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Fractional Bandwidth Mode Detection and Synchronization for OFDM-Based Cognitive Radio Systems

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Abstract—For the CR systems sharing the spectrum with narrowband primary devices, this paper presents an OFDM system supporting the fractional bandwidth (FBW) mode to avoid the interference to or from the primary devices. For the system, the preamble and FBW mode detection algorithm are provided to obtain the FBW mode information during the initial synchronization. The simulation results reveal that the FBW mode information can be obtained at the SNR region lower than $E_s/N_0 = 0$ dB. In addition, the FBW mode transmission and detection do not incur any deterioration of the synchronization performance.

I. INTRODUCTION

Cognitive radio (CR) has drawn much interest to utilize the radio spectrum efficiently as well as to enable the reliable communication whenever and wherever needed [1][2]. It utilizes the unused spectrum in an intelligent way while not interfering with other incumbent devices in the frequency bands already licensed. The ideas take shape after the Federal Communications Commission (FCC) in the US decided to adopt the open spectrum policy and to allow unlicensed radios to operate in the TV channels. Complying with the open spectrum policy, IEEE 802.22 working group has been chartered to develop the standard of wireless regional area networks (WRAN) providing broadband packet data in the TV channels [3]. With this starting point, future wireless communications systems are expected to add on cognitive functions to cope with the scarcity of the spectrum favorable to wireless transmissions.

On the other hand, orthogonal frequency division multiplexing (OFDM) has been applied to various wireless applications due to its flexibility in resource allocation and scalability with bandwidth. The WRAN standard also adopts OFDM as its radio access platform to utilize the advantages of OFDM and to provide the compatibility to the recent or future wireless communication systems. On top of the platform, various methods of observation, decision, and action for CR are currently being proposed and implemented [4]. As one method of cognitive action, the authors have proposed the fractional bandwidth (FBW) mode to avoid the interference to or from narrowband incumbent users [5]. The FBW mode divides the system bandwidth into multiple subbands and changes active subbands transmitting data according to the spectrum sensing result. To support the FBW mode, a unique set of active subbands temporally employed should be identified at the receiver during the initial set up and every sensing period to demodulate the following data packet.

In this paper, we provide an FBW mode detection method in the initial time and carrier frequency offset (CFO) synchronization. The preamble structure is half repetition in the time domain as in [6][7] with modification in the frequency domain to support the FBW mode: a different pseudo-noise (PN) sequence of different length is generated according to the set of active subbands and is transmitted on the active subbands. The receiver identifies the FBW mode jointly with the integral part of the normalized CFO (IFO) by differentially detecting the transmitted sequence in the frequency domain. In essence, the proposed method combines the IFO detection of [7] and cell identification of [8] in a generalized environment with variable bandwidth.

The detailed system model and the synchronization algorithm with FBW mode detection will be provided
in Sections II and III, respectively. Then the synchronization performance will be given using WRAN system parameters in Section IV. Finally, concluding remarks will be followed in Section V.

II. SYSTEM MODEL

A. Fractional Bandwidth (FBW) Mode

The proposed CR system with FBW mode shares the spectrum with narrowband primary devices where the system bandwidth is larger than that of primary devices. The primary devices can operate on pre-assigned bands or appear dynamically at any location of the bands where the CR system is operating. To avoid the interference to or from the primary devices, the proposed system can deactivate some of the subcarriers by transmitting zeros on that portion according to the spectrum sensing result as in Fig. 1. In addition, the proposed system can activate the deactivated subcarriers again to increase the data rate when the sensing result indicates the spectrum vacancy.

For practical implementation, we divide total of $N_u$ used subcarriers in the system band into total $B_t$ contiguous subbands, each with $N_{0_f} = N_u/B_t$ subcarriers. The subband used for transmitting data is called active subband and the total number of active subbands $B_a$ can vary from 1 to $B_t$. We assume that only contiguous subbands are allowed for active subbands to reduce the power leakage in the unused subbands. Thus, there are total $V = B_t(B_t + 1)/2$ FBW modes with $B_a = 1, 2, \ldots, B_t$ contiguous active subbands from the starting subband $B_s = 0, 1, \ldots, B_t - B_a$.

B. Transceiver Model

The block diagram of the proposed CR system is shown in Fig. 2. According to the spectrum sensing result, the transmitter decides the temporal FBW mode $i$. The preamble sequence for the FBW mode is generated and transmitted at the starting point of a frame or packet followed by OFDM symbols containing data. In the subband mapping, the modulated preamble sequence and data symbols are mapped to only the subcarriers of the active subbands of the FBW mode and null (zero) symbols are mapped to the remaining subcarriers by transmitting zeros on that portion of the bands where the CR system is operating. To avoid the interference to or from the primary devices, the proposed system can deactivate some of the subcarriers again to increase the data rate when the sensing result indicates the spectrum vacancy.

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irrespective of the FBW mode. of the

is coarsely estimated as

\[ P_{i,k} = \begin{cases} \sqrt{2G_i}(1 - 2D_{i,o(k)}), & \text{for } k \in S_i, \\ 0, & \text{otherwise}. \end{cases} \] (3)

where \( D_{i,t} \) is the PN sequence for the \( i \)th FBW mode, \( S_i \) is the set of odd subcarriers in the active subbands of the \( i \)th FBW mode, \( o(k) \) is the ascending order of \( k \) among the elements of \( S_i \), and \( G_i = \frac{R_i}{\sqrt{2}} \) is the power boosting factor to make the transmit power equal irrespective of the FBW mode.

III. SYNCHRONIZATION PROCEDURE

With the preamble designed, the proposed system performs synchronization in the order of coarse timing and FFO estimation, joint FBW mode and IFO detection, and fine timing estimation.

A. Coarse Timing and FFO Estimation

Half repetition of the preamble allows us to adopt the autocorrelation method [6] for coarse timing and FFO estimation. The starting point of the preamble \( n_o \) is coarsely estimated as

\[ n_c = \arg \max_{d} \sum_{w=-W/2}^{W/2} TM(d+w). \] (4)

In (4), \( TM(d) \) is the timing metric used in [6] as

\[ TM(d) = \frac{|P(d)|^2}{R(d)^2}, \] (5)

where

\[ P(d) = -\sum_{n=d}^{d+N-1} y_n^* y_{n+d}, \quad R(d) = \sum_{n=d}^{d+N-1} |y_n|^2. \] (6)

By accumulating \( TM(d) \) in the window of length \( (W+1) \), we can obtain the coarse timing in the CP of a preamble more reliably than the case using \( TM(d) \).

After coarse timing is obtained, the normalized CFO can be estimated with

\[ \hat{\epsilon} = \frac{1}{\pi} \angle -P(n_c) \] (7)

using the fact

\[ P(n_c) \simeq -\sum_{n=n_c}^{n_c+N-1} |y_n|^2 e^{j\pi \epsilon}. \] (8)

With (7), only the FFO \( \epsilon_F \) is estimated since the phase is measurable only on \((-\pi, \pi]\). In case of nonzero IFO, the receiver should provide IFO estimation method to extend the estimation range.

B. Joint FBW Mode and IFO Detection

After FFO compensation, the FBW mode and the IFO can be estimated in the frequency domain using the PN sequences assigned for the FBW modes. Assuming the perfect FFO compensation, the FFT output after null carrier removal is given by

\[ Y_k = \sqrt{2E_s} H_k P_{i,k+2\epsilon} I_{i,k+2\epsilon} e^{j2\pi \delta_t k/N} + W_k, \] (9)

where \( E_s \) is the average received symbol energy, \( H_k = \sum_{l=0}^{\epsilon} B_t e^{-j2\pi l k/T} \) is the residual timing error, and \( W_k \) is the AWGN in the frequency domain with \( E\{|W_k|^2\} = N_0 \). In addition, the indicator \( I_{i,k} \) is one if \( k \in S_i \) and, otherwise, zero, defined for all odd subcarriers in the system band.

Since \( Y_k Y_k^* \) is in-phase with \( P_{i,k+2\epsilon} P_{i,k+2\epsilon}^* \) except for \( \frac{2\pi \delta_t}{N} \) phase shift, the following differential correlation

\[ F_j(g) = \sum_{k \in S_j^-} Y_{k+2g} Y_{k+2g+2} P_{j,k+2+2\epsilon}^* P_{j,k+2} \] (10)

tends to have a large absolute value when the PN sequence and frequency shift match with the transmitted FBW mode and IFO incurred at the receiver. In (10), \( S_j^- \) is formed from a set \( S_j \) excluding the rightmost index. Here, we ignore some additional phase shift due to the difference between \( H_k \) and \( H_{k+2} \).

If the system experiences the IFO up to \( \pm \epsilon_{I,max} \), the FBW mode and IFO can be detected from candidate integers \( j \) and \( g \) such that

\[ (\hat{i}, \hat{\epsilon}_I) = \arg \max_{(j,g)} |F_j(g)|^2, \quad \text{for } 0 \leq j < V, \quad -\epsilon_{I,max} \leq g \leq \epsilon_{I,max}. \] (11)

Therefore, \( V(2\epsilon_{I,max} + 1) \) differential correlators are required at the receiver for joint FBW mode and IFO detection. As a special case, \( \epsilon_{I,max} = 0 \) denotes the case detecting only the FBW mode while \( V = 1 \) denotes the case estimating only the IFO.

C. Fine Timing Estimation

After FBW mode and IFO detection, the residual timing error \( \delta_t \) is estimated with the phase of the FBW mode and IFO detection metric as follows.

\[ \hat{\delta_t} = \frac{N}{4\pi} \angle F_j(\hat{\epsilon}_I). \] (12)
### TABLE I
THE SYSTEM PARAMETERS.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
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<tr>
<td>System bandwidth</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>48/7 MHz</td>
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<td>OFDM symbol duration ($T_s$)</td>
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<tr>
<td>Guard interval ($T_G$)</td>
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<td>FFT size</td>
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<tr>
<td>Number of used subcarriers ($N_u$)</td>
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<td>Total number of subbands ($B_t$)</td>
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<tr>
<td>Number of subcarriers per subband ($N_{bf}$)</td>
<td>280</td>
</tr>
<tr>
<td>Total number of VB modes ($V$)</td>
<td>21</td>
</tr>
</tbody>
</table>

**IV. PERFORMANCE EVALUATION**

The performance of the synchronization algorithm with the FBW mode detection is evaluated with typical WRAN system parameters summarized in Table I. There are $B_t = 6$ subbands in the 6 MHz TV channel with 280 subcarriers for each subband, supporting $V = 21$ FBW modes. The fading channel is generated using one of three multipath delay profiles A, B and C [9] and a fading instance is constant during one packet transmission but independent between the packets.

Figs. 3-4 show the error probability in FBW mode detection when there is no CFO with perfect timing. In Fig. 3, the detection error probability $Pr\{i \neq i\}$ is shown in the AWGN channel when the preamble for the FBW mode $i$ is transmitted. To show the effect of the number of active subbands, we select 6 FBW modes with different $B_a$ values. It is observed that the detection error probability is slightly lower with smaller $B_a$ since the metric $F_j(g)$ for correction detection contains less noise components for smaller $B_a$.

On the other hand, Fig. 4 shows the detection error probability in the various fading channels for two extreme cases as $B_a=1$ and 6. In the fading channels, the detection error probability is similar for two extreme cases since the performance is dominated by the fading rather than the AWGN. In addition, the detection error probability is the lowest in the fading B channel having the smallest rms delay spread among the three channel models. The performance becomes worsen as the rms delay spread increases since the performance loss occurs in differential correlation due to the channel variation on the adjacent subcarriers.

Figs. 5-6 show the synchronization performance of the proposed system with FBW mode in the fading A channel. The CFO is 8.62 kHz corresponding to the normalized CFO $e = 2.57$ with $\epsilon_f = 1$ and $\epsilon_t = 0.57$.

We set $W$ to 64 for coarse timing estimation and $\epsilon_{f,max}$ to 4 for the FBW mode and IFO detection.

The time synchronization performance is shown in Fig. 5, where the performance criterion is the normalized mean square error (MSE), $E\left\{\frac{\delta_t^2}{N} \right\}$. In the figure, two FBW modes with $B_a=1$ and 6, respectively, are compared with the constant bandwidth case without FBW mode detection (‘No FBW’). The figure shows that, without fine timing estimation denoted by ‘CT only’, timing errors are not reduced even in the high SNR region for all the cases. With fine timing estimation denoted by ‘CT & FT’, the MSE is significantly reduced as below $10^{-4}$ for $E_s/N_0$ larger than 15 dB. In addition, the performance of fine timing estimation is not affected by the FBW mode detection since the FBW mode detection with $10^{-4}$ error probability is obtained at the low SNR region as 0 dB in Fig. 4. It
is also observed that the performance is not affected by the number of active subbands since the detection error probability is similar irrespective of $B_a$.

The MSE performance of the CFO estimation is given in Fig. 6(a) for FFO and in Fig. 6(b) for the normalized CFO. Since the FFO is estimated in the time domain before the FBW mode and IFO detection, the existence of the FBW mode detection does not affect on the performance of FFO estimation if the number of active subbands is the same. In addition, the number of active subbands does not affect on the performance of FFO estimation since the time domain structure is similar. Although the normalized CFO including the IFO estimate would be affected by the performance of the FBW mode and IFO detection, Fig. 6(b) reveals that the MSE of the normalized CFO is similar with or without FBW mode. The performance is also almost the same for different number of active subbands due to the same reason as in the timing estimation case.

V. CONCLUSION

We have presented the OFDM-based CR system supporting the FBW mode, where the FBW mode information is obtained using the preamble during the synchronization procedure. The synchronization procedure in the paper includes the coarse timing and CFO estimation, FBW mode and IFO estimation, and fine timing estimation in the order. It is observed that the FBW mode transmission with different number of active subbands and the following FBW mode detection does not deteriorate the performance of time and frequency synchronization since the FBW mode detection is obtained at a low SNR region at a similar level irrespective of the FBW mode. Thus, the FBW mode can be successfully employed in the CR-based OFDM system from the viewpoint of synchronization.

ACKNOWLEDGEMENTS

This work was supported in part by the IT R&D program of MIC/IITA (2005-S-002-03) and by a Korea Research Foundation Grant KRF-2006-331-D00368 funded by the Korean Government (MOEHRD, Basic Research Promotion Fund).

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