Semi-blind Channel Monitoring Mechanisms for Post-switchover Wireless Microphones

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Abstract—In this paper, we discuss the use of spectrum sensing as a contingency for future wireless microphones (WM). We represent post-switchover operation conditions as a framework where WM sense for signals of digital television (DTV) and TV band devices (TVBD). Using this model, we propose two semi-blind channel monitoring mechanisms that ensure quality of service through fast and fine sensing. To implement such mechanisms, we analyze the pros and cons of five potential detection methods with respect to computational complexity, amount of prior information required for detection, classification ability, and performance under AWGN and frequency-selective fading. Our analysis suggests that methods based on the cyclic prefix (CP) are promising for fast sensing as long as portable TVBD can be detected. With respect to fine sensing, we suggest methods that exploit scattered pilots to improve classification ability and robustness against noise uncertainty, CP length variations, and multipath. The proposed mechanisms incur no performance loss in comparison to fast sensing methods in isolation.

I. INTRODUCTION

So far, wireless microphones (WM) have been allowed to operate in the TV bands with lower priority than broadcast TV. The transition from analog to digital TV (DTV) has been viewed with some worry by the WM industry in the U.S., where the Federal Communications Commission (FCC) will allow unlicensed operation of TV band devices (TVBD) in the spectrum freed up by the digital switchover. Major concerns are how to mitigate harmful interference from TVBD to DTV and WM and ensure that WM will still be able to find idle frequencies where they can operate.

In a recent Memorandum Opinion and Order, the FCC has determined that TVBD can rely only on geo-location/database access (GDA) to determine channel availability in the TV bands [1]. GDA denotes a method to obtain from a database a list of permitted channels, before operating and without sensing for incumbent signals [2]. GDA offers lower potential interference and better use of whitespaces than sensing [3], but raises other concerns, e.g., registration in advance for itinerant services, frequency of database checks/re-checks for portable TVBD, loss of connectivity between the TVBD and the database, database outage periods, etc.

Advance registration in the database may be difficult for itinerant WM services that are not at fixed locations and operate in intermittent, occasional, or one-time basis. To protect such use cases, the FCC will reserve two safe harbor channels where TVBD are not allowed to operate. However, in case the number of WM transmitters operating simultaneously is too large to be accommodated in the safe harbor channels, WM will likely have to compete with TVBD for unused frequencies.

The current trend to improve immunity to interference in future WM systems is to use cognitive radio (CR) [4] to enhance the sensing capabilities of current WM systems [5][6]. Not required for TVBD anymore [1], CR-based sensing remains a practical contingency for WM whenever protection cannot be ensured by GDA, safe harbor channels, or other means.

In this paper, we propose a framework that considers more challenging operation conditions that WM will likely have to cope with in the post-switchover era. We represent these conditions by using a multistandard operation scenario where WM share a geographical area with DTV [7] and future TVBD systems [8][9]. Unlike in the usual overlay-based hierarchical access model [10], where TVBD are secondary users that should detect and avoid incumbents, our model is concerned about sensing carried out by WM, rather than for WM. Within this framework, we propose two channel monitoring mechanisms that perform fast and fine sensing to ensure quality of service. To implement such mechanisms, we analyze the pros and cons of five potential detection methods with respect to computational complexity, amount of prior information required for detection, classification ability, and performance under additive white Gaussian noise (AWGN) and frequency-selective fading. Our analysis suggests that methods based on the cyclic prefix (CP) can be used for fast sensing as long as portable TVBD can be detected. For fine sensing, we suggest methods that exploit scattered pilots (SP) and have complementary features to fast sensing methods. In most cases, the proposed mechanisms incur no performance loss in comparison to fast sensing methods in isolation.

The rest of the paper is organized as follows. In Section II, we survey potential detection methods that we can use to implement our sensing mechanisms. Section III describes the proposed sensing framework and channel monitoring mechanisms. Simulation results are given in Section IV, while Section V presents our concluding remarks.

II. RELATED WORK

In current WM systems, most scanning receivers (SCR) rely on energy detection (ED). ED is simple, of low complexity, and does not require any knowledge about the structure of the signal to be sensed. Detection is made based on the energy of the received signal \( r(n) \) measured over \( M \) samples:
\[ Z_{ED} = \frac{1}{M} \sum_{n=0}^{M-1} |r(n)|^2 . \] (1)

ED is optimum when only the noise power \( \sigma_n^2 \) is known a priori [11]. As the received noise level may change over time, accurate estimation of \( \sigma_n^2 \) is difficult in some cases and ED becomes highly susceptible to noise uncertainty [12].

To support CR uses for WM, we are interested in methods able to detect all possible types of signals to be considered in Section III. To determine these methods, we first identify common features of such target signals, which we suppose are orthogonal frequency division multiplexing (OFDM) signals based on DTV [7] or TVBD [8][9] standards. If we impose minimum changes in traditional ED-based SCR, potential methods should be of low complexity, robust against noise uncertainty, and require little or no prior knowledge of target signals.

In [13], the trade-off between detection performance and the amount of prior knowledge required for detection was assessed for ED and five state-of-the-art OFDM detectors. Among the detectors investigated therein, autocorrelation-based detection (ACD) has performance similar to others’ but needs to know only the number of data samples per symbol \( T_D = T_{SYM}/T_S \). The test statistic used is:
\[ Z_{ACD} = \frac{1 - T_D}{M} \sum_{n=0}^{M-T_D-1} \Re(r(n)) \frac{1 - T}{M} \sum_{n=0}^{M-1} |r(n)|^2 . \] (2)

ACD evaluates the autocorrelation function (ACF) of \( r(n) \) using just one of the side peaks induced by CP. Outcomes obtained are then normalized using the energy of \( r(n) \).

Complexity in real-time implementation was investigated in [14]. Among the four CP-based methods discussed therein, blind twin peak detection (BTPD) offers the best compromise between performance and complexity, while being robust against noise uncertainty. The test statistic used is:
\[ Z_{BTPD} = \sum_{\tau} \frac{1}{M} \sum_{n=0}^{M-1} r(n)r^∗(n-\tau) , \] (3)

where \( \tau \) are time lags normalised by a sampling period \( T_S \). After having computed (3), the BTPD performs a peak search to detect the secondary peaks on both sides of the ACF, i.e., at \( \tau = ±T_FFT \). In case symmetry holds, the channel is declared occupied and the position of the positive peak is used to determine the subcarrier spacing \( 1/T_FFT \). The double \( \tau \) values required in this process makes BTPD twice as complex as ED and ACD. BTPD can distinguish between two OFDM signals that have different subcarrier spacings, but its performance is dependent on the number of subcarriers and the CP length of the target signal [15]. This dependence was also pointed out in [16] for CP-based methods in general.

TVBD use preambles for synchronization, channel estimation, frequency offset estimation, and received power estimation [8][9]. Detection based on preambles has the advantage of allowing different levels of sensitivity depending on whether the entire preamble is detected or just its training sequences [17]. DTV does not use preambles and both synchronization and channel estimation are obtained using scattered pilots (SP) modulated at boosted power level [7]. In [13], a method based on the inverse fast Fourier transform of SP is shown to outperform ED and other four state-of-the-art OFDM detectors under AWGN. However, the SP method analyzed in [13] has poor performance under multipath conditions.

This drawback can be overcome by exploiting the property that the mean of the time-domain symbol cross-correlation (TDSC) of two OFDM symbols is nonzero as long as they have the same frequency-domain SP [16][18]. The TDSC function of two OFDM symbols is given by:
\[ R(l,m) = \frac{1}{M} \sum_{n=0}^{M-1} x_1(n)x^*_m(n) , \] (4)

where indexes \( l \) and \( m \) indicate symbols having the same SP pattern. If \( v = l - m \) denotes the symbol index difference and \( S_v \) the number of correlated symbol pairs having the same SP pattern, we can define the accumulated TDSC function as:
\[ C(v) = \frac{1}{S_v} \sum_{m=0}^{M-1} R(l,m) . \] (5)

Two TDSC approaches are described in [16]. The first one, based on the Neyman-Pearson test, is referred to as TDSC-NP. The test statistic used is:
\[ Z_{TDSC-NP} = |C(v)| , \] (6)

where \( v \) is kept fixed. The second approach aims at improving performance by combining the various \( C(v) \) that arise when different \( v \) are exploited. To this end, let the conjugate product of two accumulated TDSC functions be:
\[ Q(v,v+d) = C(v)C^∗(v+d) . \] (7)

Denoted as maximum ratio combining, the TDSC-MRC approach uses the test statistic:
\[ Z_{TDSC-MRC} = \sum_v S_v S_{v+d} Q(v,v+d) . \] (8)

Besides being similar under both AWGN and multipath, the performance of the TDSC approaches above is approximately the same for different CP lengths. According to [16], TDSC-MRC outperforms TDSC-NP at the cost of increased complexity. Similar results were obtained in [18], where noise uncertainty and frequency offsets were additionally considered. Under such practical conditions, both approaches are virtually immune to carrier frequency offsets but TDSC-NP is more robust against sampling frequency offsets.

Table I summarizes the requirements of ED, ACD, BTPD, TVBD, and the state of the art of TDSC-MRC in terms of computational complexity given by the number of real multiplications (RM) and real additions (RA). The two remaining columns indicate the prior knowledge (PK) required for detection and whether the method possesses classification ability (CA), respectively.
In terms of sensing duration, ED, ACD, and BTPD are fast methods because they need just one OFDM symbol for detection. However, depending on the degree of sensing accuracy (to be dictated by the WM application), it may be interesting to consider methods that offer better performance even at the cost of longer sensing duration, e.g., TDSC approaches.

III. SYSTEM MODEL

A. Interferer System

Consider the operation scenario depicted in Figure 1 where the following OFDM systems operate co-located: DTV [7], fixed TVBD [8], and portable TVBD [9]. The location of the DTV transmitter is fixed and stored in the database. TVBD are capable of GDA and employ self-coexistence methods to negotiate access to spectrum currently unused by DTV. This allows the exploitation of whitespaces in an organized fashion, e.g., by interleaving signals from different TVBD systems.

We can express a generic target signal as an OFDM signal:

\[ \tilde{s}(t) = \sum_{k=0}^{N-1} \sum_{l=-\infty}^{\infty} c_{k,l} g(t - lT_{SYM}) e^{j \frac{2\pi}{T_{FFT}} k(t-lT_{SYM})}, \]

where \( k \) is the subcarrier index, \( l \) is the symbol index, \( c_{k,l} \) is the complex constellation transmitted by the \( k \)th subcarrier during the \( l \)th symbol, \( g(t) \) is the pulse shaping filter, \( 1/T_{FFT} \) is the subcarrier spacing, and \( lT_{SYM} \leq t \leq (l+1)T_{SYM} \).

The discrete time OFDM signal is obtained by using a sampling period \( T_s \), i.e., \( s(n) = \tilde{s}(nT_s) \). We assume the CP is appended to each transmitted symbol, so the symbol duration is \( T_{SYM} = T_{CP} + T_{FFT} \).

As shown in Tables II and III, DTV uses symbol durations up to 1.49ms (8K mode, CP=1/4) whereas portable TVBD convey information using shorter symbols around 20\( \mu \)s long. Despite being OFDM-based, the target signals considered in this paper impose different requirements on the SCR depending on the type of interferer and the FFT mode and CP length selected within an interferer system. In Section IV, we show that results of analyses based solely on DTV (as in the related work) may be misleading if directly applied to sensing WM, i.e., TVBD should also be considered in the design of sensing mechanisms for WM.

B. WM System

Consider a WM system composed of several WM transmitters controlled by a single SCR, assumed to be the only device able to perform sensing tasks. We assume further that the SCR is kept fixed while sensing is performed. As usual, the WM system is a lower priority incumbent and the SCR should select operating frequencies so as to avoid channels in use by higher priority DTV stations.

Suppose now that this WM system starts to operate in the same geographical area described in Figure 1, but it is not registered in the database. If the number of WM transmitters operating simultaneously is too large to be accommodated in the safe harbor channels, they will likely receive interference from TVBD. Hence, the SCR should be able to detect and avoid all channels it may encounter occupied by DTV or TVBD.

The sensing problem to be solved at the SCR translates into the estimation of a specific parameter of the target signal \( r(n) \) using test statistic \( Z \). By comparing \( Z \) to a threshold, the SCR decides on the channel availability using the hypothesis test:

\[ \begin{align*}
    &H_0 : r(n) = w(n), \\
    &H_1 : r(n) = \sum_{m=0}^{L-1} h(m)s(n-m) + w(n),
\end{align*} \]

where \( h(n) \) is the channel impulse response and \( L \) is the channel order. The target signal contains only noise under the null hypothesis and noise plus OFDM signals under the alternative hypothesis.

### TABLE I

**SUMMARY OF DETECTION METHODS SURVEYED IN SECTION II**

<table>
<thead>
<tr>
<th>Method</th>
<th>RM</th>
<th>RA</th>
<th>PK</th>
<th>CA</th>
</tr>
</thead>
<tbody>
<tr>
<td>ED</td>
<td>4N</td>
<td>2(2N - 1)</td>
<td>( \sigma^2 )</td>
<td>No</td>
</tr>
<tr>
<td>ACD</td>
<td>4N</td>
<td>2(2N - 1)</td>
<td>( T_d )</td>
<td>No</td>
</tr>
<tr>
<td>BTPD</td>
<td>8N</td>
<td>2(2N - 1)</td>
<td>None</td>
<td>Yes</td>
</tr>
<tr>
<td>TDSC-NP</td>
<td>4VT_d</td>
<td>(V - 1)x(TD_a + 1)</td>
<td>( \psi )</td>
<td>Yes</td>
</tr>
<tr>
<td>TDSC-MRC</td>
<td>4(( V/V_0 ))^2 + V/V_0 T_d</td>
<td>(( V/V_0 )^2 + V/V_0)x(TD_a + 1)</td>
<td>( \psi )</td>
<td>( \psi )</td>
</tr>
</tbody>
</table>

### TABLE II

**DTV [7] - OFDM PARAMETERS FOR 6MHz CHANNELS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2K Mode</th>
<th>4K Mode</th>
<th>8K Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{FFT} (\mu s) )</td>
<td>298.67</td>
<td>397.33</td>
<td>1194.67</td>
</tr>
<tr>
<td>( CP )</td>
<td>1/32 to 1/4</td>
<td>1/32 to 1/4</td>
<td>1/32 to 1/4</td>
</tr>
<tr>
<td>( T_{CP} (\mu s) )</td>
<td>9.33 to 14.67</td>
<td>18.67 to 149.34</td>
<td>37.33 to 298.67</td>
</tr>
<tr>
<td>( T_{SYM} (ms) )</td>
<td>0.31 to 0.37</td>
<td>0.62 to 0.75</td>
<td>1.23 to 1.49</td>
</tr>
<tr>
<td>( N )</td>
<td>2048</td>
<td>4096</td>
<td>8192</td>
</tr>
</tbody>
</table>

### TABLE III

**TVBD - OFDM PARAMETERS FOR 6MHz CHANNELS**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{FFT} (\mu s) )</td>
<td>298.67</td>
<td>18.67</td>
</tr>
<tr>
<td>( CP )</td>
<td>1/32 to 1/4</td>
<td>1/32 to 1/8</td>
</tr>
<tr>
<td>( T_{CP} (\mu s) )</td>
<td>9.33 to 14.67</td>
<td>5.85 to 2.33</td>
</tr>
<tr>
<td>( T_{SYM} (ms) )</td>
<td>0.31 to 0.37</td>
<td>0.019 to 0.021</td>
</tr>
<tr>
<td>( N )</td>
<td>2048</td>
<td>128</td>
</tr>
</tbody>
</table>
Due to the static behavior of DTV and, consequently, of fixed TVBD, the SCR will likely not need to sense often. So, it is possible to perform channel monitoring using more complex detection methods or even multi-stage detectors relying on more than one method. With this in mind, we now propose two channel monitoring mechanisms that suit the framework so far developed in this section.

C. Proposed Channel Monitoring Mechanisms

In the discussion that follows, we assume that the SCR has a dedicated antenna for sensing and carries out the channel monitoring mechanisms depicted in Figure 2 in an alternated fashion. The first mechanism considers out-of-band channel monitoring as shown in Figure 2(a). If the number of channels to sense is limited, the SCR can use fast sensing to scan all channels in acceptable time. These preliminary results serve to populate a list of reserve channels based on radio environment maps (REM) [19]. After all the channels have been scanned and the REM entries initialized, fine sensing is performed on the last channel declared idle through fast sensing. The SCR declares a channel as suitable for WM transmissions only if it has been declared idle also through fine sensing. Since WM transmitters are powered off during out-of-band channel monitoring, methods used in both fast and fine sensing do not need to be capable of classifying target signals.

Upon having selected a channel for use, the SCR initiates in-band channel monitoring using the second mechanism shown in Figure 2(b). In this case, sensing tasks should be performed while WM transmitters are powered on. This calls for methods with classification ability because WM systems have 100% duty cycle and quiet periods cannot be enforced. If the channel is declared occupied through fast sensing, the SCR can rely on link quality parameters, e.g., bit error rate and received signal strength indication [6], to determine the existence of a urgent coexistence situation. Comparing these parameters to the thresholds stated in the service level agreement required by the application, the SCR decides about triggering fine sensing or handling transmissions to a new channel. Assuming that out-of-band channel monitoring maintains the REM updated, a reserve channel can be retrieved on-the-fly in case of urgent coexistence situation or detection of target signals during fine sensing. In either case, before handling transmissions, the SCR double-checks the status of the reserve channel using the fine sensing loop of Figure 2(a).

Summing up the proposed mechanisms, fast sensing is used to populate/update REM and ascertain that a channel currently in use remains free of target signals. Coarse findings acquired thereby are double-checked through fine sensing only if no urgent coexistence situation has been identified through link quality monitoring. Provided that urgent coexistence situations can be properly identified and fast sensing can keep misdetection and false alarm rates low, fine sensing will occur less frequently. Complexity and sensing time become less critical in this case and we can afford using fine sensing to improve classification ability and robustness against noise uncertainty, variations in the CP length, and multipath.

IV. Simulation Results

In this section, we use computer simulations to assess ED, ACD, BTPD, and TDSC methods individually, as well as combined in the proposed sensing mechanisms. We characterize sensing performance using the probability of detection ($P_d$) obtained for a fixed probability of false alarm ($P_f$) of 0.1. To allow fair comparisons, we set the sensing duration to three times the minimum required, i.e., three OFDM symbols for ED, ACD, and BTPD, and six times the pilot repetition unit for TDSC methods. For FFT 2K CP=1/4, this leads to sensing durations of about 1ms for ED, ACD, and BTPD, and 9ms for TDSC. The channel bandwidth is 6 MHz and the sampling period is $T_s = T_{FFT}/N$. All results are averaged over 1000 and 10000 runs for $N = 2K$ and $N = 128$, respectively.

Under AWGN, the individual performance of the methods analyzed is given in Figure 3. As expected, Figure 3(a) shows that ideal ED (known $\sigma_d^2$) is the best method. It can also be seen that the performances of ACD and BTPD vary with CP, while that of ED not. This confirms the results obtained for DTV 2K in [16] and [15], which can be immediately extended for fixed TVBD signals as they have exactly the same OFDM values (see Tables II and III). Due to smaller $N$ and CP lengths, the influence of $T_{CP}$ on $T_{SYM}$ is less significant and performance losses are milder in case of portable TVBD. Results for TDSC in Figure 3(b) partially match those in [16]. On the one hand, we confirm that $P_d$ is virtually the same for different CP lengths. On the other hand, we obtain a much lower $P_d$ even for $P_f$ ten times higher. The reason for this discrepancy lies on the arbitrarily long sensing duration of 50ms adopted in [16].

In the case that the SCR may not know $\sigma_w^2$ exactly, it can be seen from Figure 3(c) that $P_d$ fairly degrades for ED while it does not vary much for ACD and BTPD. Nevertheless, ED outperforms BTPD in most cases and BTPD becomes interesting only in the low SNR regime as in [14]. TDSC approaches (not depicted) are also robust against noise uncertainty and, for $P_d = 0.95$, give gains around 8dB (TDSC-NP) and 10dB (TDSC-MRC) over BTPD. If $T_{SYM}$ is long enough as in Figure 3(a), our results for ACD match well to [13]. However, as shown in Figure 3(c), the performance of ACD is poor when shorter OFDM symbols conveyed by portable TVBD signals are considered. In this case, it becomes difficult to protect WM systems using ACD regardless of the sensing duration.
We now extend the previous simulation setting to consider frequency-selective fading. We use the multipath profile “A”, described in [20] and reproduced in Table IV. As the SCR is fixed while sensing tasks are carried out and the values of Doppler frequency shifts are very low, we treat them as negligible. Results of our fading analysis are summarized in Figure 4. In comparison to the AWGN case, Figure 4(a) reveals big performance losses for ED (16dB) and BTPD (12dB) while less than 1dB is lost by using ACD if $P_d = 0.95$. This is comparable to the results shown for TDSC in Figure 4(b), which in turn confirm the robustness against multipath and variations in the CP length reported in [16]. When noise uncertainty comes into consideration, Figure 4(c) shows that the performance loss (in comparison to the AWGN case) of BTPD under fading conditions is constant and equal to 10dB while that of ED varies from 4dB to 10dB depending on the amount of noise uncertainty.

Our analysis suggests that ED is suitable for fast sensing as long as $\sigma_w^2$ can be estimated. During out-of-band channel monitoring, estimation is possible because WM transmitters are powered off and noise-only samples can be collected [21]. However, during in-band channel monitoring, WM transmitters are powered on and it is in general difficult to guarantee the availability of noise-only samples. In this case, BTPD becomes the most promising method for fast sensing. For fine sensing, the proposed mechanisms can rely either on TDSC-NP or TDSC-MRC. We use the former because it offers lower complexity at the cost of a small performance loss in comparison to the latter.

Figure 5 provides receiver operation characteristic (ROC) curves of the proposed mechanisms when fast and fine sensing are performed in cascade to detect portable TVBD (CP=1/32) without a priori knowledge of $\sigma_w^2$. Under AWGN, the proposed out-of-band sensing mechanism incurs some performance loss when compared to ideal ED. In practice, thanks to its immunity against noise uncertainty, TDSC-NP alleviates the impact of SNR walls and these losses decrease as the noise uncertainty increases. In all other cases, full classification ability (includes distinction between OFDM signals having the same subcarrier spacing) and improved robustness against noise uncertainty, variations in the CP length, and multipath can be achieved at the cost of no performance loss.

V. CONCLUDING REMARKS

This paper has discussed the use of spectrum sensing as a contingency for post-switchover WM. We have proposed
two semi-blind channel monitoring mechanisms that ensure quality of service through fast and fine sensing. To implement such mechanisms, we have analyzed the pros and cons of five potential detection methods with respect to computational complexity, amount of prior information required for detection, classification ability, and performance under AWGN and frequency-selective fading. Our analysis suggests that methods based on the cyclic prefix are promising for fast sensing as long as portable TVBD can be detected. Except for autocorrelation-based detection, the methods analyzed were proven able to accurately detect all target signals considered in the proposed operation scenario. For fine sensing, we suggest methods that exploit scattered pilots to improve classification ability and robustness against noise uncertainty, CP length variations, and multipath. In most cases, the proposed mechanisms incur no performance loss in comparison to fast sensing methods in isolation.

As future work, we intend to extend the analysis of the sensing solution discussed in this paper to consider analogue and digital non-OFDM signals. We will also conduct an analysis of practical synchronization issues such as carrier frequency offsets and sampling frequency offsets.

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