Cooperative Detection of CMMB Signals based on Scattered Pilots and Clustering in Cognitive Radio Networks

Huiheng Liu, Zhengqiang Wang

***Abstract*—**China multimedia mobile broadcasting (CMMB) is a mobile television and multimedia standard specified in China. CMMB provides television services for mobile terminals. In cognitive radio networks (CRNs), the secondary users (SUs) can utilize the idle spectrums of CMMB primary user (PU) when CMMB signal is absent. This paper explores the cyclostationarity of CMMB signals and spectrum sensing schemes in CRNs. We propose a scattered pilots (SP) local detection scheme based on the first order lag filter. However independent detection is usually influenced by the shrinkage and shadowing problems, etc. Then a cooperative detection algorithm for CMMB signals based on scattered pilots and weighted-clustering (SPWC) is proposed. First, the SUs are classified into a few clusters according to the distances between SUs and the fusion center (FC). Second, Each SU in clusters makes a local decision based on the SP local detection scheme and sends the decision result to a cluster head. Then the cluster head will make a cluster-decision and send the result to the FC. Finally, the FC makes a final decision based on the distance weighted cluster-decisions. Simulation results show that the proposed SPWC cooperative detection algorithm can detect the spectrum holes of CMMB signals effectively and easily.

***Keywords*—**scattered pilots, weighted-clustering, cooperative detection, CMMB, cognitive radio networks.

I. Introduction

The proliferation of wireless communications and applications has resulted in a scarcity of radio spectrum. Furthermore, a number of measurements conducted in many places world-wide have shown that a lot of frequency bands licensed to radio communication systems are significantly underutilized. Such spectral underutilization has motivated cognitive radio (CR) technology [1]. Spectrum sensing is crucial to cognitive radio networks (CRNs), it has been explored comprehensively [2]-[3]. The energy detection (ED), the matched filter detection (MFD), and the cyclostationary feature detection (CFD) are the most popular spectrum sensing schemes in CRNs [4]-[5]. ED is the easiest to implement, but it may be severely impaired by the noise uncertainty and associated SNR wall phenomenon [6]. CFD can well distinguish between the signal and noises, and it is robust to the noise uncertainty. Though computational complexity, CFD is frequently used for spectrum sensing, especially for some signals with cyclostationary signature, i.e. orthogonal frequency division multiplexing (OFDM). OFDM is the most popular modulation scheme in communication and broadcasting systems, such as digital video broadcasting - terrestrial (DVB-T), worldwide interoperability for microwave access (WiMAX), long term evolution (LTE) and China multimedia mobile broadcasting (CMMB). CMMB is a mobile television and multimedia standard developed and specified in China. It provides broadcasting and television services for mobile phones, iPads, and other small screen portable terminals using S-band satellites [7].

Feature detection based on signal's unique characteristics has been proved to be effective [8]. The detection schemes exploit characteristics of the desired signal to distinguish this signal from noises. Spectrum sensing for the signals with the cyclostationarity is usually realized by calculating its cyclic autocorrelation function (CAF). Its second-order cyclic cumulants form with multiple cycle frequencies has been addressed in [9]-[10]. Unfortunately, despite its high sensitivity, high implementation complexity of these detectors prevents using them in practical applications [11]. However, for some OFDM signals embedded with pilot signals, i.e. CMMB, it is possible to reduce the complexity of this method by calculating the CAF with some special delay lags. In CMMB systems, scattered pilots are repeated in a duration of two symbols, while the amplitude of these pilots is unchanged. We consequently exploit periodical peaks of CAF in CMMB signals and propose a scattered pilots (SP) local detection scheme. According to the position of scattered pilots, some special delay lags, around $\tau = n T_u / 4$ where n=1, 2, 3, T_u is the used time of an OFDM symbol of CMMB signals, are selected to compute the decision static, CAF, with the cycle frequency $\alpha = 0$. Some peaks of CAF appear under these conditions. These peaks are used to detect the primary user (PU) of CMMB signals.

Cooperative spectrum sensing had been introduced to improve reliability in detecting a spectrum hole and overcome shrinkage and shadowing that affect the single secondary user (SU) sensing results [12]-[14]. In cooperative detection

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schemes based on hard combination, each SU needs to send the decision result to the fusion center (FC), which results in a large transmission overhead. A decision fusion (DF) detection scheme based on distance-weighting was analyzed in [15], considering the effect of distance fading on different SUs. In the application scenarios of CMMB systems based on CRNs, there are mostly portable mobile devices, e.g. cell phones. And the distances among some mobile devices are very close. Hence, we can separate these devices into a cluster, and a best SU is selected to report the decision result to the FC. This technique improves probability of detection and minimize time overhead. In this paper, we propose a cooperative detection scheme of CMMB signals based on scattered pilots and weighted-clustering (SPWC).

The rest of this paper is organized as follows. Section II briefly analyzes preliminaries and frame structure of CMMB systems. Section III discusses the cyclostationarity and the models of CMMB signals. Then the SP local detection of CMMB signals is described in detail. Section IV is devoted to the analysis of the cooperative spectrum sensing algorithm of SPWC. The basic combination methods of cooperative spectrum are also discussed. Section V presents our numerical and simulation results, followed by concluding remarks in Section VI.

II. Signal Feature of CMMB Signals

In CMMB systems, the channel's bandwidth can be either 2 or 8 MHz, depending on the data rate. One frame of CMMB consists of 40 time slots and the length is 25ms. Each time slot consists of one beacon signal and 53 OFDM symbols. The OFDM symbol of CMMB is modulated with BPSK, QPSK, QAM16, or QAM64, in which the length of cyclic prefix is 1/8 time of the data length. As depicted in Fig. 1, three types of effective subcarriers, data, scattered pilots, and continual pilots, are usually set up. For B=2MHz mode, the amount of data, scattered pilots, and continual pilots are 522, 78, and 28, respectively. If the bandwidth is 8MHz, they are 2610, 384 and 82, respectively.

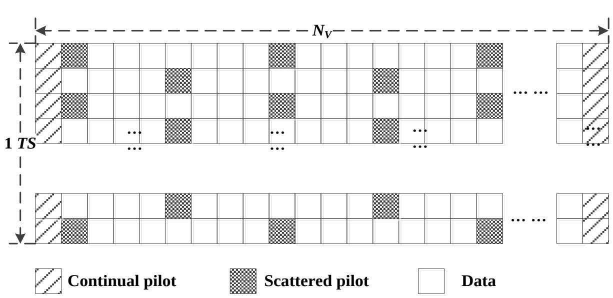

Fig. 1. The subcarrier positions of continual pilots, scattered pilots and data of CMMB signals in one time slot (1TS)

In the arrangement of circular configuration, the position of the scattered pilot subcarrier indexes in CMMB systems periodically changes, and it repeats every 8 subcarriers. The values of scattered pilots is 1+0*j*. But the starting positions of the first and second half scattered pilots are different in an OFDM symbol. For the channel bandwidths are 2MHz and 8MHz, the positions of the *m*th scattered pilot in the *n*th OFDM symbol are as follows, respectively.

$$\begin{aligned} & B = 2MHz: \\ & \text{if} \quad mod(n,2) == 0 \\ & \quad m = \begin{cases} 8p+1, & p = 0,1,\cdots,38 \\ 8p+3, & p = 39,40,\cdots,77 \end{cases} \\ & \text{if} \quad mod(n,2) == 1 \\ & \quad m = \begin{cases} 8p+5, & p = 0,1,\cdots,38 \\ 8p+7, & p = 39,40,\cdots,77 \end{cases} \end{aligned} \tag{1}$$

$$\begin{aligned} & B = 8MHz: \\ & \text{if} \quad mod(n,2) == 0 \\ & \quad m = \begin{cases} 8p+1, & p = 0,1,\cdots,191 \\ 8p+3, & p = 192,193,\cdots,383 \end{cases} \\ & \text{if} \quad mod(n,2) == 1 \\ & \quad m = \begin{cases} 8p+5, & p = 0,1,\cdots,191 \\ 8p+7, & p = 192,193,\cdots,383 \end{cases} \end{aligned} \tag{2}$$

III. SP Local Detection of CMMB Signals

A. Cyclostationarity

The process $x(t)$ is assumed to be a second-order cyclostationary if its mean and autocorrelation function are periodic with period T_0. It can be written as

$$R_{xx}(t,\tau) = R_{xx}(t+T_0,\tau) = E\left[x(t+\frac{\tau}{2})\, x^*(t-\frac{\tau}{2}) \right] \tag{3}$$

Because of the periodicity of the autocorrelation function, it can be represented by its Fourier series expansion

$$R_{xx}(t,\tau) = \sum_{\alpha} R_{xx}^{\alpha}(\tau) e^{j2\pi\alpha t} \tag{4}$$

where

$$R_{xx}^{\alpha}(\tau) = \lim_{T_0\to\infty} \frac{1}{T_0} \int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} R_{xx}(t,\tau) e^{-j2\pi\alpha t} dt \tag{5}$$

is the CAF of $x(t)$, α is called the cycle frequency, where $\alpha = m\frac{1}{T_0}$, and m is an integer.

B. Signals Model

The baseband of CMMB signals can be written as

$$S(t)=\sum_{n=-\infty}^{\infty}\sum_{i=0}^{N_u-1}Z(i,n)e^{j2\pi\frac{i}{T_u}t}p(t-nT_s) \tag{6}$$

where n is the nth OFDM symbol and i is the ith subcarrier. $Z(i,n)$ is the effective subcarriers N_v mapped to the used subcarriers N_u, i.e. N_u=1024 for B=2MHz. T_u is the used time of an OFDM symbol, and $T_s=T_u+T_{cp}$ is the total time of an OFDM symbol. T_{cp} is the duration of cyclic prefix, and $r(t-nT_s)$ is a rectangular pulse function.

Equation (6) can be written in the form of summation of data subcarriers and scattered pilot subcarriers defined as (7), where $d(i,n)$ is the data subcarriers, $p(I_1(l),n)$ and $p(I_2(l),n)$ are the first and second half of pilot subcarriers. $I_1(l)=S_1+L_pl, l=0,1,\cdots,N_p-1$, is the indexes of the first half of pilot subcarriers, S_1 is the starting pilot subcarrier and $L_p=8$ is the scattered pilot interval. N_p is the half number of pilot subcarriers. $I_2(l)=S_2+L_pl, l=N_p,N_p+1,\cdots,2N_p-1$, is the indexes of the second half of pilot subcarriers, S_2 is the starting pilot subcarrier.

$$S(t)=\sum_{n=-\infty}^{\infty}\left(\sum_{\substack{i=0\\ i\neq I_1(l),\\ i\neq I_2(l)}}^{N_u-1}d(i,n)e^{j2\pi\frac{i}{T_u}t}+\sum_{l=0}^{N_p-1}p(I_1(l),n)e^{j2\pi\frac{S_1+L_pl}{T_u}t}+\sum_{l=N_p}^{2N_p-1}p(I_2(l),n)e^{j2\pi\frac{S_2+L_pl}{T_u}t}\right)\cdot r(t-nT_s) \tag{7}$$

C. SP Local Detection

Let $R_{SS}^{o}(t,\tau)$ denote the autocorrelation function of OFDM symbols of CMMB signals. It is given by (8).

$$\begin{aligned}R_{SS}(t,\tau)=\sum_{n=-\infty}^{\infty}\Bigg\{&\sum_{\substack{i=0\\ i\neq I_1(l),\\ i\neq I_2(l)}}^{N_u-1}E\left[d(i,n)d^*(i,n)\right]e^{j2\pi\frac{i}{T_u}\tau}\\&+\sum_{l=0}^{N_p-1}E\left[p(I_1(l),n)p^*(I_1(l),n)\right]e^{j2\pi\frac{S_1+L_pl}{T_u}\tau}\\&+\sum_{l=N_p}^{2N_p-1}E\left[p(I_2(l),n)p^*(I_2(l),n)\right]e^{j2\pi\frac{S_2+L_pl}{T_u}\tau}\Bigg\}\\&\cdot r(t+\frac{\tau}{2}-nT_s)r^*(t-\frac{\tau}{2}-nT_s)\end{aligned} \tag{8}$$

Assuming the modulated signal $S(t)$ is independent, and identically distributed (*i.i.d*), then $E\left[d(i,n)d^*(i,n)\right]$ is equal to the average power σ_u^2 of data subcarriers. $E\left[p(I_1(l),n)p^*(I_1(l),n)\right]$ and $E\left[p(I_2(l),n)p^*(I_2(l),n)\right]$ are equal to the average powers of the first and the second half of scattered pilot subcarriers σ_{p1}^2 and σ_{p2}^2, respectively. Then (8) is simplified to (9).

$$\begin{aligned}R_{SS}(t,\tau)=\Bigg[&\sigma_u^2\sum_{i=0}^{N_u-1}e^{j2\pi\frac{i}{T_u}\tau}+\left(\sigma_u^2-\sigma_{p1}^2\right)\sum_{l=0}^{N_p-1}e^{j2\pi\frac{S_1+L_pl}{T_u}\tau}\\&\sum_{l=N_p}^{2N_p-1}\left(\sigma_u^2-\sigma_{p1}^2\right)e^{j2\pi\frac{S_2+L_pl}{T_u}\tau}\Bigg]\\&\cdot\sum_{n=-\infty}^{\infty}r(t+\frac{\tau}{2}-nT_s)r^*(t-\frac{\tau}{2}-nT_s)\end{aligned} \tag{9}$$

The exponential sum terms of (9) can be simplified according to Euler's formula. For example,

$$\begin{aligned}\sum_{i=0}^{N_u-1}e^{j2\pi\frac{i}{T_u}\tau}&=\frac{1-e^{j2\pi\frac{N_u}{T_u}\tau}}{1-e^{j2\pi\frac{\tau}{T_u}}}=\frac{e^{j\pi\frac{N_u}{T_u}\tau}(e^{-j\pi\frac{N_u}{T_u}\tau}-e^{j\pi\frac{N_u}{T_u}\tau})}{e^{j\pi\frac{\tau}{T_u}}(e^{-j\pi\frac{\tau}{T_u}}-e^{j\pi\frac{\tau}{T_u}})}\\&=\frac{sin(\frac{N_u\pi\tau}{T_u})}{sin(\frac{\pi\tau}{T_u})}\cdot e^{j\pi(N_u-1)\frac{\tau}{T_u}}\end{aligned} \tag{10}$$

The other two sum terms can be simplified similarly.

Considering the finite representation, the Fourier coefficient of the second term in (9) is denoted by

$$\begin{aligned}R_{pp}^{\alpha}(\tau)&=\frac{1}{T_s}\int_{-\frac{T_s}{2}}^{\frac{T_s}{2}}\sum_{n=-\infty}^{\infty}p(t+\frac{\tau}{2}-nT_s)p^*(t-\frac{\tau}{2}-nT_s)e^{-j2\pi\alpha t}dt\\&=\frac{1}{T_s}\int_{-\frac{T_s}{2}}^{\frac{T_s}{2}}p(t+\frac{\tau}{2})p^*(t-\frac{\tau}{2})e^{-j2\pi\alpha t}dt\end{aligned} \tag{11}$$

where α is an integer multiple of $\frac{1}{T_S}$. Given that $p(t)$ is a rectangular pulse with value 1 for $-T_s\le t\le T_s$ and value 0 elsewhere, if $\tau>0$, we have

$$R_{pp}^{\alpha}(\tau)=\frac{1}{T_s}\int_{\frac{-T_s+\tau}{2}}^{\frac{T_s-\tau}{2}}e^{-j2\pi\alpha t}dt=\frac{sin[\pi\alpha(T_s-\tau)]}{\pi\alpha T_s} \tag{12}$$

Similarly, if $\tau<0$, $R_{pp}^{\alpha}(\tau)$ is equal to $\frac{sin[\pi\alpha(T_s+\tau)]}{\pi\alpha T_s}$. Considering the above two cases, $R_{pp}^{\alpha}(\tau)$ becomes

$$R_{pp}^{\alpha}(\tau)=\frac{sin[\pi\alpha(T_s-|\tau|)]}{\pi\alpha T_s} \tag{13}$$

By substitution in the finite representation of (4), (5) and considering (10) and (13), the Fourier coefficient $R_{SS}^{\alpha}(\tau)$ of $R_{SS}(t,\tau)$ is given by (14).

$$R_{SS}^{\alpha}(\tau)=\left\{\sigma_u^2\frac{sin(\frac{N_u\pi\tau}{T_u})}{sin(\frac{\pi\tau}{T_u})}\cdot e^{j\pi(N_u-1)\frac{\tau}{T_u}}-\frac{sin(\frac{N_pL_p\pi\tau}{T_u})}{sin(\frac{L_p\pi\tau}{T_u})}\cdot\left[\left(\sigma_u^2-\sigma_{p1}^2\right)e^{j\pi[2S_1+L_p(N_p-1)]\frac{\tau}{T_u}}+\left(\sigma_u^2-\sigma_{p2}^2\right)e^{j\pi[2S_2+L_p(3N_p-1)]\frac{\tau}{T_u}}\right]\right\}\cdot\frac{sin[\pi\alpha(T_s-|\tau|)]}{\pi\alpha T_s} \tag{14}$$

Equation (14) show the CAFs of the PU of CMMB with the scattered pilot structure where α is an integer multiple of $1/T_s$, and the values of CAFs are influenced dominantly by the scattered pilots. Considering the periodicity of two OFDM symbols, $R_{SS}^{\alpha}(\tau)$ will generate peaks for $\alpha=0$ and approximately $\tau=2n{T_u}/{L_p}=n{T_u}/{4}$, $n=1,2,3$ .According to the CAF of OFDM symbols, we can make the decision whether the CMMB signal is active or not.

$$\begin{cases}H_1: & R_{SS}^{\alpha}(\tau)\ge\lambda\\ H_0: & R_{SS}^{\alpha}(\tau)<\lambda\end{cases} \tag{15}$$

where λ is the decision threshold of the statistics. For a target probability of false alarm, λ is obtained by Monte Carlo simulation only if the noise exists.

As shown in (14), the average powers of data subcarriers and scattered pilot subcarriers have a great influence on CAF, $R_{SS}^{\alpha}(\tau)$. However, the average powers are influenced by the noise. Hence, we use the first order lag filter to smooth the received data to mitigate the influence of noises. Assuming the smoothed data of the *n*th OFDM symbol and *i*th subcarrier is $\bar{S}(i,n)$, we have

$$\bar{S}(i,n)=(1-b)\cdot S(i,n)+b\cdot\bar{S}(i-1,n),\ b\in(0,1) \tag{16}$$

where $S(i,n)$ is the received signal interfered with the noise, $\bar{S}(i-1,n)$ is the last smoothed data, and b is the smoothing factor.

Therefore, the decision rule of the proposed SP local detection scheme is denoted by

$$\begin{cases}H_1: & \bar{R}_{SS}^{\alpha}(\tau)\ge\lambda\\ H_0: & \bar{R}_{SS}^{\alpha}(\tau)<\lambda\end{cases} \tag{17}$$

where $\bar{R}_{SS}^{\alpha}(\tau)$ is CAF of (14), and the average powers of the data and scattered pilot subcarriers are computed with the smoothed data.

IV. SPWC Cooperative Detection Algorithm

In cooperative spectrum sensing, SUs report their sensing results to a FC, in either of these two methods, hard combination or soft combination.

A. Hard Combination of Cooperative Detection

Each SU makes a local decision that the PU activity, and the binary local decision result is reported to the FC. It is convenient to apply linear fusion rules to obtain the cooperative decision. The commonly fusion methods are OR rule, AND rule, or K-out-of-N rule. Let l_i be the local decision of the *i*th SU and l be the cooperative decision made by the FC, l_i, $l\in\{0,1\}$, and an "1" and a "0" indicate a PU's presence and absence, respectively. The OR rule refers the FC determines $l=1$ if $l_i=1$, for any *i*. The final detection probability Q_d and false alarm probability Q_f for OR rule can be denoted as follows.

$$\begin{cases}Q_d=1-\prod_{i=1}^{M}(1-P_{d,i})\\ Q_f=1-\prod_{i=1}^{M}(1-P_{f,i})\end{cases} \tag{18}$$

where $P_{d,i}$ and $P_{f,i}$ are the local probability of detection and probability of false alarm, respectively, *M* is the number of cooperative users. This method maximizes to ensure that the PU's signal is not disturbed.

The AND rule refers to $l=1$ if $l_i=1$, for all *i*. The final detection probability Q_d and false alarm probability Q_f can be written as follows.

$$\begin{cases}Q_d=\prod_{i=1}^{M}P_{d,i}\\ Q_f=\prod_{i=1}^{M}P_{f,i}\end{cases} \tag{19}$$

K-out-of-N rule also can be generalized as the Majority rule. When majority of SUs reports that the PU is active, the FC will make a decision that the PU is present. The probability of detection Q_d and probability of false alarm Q_f are as follows.

$$\begin{cases} Q_d = \sum_{i=K}^{M} \binom{M}{i} (P_{d,i})^i (1-P_{d,i})^{M-i} \\ Q_f = \sum_{i=K}^{M} \binom{M}{i} (P_{f,i})^i (1-P_{f,i})^{M-i} \end{cases} \tag{20}$$

B. Soft Combination of Cooperative Detection

In soft combination, each SU will not make a local decision. They simply observe the received signal from the PU and forward to the FC. The FC make a decision that the PU is active or not according to the received data coming from different SUs. At the FC, different combination techniques can be applied, such as equal gain combination (EGC), maximum ratio combination (MRC) and selection combination (SC). For example, in the cooperative detection based on ED, normalized energies from different SUs are summed with weights and decision is based on the weighted summation. Denote the weight coefficient corresponding to the *i*th SU to be w_i, then the weighted energy summation is given by

$$Y = \sum_{i=1}^{M} w_i Y_i \tag{21}$$

where Y_i is the observed energy value of the *i*th SU. The weighted coefficients are the same for any SU in EGC method. For example

$$w_i = \frac{1}{\sqrt{M}},\ 1 \le i \le M \tag{22}$$

The difference between MRC and EGC is that in MRC method the energy received is weighted with a normalized weight coefficient and then added. The weight usually depends on the received SNR of each SU, γ_i. For instance [16]

$$w_i = \frac{\gamma_i}{\sqrt{\sum_{j=1}^{M} \gamma_j^2}} \tag{23}$$

In SC scheme, the FC selects the branch with highest SNR, γ_{SC}, which is denoted by

$$\gamma_{SC} = \max(\gamma_1, \gamma_2, \cdots\cdots, \gamma_M) \tag{24}$$

Obviously, using soft combination at the FC can achieve the best detection performance compared with hard combination at the cost of control channel overhead. The hard combination requires less control channel bandwidth with possibly the degraded detection performance due to the loss of information from quantization. Hence, for simplification, the hard combining method is applied in our proposed SPWC cooperative detection scheme.

C. SPWC Cooperative Detection for CMMB Signals

In CMMB signals based on CRNs, all SUs are assumed to have been separated into a few clusters according to the distance between SUs and the FC. Subsequently, the SPWC cooperative sensing is conducted as the following steps.

Step 1: Make local decisions. The *j*th SU in the *i*th cluster make local decision based on SP detection and send decision, $L_{i,j}$ to the cluster head

Step 2: Make cluster-decisions. The cluster head of the *i*th cluster make a cluster-decision C_i based on (25) and send it to the FC.

$$C_i = \varphi(\alpha_{i,1}L_{i,1}, \alpha_{i,2}L_{i,2}, \cdots\cdots, \alpha_{i,N_i}L_{i,N_i}) \quad 1 \le i \le K \tag{25}$$

Where $\alpha_{i,j}$ is the weight factor for the *j*th SU in *i*th cluster, $i = 1, 2, \cdots K$, $j = 1, 2, \cdots N_i$, K is the number of clusters and N_i is the number of SUs in the *i*th cluster. The function φ combinates the local decision using OR rule.

Step 3: Make a final decision. The FC make a final decision F according to the following rule.

$$F = \psi(\beta_1 C_1, \beta_2 C_2, \cdots\cdots, \beta_K C_K) \tag{26}$$

where $\beta_i, i = 1, 2, \cdots, K$, is the weight factor of the *i*th cluster. We assume that the channel condition between SU and cluster-head in each cluster is perfect because of the closed distance to each other. Thus, in the same cluster, the difference of weight factor $\alpha_{i,j}$ is nearly equal, e.g. $\alpha_{i,j} = 1, \forall i, j$. But the weight factor β_i of the *i*th cluster should not be ignored because of the long distance between clusters and the FC, and much path loss. The closer the distance between SU and the FC is, the bigger weight factor is. Then the cluster decision with a bigger weight factor has greater contribution to the final decision. Conversely, the farther the distance is, the smaller the weight coefficient is. Then for those clusters, if their decisions are not reliable, they have little impact on the final result.

The weight factor β_i is given by

$$\beta_i = \overline{L}_i / G,\ \sum_{i=1}^{K} \beta_i = 1 \tag{27}$$

$\overline{L}_i$ is the average distance coefficient of the *i*th cluster. It is shown as follows.

$$\overline{L}_i = \sum_{j=1}^{N_i} (1/d_{i,j}) \tag{28}$$

where N_i is the number of SUs in the *i*th cluster, $d_{i,j}$ is the distance between the *j*th SU in the *i*th cluster and the FC. And G is the normalized coefficient of all $\overline{L}_i$. G is denoted as

$$G = \sum_{i=1}^{K} \overline{L}_i = \sum_{i=1}^{K} \sum_{j=1}^{N_i} (1/d_{i,j}) \tag{29}$$

The FC makes the final decision that the PU is active based on different values C_i according to K-out-of N rule. Then the probability of detection Q_{d_final} and probability of false alarm Q_{f_final} can be written as follows.

$$\begin{cases} Q_{d\_final} = P\left\{ \sum_{i=1}^{K} \beta_i C_i \geq \eta \mid H_1 \right\}, \quad i = 1, 2, \cdots, K \\ Q_{f\_final} = P\left\{ \sum_{i=1}^{K} \beta_i C_i \geq \eta \mid H_0 \right\}, \quad i = 1, 2, \cdots, K \end{cases} \tag{30}$$

where η is the decision threshold. It can be set according to the factual environment.

V. Simulations Results

In simulations, CMMB signal is generated with bandwidth of 2MHz, modulation of QAM16. The special delay lag τ is set to $T_u/4$. The smoothing factor b=0.99 is set for all simulations. The channel is assumed to be AWGN. To obtain good statistic values, the simulations are carried out with 10,000 Monte Carlo trials. We assume that there are 3 clusters and 4 users in each cluster. The average distances between the clusters and the FC are 30m, 40m and 50m, respectively. According to (31), given the average SNR value of a cluster, we can obtain the average SNRs of other two clusters.

$$Lbs(dB) = 32.45 + 20\lg f(MHz) + 20\lg d(Km) \tag{31}$$

where Lbs is the loss of free space. For example, given the SNR of the second cluster, γ_2 = -13dB, we can compute the SNR of other two clusters are γ_1 = -10.5dB, γ_3 = -15dB, respectively.

The performance of the SPWC cooperative detection algorithm is simulated in Fig. 2 and Fig. 3. The detection probabilities of the DF scheme, OR rule and K-out-of-N rule are also compared, in which the local detection scheme is still the SP detection method. The SP local detection for single SU under γ= -10.5dB is also shown for comparison. The simulation parameters for Fig. 2 and Fig. 3 are shown in Table 1. The number of OFDM symbols used for spectrum sensing is 108, which is equal to two slot times (50ms) of a CMMB frame. It can be verified that the SPWC cooperative detection algorithm outperform the cooperative DF scheme and K-out-of-N rule. It can be seen from Fig. 2 that the detection probability of the SPWC scheme is worse than that of OR rule when SNR is low and the probability of false alarm is small. When the surroundings of SUs are better, we can see that the performance of the SPWC scheme is very close to that of OR rule in Fig. 3. For example, for the probability of false is 0.05, the detection probabilities of the SPWC scheme and OR rule are 96.5% and 99.9%, respectively. Meanwhile, it is known that there is a high probability of false alarm for OR rule when the target probability of detection is set. Obviously, the sensing performance of the SPWC cooperative detection scheme outperforms the SP local detection method significantly. For instance, the improvement of detection performance is up to about 28% and 18% under the γ_2 = -13dB and γ_2 = -11dB, respectively.

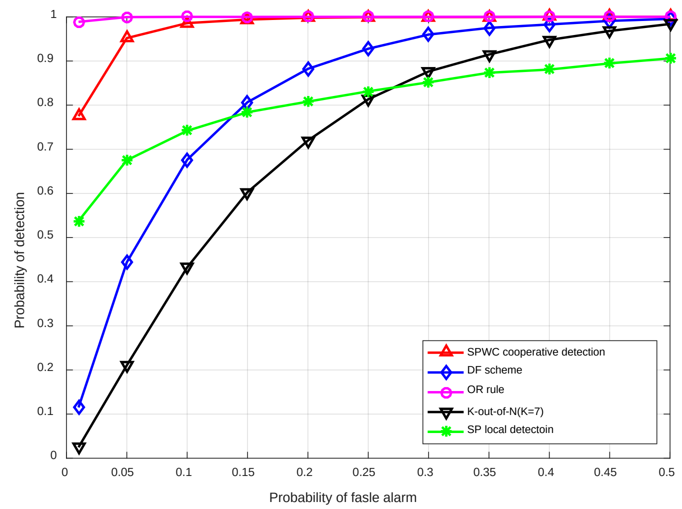

Fig. 2. Probabilities of detection under the average SNR, $\overline{\gamma}_2$= -13dB

Table 1. Simulation parameters

Freq. (GHz)	Number of clusters	Number of SUs in each cluster	Average SNRs in each cluster (dB)			Number of Symbols
			$\overline{\gamma}_1$	$\overline{\gamma}_2$	$\overline{\gamma}_3$	
2.5	3	4	-10.5	-13	-15	108

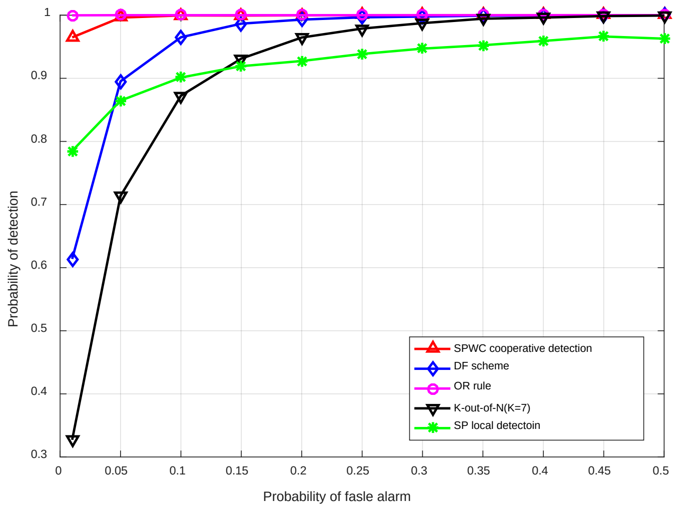

Fig. 3. Probabilities of detection under the average SNR, $\bar{\gamma}_2$ = -11dB

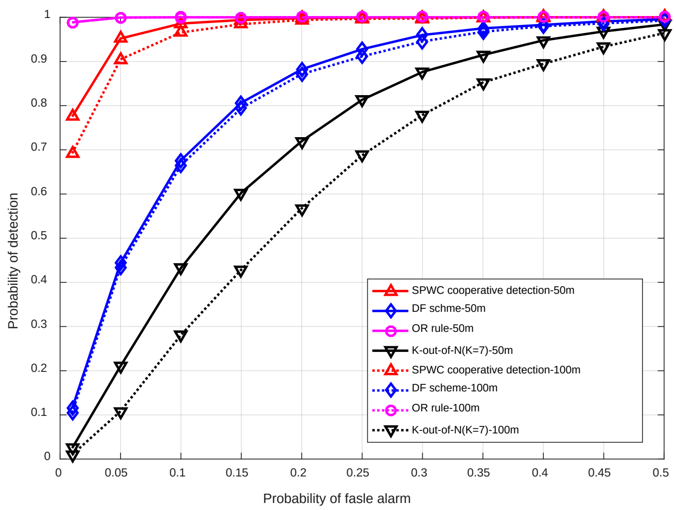

Fig. 4. Probabilities of detection under different distances between the third cluster and the FC

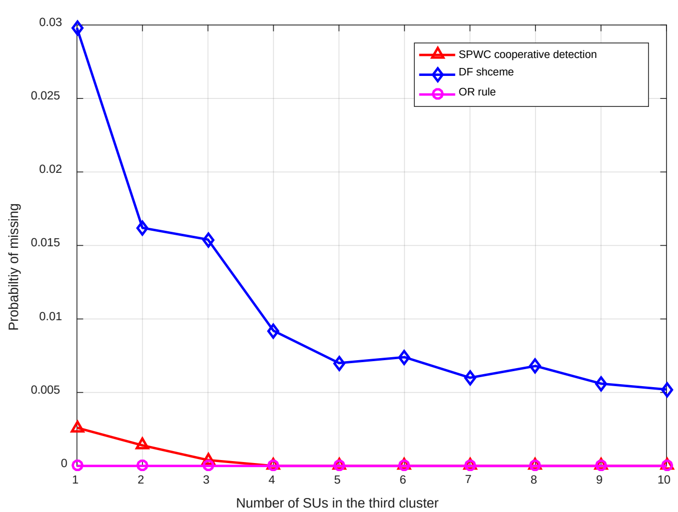

Fig. 5. Probabilities of missing with different cooperative users under the average SNR, $\bar{\gamma}_2$ = -10.5dB

In order to analyze the influence of distances, we assume that the distances between the third cluster and the FC are 50m and 100m, respectively. We still assume that the average SNR is -13 dB for the second cluster. Then we can evaluate the average SNR of the third cluster is -21 dB under the distance of 100m. Fig. 4 shows that ROC curves as compared to the OR rule and DF scheme. It can be verified that the detection performance of the SPWC algorithm has a 10% improvement for a close distance at the probability of false alarm of 0.01. The detection performances of the DF method are almost same under both cases. The reason is that each SU will be weighted according the distance coefficient in the DF scheme. The distances between 4 SUs and the FC are changed. The distances of 8 SUs in other two clusters are the same in both cases. Therefore, there is a slightly improvement when distance of one cluster decreases from 100m to 50m in the DF method. The detection probability of the K-out-of-N rule also has an obvious degradation when the distance is doubled. Because the attenuation of reported results is increased when the propagation distance is far.

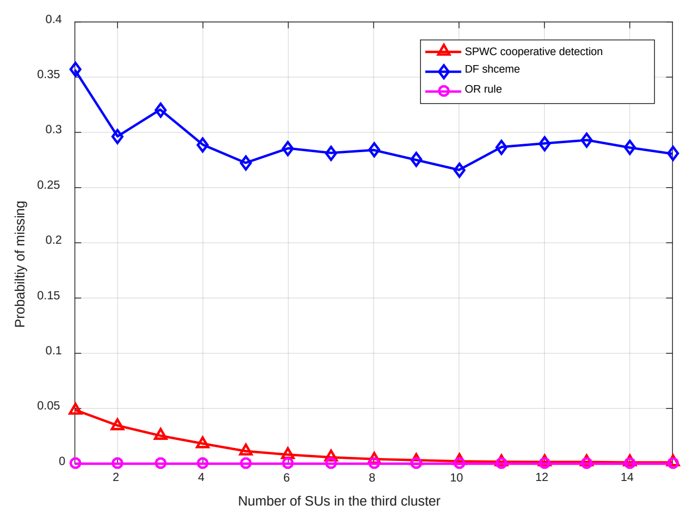

Fig. 6. Probabilities of missing with different cooperative users under the average SNR, $\bar{\gamma}_2$ = -13dB

Figure 5 and Fig. 6 show the probabilities of missing for different number of cooperative users under the average SNRs of the second cluster are -10.5dB and -13dB, respectively. In both cases the OR rule and DF scheme are shown for comparison. The other parameters are same with that of Fig. 2. The number of SUs in the third cluster is changing, which means the total number of cooperative users is unfixed. We observe that as the number of SUs increases, the probabilities of missing of all methods decrease. It can be seen for $\bar{\gamma}_2$ = -10.5dB that the probability of missing of the SPWC scheme will approximately be 0 with 12 cooperative SUs. However, the missing probability of the DF method is still about 0.005 with 18 cooperative SUs. When the SNR is much low, the detection performance of the proposed scheme can be improved by increasing the cooperative SUs. For example, in Fig. 6, it can be verified that the missing probability is equal to 0 under 18 cooperative SUs when the SNR of the second cluster is -13dB. Note that the missing probability is always 0 with more than 10 cooperative users in the third cluster.

VI. CONCLUSION

The cyclostationarity of CMMB signals is studied and analyzed. Scattered pilots are repeated in a duration of two symbols in CMMB systems. Fully considering the feature of CMMB signals, a SP local detection method is proposed. For the cycle frequency $\alpha = 0$ around the delay lags $\tau = n T_u / 4$ where n = 1,2,3, some peaks of scattered pilots appear in the CAF of CMMB signals. These dominant peaks of CAF are used to detect the PU of CMMB. Further, the individual detection may be influenced by the fading, shadowing problems. A SPWC cooperative detection scheme is considered. In this cooperative method, each SU in clusters make local decision based on the SP algorithm. Each cluster-decision is reported to the FC by the cluster head. The FC makes a final decision using Majority rule based on the distance weighted cluster-decisions. Simulation results show that the proposed cooperative detection algorithm outperform the DF scheme and Majority rule. It is verified that the proposed algorithm has an approximate detection performance compared with the OR rule, especially when the surroundings of CRNs is better, i.e. SNR is higher. Obviously, the detection probability is degraded when the distances between some SUs and the FC are increased in all the above schemes. In addition, our results indicate that a significant performance enhancement may be achieved by increasing the number of cooperative SUs for a low SNR. However, there may be no performance improvement by using much more SUs in the cooperative sensing. Unexpectedly, too many cooperative SUs will increase network overheads.

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