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A Novel Spectrum Sensing Scheme Based on Periodicity of DVB-T Pilot Signals

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Abstract—This paper proposes a novel spectrum sensing technique for the digital video broadcasting-terrestrial (DVB-T) systems, which utilizes the periodicity of pilot signals in the orthogonal frequency division multiplexing (OFDM) symbols. The proposed scheme can overcome the effect of the timing synchronization error by re-correlating the correlation values in the same sample distances. The numerical results demonstrate that the detection probability performance of the proposed scheme outperforms that of the conventional scheme when there exists a timing synchronization error.

Keywords—DVB-T, spectrum sensing, OFDM, timing synchronization error.

I. INTRODUCTION

THE spectrum sensing is one of the most essential technologies for the implementation of cognitive radio (CR) systems [1], [2], which continually searches for a vacant spectrum band and helps the CR to utilize the unoccupied band. Recently, there have been many countries allowing the CR to access the digital television bands [3], and thus, its use in digital video broadcasting-terrestrial (DVB-T) systems has attracted much attention.

Considering the known patterns of pilots in DVB-T systems, several schemes suitable for the spectrum sensing have been proposed to scan the frequency band of interest and investigate the existence of the primary user (PU), the licensed user of the frequency band [4], [5]. The scheme in [4] senses the spectrum of PU by using the correlation between the local pilots generated in the receiver and the pilots in the received orthogonal frequency division multiplexing (OFDM) symbol; however, this scheme is operational only for the ideal additive white Gaussian noise (AWGN) environment. Considering the fact that the effect of the channel on the adjacent pilots can be generally assumed to be the same, the scheme in [5] has overcome the effect of multipath fading by using the correlations between a continual pilot (CP) and its nearest scattered pilot (SP) in an OFDM symbol. However, they are not straightforwardly applicable to the practical CR systems, requiring the perfect timing synchronization before the spectrum sensing process.

In this paper, thus, we propose a novel spectrum sensing scheme for the practical DVB-T systems, which can overcome the effect of the synchronization error. The novel scheme first partitions the correlation values between the CPs and SPs nearest to the CPs into several groups based on the distance between the CP and SP, and then, combines the correlation values in the same group eliminating the effect of the timing synchronization error.

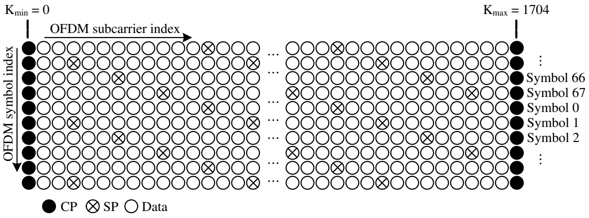

Fig. 1. Pilot arrangement in the DVB-T systems with 2K mode.

II. SYSTEM MODEL

The DVB-T system can be operated with one of the 2K or 8K mode, depending on the total number of subcarriers. In this paper, we focus on the DVB-T system with 2K mode, where 1705 subcarriers among 2048 total subcarriers are used to transmit data, 45 CPs, and 142 or 143 SPs. Fig. 1 describes the pilot arrangement in the DVB-T systems with 2K mode, where $\mathrm{K}_{\mathrm{min}}$ and $\mathrm{K}_{\mathrm{max}}$ are the smallest and largest subcarrier indices of the active subcarriers, respectively. The SPs are periodically inserted every twelve subcarriers in an OFDM symbol and their locations are periodic for every four OFDM symbols [6], where the values of pilots with the same subcarrier index in all OFDM symbols are the same.

Since the signal features for the DVB-T systems are well-standardized in [6], the CR may have the rough information on the frequency band of the PUs. Thus, using the information as the initial estimate of the frequency band of the PU, the spectrum sensing schemes search for the exact location of the PU on the frequency domain and help the CR to avoid the occupied frequency band.

In the DVB-T systems, the complex baseband OFDM symbol is generated by taking the inverse FFT (IFFT) of the quadrature amplitude modulation (QAM) data and inserting the guard interval at the beginning of the OFDM symbol to prevent the intersymbol interference. Then, the n-th sample of the l-th received OFDM symbol in the receiver can be expressed as

$$y_l(n) = x_l(n+\tau)\mathrm{e}^{j2\pi\Delta(lN_T+n+\tau)/N} + w_l(n), \quad \text{for} \;\; l = 0,\ 1,\ \cdots,\ \text{ and } \; n = 0,\ 1,\ \cdots,\ N-1, \tag{1}$$

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where τ is the timing synchronization error normalized to the sampling interval; Δ is the frequency difference between the initial frequency estimate and real frequency of the PU normalized to the subcarrier spacing; N is the size of the IFFT; N_T is the number of the samples in the OFDM symbol including the guard interval; and $w_l(n)$ is the AWGN sample with zero-mean and variance of $\sigma_w^2 = \mathbf{E}\{|w_l(n)|^2\}$, respectively. Here, the signal $x_l(n)$ can be represented as

$$x_l(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_l(k) H_l(k) \mathrm{e}^{j2\pi kn/N}, \\ \text{for} \quad l = 0,\ 1,\ \cdots,\ \text{ and } \ n = 0,\ 1,\ \cdots,\ N-1, \qquad (2)$$

where $X_l(k)$ is a pilot or data transmitted through the k-th subcarrier of the l-th OFDM symbol and $H_l(k)$ is the channel frequency response on the k-th subcarrier of the l-th OFDM symbol.

Then, the FFT output corresponding to the k-th subcarrier of the l-th received OFDM symbol is given as

$$\begin{aligned} Y_l(k) =& \mathrm{e}^{j2\pi\Delta l N_T/N} \mathrm{e}^{j2\pi\tau k/N} \\ & \times H_l(k-\Delta_i) X_l(k-\Delta) + W_l(k), \end{aligned} \qquad (3)$$

where $W_l(k)$ is the FFT output of the AWGN sample $w_l(n)$. From (1), we can observe that the timing synchronization error causes the phase shift in the received OFDM symbol, resulting in the degradation of the spectrum sensing performance.

III. CONVENTIONAL SCHEME

The conventional scheme searches for the frequency difference Δ by exploiting information on the indices and values of the CPs and its nearest SPs in an OFDM symbol [5]. At first, the conventional scheme generates a template

$$T_m(k) = \frac{X^{(m)}(k')}{X^{(m)}(k)}, \\ \text{for} \quad k \in C_{cp} \ \text{ and } \ m \in \{0,1,2,3\}, \qquad (4)$$

where C_{cp} is the set of subcarrier indices of CPs; m is the OFDM symbol index indicating one of the the four different pilot patterns described in Section II; $X^m(k)$ $(X^m(k'))$ denotes the CP with the subcarrier index k (SP the nearest to the $X^m(k)$) in the m-th pilot pattern. The value of the template is either +1 or -1 and known to the both transmitter and receiver, which will be used to align the sign of the correlation values

To search for the exact location of the PU on the frequency domain, the pilot pattern of the PU needs to be estimated prior to the estimation of frequency difference Δ. By taking all the trial values of the Δ into consideration, the pilot pattern estimate m_0 is obtained as

$$m_0 = \underset{m\in\{0,1,2,3\}}{\arg\max} \Big\{ \mathbf{Re}\big(\Psi(f,m)\big) \Big\}, \quad \text{for} \quad |f| \le N/2, \quad (5)$$

where $\Psi(f,m) = \sum_{k\in C_{cp}} Y_0(k_m + f) Y_0^*(k'_m + f) T_m(k_m)$; f is the trial value of the frequency difference Δ; and k_m is (k'_m) the index of the CP with the index k (SP the nearest to k_m) in the m-th pilot pattern. Then, the relatively reliable α trial values among all the trial values are selected as

$$\begin{aligned} \{f_1,\ \cdots, f_\alpha\} =& \underset{|f|\le N/2}{\arg\max{}_c} \Big\{ \mathbf{Re}\Big(\sum_{k\in C_{cp}} Y_0(k_{m_0} + f) \\ & \times Y_0^*(k'_{m_0} + f) T_{m_0}(k_{m_0}) \Big) \Big\}, \end{aligned} \qquad (6)$$

where $\underset{|f|\le N/2}{\arg\max{}_c}(\cdot)$ collects the α largest values among f in descending order. By exploiting the selected α trial values , we can calculate the correlation value of the pilots in the D consecutive OFDM symbols as

$$\begin{aligned} \Omega(\overline{f}) = \sum_{k\in C_{cp}} \sum_{l=0}^{D-1} & Y_l(k_{m_0\oplus l} + \overline{f}) \\ & \times Y_l^*(k'_{m_0\oplus l} + \overline{f}) T_{m_0\oplus l}(k_{m_0\oplus l}), \end{aligned} \qquad (7)$$

for $\overline{f} \in \{f_1, f_2,\ \cdots, f_\alpha$, where $m_0 \oplus l$ is the residue when the sum of the m_0 and l is divided by 4, and D is the OFDM symbols used for estimation of Δ. Then, the trial value

$$\widehat{\Delta} = \underset{\overline{f}\in\{f_1, f_2,\ \cdots, f_\alpha\}}{\arg\max{}_c} \Big\{ \mathbf{Re}\big(\Omega(\overline{f})\big) \Big\}, \qquad (8)$$

which maximizes the real value of (7) is determined to be the frequency difference between the initial frequency estimate and real frequency of the PU. If α is set to be 1, the conventional scheme searches for the spectrum of PU by using only one received OFDM symbol.

In order to clarify the effect of the timing synchronization error on the conventional scheme, we can rewrite (7) as

$$\begin{aligned} \Omega(\overline{f}) = \sum_{k\in C_{cp}} \sum_{l=0}^{D-1} & \mathrm{e}^{j2\pi\tau(k_{m_0\oplus l} - k'_{m_0\oplus l})/N} \\ & \times \Big| H_l(k_{m_0\oplus l} + \overline{f} - \Delta) \Big|^2 X_l(k_{m_0\oplus l} + \overline{f} - \Delta) \\ & \times X_l^*(k'_{m_0\oplus l} + \overline{f} - \Delta) \frac{X^{(m_0\oplus l)}(k'_{m_0\oplus l})}{X^{(m_0\oplus l)}(k_{m_0\oplus l})} \\ & + \widehat{W}_l(k_{m_0\oplus l}), \end{aligned} \qquad (9)$$

where $\widehat{W}_l(k_{m_0\oplus l})$ is the noise component. As shown in (9), the timing synchronization error τ causes the phase rotation, resulting in the performance degrade of the conventional spectrum sensing scheme.

IV. PROPOSED SCHEME

When we correlate the value between each CP and the SP the nearest to the CP for every CPs, the correlation values can be classified into several groups depending on the predetermined sample distances (±3, ±6, ±9, and ±12), which stems from the fact that the pilot signals are located periodically over the consecutive OFDM symbols. Then the correlation values in the same group have the same effect of the timing synchronization error, since the correlation values with the same sample distance undergo the same effect of the timing synchronization error. Thus, we propose a novel spectrum sensing scheme which overcomes the effect of the timing synchronization error by re-correlating a correlation value with the correlation value in the same group. This procedure is performed for all pilot patterns and all trial values of the frequency difference Δ, then the trial value which maximizes the real value of the re-correlation is determined to be the estimate of the frequency difference Δ between the initial frequency estimate and real frequency of the PU.

With the same approach as in (4), the proposed scheme generates a template

$$T_m\big(I_{g,m}(k)\big) = \frac{X^{(m)}(I_{g,m}(k)+g)}{X^{(m)}(I_{g,m}(k))}, \quad \text{for} \quad m \in \{0,1,2,3\}, \tag{10}$$

where g is the sample distance between the CP and the SP the nearest to the CP and $I_{g,m}(i)$ is the subcarrier index of the i-th CP that belongs to the group with the sample distance g in the m-th pilot pattern. Then, the pilot pattern in the received OFDM symbol is estimated as

$$m_0 = \underset{m\in\{0,1,2,3\}}{\arg\max} \Big\{ \mathbf{Re}\big(\Lambda(f,m)\big) \Big\}, \quad \text{for} \quad |f| \le N/2, \tag{11}$$

where $\Lambda(f,m)$ is given as

$$\begin{aligned}\Lambda(f,m) =& \sum_{l=0}^{D-1}\sum_{g\in G}\sum_{i=1}^{G_n(g)-1}\sum_{j=i+1}^{G_n(g)} Y_l(I_{g,m\oplus l}(i)+f) \\ &\times Y_l^*(I_{g,m\oplus l}(i)+g+f)T_{m\oplus l}(I_{g,m\oplus l}(i)) \\ &\times \Big\{ Y_l(I_{g,m\oplus l}(j)+f)Y_l^*(I_{g,m\oplus l}(j)+g+f) \\ &\times T_{m\oplus l}(I_{g,m\oplus l}(j)) \Big\}^*,\end{aligned} \tag{12}$$

where G is the set of the sample distances and $G_n(g)$ is the number of the CPs with the sample distance g.

As mentioned previously, then, we classify the correlation values between a CPs and the SPs the nearest to the CPs into several groups according to the predetermined sample distances. Then, we re-correlate the correlation values in the same group as

$$\begin{aligned}\Gamma(f) =& \sum_{l=0}^{D-1}\sum_{g\in G}\sum_{i=1}^{G_n(g)-1}\sum_{j=i+1}^{G_n(g)} Y_l(I_{g,m_0\oplus l}(i)+f) \\ &\times Y_l^*(I_{g,m_0\oplus l}(i)+g+f)T_{m_0\oplus l}(I_{g,m_0\oplus l}(i)) \\ &\times \Big\{ Y_l(I_{g,m_0\oplus l}(j)+f)Y_l^*(I_{g,m_0\oplus l}(j)+g+f) \\ &\times T_{m_0\oplus l}(I_{g,m_0\oplus l}(j)) \Big\}^*.\end{aligned} \tag{13}$$

Finally, the proposed spectrum sensing scheme determines the trial value of f which maximizes the correlation value in (13) to be the estimate of the frequency difference Δ and informs the CR to avoid the frequency band occupied by the PU.

$$\widehat{\Delta} = \underset{|f|\le N/2}{\arg\max} \Big\{ \mathbf{Re}\big(\Gamma(f)\big) \Big\}. \tag{14}$$

It should be noted that proposed spectrum sensing scheme is not influenced by the timing synchronization error, which can be confirmed by rewriting the (13) as

$$\begin{aligned}\Gamma(f) =& \sum_{l=0}^{D-1}\sum_{g\in G}\sum_{i=1}^{G_n(g)-1}\sum_{j=i+1}^{G_n(g)} \Big|H_l(A)\Big|^2 X_l(A) \\ &\times X_l^*(A+g)\frac{X^{(m_0\oplus l)}(I_{g,m_0\oplus l}(i)+g)}{X^{(m_0\oplus l)}(I_{g,m_0\oplus l}(i))}\Big|H_l(B)\Big|^2 \\ &\times X_l^*(B)X_l(B+g) \\ &\times \left\{ \frac{X^{(m_0\oplus l)}(I_{g,m_0\oplus l}(j)+g)}{X^{(m_0\oplus l)}(I_{g,m_0\oplus l}(j))} \right\}^* \\ &+ \widehat{W}_l(I_{g,m_0\oplus l}(j)),\end{aligned} \tag{15}$$

where $A = I_{g,m_0\oplus l}(i)+f-\Delta$, $B = I_{g,m_0\oplus l}(j)+f-\Delta$, and $\widehat{W}_l(I_{g,m_0\oplus l}(j))$ is the noise components.

V. SIMULATION RESULTS

In this section, the proposed scheme is compared to the conventional scheme in terms of the detection probability in the Rayleigh multipath channel environment. We consider DVB-T systems with 2K mode and 4-QAM data modulation. The simulation parameters used in the simulation are as follows: the guard interval size of 128, $D = 1$ or 2, $N = 2048$, $\Delta = 1$, and $\alpha = N$. Also, the number of the multipath is set to be 10 with path delays of 0, 10, $\cdots$, 90 samples. The amplitude of each path varies independently from the others according to the Rayleigh distribution with an exponential power delay profile and the power ratio of the first fading tap to the last fading tap is set to be 20 dB. The phase of each path is uniformly distributed in $(-\pi, \pi]$ and the Doppler frequency is set to be 100 Hz.

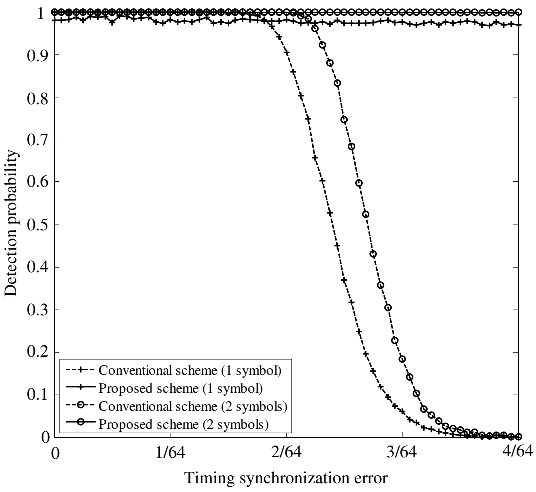

Fig. 2. Detection probabilities of the conventional and the proposed schemes when the SNR is 5 dB.

Fig. 2 shows the detection probabilities of the conventional and proposed schemes as the function of the timing synchronization error. The signal to noise ratio (SNR) ρ is defined as $\rho \triangleq \sigma_x^2/\sigma_w^2$ with $\sigma_x^2 = \mathbf{E}\{|x_l(n+\tau)|^2\}$, which is set to be 5 dB and the timing synchronization error is normalized to the length of one OFDM symbol. From the figure, we

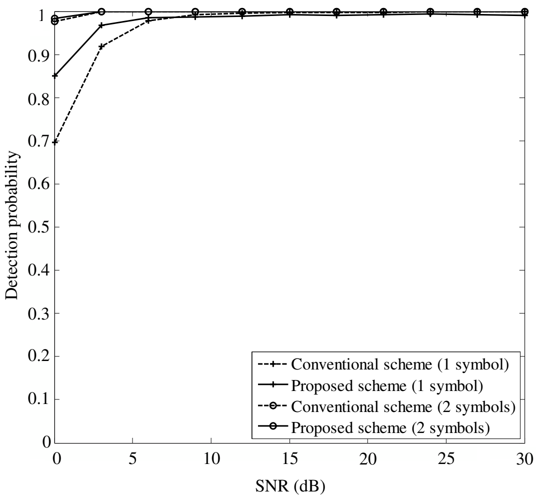

Fig. 3. Detection probabilities of the conventional and the proposed schemes when the timing synchronization error is 60 samples.

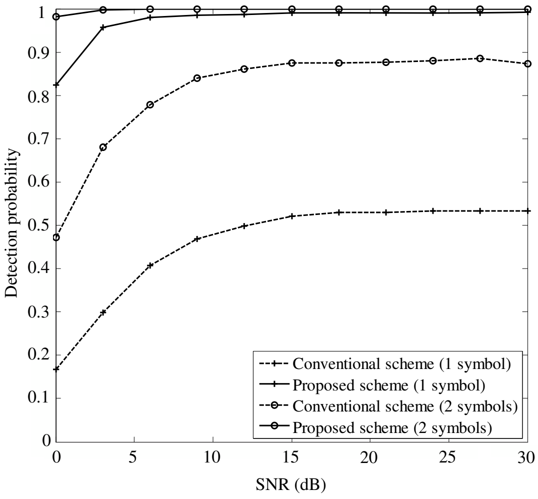

Fig. 4. Detection probabilities of the conventional and the proposed schemes when the timing synchronization error is 80 samples.

can see that the detection probability of the conventional scheme degrades as the timing synchronization increases, whereas the proposed scheme searches for the spectrum of PU robustness to the timing synchronization error. Fig. 3 and Fig. 4 compare the detection probabilities of the conventional and the proposed schemes with the fixed timing synchronization error of 60 and 80 in terms of the SNR, respectively. When they are normalized to the length of one OFDM symbol, the timing timing synchronization errors are $15/512$ and $5/128$, respectively. From Fig. 3 and Fig. 4, we can also confirm that the proposed scheme outperforms the conventional scheme in terms of the detection probability regardless of the value of timing synchronization error.

VI. CONCLUSION

In this paper, we have proposed a novel spectrum sensing scheme based on the periodicity of the pilot signals in the OFDM symbol of the DVB-T systems. The proposed scheme is robust to the timing synchronization error by partitioning the correlation values between the CPs and SPs nearest to the CPs into several groups based on the sample distances, and then, combining the correlation values in the same group eliminating the effect of the timing synchronization error. From the simulation results, it has been shown that the detection probability of the proposed scheme does not degrade when there exists a timing synchronization error, whereas the conventional scheme fails to sense the spectrum of PU.

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