SPECTRAL MONITORING AND PARAMETER ESTIMATION FOR ZP-OFDM SIGNALS

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ABSTRACT

Spectral monitoring has received considerable attention in the context of opportunistic and cognitive radio systems. The increasing number of wireless technologies calls for efficient techniques to monitor the radio frequency spectrum. Spectral monitoring is based on signal detection tools to reduce the spectral search to the signals of interest as well as estimation tools to identify their characteristics (carrier frequency, bandwidth, power, modulation, symbol duration...). In this paper, the spectral components are estimated by the averaged periodogram non-parametric approach using an FFT. The signals of interest are further processed to determine the type of modulation (single-carrier or multi-carrier). In particular, we develop a parameter estimation tool for ZP-OFDM signals based on power autocorrelation to determine their symbol and zero padding duration. Simulation results are provided for an extensive number of generated signals under frequency selective channels, to assess the performance of the signal detection in realistic scenarios.

1. INTRODUCTION

Spectral monitoring has received considerable attention in the context of opportunistic and cognitive radio systems. The increasing number of wireless technologies calls for efficient techniques to monitor the radio frequency spectrum. Unlike in coherent detection, the receiver does not have any prior knowledge on the time and frequency distribution of the transmitted signals. As a combined implementation of all possible coherent detectors is infeasible, it is necessary to extract key features of the signals to build a generic recognizer of the different types of modulations. Spectral monitoring is based on signal detection tools to reduce the spectral search to the signals of interest as well as estimation tools to identify their characteristics (carrier frequency, bandwidth, power, modulation, symbol duration...). Spectral components can be estimated using parametric or non-parametric approaches [1]. While parametric approaches are best suited for short data records, non-parametric approaches usually require less computational complexity for long data records. In this paper, the spectral components are estimated by the averaged periodogram non-parametric approach using a Fast Fourier Transform (FFT). An iterative algorithm based on rectangular frequency windows is performed on the averaged periodogram to estimate the carrier frequency, the bandwidth and the average power of each signal of interest.

The signals of interest are further processed to determine the type of modulation (single-carrier or multi-carrier). A survey of algorithms currently available in the literature for the classification of single-carrier modulations can be found in [2]. For multi-carrier modulations, a number of procedures have been proposed using autocorrelation and cyclic autocorrelation based features to extract parameters of Orthogonal Frequency Division Multiplex (OFDM) signals with a Cyclic Prefix time guard interval (CP-OFDM) and propagating through a frequency selective channel [3, 4, 5]. In this paper, we develop a parameter estimation tool for OFDM signals with a Zero Padding time guard interval (ZP-OFDM) and propagating through a frequency selective channel, based on power autocorrelation to determine the symbol duration and the ZP duration. Simulations results are provided for an extensive number of generated signals under frequency selective channels with time and frequency offsets to assess the performance of the parameter estimation in realistic scenarios. Compared to [6], we study the influence of the symbol duration, the ZP duration, and the data record length with different channel models.

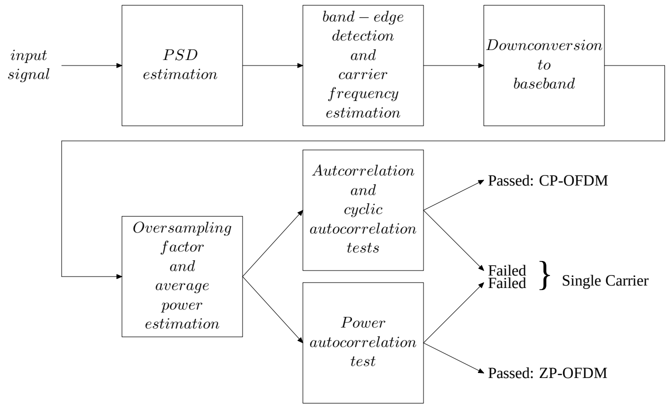


Figure 1: Spectral monitoring block scheme for parameter estimation of multi-carrier modulations

The spectral monitoring block scheme is presented in Figure 1. The received sampled data are fed to a Power Spectral Density (PSD) estimation block consisting of the averaged periodogram non-parametric approach using an FFT [1]. The result is passed to a carrier frequency and band edge frequency estimation block that iteratively estimates spectral components of multiple signals (average power, carrier frequency and bandwidth). Each signal of interest is then down-converted into baseband and low-pass filtered. As the cut-off frequency of the low-pass filter can be chosen larger than the bandwidth of the signal of interest, the oversampling factor and the average power are estimated on the corresponding baseband signal. Finally, this signal is processed in a parallel way through autocorrelation and cyclic autocorrelation tests to detect the presence of a CP-OFDM signal and through power autocorrelation tests to detect the presence of a ZP-OFDM signal. If neither of these multi-carrier modulations are detected, known algorithms for single-carrier modulation can be used to determine the constellation size[2].

In section 2, we review the averaged periodogram technique and we present the iterative algorithm based on rectangular frequency windows for multiple signals to estimate the carrier frequency, the bandwidth and the average power of each signal of interest. In section 3, we review the parameter estimation tools based on autocorrelation and cyclic autocorrelation for CP-OFDM signals in frequency selective channels. The symbol duration, the CP duration and the number of subcarriers can be estimated from these features. We develop parameter estimation tools based on power autocorrelation for ZP-OFDM signals in frequency selective channels in section 4. Simulations results are given in section 5 for an extensive number of generated signals.

2. ESTIMATION OF THE SPECTRAL COMPONENTS

An overview of various spectral estimation methods using parametric as well as non-parametric approaches can be found in [1]. While parametric approaches are best suited for short data records, non-parametric approaches usually require less computational complexity for long data records. In the following, the spectral properties are estimated by the averaged periodogram non-parametric approach using an FFT. Consider the received sampled data sequence $\mathbf{s} = [s(0)\dots s(N-1)]^T$ with N the number of samples. We wish to estimate the spectral components of K signals of interest present in the observed spectrum. The carrier frequencies f_k^c, $k = 0\dots K-1$ are estimated indirectly by estimating band edge frequencies B_k^{low} and B_k^{high}, $\forall k = 0\dots K-1$. The periodogram $\mathbf{S}$ gives an estimate of the Power Spectral Density (PSD) of the received sequence by:

$$\mathbf{S} = |FFT(\mathbf{s})|^2 \tag{1}$$

To calculate the averaged periodogram, the sequence $\mathbf{s}$ of length N is divided into M vectors $\mathbf{s}_m$ of size T and the corresponding periodograms are then averaged. Note that the larger the number of samples T, the higher the frequency resolution provided by the FFT grid (which is maximum when M=1). The averaged periodogram $\mathbf{S}_{avg}$ gives an estimate of the PSD of the received sequence by:

$$\mathbf{S}_{avg} = \frac{1}{M}\sum_{m=0}^{M-1} |FFT(\mathbf{s}_m)|^2 \tag{2}$$

The estimated PSD is used in an iterative algorithm to determine the spectral properties of the different signals of interest (average power, carrier frequency and bandwidth). A description of the algorithm is given in **Algorithm 1**. First, the total energy in the spectrum A_1 is calculated and an exhaustive search based on a rectangular frequency window is performed to find the band edge frequency indices i and $i+j$ of the first signal of interest, according to a Least Squares Error (LSE) criterion. The energy difference A_1^{diff} between the target signal (i.e. the energy of the full spectrum) and the measured data in the bandwidth of interest is calculated. Finally, the average power of the first signal is estimated as the difference $A_1 - A_1^{diff}$. The remaining energy is used to detect a second signal of interest with $A_2 = A_1^{diff}$ on the updated received spectrum $signal_2$ (where the frequency components in the bandwidth of the first signal of interest are removed from the initially received spectrum). This procedure is repeated iteratively until the K signals are detected (or until the remaining energy is too small to contain a signal of interest, i.e. $A_k < tolerance$ compared to the noise power).

Algorithm 1 Iterative algorithm for the estimation of multiple spectral components

init $k = 1$
init $A_k = sum(\mathbf{S}_{avg})$
init $signal_k = \mathbf{S}_{avg}$
init $obj(i,j) = 1\ \forall i,j$
while $A_k > tolerance$
  init $min_{obj} = 1$
  for i=0 to $T-1$
   for j=0 to $T-i$
    $target = [\mathbf{0}_{(1\times i)}, \frac{A_k}{j}\mathbf{1}_{(1\times j)}, \mathbf{0}_{(1\times T-(i+j))}]$
     $obj(i,j) = sum((signal_k - target)^2)$
     if $obj(i,j) < min_{obj}$
      $min_{obj} = obj(i,j)$
      $B_k^{low} = i$
      $B_k = j$
      $B_k^{high} = B_k^{low} + B_k$
     end if
    end for
  $target_k^{tmp} = [\mathbf{0}_{(1\times B_k^{low})}, \frac{A_k}{B_k}\mathbf{1}_{(1\times B_k)}, \mathbf{0}_{(1\times T-(B_k^{low}+B_k))}]$
  end for
  $A_k^{diff} = sum(target_k^{tmp}) - sum(signal_k(B_k^{low}, B_k^{high}))$
  $target_k^{final} = [\mathbf{0}_{(1\times B_k^{low})}, \frac{A_k - A_k^{diff}}{B_k}\mathbf{1}_{(1\times B_k)}, \mathbf{0}_{(1\times T-(B_k^{low}+B_k))}]$
  $k = k+1$
  $A_k = A_{k-1}^{diff}$
  $canceler = [\mathbf{1}_{(1\times B_k^{low})}, \mathbf{0}_{(1\times B_k)}, \mathbf{1}_{(1\times T-(B_k^{low}+B_k))}]$
  $signal_k = (signal_{k-1}).(canceler)$
end while

In this algorithm, $\mathbf{0}_{(1\times i)}$ is the all zeros vector of length i, $\mathbf{1}_{(1\times j)}$ is the all ones vector of length j, $().()$ is the element-by-element vector multiplication, and $target_k^{final}$ is the estimated rectangular window around the k^{th} signal with average power $A_k - A_k^{diff}$, bandwidth B_k and carrier frequency:

$$f_k^c = \frac{B_k^{low}+B_k^{high}}{2} \quad \forall k = 1\dots K \tag{3}$$

Figure 2 shows an example with two OFDM signals, one narrowband signal around 5 GHz and one wideband signal around 2.5 GHz. One can see that the algorithm provides good estimates of the spectral properties of the received

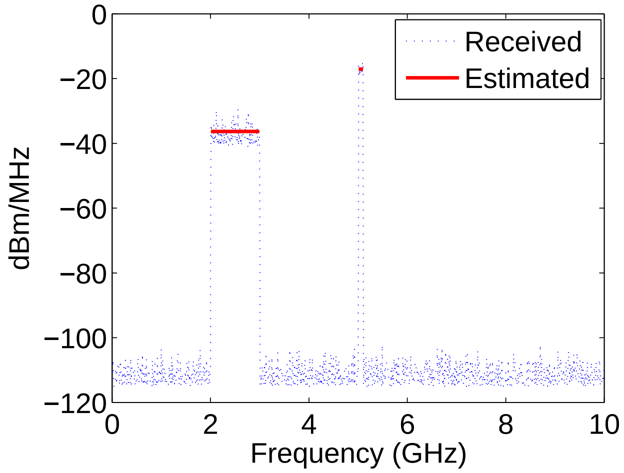


Figure 2: Spectral components estimation of multiple signals

signals. In this case we considered two signals with non-overlapping spectrum. Note that if two or more signals share the same bandwidth, the cancelling operation in **Algorithm 1** should be relaxed in order to obtain useful estimates of the spectral properties of the multiple signals. Based on the estimate of the average power, bandwidth and carrier frequency, each signal of interest can be downconverted into baseband and low-pass filtered. Depending on the cut-off frequency of the low-pass filter, the oversampling factor q can be determined as the ratio between the bandwidth of the low-pass filter and the bandwidth of the signal of interest.

3. PARAMETER ESTIMATION TOOLS FOR CP-OFDM SIGNALS

In this section, we review some parameter estimation tools based on autocorrelation and cyclic autocorrelation to estimate CP-OFDM signal parameters in frequency selective channels, which have been described in [3, 4, 5].

The parameter estimation block scheme for CP-OFDM is presented in Figure 3. First, an autocorrelation test is performed on the baseband signal of interest in order to detect peaks of correlation. The most significant peak, corresponding to the symbol duration T_u, is stored for further analysis. With the knowledge of the oversampling factor q, the number of subcarriers can be estimated by the ratio between the symbol duration and the oversampling factor T_u/q assuming that we have normalized the receiver sampling period $T_r = 1$. The overall symbol duration T_s is determined using a cyclic autocorrelation at delay T_u. The CP duration is easily computed as the difference between the overall symbol duration and the useful signal $T_{cp} = T_s - T_u$. The input signal can be modeled as a received sequence $\mathbf{y} = [y(0)\dots y(N-1)]^T$ of length N (which corresponds to a single spectral component of the received signal $\mathbf{s}$) such that:

$$y(i) = e^{j(2\pi\varepsilon i+\phi)} \sum_{l=\theta}^{L-1+\theta} h(l-\theta)x(i-l)+n(i) \quad i \in [0\dots N-1] \tag{4}$$

where $\mathbf{x} = [x(0)\dots x(N-1)]^T$ is the oversampled transmitted signal vector, the $h(l)$'s are the oversampled multipath channel coefficients with L the number of channel taps, $\mathbf{n} = [n(0)\dots n(N-1)]^T$ is the vector of Additive White Gaussian

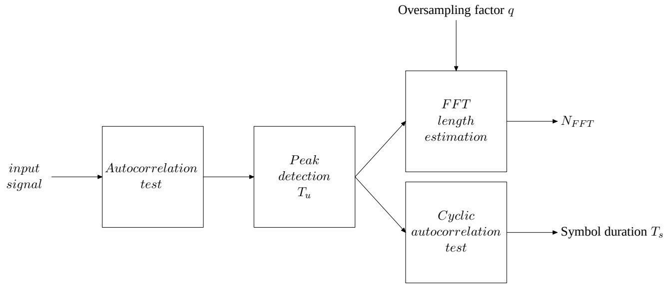


Figure 3: Block scheme for parameter estimation of CP-OFDM signals

Noise (AWGN), ϕ the receiver phase offset, ε the receiver frequency offset and θ the receiver time offset. The autocorrelation of the received sequence can be written as:

$$r(k) = \frac{1}{N}\sum_{i=0}^{N-1} y(i)y^*(i-k) \quad k \in [0\dots N-1] \tag{5}$$

with k the shift index. We assume that two vectors $\mathbf{y}$ are concatenated in order to cope with the data outside the interval $i \in [0, N-1]$. For CP-OFDM, the last part of the OFDM symbol is copied at the beginning to prevent Inter Symbol Interference (ISI) after multipath propagation. Therefore, a peak in the autocorrelation function can be observed at delay T_u (assuming T_r=1). The autocorrelation function can be derived from the received sequence model in (4), leading to:

$$r(k) = \begin{cases} \sum_{l=0}^{L-1} |h(l)|^2\sigma_x^2 + \sigma_n^2 & k=0 \\ e^{j2\pi\varepsilon T_u}\sum_{l=0}^{L-1} |h(l)|^2 \frac{T_{cp}}{T_s}\sigma_x^2 & k=T_u \\ e^{j2\pi\varepsilon k}\sum_{l=0}^{L-1} h(l+k)h^*(l)\sigma_x^2 & k=1,\dots,L-1 \\ e^{j2\pi\varepsilon k}\sum_{l=0}^{L-1} h(l+k-T_u)h^*(l)\frac{T_{cp}}{T_s}\sigma_x^2 & k=T_u+(1,\dots,L-1) \\ 0 & otherwise \end{cases} \tag{6}$$

with σ_x^2 the variance of the transmitted signal and σ_n^2 the variance of the AWGN. As stated by these equations, there are $2L$ peaks due to the multipath coefficients when the channel is stationary over the observation window. We assume that the maximum channel delay spread τ_{max} is smaller than the symbol duration T_u, therefore the peaks corresponding to the CP insertion will appear as a second cluster of peaks at higher values of k. Hence we discard the peaks in the first cluster and we keep the highest peak in the second cluster for the estimation of the symbol duration. The cyclic autocorrelation is given by:

$$c^\beta(k) = \frac{1}{N}\sum_{i=0}^{N-1} y(i)y^*(i-k)e^{-2\pi j\beta i/N} \quad (k,\beta) \in [0\dots N-1] \tag{7}$$

We can determine the overall symbol duration $T_s = N/\beta_{opt}$ (assuming T_r=1) with an exhaustive search on the cyclic autocorrelation at delay T_u using the following optimization problem:

$$\beta_{opt} = \max_{\beta\neq 0} |c^\beta(T_u)|^2 \tag{8}$$

This exhaustive search can be restricted to $\lceil N/T_u \rceil$ to reduce complexity, by assuming that $T_s > T_u$.

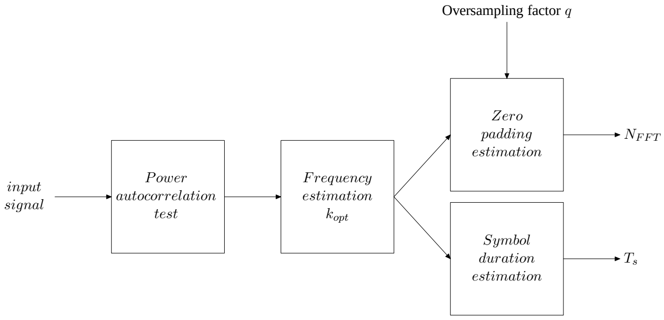


Figure 4: Block scheme for parameter estimation of ZP-OFDM signals

4. PARAMETER ESTIMATION TOOLS FOR ZP-OFDM SIGNALS

In this section, we develop a parameter estimation tool based on power autocorrelation to estimate ZP-OFDM signal parameters in frequency selective channels.

The proposed block scheme is presented in Figure 4. First, a power autocorrelation test is performed on the baseband signal of interest in order to detect the presence of a zero padding suffix. If the received signal is a ZP-OFDM signal, the power autocorrelation becomes a periodic triangular function with a period corresponding to the overall symbol duration $T_s = N/k_{opt}$ where k_{opt} is the most significant frequency component of the power autocorrelation (assuming that we have normalized the receiver sampling period T_r=1). The symbol duration T_u and the ZP duration T_{zp} are estimated with an exhaustive search based on a target train of triangular windows according to the LSE criterion. Finally, with the knowledge of the oversampling factor q, the number of subcarriers can be estimated by the ratio between the symbol duration and the oversampling factor T_u/q (assuming T_r=1). The power autocorrelation of the received sequence can be written as:

$$d(k) \stackrel{\triangle}{=} \frac{1}{N}\sum_{i=0}^{N-1}|y(i)|^2|y(i-k)|^2 \quad k \in [0\dots N-1] \tag{9}$$

with k the shift index. Defining $c = |k - tT_s|$ with t the train index corresponding to the t^th triangular function, the values of the power autocorrelation are given by:

$$d(k) = \begin{cases} \frac{T_u}{T_s}(\sum_{l=0}^{L-1}|h(l)|^4\mu_x^4 + 4\sigma_x^2\sigma_n^2 + \mu_n^4) & \\ +\frac{T_{zp}}{T_s}\mu_n^4 & k,t = 0 \\ \frac{T_u-c}{T_s}(\sum_{l=0}^{L-1}|h(l)|^2\sigma_x^2 + \sigma_n^2)^2 & \\ +\frac{2c}{T_s}\sigma_n^2(\sum_{l=0}^{L-1}|h(l)|^2\sigma_x^2 + \sigma_n^2) & 0 < c < T_{zp} \\ +\frac{T_{zp}-c}{T_s}\sigma_n^4 & \forall t \neq 0 \\ \frac{T_u-T_{zp}}{T_s}(\sum_{l=0}^{L-1}|h(l)|^2\sigma_x^2 + \sigma_n^2)^2 & \\ +\frac{2T_{zp}}{T_s}\sigma_n^2(\sum_{l=0}^{L-1}|h(l)|^2\sigma_x^2 + \sigma_n^2) & otherwise \end{cases} \tag{10}$$

with μ_x^4 the 4^th order moment of the transmitted signal and μ_n^4 the 4^th order moment of the AWGN. One can observe that the phase and frequency offsets do not affect the power autocorrelation feature. To find the number of periods k_{opt} in the power autocorrelation function, we define the vector $\mathbf{d} = [d(0)\dots d(N-1)]$, its frequency transform $\mathbf{D} = FFT(\mathbf{d})$ and we compute:

$$k_{opt} = \underset{k\neq 0}{max}|\mathbf{D}(k)|^2 \tag{11}$$

Assuming that the received power has been normalized to unity, the distance between the peak and the minimum of the power autocorrelation function for a target train of triangular windows with a zero padding of length i is $l_1 = T_s i/(T_s - i)^2$. We can also define the distance between the minimum of the power autocorrelation function and the zero axis $l_2 = T_s(T_s - 2i)/(T_s - i)^2$. Therefore, the surface of the power autocorrelation shifted by l_2 ($\mathbf{d}^{shifted} = \mathbf{d}^{norm} - l_2$) is defined as:

$$A_i = sum\left(\mathbf{d}^{norm} - T_s\frac{T_s - 2i}{(T_s - i)^2}\right) \tag{12}$$

We design a target train of triangular windows (using $dec = [0, \frac{1}{i}, \frac{2}{i}, \dots, 1]$ and $decr = [1, \dots, \frac{2}{i}, \frac{1}{i}, 0]$) as follows:

$$\begin{aligned} \mathbf{d}_i^{target} &= [\tfrac{A_i}{ik_{opt}}(ones(i) - dec), zeros(\tfrac{N}{k_{opt}} - 2i), \\ &\tfrac{A_i}{ik_{opt}}(ones(i) - decr)]^T \times k_{opt} \end{aligned} \tag{13}$$

The ZP duration is then estimated as $T_{zp} = i_{opt}$ using an exhaustive search in the following optimization problem:

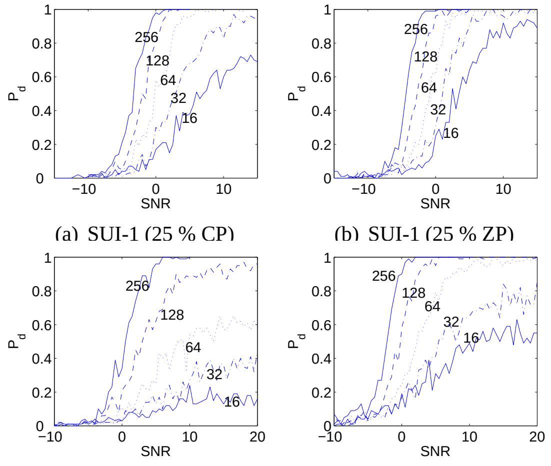
$$i_{opt} = \underset{i}{min}(\mathbf{d}^{shifted} - \mathbf{d}_i^{target})^2 \tag{14}$$

The exhaustive search can be reduced to $\lceil T_s/2 \rceil$ by assuming that the ZP duration cannot exceed half of the symbol duration T_s.

5. RESULTS

Simulation results are presented based on 100 Monte Carlo realizations of signals and frequency selective channels with time and frequency offsets to assess the performance of the parameter estimation in realistic scenarios. In particular, we study the influence of the number of subcarriers, the CP or ZP duration, and the data record length.

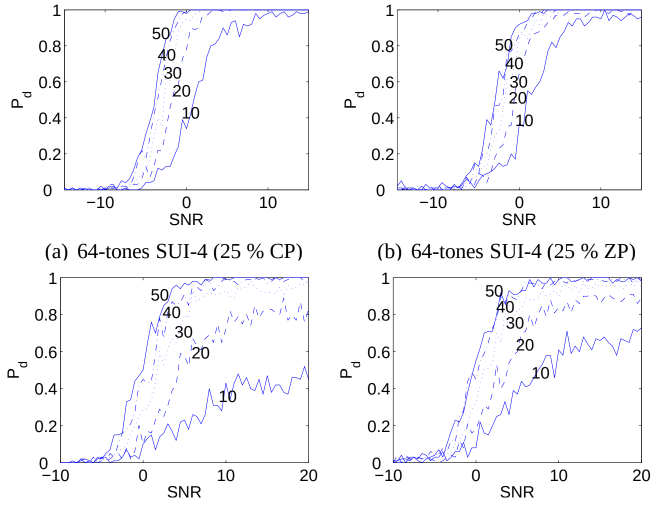
The left figures of Figure 5 show the influence of the number of subcarriers and the CP duration expressed in percentage of the symbol duration T_u on the probability of correct detection P_d (which indicates that the algorithm correctly estimates the symbol duration T_u and the CP duration T_{cp}) for the CP-OFDM parameter estimation tool presented in section 3. The right figures of Figure 5 show the influence of the number of subcarriers and the ZP duration expressed in percentage of the symbol duration T_u on the probability of correct detection P_d (which indicates that the algorithm correctly estimates the symbol duration T_s, the zero padding estimator T_{zp} being more sensitive to noise) for the ZP-OFDM parameter estimation tool presented in section 4. Simulation results are performed on the Stanford University Interim (SUI)-1 channel model with 10 MHz bandwidth signals (q=1) and 10 OFDM symbols [7]. These results show that the number of subcarriers and the CP or ZP duration have a significant impact on the performance. Indeed, for CP-OFDM signals, 256



(a) SUI-1 (25 % CP) (b) SUI-1 (25 % ZP)

(c) SUI-1 (12.5 % CP) (d) SUI-1 (12.5 % ZP)

Figure 5: Influence of the number of subcarriers



(a) 64-tones SUI-4 (25 % CP) (b) 64-tones SUI-4 (25 % ZP)

(c) 64-tones SUI-4 (12.5 % CP) (d) 64-tones SUI-4 (12.5 % ZP)

Figure 6: Influence of the data record length

subcarriers and 25% CP duration lead to P_d=1 at SNR=2dB, while 64 subcarriers and 12.5% CP duration lead to P_d=0.4 at SNR=20dB. The parameter estimation tool for ZP-OFDM signals gives a better performance than the parameter estimation tool for CP-OFDM signals (256 subcarriers and 25% ZP duration lead to P_d=1 at SNR=-1dB). However, for a small number of subcarriers and small ZP durations the ZP-OFDM tool has a reduced probability of correct detection.

Figure 6 shows the influence of the data record length (number of OFDM symbols) on the probability of correct detection P_d with the SUI-4 channel model and 64 subcarriers (typical Wifi signals with 25% CP duration). One can see that the performance can be increased when the number of OFDM symbols is increased. The SUI-4 channel has its maximum delay spread lower than the symbol duration T_u ($T_u > \tau_{max}$) and has stronger Non-Line Of Sight (NLOS) components than SUI-1. With 12.5% CP duration, 10 OFDM symbols lead to P_d=0.44 at SNR=15dB, while 50 OFDM symbols lead to P_d=1 at 8 dB. For ZP-OFDM signals, increasing the number of OFDM symbols has the same impact as for CP-OFDM signals, i.e. the probability of correct detection increases for lower SNRs.

The influence of the channel is relatively small compared to the influence of the number of subcarriers, the CP or ZP duration, and data record length. These parameter estimation tools work particularly well on current standards like WiMAX (256 subcarriers and 25% CP duration), WiMedia (128 subcarriers and 22.4% ZP duration). Indeed, simulation results show that P_d=1 can be reached with 5 OFDM symbols at SNR=5 dB for WiMAX on SUI channel models and for WiMedia on typical Ultra Wide-Band (UWB) channel models. These characteristics are used to discriminate between multi-carrier and single-carrier modulations, i.e. if two or more consecutive blocks provide the same estimate of the parameters (T_u for CP-OFDM signals and T_s for ZP-OFDM signals), we declare that a multi-carrier modulation has been detected. If the consecutive blocks provide different estimate of these parameters, then the signal is declared either noise or single carrier transmission.

6. CONCLUSION

In this paper, a spectrum monitoring scheme has been presented where the spectral properties of a received signal containing multiple signals of interest are first estimated by the averaged periodogram non-parametric approach using an FFT. The signals of interest are further processed to determine the type of modulation (single-carrier or multi-carrier) and to estimate their parameters. In particular, we have developed a parameter estimation tool for ZP-OFDM signals based on power autocorrelation to determine the symbol and zero padding duration. Simulation results have shown that OFDM signals without a CP (as used in WiMedia) can be detected based on their zero padding without any loss in performance compared to similar CP-OFDM parameter estimation tools.

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