Blind Demodulation for CP-OFDM and ZP-OFDM transmission over frequency selective channels

Vincent Le Nir, Toon van Waterschoot, Jonathan Duplicy, and Marc Moonen

***Abstract*—In this paper, we focus our attention on blind demodulation for multi-carrier modulation in the context of radio surveillance and military applications. We present a blind demodulation technique for CP-OFDM and ZP-OFDM transmission over frequency selective channels. The technique exploits the cyclic prefix or zero padding structure of the transmitted signal to estimate the parameters and to demodulate the transmitted symbols without requiring any additional pilots. Simulation results are performed on various channel models with timing and frequency offsets. The presented technique shows that the different transmitted symbols can be retrieved whenever the channel exhibits some correlation in the time and frequency domains, i.e. as for instance in LOS channels.**

***Index Terms*—orthogonal frequency division multiplexing (OFDM), blind demodulation.**

I. Introduction

In this paper, we describe a technique to blindly demodulate digital communications systems employing orthogonal frequency division multiplexing (OFDM). The technique exploits the cyclic prefix (CP) or zero padding (ZP) structure of the transmitted signal to estimate the parameters and to demodulate the transmitted symbols without requiring any additional pilots. The aim of the paper is to show that the different transmitted symbols can be retrieved whenever the channel exhibits some correlation in the time and frequency domains, i.e. as for instance in line of sight (LOS) channels.

The literature on blind demodulation can be divided in two categories: data-aided and non-data-aided techniques. Data-aided techniques use additional pilot symbols known at the receive side to estimate the channel or to demodulate directly the transmitted signal. Non-data-aided techniques require an exhaustive search on the transmitted constellation or a differential constellation to solve phase ambiguity issues, but they are compulsory in the context of radio surveillance and military applications since they do not require additional pilot symbols.

In this paper, we propose a new non-data-aided approach for blind demodulation of CP-OFDM and ZP-OFDM transmission in frequency selective channels. We assume that the cyclic prefix or zero padding length is larger than the channel impulse response. Moreover, we assume the knowledge of the useful time interval T_u, cyclic prefix duration T_{cp} or zero padding duration T_{zp} and number of subcarriers N_c which can indeed be estimated blindly with the algorithms described in [1]. We also assume the knowledge of the timing and frequency offsets.

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We utilize a timing offset estimation technique that exploits the cyclic prefix or zero padding structure of the OFDM signal and tracks time domain symbol energy variations based on a transition metric [2]. Contrary to the autocorrelation metric [3], [4], the transition metric based technique is able to estimate the timing offset in frequency selective channels with strong multipath components. We also use the autocorrelation properties of CP-OFDM signals to estimate the frequency offset as in [3], [4]. After synchronization and conversion to the frequency domain, the channel amplitudes and phases can be tracked whenever the channel channel exhibits some correlation in the time and frequency domains, i.e. as for instance in LOS channels.

The paper is organized as follows. In section II, we present the OFDM signal model, we review the estimation techniques for the useful time interval T_u, cyclic prefix duration T_{cp} or zero padding duration T_{zp}, number of subcarriers N_c, timing and frequency offsets. Then, we present the technique for amplitude and phase estimation for each subcarrier. In section III, simulation results are presented with realistic channels models. Finally, conclusions are drawn in section IV.

II. Description of the algorithm

The non-data-aided technique presented in this paper has been developed in the context of radio surveillance and cognitive radio systems for multi-carrier modulations. The wideband received signal may contain multiple OFDM signals of interest. Therefore, the received signal is sampled in a large bandwidth to include existing and future OFDM standards, such as Wifi (2.4 GHz or 5 GHz), WiMAX (3.5 GHz), Long Term Evolution (LTE) or WiMedia (3.1-10.6 GHz) signals. The carrier frequencies, bandwidths, and average powers of the detected signals are estimated. After downconversion to baseband and low-pass filtering, each signal of interest is processed through a feature detection block to determine whether or not it is an OFDM signal and to estimate blindly its useful time interval T_u, its cyclic prefix duration T_{cp} or zero padding duration T_{zp} and its number of subcarriers N_c [1]. Each signal of interest can be modeled as a received sequence $\mathbf{y} = [y(0) \dots y(N-1)]^T$ of length N such that:

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

where $\mathbf{x} = [x(0) \dots x(N-1)]^T$ is the transmitted signal vector oversampled by the ratio between the cut-off frequency of the low-pass filter and the transmitter maximum frequency, 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 Noise (AWGN), ϕ the receiver phase offset, ϵ the receiver frequency offset and θ the receiver timing offset.

To synchronize with the CP-OFDM symbols, we propose to use a metric based on the difference between the received sequence and the same sequence shifted by the useful time interval T_u [2]. We assume that the cyclic prefix duration T_{cp} is larger than the channel impulse response τ_{max}. The correlated duration $T_{cp} - \tau_{max}$ of the cyclic prefix is canceled out in this operation. In this way, the cyclic prefix structure of the OFDM signal is exploited by tracking time domain symbol energy variations based on a transition metric between the end of the correlated duration $T_{cp} - \tau_{max}$ and the beginning of a new OFDM symbol. Contrary to the autocorrelation metric [3], [4], the transition metric based technique is able to estimate the timing offset in frequency selective channels even with strong multipath components. The received sequence of length N is divided into M blocks of size $T_s = T_u + T_{cp}$ where the transition metric is performed on the available blocks except the edge blocks. The proposed transition metric is given by:

$$\theta_{opt} = \underset{\theta}{\operatorname{argmax}} \sum_{m=1}^{M-2} \frac{(|y(i+1)| - |y(i+1-T_u)|)^2}{(|y(i)| - |y(i-T_u)|)^2} \Bigg|_{i=mT_s+\theta+T_{cp}-1} \tag{2}$$

The use of the modulus $|.|$ operation makes the algorithm insensitive to large CFOs (in case of small CFOs the modulus operation can be used outside the difference operation). Knowing the useful time interval T_u, cyclic prefix duration T_{cp}, and timing offset, the techniques in [3], [4] based on an autocorrelation metric can be used to estimate the frequency offset. A similar algorithm which tracks time domain symbol energy variations can be used for ZP-OFDM signals, where we assume that the symbol duration T_s and the zero padding duration T_{zp} have been estimated blindly according to the algorithm described in [1]. We also assume that the zero padding duration T_{zp} is larger than the channel impulse response τ_{max}. In this case, the zero padding structure of the received OFDM signal is exploited by tracking time domain symbol energy variations (transition metric) between the end of the duration $T_{zp} - \tau_{max}$ (noise only) and the beginning of a new OFDM symbol [2]. The transition metric is performed on the available blocks except the last block, and is given by:

$$\theta_{opt} = \underset{\theta}{\operatorname{argmax}} \sum_{m=0}^{M-2} \frac{|y(i+1)|^2}{|y(i)|^2} \Bigg|_{i=(m+1)T_s+\theta-1} \tag{3}$$

After synchronization, we can discard the cyclic prefix and convert the CP-OFDM symbols to the frequency domain by the discrete Fourier transform (DFT) operation. For ZP-OFDM signals, the overlap-add (OLA) method converts the channel convolution into a circular convolution [5]. Then, the ZP-OFDM symbols are transformed to the frequency domain by the discrete Fourier transform (DFT) operation. As there is no interference between two consecutive OFDM symbols we obtain independent subcarriers with the following channel model:

$$Y_{m,k} = H_{m,k} X_{m,k} + N_{m,k} \tag{4}$$

where $Y_{m,k}$ is the demodulated data for the m^{th} block and the k^{th} subcarrier, $H_{m,k}$ is the channel frequency response, $X_{m,k}$ is the transmitted symbol and $N_{m,k}$ is the corresponding channel noise. In order to determine blindly the constellation used on each subcarrier, we assume that some correlation exists between several consecutive blocks and we calculate the fourth-order normalized cumulant on each tone for several blocks. Assuming the channel invariant over the M blocks, the normalized fourth order cumulant is given by:

$$\begin{aligned} \tilde{C}_{42,Y_k} &= \frac{C_{42,Y_k}}{C_{21,Yk}} \\ &= \frac{\frac{1}{M}\sum\limits_{m=0}^{M-1} |Y_{m,k}|^4 - |\frac{1}{M}\sum\limits_{m=0}^{M-1} Y_{m,k}^2|^2 - 2(\frac{1}{M}\sum\limits_{m=0}^{M-1} |Y_{m,k}|^2)^2}{(\frac{1}{M}\sum\limits_{m=0}^{M-1} |Y_{m,k}|^2)^2} \end{aligned} \tag{5}$$

The theoretical values for the normalized fourth order cumulant are shown on Table I. We need to set some thresholds between the theoretical values of the different constellation sizes. The fourth order cumulant is noise independent but the normalized fourth order cumulant is noise dependent owing to the normalization by the power of each subcarrier. Therefore, an estimate of the noise variance can lead to better performance by subtracting the noise power at the denominator of the normalized fourth order cumulant.

Constellation	BPSK	QPSK	16QAM	64QAM
$\tilde{C}_{42,y}$	-2.0000	-1.0000	-0.6800	-0.6191

TABLE I
THEORETICAL VALUES FOR THE NORMALIZED FOURTH ORDER CUMULANTS

Then, we perform a per-tone phase offset estimation based on modulation stripping [6], [7]. The principle of modulation stripping is to calculate the rotated angle of the received constellation. For QPSK constellation, the angle of the fourth order moment is calculated for each subcarrier taking into account several blocks and then divided by four. The modulation stripping formula for QPSK on tone k is given by:

$$\phi_k = arg\left(\frac{1}{M}\sum_{m=0}^{M-1} Y_{m,k}^4\right) \tag{6}$$

Moreover, assuming that the transmitted constellations exhibit unitary variance on each subchannel k ($\frac{1}{M}\sum\limits_{m=0}^{M-1} |X_{m,k}|^2 = 1$), the estimated channel amplitude is given by:

$$|\hat{H}_k|^2 = \frac{1}{M}\sum_{m=0}^{M-1} |Y_{m,k}|^2 \tag{7}$$

The knowledge of the noise variance leads to a better estimation as we can subtract it from equation (7). Knowing the phase offset and the amplitude for each subcarrier, we can track the channel in the frequency domain. The phase ambiguity problem can be solved by phase unwrapping. Phase unwrapping consists in avoiding abrupt changes of 2π in the phase. The phase unwrapping is performed using the following procedure:

- if ϕ_{k-1}-$\phi_k > x$ then ϕ_k=ϕ_k+2π
- if ϕ_{k-1}-$\phi_k < -x$ then ϕ_k=ϕ_k-2π

with x the threshold chosen according to the channel, for instance π for SUI-1 channels which do not exhibit large phase variations between subcarriers.

III. Simulation results

In this section, we evaluate the performance of the presented techniques for WiMAX [8] and ZP-OFDM signals with WiMAX parameters on Stanford University Interim (SUI) [10] channel models with various time and frequency offsets. Simulations results are performed on 100 Monte Carlo trials with 10 OFDM symbols. Two types of channels are chosen, the SUI-1 channel which have LOS components for flat terrain with light tree density and the SUI-4 channel which has NLOS components for hilly terrain with heavy tree density.

The performance results for the estimation of the useful time interval T_u, cyclic prefix duration T_{cp} or zero padding duration T_{zp}, number of subcarriers N_c and timing offset can be found in [1], [2]. The following simulation results take into account the full receiver communication chain and errors during the previous parameter estimation steps. Then, we can convert the OFDM symbols to the frequency domain using a DFT. Figure 1 shows a single demodulated OFDM symbol with WiMAX parameters and QPSK constellation on a SUI-1 channel model before modulation stripping and after modulation stripping. We can see that modulation stripping corrects the phase offset introduced by the channel response for each subcarrier.

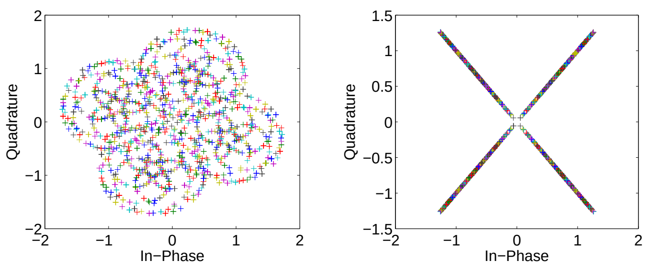

Fig. 1. Frequency domain demodulated CP-OFDM symbol before and after phase offset correction by modulation stripping with WiMAX parameters and QPSK constellation on a SUI-1 channel model

Figure 2 shows the amplitude and phase channel estimates before phase unwrapping and after phase unwrapping with WiMAX parameters and QPSK constellation on a SUI-1 channel model. LOS channels such as the SUI-1 channel model have weak fading deeps as low as -2 dB. We can see that the phase unwrapping algorithm tracks and corrects the abrupt phase changes in the frequency domain.

Figure 3 shows the amplitude and phase channel estimates before phase unwrapping and after phase unwrapping with WiMAX parameters and QPSK constellation on a SUI-4 channel model. NLOS channels such as the SUI-4 channel model have strong fading deeps up to -20 dB. The phase becomes unstable in these deeps and therefore the phase unwrapping algorithm has some difficulties to track abrupt changes in the frequency domain.

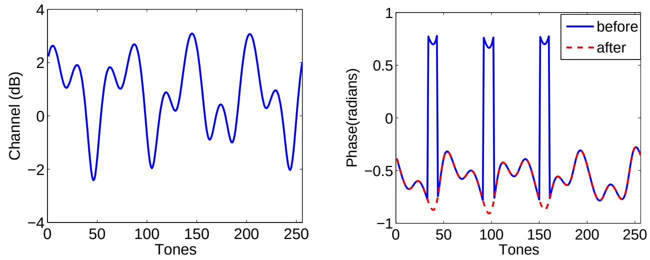

Fig. 2. Amplitude and phase channel estimates before phase unwrapping and after phase unwrapping with WiMAX parameters and QPSK constellation on a SUI-1 channel model

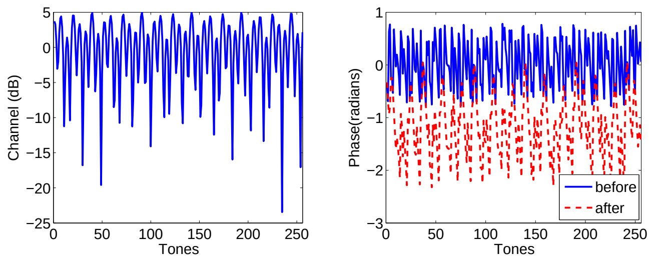

Fig. 3. Amplitude and phase channel estimates before phase unwrapping and after phase unwrapping with WiMAX parameters and QPSK constellation on a SUI-4 channel model

Figure 4 shows Monte Carlo simulations with 100 SUI-1 channel realizations and CP-OFDM or ZP-OFDM tranmsission. For each channel realization, we compare the 4 possible received bit sequence with the transmitted bit sequence. The left figure shows the Bit Error Rate (BER) versus the Signal to Noise Ratio (SNR) for CP-OFDM transmission with a single channel realization and an average of 100 SUI-1 channel realizations. A floor can be observed at high SNR on due to some bad channel realizations which can have lower deeps and phase instability. Actually, 97% of the SUI-1 channel realizations lead to the single BER curve. For NLOS channels such as SUI-4 channel models, it is too difficult to track the phase in the frequency domain, leading to bad average BER curves (20% of the SUI-4 channel realizations lead to the single BER curve). The right figure shows the single and average BER for ZP-OFDM tranmission. As the estimation of the zero padding duration is quite sensitive to the noise [1], we compare different values around the estimated zero padding duration such that the normalized fourth order cumulant is minimized similarly to [12]. Considering the full communication chain, this leads to similar conclusions as CP-OFDM transmission, i.e. 92% of the SUI-1 channel realizations lead to the single BER curve while this percentage drops to 20% for SUI-4 channels. Therefore, we can conclude that it is possible to retrieve the transmitted bits of an unknown CP-OFDM or ZP-

OFDM transmitter as long as the receiver is placed in a LOS situation.

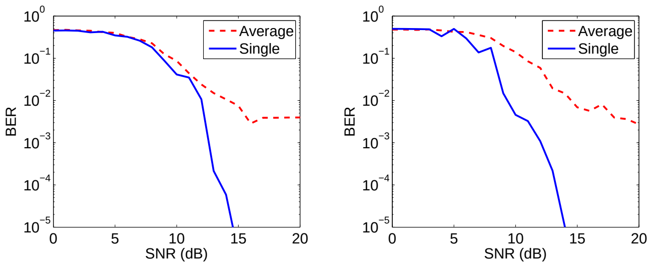

Fig. 4. BER curves for blind demodulation of CP-OFDM (left) and ZP-OFDM (right) transmission

IV. Conclusion

In this paper, we have described a technique to blindly demodulate digital communications systems employing orthogonal frequency division multiplexing (OFDM). The proposed technique has exploited the cyclic prefix or zero padding structure of the transmitted signal to estimate the parameters and to demodulate the transmitted symbols without requiring any additional pilots. The results have shown that the different transmitted symbols can be retrieved whenever the channel exhibits some correlation in the time and frequency domains, i.e. as for instance in LOS channels.

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