# Spectrum Sensing for DVB-T Signals Employing Pilot Tones

Ronghong Mo, Ser Wah Oh, Bo Wang
(rmo, swoh, bowang)@i2r.a-star.edu.sg, Institute for Infocomm Research, A*STAR, Singapore

***Abstract*—In this paper, a spectrum sensing algorithm to detect the presence of OFDM based system (DVB-T) with pilot signal insertion is presented. The proposed algorithm makes use of time domain auto-correlation of pilot signals, however is able to differentiate spurious modeled by single tone, unlike existing algorithms which detect spurious as signals rather than noise. Simulation results show that the proposed algorithm achieves performance equal to that of existing algorithms based on auto-correlation of pilot signals. Moreover simulation results show that the proposed algorithm achieves better performance in terms of false alarm rate (<0.01) than the existing algorithm (>0.8). This observation indicate that our proposed algorithm is more robust to spurious, without performance loss in probability of detection.**

***Index Terms*—DVB-T, Spectrum sensing, Spurious, Pilot, Auto correlation**

## I. Introduction

Recently, the regulatory bodies include the FCC in the US and the Ofcom in the UK, have approved the operation of unlicensed devices over licensed spectrum such as TV white space (TVWS), under the protection of incumbents' transmissions over the licensed spectrum [1] [2]. Moreover, the development of cognitive radio technology has also made possible the unlicensed exempt access over the licensed spectrum, where the radio transmission parameters including center frequency and bandwidth need to be adjusted based on the availability of radio spectrum [3].

In order to access the licensed bands, the unlicensed devices are required to determine the availability of the bands based on the detection of signals of incumbents over the interested bands. The challenge is that the unlicensed devices are required to reliably detect the presence of incumbents' signals at very low signal level, for example -114dBm, in order not to interfere the transmission of incumbents. To this end, robust spectrum sensing algorithms have been intensively investigated, such as energy based detection, match filter based detection, cyclostationarity based detection and eigen-value based detection [**?**].

Othogonal frequency division multiplexing (OFDM) technology which divides the available spectrum into a number of orthogonal subcarriers and transmits data over subcarriers in parallel, has been adopted by many applications, e.g. DVB-T and LTE [5] [6]. A few Spectrum sensing algorithms for OFDM based systems making use of either the spectrum feature or the frame structure of OFDM systems, including the auto-correlation of cyclic prefix, the auto-correlation of pilot signals and the cyclostationarity of OFDM signals have been studied in the literature [7] [8] [9]. Among them, the spectrum sensing algorithm utilizing the in-band pilot tone of OFDM system achieves best performance [8].

The above mentioned spectrum sensing algorithms are capable to predict the presence of OFDM signals when the noise does not exhibit periodic structure in time or frequency domain. However, when noise with periodic structure is present, for example, spurious which is almost a single tone signal, these sensing algorithms will fail to predict the presence of OFDM signals. As a result, in this paper, we propose a simple but practical spectrum sensing algorithm making use of pilot signals of OFDM systems, however able to differentiate OFDM signals with spurious signals. The rational behind the proposed spectrum sensing algorithm is that, for single tone spurious signals, the auto-correlations at any delay are roughly identical , while for OFDM systems with periodic pilot tone insertion, the non-zero auto-correlation only appears for certain delays.

The paper is organized as follows. The OFDM system model and the channel model are introduced in Section II. In the Section III, a new spectrum sensing algorithm is proposed and the false alarm rate and miss detection rate are analyzed theoretically. The performance of the proposed sensing algorithm is evaluated in Section IV followed by conclusions in Section V.

## II. System Model and Channel Model

Consider a typical DVB-T system with total $N$ subcarriers but with $N_u$ used subcarriers. To avoid intersymbol interference (ISI) and intercarrier interference (ICI), the last $N_g$ samples of the output of IFFT (cyclic prefix (CP)) are appended to the beginning to form an OFDM symbol of $M = N + N_g$ samples. There are two modes defined in DVB-T system, 2k mode and 8k mode where $N = 2048, 8096$ respectively. The length of CP can be $N_g = (1/4, 1/8.1/16, 1/32)N$. Although we adopt DVB-T as our system model, the spectrum sensing algorithm can be used for any OFDM based systems with periodic pilot tone insertion.

In order to aid channel estimation and synchronization, DVB-T systems insert pilot signals in predetermined subcarriers. There are two kinds of pilot signals in DVB-T systems: 1) Continual pilots: these pilot signals are inserted in every OFDM symbol. There are 45 continual pilots in the 2k mode and 177 continual pilot in 8k mode. 2) Scattered pilots: these pilots are inserted periodically in subcarriers, e.g. every $12^{th}$ subcarrier. The locations of pilot subcarriers are offset three

978-1-4673-1881-5/12/$31.00 ©2012 IEEE

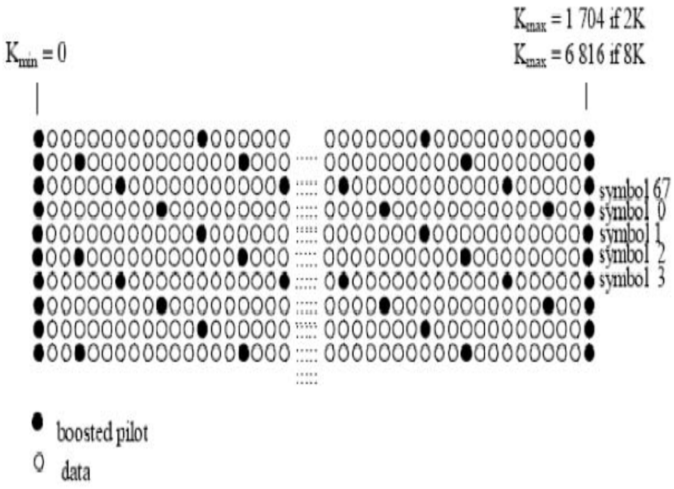


Fig. 1. Illustration of DVB-T pilot tones

subcarriers in consecutive OFDM symbols. The pilot patterns repeat every 4 OFDM symbols.

The continual pilots and scattered pilots of DVB-T systems are illustrated in Fig. 1.

With discrete time domain presentation, the $k^{th}$ sample of OFDM signals received at the receiver side is given as

$$r(k) = \sum_{L=0}^{L_m-1} h_L s(k-L-\delta) e^{j2\pi k\varepsilon/N} + n(k) \qquad (1)$$

where $h_L$ denotes the complex fading gain of the $L^{th}$ path of multipath channel, while $n(k)$ is the $k^{th}$ sample of additive white Gaussian noise (AWGN). Here we assume that the fading gains of different paths are independent and remain unchanged during a duration of a few OFDM symbols. $\delta$ is an integer denoting the delay of the first OFDM time domain sample at the receiver. $\varepsilon$ is the frequency offset normalized to the subcarrier spacing. $s(k)$ is the $k^{th}$ sample of one OFDM symbol transmitted and given as

$$\begin{aligned} s(k) &= \frac{1}{\sqrt{N}} \sum_{m\in M_p} X_p(m) e^{j2\pi \frac{km}{N}} + \\ &\quad \frac{1}{\sqrt{N}} \sum_{m\in M_d} X_d(m) e^{j2\pi \frac{km}{N}} \qquad (2) \end{aligned}$$

where $X_p(m), X_d(m)$ are the pilot signals transmitted over the $m^{th}$ subcarrier and the data signals transmitted over the $m^{th}$ subcarrier drawn from finite complex alphabet constellation respectively. $M_p, M_d$ are the sets of subcarriers carrying pilot signals and data signals, respectively. We assume that the data signals transmitted over different subcarriers are independent and identically distributed.

It is always true that the length of cyclic prefix is not shorter than the length of multipath channel. Substitute (2) into (1), the $k^{th}$ received sample can then be rewritten as

$$\begin{aligned} r(k) &= \frac{1}{\sqrt{N}} \sum_{m\in M_p} \sum_{L=0}^{L_m-1} h_L X_p(m) e^{j2\pi \frac{(k-L-\delta)m}{N}} e^{j2\pi k\varepsilon/N} \\ &+ \frac{1}{\sqrt{N}} \sum_{m\in M_d} \sum_{L=0}^{L_m-1} h_L X_d(m) e^{j2\pi \frac{(k-L-\delta)m}{N}} e^{j2\pi k\varepsilon/N} + n(k) \quad (3) \end{aligned}$$

The sample autocorrelation of received OFDM signals with any delay $d$ in samples is defined as

$$R(d) = \frac{1}{W} \sum_k r(k) r^*(k+d) \qquad (4)$$

where $W$ is the number of received samples being observed.

As observed from Fig. 1, a typical DVB-T system has pilot tones repeatedly transmitted over predefined OFDM symbols. This feature makes the autocorrelation of DVB-T systems at particular delays unique, compared to other OFDM based systems.

## III. Pilot Based Spectrum Sensing Algorithm

Let $u, v$ denote the two nearest OFDM symbols having identical pilot patterns and $d = (u-v)M$. Note that the pilot signals transmitted over these two symbols are identical thus $X_p^{(u)}(m) = X_p^{(v)}(m)$, while the data signals transmitted in these two OFDM symbols are randomly generated and generally $X_d^{(u)}(m) \neq X_d^{(v)}(m)$. Consider the autocorrelation between the $k^{th}$ received sample of the $u^{th}$ OFDM symbol $r^{(u)}(k)$ and the $(k+d)^{th}$ OFDM sample $r(k+d)$ which is equivalent to the $k^{th}$ received sample of the $v^{th}$ OFDM symbol $r^{(v)}(k)$. Based on (3), we have

$$\begin{aligned} & r^{(u)}(k) r^{*(v)}(k) = \sum_{m\in M_p} |H(m) X_p(m)|^2 e^{j2\pi d\epsilon/N} + \\ & \sum_{m\in M_d} |H(m)|^2 X_d^{(u)}(m) X_d^{(v)*}(m) e^{j2\pi d\epsilon/N} + \\ & \sum_{m=0}^{m=N-1} H(m) X^{(u)}(m) n^{(v)*}(k) e^{j2\pi \frac{(k-\delta)m}{N}} e^{j2\pi k\varepsilon/N} + \\ & \sum_{m=0}^{m=N-1} H^*(m) X^{(u)*}(m) n^{(v)}(k) e^{-j2\pi \frac{(k-\delta)m}{N}} e^{-j2\pi (k+d)\varepsilon/N} + \\ & n^{(u)}(k) n^{(v)*}(k) \qquad (5) \end{aligned}$$

where $H(m) = \sum_{L=0}^{L_m-1} h_L e^{-j2\pi mL/N}$ is the channel gain of the $m^{th}$ subcarrier. "$*$" denotes the conjugate and $X(m)$ denotes the transmitted pilot signals or data signals over the $m^{th}$ subcarrier

From (5), it is easy to see that, since $X_d^{(u)}(m), X_d^{(v)}(m), n^u(k)$ and $n^{(v)}(k)$ are independent of each other, the mean of the second term, the third term and the fourth term of (5) will be zero, while the first term of (5) is not zero when pilot signals are transmitted. This feature gives rise to a method to detect the presence of DVB-T signals.

Substitute (5) into (4), and denote

$$\nu = \frac{1}{W}\sum_{k=0}^{W-1}\Big\{\sum_{m\in M_d}|H(m)|^2 X_d^{(u)}(m)X_d^{(v)*}(m)e^{j2\pi d\epsilon/N}$$
$$+\sum_{m=0}^{m=N-1} H(m)X^{(u)}(m)n^{(v)*}(k)e^{j2\pi\frac{(k-\delta)m}{N}}e^{j2\pi k\varepsilon/N}+$$
$$\sum_{m=0}^{m=N-1} H^*(m)X^{(u)*}(m)n^{(v)}(k)e^{-j2\pi\frac{(k-\delta)m}{N}}e^{-j2\pi(k+d)\varepsilon/N}$$
$$+n^{(u)}(k)n^{(v)*}(k)\Big\} \tag{6}$$

The autocorrelation is given as

$$R(d) = \frac{1}{W}\sum_{k=0}^{W-1}\sum_{m\in M_p}|H(m)X_p(m)|^2 e^{j2\pi d\epsilon/N}+\nu \tag{7}$$

The existing spectrum sensing algorithms [7] [8] [9] focused on differentiating DVB-T signals from AWGN by employing Neyman-Pearson (NP) test [10]. Denote $H_0$ and $H_1$ as the event with noise only and the event with DVB-T signals, these two hypotheses can be given by

$$H_0 : R(D) = \nu \tag{8}$$

$$H_1 : R(D) = \frac{1}{W}\sum_{k=0}^{W-1}\sum_{m\in M_p}|H(m)X_p(m)|^2 e^{j2\pi d\epsilon/N}+\nu \tag{9}$$

where $\nu$ can be modeled as a circularly symmetric zero mean complex Gaussian random variable for sufficiently large $W$, by invoking Central Limit Theorem (CLT).

The decision statistics of this NP test is given by [8]

$$T_{NP} = |R(D)| \tag{10}$$

It is clear that, when DVB-T signals are present, the $T_{NP}$ will have non-zero value at delay $d, 2d, \cdots$ and so on, while without presence of DVB-T signals, $T_{NP}$ will approach zero at any delay.

This method makes use of the correlation of pilot signals and is able to differentiate the DVB-T signals with AWGN. However, when the noise are periodic in time domain, e.g. single tone spurious, this method will cause false alarm since the single tone noise will also generate non-zero autocorrelations at any delays, as shown in the following.

Normally, the time domain single tone spurious can be represented by,

$$x_s(t) = Ae^{j2\pi f_s t} \tag{11}$$

where $f_s$ is the frequency of the tone and $A$ is the amplitude of the single tone spurious.

The autocorrelation of single tone spurious with any delay $d_s$ is given as

$$R_s(d_s) = |A_f H(m_s)|^2 e^{-j2\pi f d_s}+\nu_s \tag{12}$$

where $H(m_s)$ is the frequency domain fading gain of the single tone spurious and $A_f = A/2$.

It can be seen from (12) that, for any delay $d_s$, the single tone spurious gives a autocorrelation with constant absolute value. When strong spurious is present, for example, the autocorrelation contributed by spurious can no longer be negligible. The existing algorithms will then falsely predict the presence of incumbents.

A close look at the autocorrelation of single tone spurious and the DVB-T signals reveals that, the amplitude of autocorrelation of single tone spurious remains constant regardless of delays, while for DVB-T systems, the non-zero autocorrelation appears only at fixed delays, for example, delays of 4 OFDM symbols, 8 OFDM symbols, 12 OFDM symbols and so on. Based on this observation, we propose a new algorithm to overcome this problem as following.

Since the pilot patterns of DVB-T systems repeat every 4 OFDM symbols, the autocorrelation have peaks at delays of $4, 8, 12, \cdots$ OFDM symbols. Generally we can combine the autocorrelations at these delays to achieve performance gain.

Denote $d = -4M$, with sufficient large $W$, we have $\nu \approx 0$. Based on (7), theoretically we have

$$R(2d) = R(d)e^{-j2\pi d\epsilon} \tag{13}$$
$$R(3d) = R(2d)e^{-j2\pi d\epsilon} \tag{14}$$
$$\vdots \tag{15}$$

and

$$|R(d)| = |R(2d)| = \cdots \tag{16}$$

We combine the autocorrelation at these delays as

$$\begin{aligned}R_{com}(d) &= \sum_{g=1}^{G} R(gd)R^*((g+1)d)\\ &= \sum_{g=1}\left|\frac{1}{W}\sum_{k=0}^{W-1}\sum_{m\in M_p}|H(m)X_p(m)|^2\right|^2 \times\\ &e^{j2\pi d\epsilon/N}+\nu_{com}\end{aligned} \tag{17}$$

where $G$ is the number of delays in 4 OFDM symbol.

The mean and variance of $R_{com}(d)$ are given by

$$\mu_d^D = \sum_{g=1}^{G}\left|\frac{1}{W}\sum_{k=0}^{W-1}\sum_{m\in M_p}|H(m)X_p(m)|^2\right|^2 e^{j2\pi d\epsilon/N} \tag{18}$$

$$\sigma_d^D = \frac{2\sigma_n^4}{W}\sum_{g=1}^{G}\left|\frac{1}{W}\sum_{k=0}^{W-1}\sum_{m\in M_p}|H(m)X_p(m)|^2\right|^2+\frac{\sigma_n^8}{W^2} \tag{19}$$

For autocorrelations of DVB-T signals at other delays, or $d \neq 4M$, due to the independent data symbols transmitted over subcarriers of different OFDM symbols, based on (5), theoretically

$$R_{com}(d) = \nu_{ncom} \tag{20}$$

where $\nu_{com}$ is a zero mean Gaussian random variable.

Consider the case that the received power of DVB-T signal is low, the mean of $\nu_{ncom}$ ($\mu_{comQ}^D$) is zero and the variance of $\nu_{ncom}$ will be given as

$$\sigma_{comQ}^D = \frac{\sigma_n^8}{W^2} \tag{21}$$

When DVB-T signals are not presented, the combined autocorrelation of AWGN at any delay can also be modeled by zero mean ($\mu_d^A = 0$) Gaussian random variable with variance $\sigma_d^A = \sigma_{comQ}^D$.

In contrast, for single tone spurious, at any delay including $d = -4M$, theoretically

$$R_{s,com}(d) = \sum_{g=1} |A_f H(m_s)|^4 e^{j2\pi d\epsilon} + \nu_{s,com} \tag{22}$$

The mean and variance of $R_{s,com}(d)$ are given by

$$\mu_d^S = \sum_{g=1} |A_f H(m_s)|^4 e^{j2\pi d\epsilon} \tag{23}$$

$$\sigma_d^S = \frac{2\sigma_n^4}{W} \sum_{g=1} |A_f H(m_s)|^4 + \frac{\sigma_n^8}{W^2} \tag{24}$$

Assume a set of combined autocorrelations $R_{com}(\delta_q), q = 1, \cdots, Q$ at various delays $\delta_q = d + q\Delta, \forall \delta_q \neq md$, where $\Delta, q, m$ are any positive integers and $Q$ is the number of delays satisfying the requirement.

The proposed statistic metric is then given by

$$T_{NP1} = \frac{\sum_q |R_{com}(\delta_q)|^2}{Q|R_{com}(d)|^2} \tag{25}$$

Note that, when there is only AWGN, $R_{com}(d) \approx 0$, $R_{com}(\delta_q) \approx 0$ thus $\lim(T_{NP1}) \approx \frac{1}{Q}$. When single tone spurious is present, $R_{com}(d) \approx R_{com}(\delta_q) \neq 0, \forall q$, we also have $T_{NP1} \approx \frac{1}{Q}$. $T_{NP1} \approx 0$ only when DVB-T signals are present, since $R_{com}(\delta_q) \approx 0$ while $|R_{com}(d)|^2 >> 0$.

## IV. Misdetection and False Alarm

Based on (17), if the number of terms to be added is sufficiently large, by CLT, both $R_{com}(d)$ and $R_{com}(\delta_q), \forall q$ can be modeled as Gaussian random variables.

When DVB-T signals are present, the pdf of $|R_{com}(d)|^2$ is given by non-central chi-square distribution with degree of 2 as

$$f_{com}^D(x) = \frac{1}{\sigma_d^D} e^{-\frac{1}{2}\left(\frac{2x}{\sigma_d^D} + \frac{|\mu_d^D|^2}{\sigma_d^D}\right)} I_0\left(\sqrt{2\frac{|\mu_d^D|^2}{(\sigma_d^D)^2} x}\right) \tag{26}$$

where $I_0()$ is the modified Bessel function of the first-kind and zero order.

When DVB-T signals are present, we model $R_{comQ} = \sum_q |R_{com}(\delta_q)|^2$ as Gaussian random variable with mean $Q\sigma_{comQ}^D + \frac{Q(\mu_{comQ}^D)^2}{2}$ and variance $Q(\sigma_{comQ}^D)^2 + Q(\mu_{comQ}^D)^2 \sigma_{comQ}^D$, the pdf of $R_{comQ}$ is then given by

$$f_{comQ}^D(x) = \frac{1}{\sqrt{2\pi Q((\sigma_{comQ}^D)^2 + (\mu_{comQ}^D)^2 \sigma_{comQ}^D)}} \times e^{-\frac{(x - Q\sigma_{comQ}^D - \frac{Q(\mu_{comQ}^D)^2}{2})^2}{2Q((\sigma_{comQ}^D)^2 + (\mu_{comQ}^D)^2 \sigma_{comQ}^D)}} \tag{27}$$

with $\mu_{comQ}^D = 0$.

Given (26) and (27), the pdf of $T_{NP1}$ is given as

$$f_{NP1}^D(z) = \int_0^\infty Qy f_{com}^D(y) f_{comQ}^D(Qyz) dy \tag{28}$$

The miss detection probability is easily given by

$$P_m = \int_\gamma^\infty f_{NP1}^D(z) dz \tag{29}$$

where $\gamma$ is a predefined threshold determined by the required false alarm rate.

There are two situations causing false alarm, when AWGN is present and $|T_{NP1}| > \gamma$ and when spurious is present and $|T_{NP1}| > \gamma$. Assume the required false alarm rate is $P_{fa} = P_{nfa} + P_{sfa}$ with $P_{nfa}, P_{sfa}$ being the false alarm rate for the situation of AWGN and the situation of spurious respectively.

When there is only AWGN, the mean of $R_{comQ}$ ($\mu_{comQ}^A$) is zero and the variance of $R_{comQ}$ $\sigma_{comQ}^A = \sigma_d^A$, the pdfs of $R_{com}(d)$ and $R_{comQ}$, $f_{com}^A, f_{comQ}^A$ are still given by (26) and (27) but with $\mu_d^A = 0, \mu_{comQ}^A = 0$. Likewise, the pdf of $T_{NP1}$, $f_{NP1}^A(x)$, for the AWGN situation is also given by (28).

Given the required false alarm rate caused by AWGN, the required threshold $\gamma^A$ for AWGN only situation is obtained by solving

$$\gamma^A : \int_0^{\gamma^A} f_{NP1}^A(x) dx \leq P_{nfa} \tag{30}$$

Similarly, following the same approach, and notice that, for spurious signals, $\mu_d^S = \mu_{comQ}^S, \sigma_d^S = \sigma_{comQ}^S$, the pdf of $T_{NP1}$ for spurious signal, $f_{NP1}^S$ can be obtained. The required threshold $\gamma^S$ for this situation is obtained by solving

$$\gamma^S : \int_0^{\gamma^S} f_{NP1}^S(x) dx \leq P_{sfa} \tag{31}$$

The $\gamma^A, \gamma^S$ obtained above are not identical in most of the cases. After obtaining $\gamma^A, \gamma^S$, the required threshold to ensure the false alarm rate $P_{fa}$ will be given as $\gamma = \max(\gamma^A, \gamma^S)$. In practical, given $P_{fa}$, we can select $P_{nfa}, P_{sfa}$ so that $\gamma^A, \gamma^S$ are roughly identical. Note that, although a higher $\gamma$ gives a smaller false alarm rate, it will result in higher miss detection probability, as seen from (29).

## V. Simulation Results

To evaluate the performance of the proposed spectrum sensing algorithm for DVB-T systems, in this section, the probability of detection is investigated by simulations. The DVB-T signals are captured from DVB-T broadcasting by spectrum analyzer for 8k mode. Rayleigh multipath fading channel with order of nine is randomly generated. The captured DVB-T signals are propagated through multipath channel and corrupted by AWGN. The spurious is modeled by a single tone signal. The performance of the proposed algorithm is evaluated by Monte Carlo runs. The sensing period is 20ms.

The probabilities of detection for DVB-T signals and spurious given various false alarm rate 0.0001, 0.01 and 0.1 caused by AWGN are shown in Fig. 2, Fig. 3 and Fig. 4, respectively. It can be seen that the probability of detection increases with the false alarm rate. The required SNR to

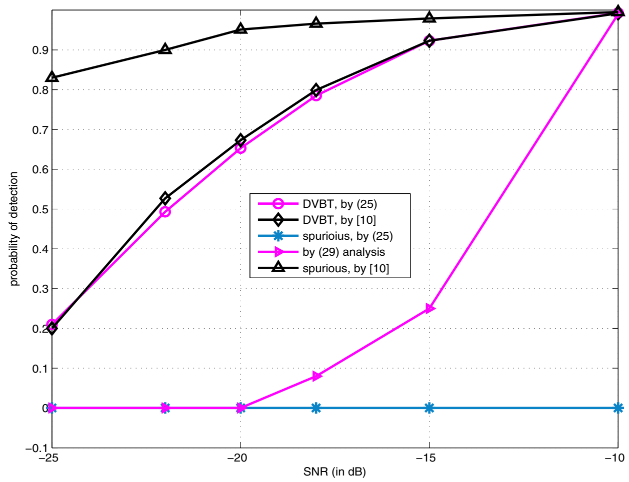


Fig. 2. Probability of detection for false alarm 0.0001

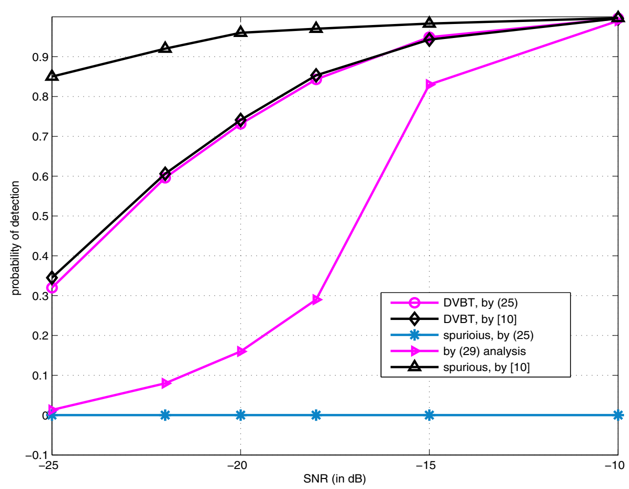


Fig. 3. Probability of detection for false alarm 0.01

achieve 90% detection for false alarm rate 0.0001, 0.01 and 0.1 are -15dB, -16dB and -18dB respectively.

The probability achieved by the proposed spectrum algorithm and the algorithm studied in [8] are also compared in Fig. 2, Fig. 3 and Fig. 4. We observe that, the two algorithms perform equally well in terms of probability of detection. However, as can be seen from these figures, given the false alarm rate, the probability of detection of spurious by our proposed algorithm is roughly zero from -25dB to -10dB, although the probability of detection of DVB-T signals is much higher. This observation indicates that our proposed algorithm is robust to spurious. In contrast, as shown in the figures, the algorithm by [8] detect the spurious with high probability, even at a SNR of -25dB for false alarm rate 0.0001.

The probability of detection of our proposed algorithm predicted by (29) is also presented in Fig. 2, Fig. 3 and Fig. 4. At low SNR (¡-15dB) and low false alarm rate, the predicted probability of detection is much smaller than the simulated

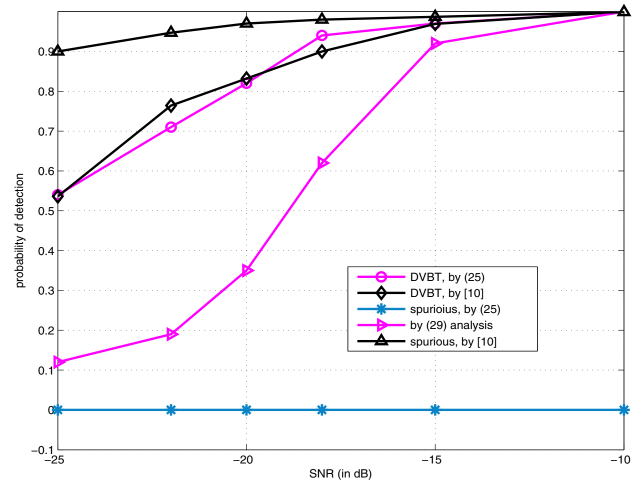


Fig. 4. Probability of detection for false alarm 0.1

value, while for SNR¿-15dB, the predicted value approaches the simulated value, particularly with increased false alarm rate of AWGN.

## VI. Conclusions

In this paper, a spectrum sensing algorithm to detect the presence of OFDM based system (DVB-T) with pilot signal insertion is presented. The proposed algorithm makes use of time domain auto-correlation of pilot signals, however is able to differentiate single tone spurious with DVB-T signal. Simulation results show that the proposed algorithm achieves performance equal to that of existing algorithm based on auto-correlation of pilot signals. Moreover simulation results show that our proposed spectrum sensing algorithm performs better than existing algorithms in terms of false alarm rate. This observation indicate that our proposed algorithm is more robust to spurious, without performance loss in probability of detection.

## References


[1] FCC, *Initial evaluation of the performance of prototype TV-band white space device*, OET Report FCC/OET 07-TR-1006, FCC OET, July 2007.

[2] OFCOM, *Digital dividend review, a statement on our approach towards awarding the digital dividend*, Dec. 2007.

[3] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE J. Select. Areas Commun.*, vol. 23, pp. 201-220, Feb. 2005.

[4] A. Sahai and D. Cabric, "Spectrum sensing: fundament limits and practical chanllenges," in *Proc. IEEE DySPAN'05*, Nov. 2005.

[5] ETSI, "Digital video broadcasting: framing structure, channel coding, and modulation for digital terrestrial television," European Telecommun. Standard EN300744, Aug. 1997.

[6] F. Khan, *LTE for 4G Mobile Broadband*, Cambridge University Press, New York, 2009.

[7] L. P. Goh, Z. Lei and F. Chin, "DVB detector for cognitive radio," *Proc. IEEE ICC 2007*, pp. 6460-6465, 2007.

[8] H-S. Chen, W. Gao and D. V. Daut, "Spectrum sensing for OFDM systems employing pilot tones," *IEEE Trans. Wireless Commun.*, No. 12, pp. 5862-5870, Dec. 2009.

[9] A. Zahedi-Ghasabeh, A. Tarighat and B. Daneshrad, "Spectrum sensing of OFDM waveforms using embedded pilot subcarriers," *Proc. IEEE ICC 2010*, pp. 1-6, May 2010.

[10] S. M. Kay, *Fundamental of Statistical Signal Processing, Detection Theory*, Upper Saddle River, NJ: Prentice Hall, 1993.