MTM Parameters Optimization for 64-FFT Cognitive Radio Spectrum Sensing using Monte Carlo Simulation

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***Abstract*—This paper presents parameter optimization of the multi taper spectrum estimation method (MTM) for 64-FFT based cognitive radio (CR) spectrum sensing. The design problem is formulated to determine the MTM parameters pair; the half time bandwidth product, and the number of tapers that maximize the performance at a fixed number of data samples. Maximum performance is defined by the highest probability of detection at a fixed false alarm probability. A Monte Carlo simulation is implemented to find the optimal parameters. The binary hypothesis test is developed to insure that the effect of choosing optimum MTM parameters is based upon performance evaluation. The whole band under sensing is divided into subbands, some contain primary user signal (PR), and the other does not. Consequentially, in addition to the variance of the estimate, the spectral leakage outside the PR subband is included in the performance evaluation. We found that the half time bandwidth product of 4 and 5 tapers gives the highest performance. We examined both MTM and periodogram (i.e., energy detector) methods in Gaussian (AWGN) and Rayleigh flat fading environments. The CR system performance using the MTM technique outperforms the performance of the same system that uses periodogram in all the cases we examined.**

Keywords-cognitive radio; spectrum sensing; multitaper spectrum estimation.

I. INTRODUCTION

High data rate applications in the emerging wireless technologies are faced with the problem of the ever-increasing scarcity of spectrum, coupled with the underutilization of the current licensed spectrum. Cognitive radio's basic idea is the opportunistic use of the unused spectrum of a licensed PR user. Consequently, CR technology is expected to become an increasingly popular part of future wireless networking technologies.

Cognitive radio, proposed by Mitola in 1999 [1], addresses the problem of secondary usage of underutilized spectrum using techniques of accurate spectrum sensing. It intelligently interacts with its operational environment to dynamically and autonomously adjust the radio operating parameters accordingly, to avoid interference with PR transmission.

The key enabling functionality for practical CR concept is a reliable spectrum sensing scheme to avoid harmful interference to licensed users. The classical spectrum sensing techniques such as the matched filtering and the cyclostationary detector have high performance for CR applications [2-4]. But such techniques require prior information about PR's signaling. The periodogram (i.e., energy detector) is a simple method at the expense of performance. Large variance, and bad biasing of the power spectrum estimates are main drawbacks of periodogram [5].

Thomson proposed the 'Multitaper spectral estimation Method (MTM)' to produce single spectrum estimate by multiplying the sampled data by several leakage resistant tapers [6]. Haykin , on the other hand, suggested the use of MTM as an efficient method for spectrum sensing in cognitive radio systems [7].

The CR systems using the Orthogonal Frequency Division Multiplexing (OFDM) technology have the ability to dynamically fill the spectrum holes by activating the available OFDM subcarriers, and deactivating the remaining subcarriers. The FFT operation in the OFDM demodulation process can be used for the analysis of the spectral activity of the licensed users [8].

Practically, using the MTM in the OFDM-based CR systems will be supported by the already available IFFT/FFT processors to perform the spectrum estimations. MTM has to be optimized for implementation in OFDM-based CR systems. Half time bandwidth product (*NW*) and the number of tapers (*K*) play key functions in the MTM process. In [9], and in [10], the recommended range of *NW* is recommended to be between 4 and 10, and *K* between 10 and 16.

Based on these recommendations, it is clear that such parameters are still an open issue, and have to be optimized towards achieving high performance and low complexity by determining a specific number of tapers.

In this paper, we consider issues of optimizing the MTM parameters for 64-FFT CR systems. In order to determine the optimal *NW,* and *K* we examine the performance using the

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binary hypothesis. The objective is to include the spectral leakage effect and the large variance as performance metric parameters in the evaluation to determine the NW, and K that maximize the performance. A Monte Carlo simulation is implemented for the formulated problem. A comparison to the periodogram is presented in term of performance and complexity.

The rest of the paper is organized as follows: Section II defines the model for the system under consideration and reviews MTM technique. Section III considers the optimization of the MTM parameters used in the system model. Section IV presents the results and Section V concludes the paper.

II. System Model

Our system model consists of a single PR transmit/receive node, transmitting QPSK-OFDM signal in the sub-band between f_a and f_b as shown in Fig. 1, and an OFDM-based CR sensor (node) that detects the PR user's signal and decides whether the PR's signal is present or absent in the searched frequency band.

A family of orthonormal tapers is generated using Discrete Prolate Slepian Sequences (DPSS) [10], of length N to concentrate the received PR energy in the frequency interval Δf between$(-W\ ,W)$. The total number of sequences (tapers) produced, is $N_{tapers} = 2NW = N\,\Delta f$, and K is the number of tapers used in the estimation. The associated eigenvalues of the K tapers, are $1 > \lambda_0(N,W) > \lambda_1(N,W) > \lambda_2(N,W) > \cdots > \lambda_{K-1}(N,W) > 0$. The k^{th} taper is represented by $v_t^{(k)}(N,W)$, where $t = 0,1,\ldots,N-1$, is a time index.

The received PR signal at a CR sensor (node) is sampled to generate a finite discrete time samples series $\{x_t; t = 0,1,\ldots,N-1\}$ that is 'dot multiplied' with different tapers. The product is applied to Fourier Transform to compute the energy concentrated in the bandwidth $(-W,W)$ centred at frequency f . For K orthonormal tapers, there will be K different eigenspectrums produced and defined as :

$$Y_k(f_i) = \sum_{t=0}^{N-1} v_t^{(k)}(N,W)x_t e^{-j2\pi f_i t} \quad (1)$$

where $f_i = 0,1,2,\ldots,N-1$ are the normalized frequency bins.

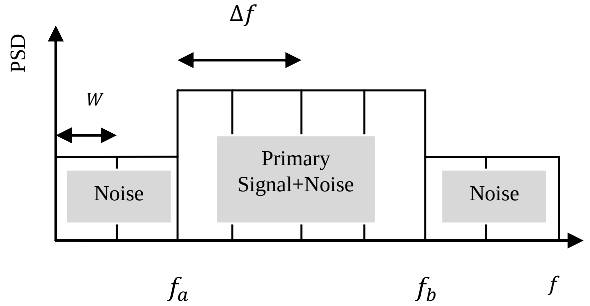

Fig. 1. System Model.

The spectrum estimate given by Thomson's theoretical work is defined as:

$$S_{MTM}(f_i) = \frac{\sum_{k=0}^{K-1} \lambda_k(N,W)|Y_k(f_i)|^2}{\sum_{k=0}^{K-1} \lambda_k(N,W)} \quad (2)$$

On the other hand, the periodogram method, when the samples are taken at uniform time spacing, gives the power spectrum density estimation as:

$$S_{PE}(f_i) = \frac{1}{N}\left|\sum_{t=0}^{N-1} x_t e^{-j2\pi f_i t}\right|^2 \quad (3)$$

III. Optimaziation of MTM Parameters

Maximum-likelihood methods provide an optimal estimate of the power spectrum. MTM technique is an approximation to the Maximum-likelihood power spectral estimates but at reduced computation [11], [12]. The main motivation of the work presented in this paper is to fnd the MTM parameters that optimize the performance of this technique.

In this section, we investigate the optimization of MTM parameters in OFDM-based CR systems. The CR transceiver carries out 64-IFFT/FFT digital processing for both transmission and receiving operations. Consequently, the MTM processing in the spectrum sensing will not add additional hardware at the receiver except for taper sequences generation, multiplication and adding operations.

MTM tolerates the classical problems which occurred in spectrum estimation by averaging over a number of orthonormal tapers/windows. The tapering sequences concentrate the energy within a bandwidth $2W$, where $0 < W < 1/2$. The half time bandwidth product NW determines the bandwidth resolution for fixed length$N$. As the half time-bandwidth product decreases, the half bandwidth W decreases resulting in higher resolution in the spectrum sensing and vice versa. The main spectrum lobe of each taper/window is $2NW$ frequency bins (where the FFT- frequency bin spacing is $1/N$) [13]. Thus in OFDM-based CR applications with 64-FFT, the main band under sensing can be divided into a number of subbands based on the half time bandwidth product. For example using NW=2, means that there will be 16 subbands with $2W$ width each, and then the main lobe is 4 frequency bins out of the 64. Therefore in such applications the useful half time bandwidth products should be 0.5,1,2,4,8, or 16, and 32 to concentrate the energy in one band, which is the whole band under sensing; consequently, the higher edge of the half time bandwidth is 16.

Furthermore, the number of the tapers in the higher resolution sensing is smaller than that in the lower resolution since the total number of tapers is $N_{tapers} = 2NW$.

The eignevalues $\lambda_k(N,W)$ of the first few tapers for the higher bandwidth resolution is much smaller than eignvalues in the lower resolution which implies that lower bandwidth resolution sequences have more energy concentration than sequences in the higher bandwidth resolution.

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Furthermore, the first few eigenvalues of a specific time half bandwidth product are close to one. As the number of taper sequences increases, the eigenvalues decrease indicating bad bias properties, and as the number of tapers decreases, the eigenvalues increase towards 1 indicating good bias properties.

Our work for choosing appropriate values of *NW* and *K* for MTM estimator uses two approaches: in the first approach, we compute the power spectral density using (2) to show that random choice of these values may generate a lot of leakage causing an increase in false alarm probability during the estimation process. These results are presented in Fig. 2, and Fig. 3. The second approach is Monte Carlo simulation to estimate the probabilities of detection and false alarm for various values of *NW*, *K* and SNR, and then to find the optimal (*NW*, *K*).

Fig. 2 shows the PR's power spectral density (PSD) computed using (2) with *NW*=4, and 16 where the number of tapers used is *K*=5, and 25 respectively at AWGN channel with SNR=−15dB and number of averaged samples is 2500. PR transmits OFDM-QPSK signal from normalized frequency $f_a = 16$ to $f_b = 48$ with power normalized to one over the whole band. Both PR and CR use 64-IFFT/FFT signal processing. CR receiver implements MTM to estimate the PR's PSD using different values for *NW* and *K* parameters. The ideal curve represents the levels of noise, and noise plus signal. We can clearly note how much power spectral leakage outside the PR's signal band when using *NW*=16 and *K*=25. Such leakage of power will affect the decision outside the PR's band by introducing more false alarms. At the same time we can see how such leakage is reduced when using *NW*=4 and *K*=5.

Fig.3 shows the PSD for the same system with *NW*=8 computed using (2). This figure clearly shows that using a small number of tapers *K*=2 introduces large variance in the estimate due to the averaging over small number of tapers. At the same time using a large number of tapers *K*=14 improves the variance but at the expense of spectral leakage which is noticeable in the figure. Using *K*=5 produces leakage that is between the previous two cases.

We may conclude from these two figures that an unwise choice of *NW* and *K* within the range, suggested by Haykin, may have catastrophic results on false alarm of the MTM estimator.

Fig. 4 shows a representative diagram of the MTM parameters' optimization problem in a 64-FFT based CR system that is used in the simulation. In our case *NW* axes values are *NW*=0.5, 1, 2, 4, 8, and 16. On the *K* axes values are *K*=1, 2, 3,…, 32. In regions (R_1), and (R_3), the half time bandwidth *NW* has higher resolution than the other two regions (R_2), and (R_4). At the same time R_1, and R_2 have a small number of tapers with good bias properties at the expense of higher variance when used in computing the PSD using (2). R_3, and R_4 regions have large number of tapers that improve the variance of the spectrum estimate, but at the expense of larger spectral leakage. The recommended values of *NW*, and *K* ranges in the literature are shown in the figure. Although these ranges are useful in the CR spectrum sensing, they still need to be optimized to get the highest performance for 64-FFT CR systems. In addition to maximizing the performance, optimum parameters will contribute to reducing the MTM estimator complexity.

The mathematical derivation of the optimal MTM parameters is intractable. Therefore, a Monte Carlo simulation program has been used in this paper to examine the effect of the different values of *NW* and *K* on the spectral leakage outside the PR's subband and the MTM estimator decision statistic. Consequently the binary hypotheses at each frequency bin will be used to evaluate MTM estimator performance.

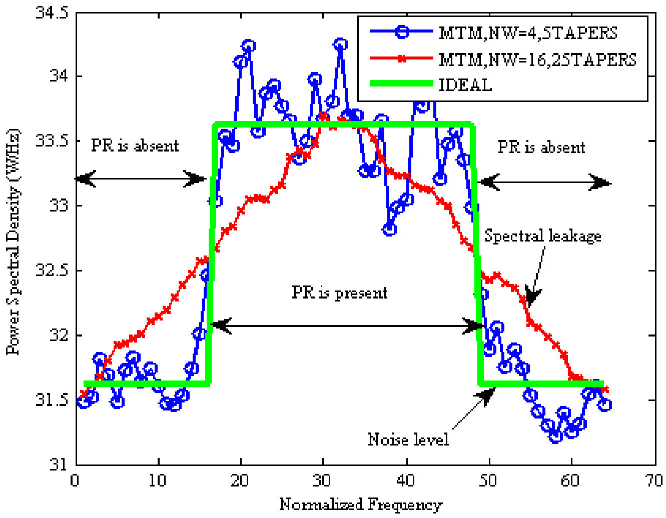

Fig. 2. Power spectral density (PSD) using MTM computed with *NW*=4, and 16 and different values of *K* at AWGN with SNR=−15dB.

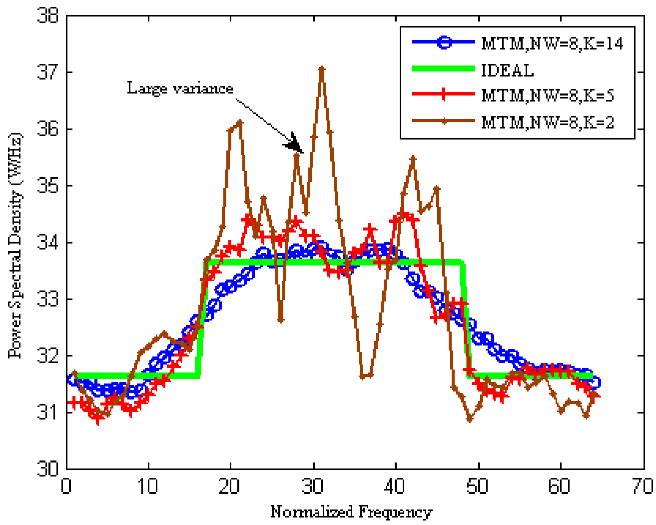

Fig. 3. Power spectral density (PSD) using MTM with *NW*=8, and different values of *K* at AWGN with SNR=−15dB.

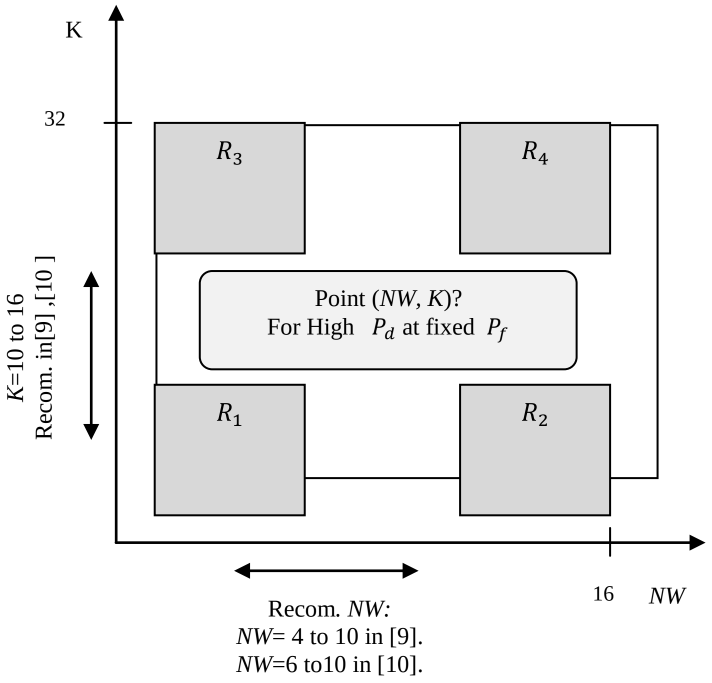

Fig. 4. Representative diagram of the MTM parameters optimization problem for 64-FFT based CR systems.

Clearly, optimizing the MTM estimator performance requires maximizing probability of PR signal detection P_d for a predefined probability of false alarm P_f. Here P_d is the probability the MTM estimator decides correctly the presence of the PR's signal, and P_f is the probability that the MTM estimator decides the PR's signal is present when it is absent.

The binary hypothesis test for MTM spectrum sensing at the l^{th} time is given by:

$$\begin{aligned} \mathcal{H}_0: &\quad x(l) = w(l) \\ \mathcal{H}_1: &\quad x(l) = hs(l) + w(l) \end{aligned} \tag{4}$$

where l = 0,1,…,L-1 is OFDM block's index, $x(l)$, $w(l)$ and $s(l)$ denote the CR received, noise, and PR transmitted samples. The transmitted PR signal is distorted by the zero mean additive white Gaussian noise $w(l) \sim \mathcal{CN}(0, \sigma_{noise}^2)$. Additionally the channel between PR transmitter and CR receiver is subjected to flat fading. The channel gain h is assumed to be constant during the sensing time. The time instant l comes from the samples over different OFDM blocks; and time instant t comes from the samples from the same OFDM block (i.e., IFFT/FFT samples).

Decision *DEC* over time interval L, and at a specific frequency bin using the MTM can be formulated as:

$$DEC_{MTM}(f_i) = \frac{1}{L}\sum_{l=0}^{L-1} S_{MTM}^{l}(f_i) \tag{5}$$

Thus, we can reformulate the eigenspectrum in (1), using (4) at the l^{th} time when the binary hypothesis $\mathcal{H}_1$ is valid to be as follows:

$$Y_k(f_i) = \sum_{t=0}^{N-1} v_t^{(k)}(N,W)(hs_t(l) + w_t(l))e^{-j2\pi f_i t} \tag{6}$$

The decision at a specific frequency bin over the spectrum sensing time duration L can be rewritten using (6) to be as follows:

$$DEC_{MTM}(f_i) = \frac{1}{L}\sum_{l=0}^{L-1} \frac{\sum_{k=0}^{K-1}\lambda_k(N,W)\left|\sum_{t=0}^{N-1} v_t^{(k)}(N,W)(hs_t(l)+w_t(l))e^{-j2\pi f_i t}\right|^2}{\sum_{k=0}^{K-1}\lambda_k(N,W)} \tag{7}$$

When using the periodogram, the decision can be formulated as:

$$DEC_{PE}(f_i) = \frac{1}{L}\sum_{l=0}^{L-1} S_{PE}^{l}(f_i) \tag{8}$$

By rewriting (8) using (3) and (4), the decision at a specific frequency bin using the periodogram when the binary hypothesis $\mathcal{H}_1$ is valid, is as follow:

$$DEC_{PE}(f_i) = \frac{1}{LN}\sum_{l=0}^{L-1}\left|\sum_{t=0}^{N-1}(hs_t(l) + w_t(l))e^{-j2\pi f_i t}\right|^2 \tag{9}$$

The detection and false alarm probabilities at each frequency bin are defined as:

$$\begin{aligned} P_D(f_i) &= Pr\{DEC_{MTM}(f_i), DEC_{PE}(f_i) > \gamma | \mathcal{H}_1\} \\ P_F(f_i) &= Pr\{DEC_{MTM}(f_i), DEC_{PE}(f_i) > \gamma | \mathcal{H}_0\} \end{aligned} \tag{10}$$

The threshold γ , is defined according to the noise variance σ_{noise}^2 . The decision statistics ($DEC_{MTM}(f_i)$, $DEC_{PE}(f_i)$) are calculated at each frequency bin using (4) to (9), and then the probabilities of detection and false alarm can be evaluated by comparing the decision statistic to the predefined threshold over a number of realizations using (10).

The binary hypothesis $\mathcal{H}_0$ will be examined through all frequency bins that don't contain PR' signal (i.e., $\{f_i \in ([0, f_a) \cup (f_b, 63])\}$) . The binary hypothesis $\mathcal{H}_1$ will be examined through all frequency bins that contain the PR's (i.e., $\{f_i \in [f_1, f_2]\}$).

The probability of detection P_d over the band under sensing can be achieved from the averaged summation of the individual probability of detection $P_D(f_i)$ of the all the bins which lie within the subbands used by the PR user, and can be written as:

$$P_d = \frac{\sum_{f_i=f_a}^{f_i=f_b} P_D(f_i)}{32} \tag{11}$$

The probability of false alarm P_f over the band under sensing can be achieved from the averaged summation of the individual probability of false alarm $P_F(f_i)$ of the all the bins which lie within the subbands outside the PR's subband, and can be written as:

$$P_f = \frac{\sum_{f_i=0}^{f_i=f_a-1} P_F(f_i) + \sum_{f_i=f_b+1}^{63} P_F(f_i)}{32} \qquad (12)$$

where 32 represents the total number of frequency bins of the hypotheses $\mathcal{H}_0$, and $\mathcal{H}_1$ of the model.

The optimization problem here can be written simply as:

$$find\ (NW^*, K^*)\ \ that\ maximizes\{P_d\}\ at\ P_f = \alpha \qquad (13)$$

where α is a constant false alarm, and is assumed as 10% in this paper.

The complexity of MTM estimator for producing the spectrum estimate at a specific frequency bin f_i and N-FFT over L OFDM-Blocks, in terms of the number of mathematical operations (i.e., adding, and multiplication) is defined as:

$$com_{MTM} = L[K(3N-1) + 4K - 2] \qquad (14)$$

Using the periodogram to produce spectrum estimate at a specific frequency bin f_i , the complexity can be defined as follows:

$$com_{PE} = L(2N) \qquad (15)$$

IV. Simulation Results

The frequency band under study is divided into three non-overlapped subbands as shown in Fig. 1. The PR user is transmitting QPSK-OFDM signal using the subband between the frequencies $f_a = 16$ to $f_b = 48$, and with normalized averaged power of 1 over the whole band. The PR user's transmitter uses 64-IFFT with sampling frequency 20 MHz, where the symbol duration T_s =0.05µs. The CR's node uses 64-FFT with sampling frequency 20 MHz as well. The performance is evaluated using number of samples at the CR user' node as $N_{samples} = 20(N_{FFT}) =$ 1280, which corresponds to sensing time of $64\mu s$, that is sensing process is carried out every $L = 20$ OFDM blocks. In all cases of simulations the results are averaged over 100000 simulation runs. The channels considered in the simulation are AWGN with zero mean and variance σ^2_{noise}, and Rayleigh flat fading.

The probabilities of detection for *NW*= 0.5, 1, and using different number of tapers are shown in table I. The wireless channel is assumed to be AWGN with SNR = −5 dB. The threshold γ that gives probability of false alarm 10% was estimated by Monte Carlo simulation using computer software platform. This threshold is then substitutes in (7) to (12) to find probability of detection and in (13) to find optimum *NW* and *K*. The highest probability of detection was found as P_d=98.8150%, which is achieved using *NW*=2 and *K*=3 tapers in the spectrum sensing.

Fig. 5 shows the probability of detection versus the number of tapers when the half time bandwidth product was as *NW*= 4, 8, and 16, at the same wireless environment applied before. We note that each curve has three different behaviors. It starts from a lower point that represents the minimum probability of detection which is achieved by the first taper. Then it increases sharply to a peak point, and starts finally to level off. The peak point for the different *NW* in this case is at *K*=5 tapers. Table II summarizes the probability of detection for *NW*=4, 8, and 16 for *K*=1, and 5 that obtained from Fig. 5.

The highest probability of detection is P_d =99.7138%, which is achieved using *N*W=4, and *K*=5. Generally, 5 tapers is a good compromise between the good bias properties, and improved variance. However, the maximum value of P_d may vary with the wireless environment conditions Additionally, *NW*=4 is the optimal resolution that gives the highest performance.

TABLE I. PROBABILITY OF DEDECTION FOR *NW*=0.5, 1,2 AND DIFFERENT *K* AT AWGN (SNR=−5dB) WHEN FALSE ALARM IS 10%.

NW	P_d (%)			
	K=1	*K*=2	*K*=3	*K*=4
0.5	83.233	-	-	-
1	81.2166	87.7376	-	-
2	75.9459	90.7959	98.8150	98.560

TABLE II. PROBABILITY OF DEDECTION FOR *NW*=4,8,16 AND DIFFERENT *K* AT AWGN (SNR=−5dB) WHEN FALSE ALARM IS 10%.

NW	P_d (%)	
	K=1	*K*=5
4	73.4531	99.7138
8	71.6678	99.2422
16	69.1575	98.6350

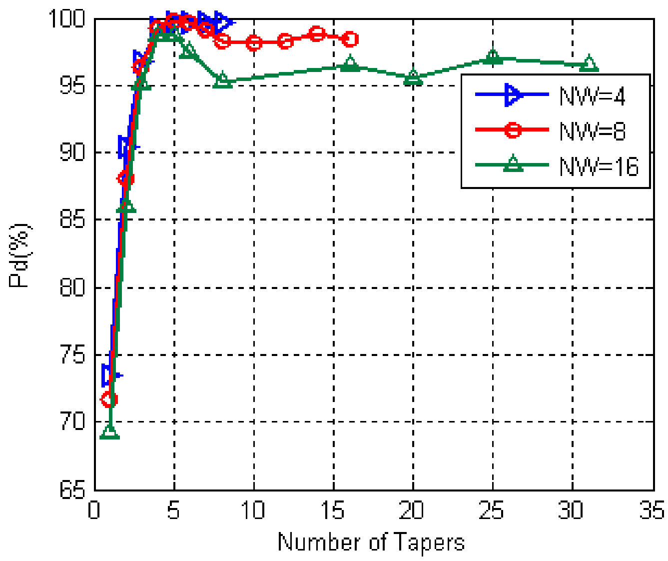

Fig. 5. Probability of detection versus number of tapers (*K*) using MTM with different half time bandwidth products (*NW*) where the probability of false alarm was 10% and at channel AWGN with SNR=−5dB.

Fig. 6 shows the probability of detection versus probability of false alarm for MTM with *NW*=4 using 5 tapers at AWGN with SNR= −5, and −10 dB. The results are compared with those obtained from the periodogram estimator to the same system. When the probability of false alarm is fixed at 10% and SNR = −5 dB, the probability of the detection using the periodogram is less than that using the MTM with *NW*=4 and 5 tapers by16 % .

When the SNR is decreased to −10 dB, the probability of detection of the MTM spectrum sensing with *NW*=4, and 5 tapers, is better than that for the periodogram by approximately 40% when the probability of false alarm is fixed at 10%. Consequently we can conclude that the MTM spectrum sensing performance is more robust than the periodogram at low SNR.

Fig. 7 shows the probability of detection versus probability of false alarm using periodogram and MTM with *NW*=4 and *K*=5 tapers schemes. The wireless channel is Rayleigh flat fading channel and SNR = −5 dB. We note that the probability of detection using the MTM, *NW*=4 and 5 tapers case is better than that using the periodogram by 8% when probability of false alarm $P_f = 10\%$.

Furthermore, comparing the results in Fig.7 with those in Fig.6, we conclude that the probability of detection is degraded in a flat fading channel compared to Gaussian channel for both schemes for the same probability of false alarm, *NW*, number of tapers, and SNR.

Table III shows the complexity of the MTM spectrum sensing based on (14) for different number of tapers *K* with length *N*=64 over one OFDM block(i.e., *L*=1).

It is clear that, in addition to the high performance achieved by *K*=5, it requires less mathematical operations for computation compared to $K > 5$ cases. The periodogram complexity is found as 128 operations at the same conditions of MTM using (15).

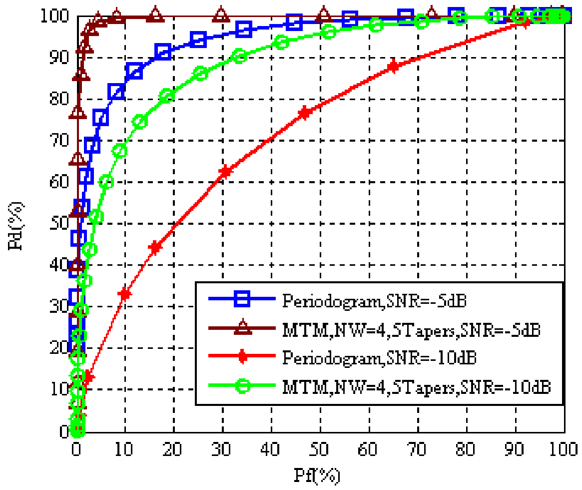

Fig. 6. Probability of detection versus probability of false alarm using MTM with *NW*=4, and *K*=5 compared to the periodogram at AWGN with SNR=−5 and− 10dB.

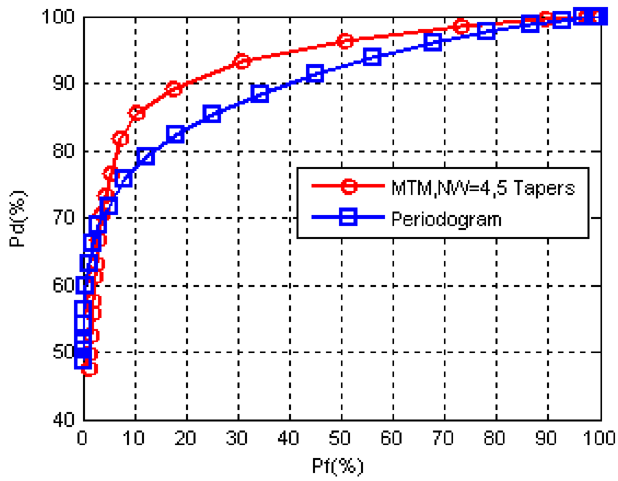

Fig. 7. Probability of detection versus probability of false alarm using MTM with *NW*=4 and *K*=5 tapers and periodogram using Rayleigh flat fading channel with SNR=− 5dB.

TABLE III. MTM COMPLEXITY EVALUATION FOR 64-FFT OVER L=1 USING DIFFERENT *K*.

MTM	*K*=1	*K*=5	*K*=10	*K*=20	*K*=31
Complexity	193	973	1948	3898	6043

V. CONCLUSION

In this paper, we have investigated the effects of the system parameters, within the range suggested in the literature, on the performance of the MTM spectrum sensor for opportunistic use by OFDM-based CR users. We have examined the MTM parameters to find their optimality to give higher probability of detection at lower probability of false alarm, and minimal complexity. The MTM technique has been analyzed and simulated in AWGN, and Rayleigh flat fading environments. Our primary and secondary users were communicating through OFDM-based systems with 64-IFFT/FFT.

Although the first few tapers (Slepian sequences) have the best spectral leakage properties, we found that they give the worst performance in terms of detection and false alarm probabilities. We found that unwise choice of *NW* and *K* from the range suggested in [9] produces catastrophic false alarms in the system. In our chosen 64-IFFT/FFT systems, the optimal number of tapers was 5 for the *NW*=4, 8, and 16 cases, and the optimal half time bandwidth product is given by *NW*=4 for 10% false alarm when system is operating in AWGN channel with SNR=– 5 dB. For cases where *NW*< 4, for example when *NW*=2, the bad bias properties of the tapers overcome the high resolution in this system. Generally, 5 tapers, and half time bandwidth *NW*=4 can be considered as optimal parameters for different FFT-sizes, since the change in FFT affects only resolution. We found that the performance of the system using MTM estimator is better than when using the periodogram estimator for any number of tapers except for one taper when both systems are operating at the same channel conditions.

Both estimators suffer by the Rayleigh flat fading compared to AWGN environment. Furthermore, the MTM technique performance is more robust than the periodogram in the AWGN channel. Finally, the improvement in performance of the MTM estimator over the periodogram estimator comes at the cost of a slightly higher computational complexity. The additional complexity seems to be justifiable considering the advantages gained from using the MTM technique.

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