutions, each node senses the spectrum locally and distributes its observation to all one-hop neighboring nodes. Afterwards, each node reaches the final decision based on its own and the received sensing observations [8]. The *cluster-based* solution applies a two level hierarchical approach. The nodes first contribute to the spectrum sensing decision process into the cluster. The cluster-heads then report the sensing decision to a common receiver that gives the sensing result [9, 10]. Generally, the collaboration is reduced to collecting the sensing reports and combining them in the decision making process.

The collaboration among network nodes can eminently improve the sensing performance because of the introduced spatial diversity. On the other hand, the collaboration gain causes additional control overhead [11]. Based on the way that the common receiver combines (i.e. fuses) the sensing reports, the following types of collaborative spectrum sensing schemes exist:

- Hard Decision Combining (HDC),
- Soft Decision Combining (SDC) or
- Quantized Decision Combining (QDC).

HDC schemes use one bit decisions of local nodes that are sent to the common receiver. The receiver combines the collected decisions with some specific fusion rule, e.g. AND, OR, Majority Voting etc. [12]. The SDC schemes combine the locally measured soft sensing results and operate better than HDC, but include higher control overhead compared with the one bit decisions in HDC [13]. The QDC schemes use quantization of the measurement reports in order to reduce the control overhead. These schemes are based on combining the quantized measured observation and usually operate better than HDC and worse than SDC [14]. Additionally, the censoring schemes exclude the nodes with unreliable observations from the collaboration, thus reducing the control overhead [8, 15].

This paper introduces a novel, bandwidth efficient, scheme for collaborative spectrum sensing, called Quantized Weighting with Censoring (QWC). In the QWC scheme, local node observations obtained with energy detectors are censored when they belong in the uncertainty area. Otherwise, the observations are quantized to one of four possible quantization levels. Additionally, a node calculates a weighting coefficient based on the amount of observed energy and forms a three bit local sensing report. These sensing reports are then linearly combined at the common receiver. The paper also introduces a novel method for optimal threshold selection for the quantized decision combining schemes. Furthermore, the Receiver Operating Characteristics (ROCs) of the newly introduced QWC scheme are elaborated in a comparison with the well known Equal Gain Combining (EGC) [13] and Majority Voting (MV) [12] combining rules. The results show that the QWC scheme outperforms both rules.

The QWC model for collaborative spectrum sensing performs the quantization differently from the existing models. The model proposed in [14] bases on uniform quantization method taken from the classical quantization approaches, while the QWC takes the PDF of the received signal when the primary user is present as a base for quantization. Furthermore, the QWC includes weighting coefficients, while the already known methods for collaborative spectrum sensing do not take weighting coefficients when performing quantization [14, 16]. Another novelty introduced in this paper is a method for decision thresholds calculation in a quantized decision combining model for collaborative spectrum sensing, based on the source definition for thresholds selection.

This paper is organized as follows. Section 2 describes the basic system model. Section 3 elaborates the collaborative quantized weighting with censoring strategy. Section 4 gives performance analysis of the proposed scheme. Finally, section 5 concludes the paper.

2 Analytical Background

This section explains the analytical background of the newly proposed QWC scheme. The targeted scenario of interest assumes one common receiver, several collaborating nodes and one primary user. However, the analysis is general enough, since the QWC scheme can be easily adapted to operate in decentralized scenarios as well as larger scenarios.

The secondary users sense a single path Rayleigh fading channel (i.e. narrowband flat fading channel). They use energy detectors to get an initial sensing observation and the received signal at the local nodes is:

$$y(t) = \begin{cases} h \cdot x(t) + n(t) & H_1 \\ n(t) & H_0 \end{cases} \tag{1}$$

where the received signal is given for the two possible hypotheses: H_1 when a primary user exists and H_0 when a primary user does not exist, $x(t)$ is a QPSK modulated primary user signal, $n(t)$ is a zero mean complex Gaussian noise and h represents the channel gain.

The energy detector calculates the sum of the squared samples of the received signal:

$$E_y = \sum_{n=1}^{N} |y[n]|^2 \tag{2}$$

where N is the number of sampling points.

The Probability Density Function (PDF) of the received signal with the energy detector under both hypotheses is [17]:

$$f_Y(y) = \begin{cases} \dfrac{1}{2^u \Gamma(u)} y^{u-1} e^{-\frac{y}{2}} & H_0 \\ \dfrac{1}{2}\left(\dfrac{y}{2\gamma}\right)^{\frac{u-1}{2}} e^{-\frac{2\gamma+y}{2}} I_{u-1}\left(\sqrt{2\gamma y}\right) & H_1 \end{cases} \tag{3}$$

where $\Gamma(u)$ is a gamma function, $I_n(.)$ is the n^{th} order modified Bessel function of the first kind, $u = TW$ is the time bandwidth product and γ is the received Signal to Noise Ratio (SNR). The PDF of the received signal $f_Y(y)$, given with eq. (3) is chi-quadrate with $2u$ degrees of freedom under the hypothesis H_0 and non central chi-quadrate under the hypothesis H_1 with $2u$ degrees of freedom and parameter of non centrality 2γ. For large u ($u > 100$) these distributions become Gaussian.

The analysis in this paper assumes that the collaborating nodes exchange the sensing reports over an already established and error-free control channel because of the spatial proximity of the collaborating nodes. Generally, the establishment of the control channel and its impact on the sensing reports must be considered. The RAC^{2}E protocol, introduced in [18], can be used in a distributed network of cognitive users. It operates successfully and overcomes the problem of synchronization among secondary nodes.

3 Collaborative Spectrum Sensing Scheme

This section concentrates on a novel bandwidth efficient scheme for collaborative spectrum sensing, named Quantized Weighting with Censoring (QWC). QWC operates in a bandwidth efficient manner because the control channel relays only the quantized measurement reports and the scheme censors the nodes with unreliable observations. This scheme achieves better performances than the schemes with higher control overhead. The QWC scheme functions through the following phases: *quantization*, *weighting coefficients* selection, *thresholds determination* and *decision making* procedure.

3.1 Quantization

The main idea behind the quantization levels and thresholds selection is to divide the critical range of received energies in several segments (the QWC in this paper considers four segments). For this purpose, the Cumulative Density Function (CDF) of the received signal under H_1 is used. This CDF represents the probability for a primary user to be present over the range of received energies and it is used for quantization thresholds selections.

Each node determines the CDF under H_1 for the appropriate received SNR γ, by means of eq. (3). However, in some real implementation scenario the CDF should be predicted using one of the methods for PDF estimation elaborated in [19].

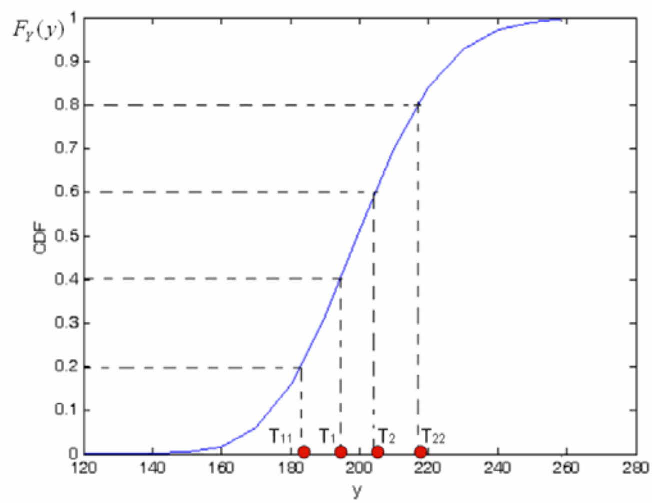

Fig. 1. Quantization threshold selection

Fig. 1 depicts the CDF of chi-quadrate distribution, $F_Y(y)$ for primary user presence under H_1 with $2u$ degrees of freedom and $\gamma = 0$. The quantization thresholds and levels are determined as follows.

- If $Ey \leq T_{11}$ then the quantization level is:

$$q_1 = T_{11} - (T_{11} - T_{11}^{'})/2 \tag{4}$$

where Ey is the amount of the received energy of a sensing node and T_{11} is the threshold for which the probability for primary user presence is 0.2

($F_Y(T_{11}) = 0.2$, Fig. 1). The threshold $T_{11}^{'}$ for which $F_Y(T_{11}^{'}) = 0.01$ is introduced because the quantization must be in some finite set of values.

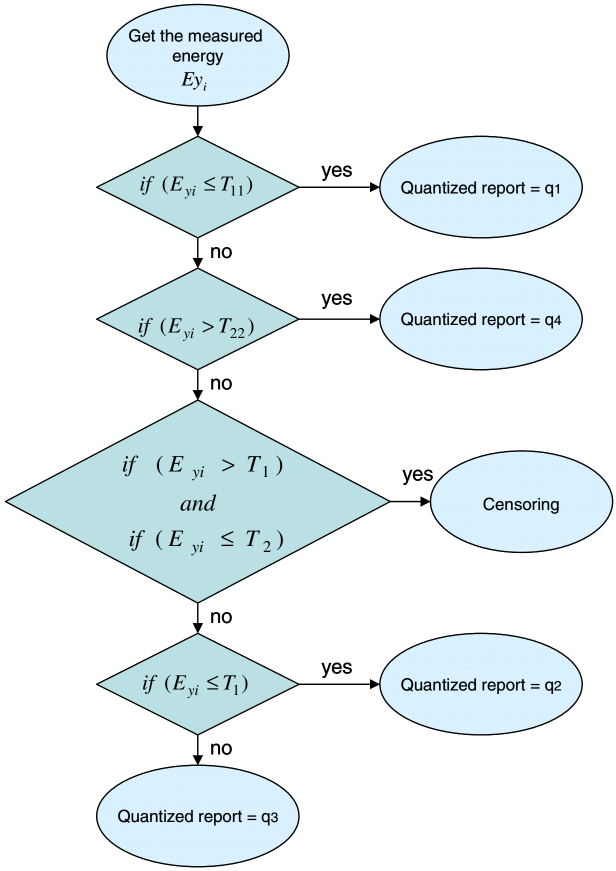

Fig. 2. Quantization flowchart

- If $T_{11} < Ey \le T_1$ then the quantization level is:

$$q_2 = T_{11} + (T_1 - T_{11}) / 2 \tag{5}$$

where, T_1 is chosen so that $F_Y(T_1) = 0.4$.

- If $T_1 < Ey \le T_2$, then the QWC scheme censors the node.

The T_2 threshold is chosen so that $F_Y(T_2) = 0.6$. Thus, when Ey falls in an interval of $[T_1 \text{-} T_2]$, the probability for a primary user to be present (or absent) has the largest uncertainty (i.e. $0.4 < F_Y(E_y) < 0.6$) and therefore the node remains *censored*. Only nodes with reliable observations (i.e. lower uncertainty in terms of $F_Y(y)$) contribute to the decision making process for the presence of the primary user.

- If $T_2 < Ey \leq T_{22}$ then the quantization level is:

$$q_3 = T_{22} - (T_{22} - T_2)/2 \tag{6}$$

where T_{22} is chosen so that $F_Y(T_2) = 0.8$.

- If $T_{22} < Ey \leq T_{22}^{'}$ then the level of quantization is:

$$q_4 = T_{22} + (T_{22}^{'} - T_{22})/2 \tag{7}$$

where the QWC scheme introduces the threshold $T_{22}^{'}$ for which $F_Y(T_{22}^{'}) = 0.99,$ because the quantization thresholds must be fixed when determining the quantization level.

Fig. 2. depicts the quantization procedure with a flowchart for getting the quantized report from the measured energy observation E_{yi} , for the i^{th} node.

3.2 Weighting Coefficients

The main idea behind the *weighting coefficients* selection is to assign an appropriate weighting coefficient for each measured E_y . The weighting coefficients emphasize the importance (i.e. reliability) of each local observation. This will result in intensifying the best sensing results for primary user presence and weakening the impact of the unimpressive ones.

The scheme chooses the weighting coefficients according to the CDF for primary user presence $F_Y(y),$ and they are calculated by each node locally using:

$$w_i = P(\gamma = E_{yi} / H_1) = F_Y(E_{yi}) \tag{8}$$

In order to avoid additional overhead, (because w_i should be also sent to the fusion centre) the number of coefficients is limited to eight. The calculated w_i-s are rounded to the closest coefficient from the set of determined eight coefficients.

The weigthing coefficients procedure uses only two coefficients per quantization level and this results in a total number of eight quantization levels. The final sensing report (quantized and weighted) from the i^{th} node is given with:

$$\hat{E}_i = w_i q_i \tag{9}$$

The existence of only eight sensing report combinations reduces the control overhead to only three bits of information.

In general case, more than two coefficients per quantization level can be used. However, this increases the control overhead and imposes higher computation complexity calculating the decision thresholds.

3.3 Threshold Determination

The QWC scheme combines the quantized and weighted sensing reports from all nodes at the common receiver as a simple sum of individual sensing reports. The result of the combining is:

$$\hat{Y} = \sum_{i=1}^{Nu} \hat{E}_i = \sum_{i=1}^{Nu} w_i * q_i \tag{10}$$

where N_u is the number of collaborating users. The common receiver has to compare $\hat{Y}$ with a *threshold* in order to decide about the presence (or absence) of the primary user.

In general, the threshold for comparison is selected for a fixed false alarm probability, eq. (11):

$$P_{fa} = P(\hat{y} > Thr./H_0) = \int_{Thr.}^{\infty} f_{\hat{Y}/H_0}(\hat{y})dy = 1 - F_{\hat{Y}/H_0}(Thr.) \tag{11}$$

Adapted to the QWC scheme, $f_{\hat{Y}/H_0}(\hat{y})$ in eq. (11) represents the PDF of the quantized weighted and censored received signal under H_0 hypothesis. Then, $F_{\hat{Y}/H_0}(\hat{y})$ in eq. (11) is the appropriate CDF for $f_{\hat{Y}/H_0}(\hat{y})$.

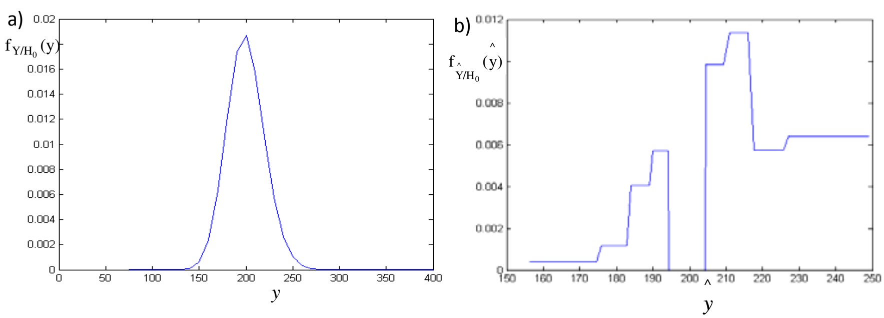

Fig. 3. PDF of the received signal with energy detector under H_0 a) without quantization, weighting and censoring, b) QWC case

The $f_{\hat{Y}/H_0}(\hat{y})$ needs to be calculated in order to find the optimal decision thresholds for QWC, following eq. (11). Fig. 3a represents the PDF of the received signal at a sensing node with energy detector under H_0, $f_{Y/H_0}(y)$ without quantization, censoring and weighting. The PDF at Fig. 3a is used for obtaining the PDF at a sensing node with QWC method, $f_{\hat{Y}/H_0}(\hat{y})$, where quantization, censoring and weighting are applied. Fig. 3b shows the PDF of the received signal under H_0 calculated for a sensing node that applies QWC, $f_{\hat{Y}/H_0}(\hat{y})$.

The $f_{\hat{Y}/H_0}(\hat{y})$, at Fig. 3b calculated from $f_{Y/H_0}(y)$ at Fig. 3a, uses the same quantization procedure (the same quantization thresholds and levels introduced in subsection 3.1).

The optimal thresholds determination when more than one node is implemented in the QWC scheme requires calculation of the joint distribution of the combined QWC sensing reports under H_0. The joint PDF is calculated as a convolution of the PDFs of quantized weighted and censored noise samples, $f_{\hat{Y}/H_0}(\hat{y})$ (depicted in Fig. 3b), since the QWC sensing reports are simply summed at the common receiver. Fig. 4 demonstrates these PDFs for different number of collaborating nodes.

The QWC scheme calculates the optimal decision thresholds for the appropriate number of collaborating nodes in accordance to eq. (11), integrating the PDFs on Fig. 4. Each value assigned to the P_{fa} results in a different decision threshold. This model for thresholds calculation assumes that noise PDF can be estimated at the common receiver through the methods for PDF estimation (elaborated in [19]). It should be noticed that the thresholds are simply the margin of noise for the collected sensing reports, above which the primary user signal is proclaimed as present.

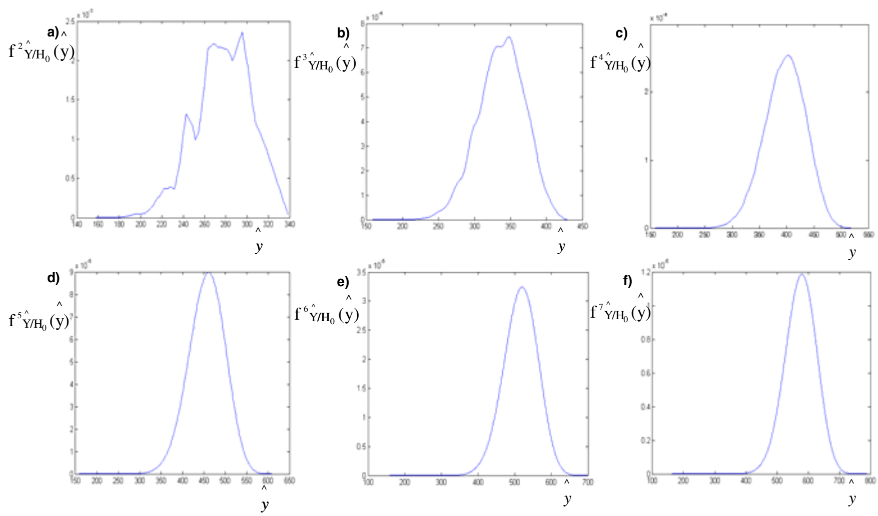

Fig. 4. The PDFs of the combined signal with QWC under H_0 for a) 2 nodes, b) 3 nodes, c) 4 nodes, d) 5 nodes, e) 6 nodes and f) 7 nodes

The common receiver computes the thresholds depending on the number of collaborating nodes after the initial establishment of collaboration group based on the measured noise statistics. For further operation the thresholds are already calculated and may be periodically refreshed based on updates of noise statistic estimations.

3.4 Decision Making Process

The decision making process results in the final collaborative sensing decision regarding primary user presence. The common receiver decides about the presence of the primary user comparing the combined sensing report with a threshold. The decision $d(\hat{Y})$ is either 1, when $\hat{Y}$ is larger than a predicted *threshold* (i.e. a primary user is found), or 0, when $\hat{Y}$ is lower than a predicted *threshold* (i.e. a primary user is not found):

$$d(\hat{Y}) = \begin{cases} 1, & if \quad \hat{Y} > Threshold \\ 0, & if \quad \hat{Y} \leq Threshold \end{cases} \qquad (12)$$

4 Performance Analysis

This section elaborates the performances of the QWC collaborative spectrum sensing scheme. It compares the ROC curves of the QWC scheme for different number of collaborating nodes with the MV decision rule as the most common representatives of the HDC [12] and EGC schemes respectively [13]. Additionally, the section observes the detection probability dependence from the received SNR at the nodes.

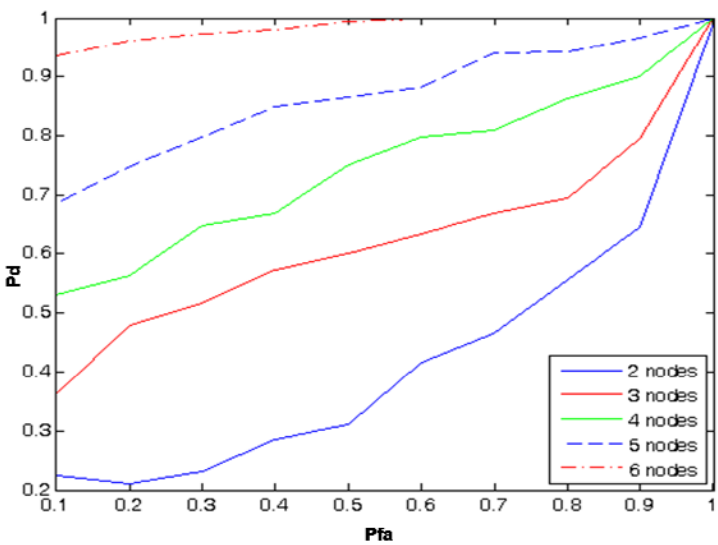

Fig. 5. ROC curves for different number of nodes in QWC scheme

The ROC curves for various numbers of collaborating nodes for QWC are depicted on Fig. 5. It is obvious that collaboration leads to significant collaboration gain as the number of collaborating nodes increases. Fig. 6 demonstrates the comparison between the QWC, MV and EGC for different number of collaborating nodes. The collaboration gain of QWC exceeds those of the MV and EGC for the case of six collaborating nodes (Fig. 6a). When the number of collaborating nodes decreases, the collaboration gain for QWC also decreases (Fig. 6b and 6c). For two collaborating nodes (Fig. 6c), the detection probability of QWC is smaller than EGC, but still higher than MV. The tendency of the QWC scheme to perform better than the EGC is due to the changed noise and signal statistics. As a result, the ROC curves of QWC have tendencies to increase faster with increased number of nodes and vice versa. The considered sampling frequency for the results on Fig. 5 and 6 is 10 KHz, the time bandwidth product u is 100, which means the number of sampling points is $N = 2*u$ and the received SNR γ at the nodes is 0 dBm. The results are obtained by Monte Carlo simulations done in MATLAB [20] based on centralized scenario with several collaborating nodes, one primary user and one common receiver, as supposed in section 2.

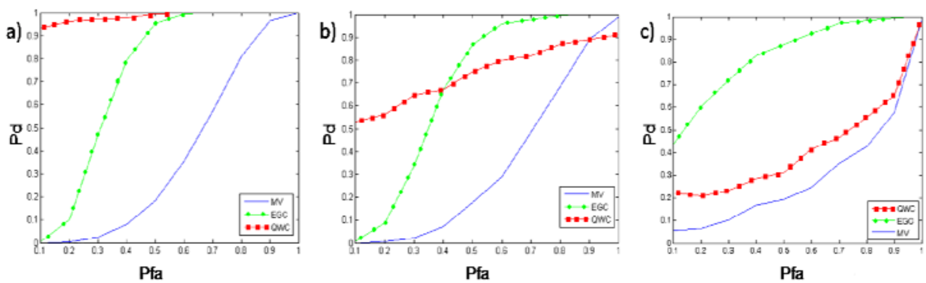

Fig. 6. Comparison of MV, EGC and QWC, for: a) 6 nodes, b) 4 nodes and c) 2 nodes

It is evident that the minimal required number of nodes for justifiable QWC usage in the targeted scenario is six. As the number of collaborating nodes decreases, the detection probability also decreases faster than in the EGC and MV cases. Additionally, it is recommended to use more than six nodes in collaborating groups since the censoring scheme itself yields frequent operation of various nodes in the censored fashion. This will avoid the collaboration gain reduction.

Fig. 7 shows the detection probability versus SNR for a fixed value of false alarm probability of 0.5. It can be concluded that all schemes operate well when the received SNR is higher than 0 dBm. For six collaborating nodes the QWC scheme achieves better detection probability than the EGC and MV schemes for the same value of SNR (Fig. 7a). For two nodes (Fig. 7c), the QWC operates worse than EGC and slightly better from MV as expected.

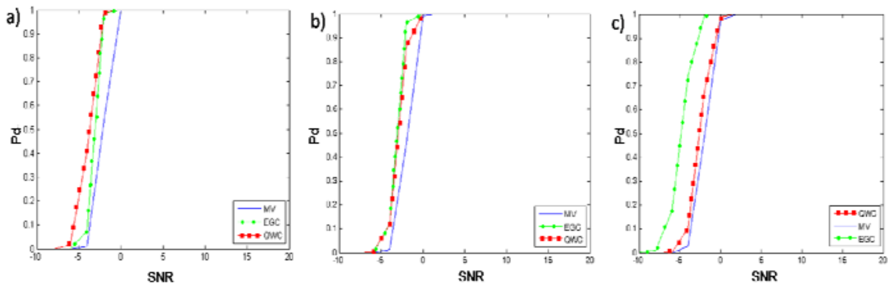

Fig. 7. Detection probability versus SNR, for Pfa=0.5 for: a) 6 nodes, b) 4 nodes, c) 2 nodes

5 Conclusion

This paper introduced a novel method (i.e. QWC) for combining the quantized measurement reports from the individual nodes that participate in collaborative spectrum sensing. The QWC is a bandwidth and energy efficient method that censors the unreliable nodes, while the remaining ones are allowed to send only three bits of quantized sensing report to the common receiver. The QWC outperforms the EGC, even with smaller overhead, because the quantization and weighting coefficients modify the test statistics of the received signal and the optimal decision thresholds are calculated, accordingly.

Future work will be concentrated on expanding the QWC scheme to joint multiband collaborative spectrum sensing.

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