Performance Evaluation of WPMCM with Carrier Frequency Offset and Phase Noise

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***Abstract*—Wavelet Packet based Multi-Carrier Modulation (WPMCM) offers an alternative to the well-established OFDM as an efficient multicarrier modulation technique. It has strong advantage of being a generic transmission scheme whose actual characteristics can be widely customized to fulfill several requirements and constraints of an advanced communication systems. However, a few research questions remain to be addressed before the novel WPMCM can be used in practice. One of the major concerns is the performance of WPMCM transceivers in the presence of analogue radio frequency front-end imperfections. In this paper we analyze the impact of interference in WPMCM transmission caused by the carrier frequency offset and phase noise. The sensitivity of WPMCM transceivers to these errors using standard wavelets is evaluated through simulation studies and their performances are compared and contrasted with OFDM.**

***Index Terms*—WPMCM, Wavelet Packets, Carrier Frequency Offset, Phase Noise, Multicarrier Modulation**

I. Introduction

Multi-Carrier Modulation (MCM) is a widely used communication technique which divides the incoming high rate data among multiple carriers modulated at lower rates. By transmitting simultaneously N constellation symbols through N subcarriers the symbol rate is reduced to the one N^{th} of the original rate, and therefore the symbol duration is increased by N times. This leads to a transmission system which is robust against channel dispersions/fading, impulse noise and multipath interference. Traditionally the Fast Fourier Transform (FFT) based Orthogonal Frequency Division Multiplexing (OFDM) has been recognized as the most cost-effective and bandwidth efficient realization of multicarrier transceivers. In the last 15 years OFDM has been widely adopted and standardized across the world. Few of the applications and standards which use OFDM are Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), WiFi (IEEE 802.11a/g/j/n), World Wide Interoperability for Microwave Access (WiMAX - IEEE 802.16), Ultra Wide Band wireless Personal Area Network (UWB Wireless PAN - IEEE 802.15.3a) and Mobile Broadband Wireless Access (MBWA - IEEE 802.20).

Recently wavelet transformation has emerged as a strong candidate for digital modulation [1]–[2]. Wavelet Packet based Multi-Carrier Modulation (WPMCM) is a novel multicarrier modulation technique and a promising alternative to the well established OFDM. WPMCM was first proposed in [3] where the theoretical foundations were laid out for this novel orthogonal MCM technique and its use as an alternative to OFDM was propounded. The greatest motivation for pursuing WPMCM systems lies in the freedom they provide to communication systems designers. Unlike the Fourier bases which are static sines/cosines, WPMCM uses wavelets which offer flexibility and adaptation that can be tailored to satisfy an engineering demand. By tailoring the design specifications a wavelet based system that best suits a wireless engineering requirement could be conceived.

However a few key research questions remain to be addressed before WPMCM can become practically viable. One of them is its sensitivity and vulnerability to radio front-end induced impairments such as frequency offset and phase noise.

OFDM and WPMCM achieve high spectral efficiency by allowing the spectra of their subcarriers to overlap over one another. In OFDM the subcarriers overlap only in the frequency domain while subcarriers in WPMCM overlap in frequency as well as in time domain. When the transceivers are perfectly synchronized the subcarriers are mutually orthogonal and therefore they do not interfere one with another. However, the imperfection in the radio front-end, such as frequency offset and/or phase noise, can cause the subcarriers to lose their orthogonality. The rise of interference level due to loss of orthogonality among the subcarriers is only experienced in the

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multicarrier transmission. Therefore, multicarrier systems with overlapping subcarriers are much more sensitive to the frequency offset and phase noise when compared to single carrier systems. This disadvantage of multicarrier systems sets high demands on the quality of the analog radio frequency part, like the oscillator stability.

In case of OFDM the effects of frequency offset and phase noise are well documented in the literature [4]–[10] and a number of synchronization techniques are reported to estimate and reduce the frequency offset and phase noise effects [11]–[17]. While for the WPMCM the literature is far less comprehensive and until now very few attempts have been made to estimate the effect of radio front-end induced impairments.

In this paper we extend our previous work [18] by additional study of interferences caused by frequency offset and phase noise in WPMCM. Furthermore, the performance of WPMCM transceivers employing some standard wavelets is numerically evaluated under different conditions.

The rest of the paper is organized as follows. The system blocks of OFDM and WPMCM transceivers are outlined in section II. Carrier frequency offset is discussed in Section III followed by numerical results acquired for frequency offset which appear in Section IV. In Section V analysis of phase noise is given and in Section VI the results obtained by computer simulation for phase noise are shown. Finally, Section VII concludes the paper.

II. Multicarrier Transceivers

A. OFDM

OFDM transmission system can be efficiently implemented using IFFT at the transmitter side and FFT at the receiver side. The transmitter and receiver blocks of an OFDM communication system are illustrated in Fig.1 and Fig.2, respectively.

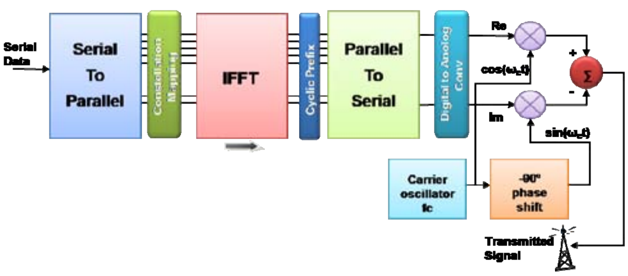

Figure 1. OFDM Transmitter

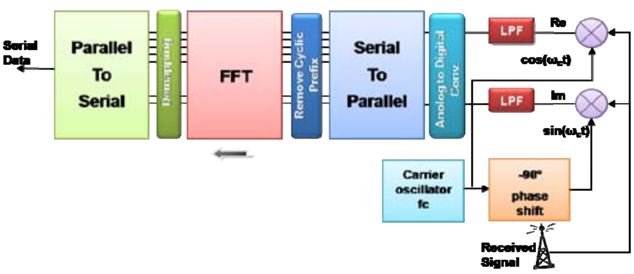

Figure 2. OFDM Receiver

Each OFDM symbol contains N subcarriers, a number that is determined by the size of a used FFT. If an OFDM system has a symbol period of T and uses N subcarriers with intercarrier spacing $\Delta f = {}^{1}/_{T}$, the output of the transmitter in one symbol period can be expressed as

$$S(n) = \sum_{k=0}^{N-1} a_k e^{j2\pi\frac{kn}{N}}, \quad 0 \le n \le N-1 \tag{1}$$

In (1) a_k represents mapped complex data symbols which are obtained from binary input stream using one of the standard multilevel modulation techniques, such as M-QAM or M-PSK.

If we assume ideal channel and perfect synchronization between OFDM transmitter and receiver, the received sequence $R(n)$ is identical to the transmitted signal, i.e. $R(n)=S(n)$. Under these conditions the demodulated data after FFT for the k'^{th} subcarrier can be expressed as

$$\begin{aligned} \hat{a}_{k'} &= \frac{1}{N}\sum_{n=0}^{N-1} R(n) e^{-j2\pi\frac{k'n}{N}} \\ &= \frac{1}{N}\sum_{n=0}^{N-1}\sum_{k=0}^{N-1} a_k e^{j2\pi\frac{kn}{N}} e^{-j2\pi\frac{k'n}{N}} \\ &= \sum_{k=0}^{N-1} a_k \left(\frac{1}{N}\sum_{n=0}^{N-1} e^{j2\pi\frac{n(k-k')}{N}} \right) \\ &= \sum_{k=0}^{N-1} a_k \delta(k-k') \\ &= a_{k'} \end{aligned} \tag{2}$$

In (2) δ denotes the Kronecker delta function.

B. WPMCM

WPMCM is a multiplexing method that makes use of orthogonal wavelet packets waveforms to combine a collection of parallel signals into a single composite signal. Fundamentally OFDM and WPMCM have many similarities as both use orthogonal waveforms as subcarriers and they achieve high spectral efficiency by allowing their subcarriers' spectra to overlap one another. The main differences between OFDM and WPMCM lie in the shape of the subcarriers and in way they are created.

One important property of wavelet based transformation is that the waveforms used in general are longer than the transform duration of one symbol. This causes WPMCM symbols to overlap in time domain. Thanks to the fulfillment of double shift orthogonality the overlap of the symbols does not automatically lead to Inter Symbol Interference (ISI) [19].

Longer waveforms allow better frequency localization of WPMCM's subcarriers while in OFDM the rectangular shape of DFT window generates large side lobes. Fig.3 and Fig.4 illustrate the spectra of 8 adjacent subcarriers for WPMCM and OFDM transceiver, respectively.

The other non-palatable consequence of time overlap is the inability to use guard intervals in wavelet based systems. Although adding guard intervals severely decrease spectral efficiency, they are effective and low complexity method to cope with dispersive channels and time offset.

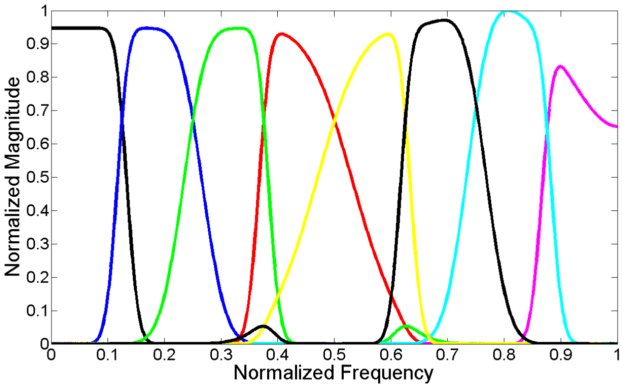

Figure 3. Spectrum of 8 WPMCM Subcarriers (Daubechies Wavelet with 20 Coefficients)

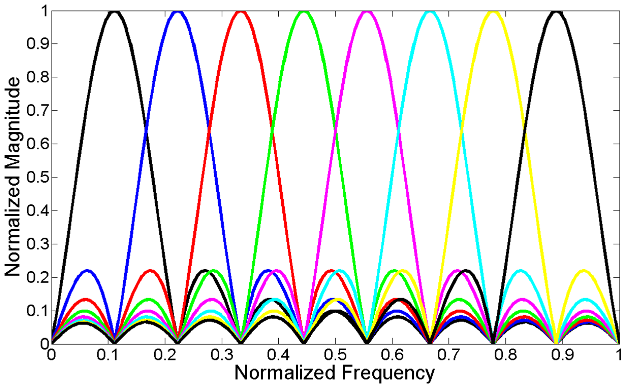

Figure 4. Spectrum of 8 OFDM Subcarriers

WPMCM employs Inverse Discrete Wavelet Packet Transform (IDWPT) at the transmitter side and Discrete Wavelet Packet Transform (DWPT) at the receiver side, analogous to the IFFT and FFT used by the OFDM transceivers. The IDWPT is implemented by wavelet packet synthesis filter bank which combines different parallel streams into a single signal. This composite signal is afterwards decomposed at the receiver using wavelet packets analysis filter bank or so called DWPT.

In Fig.5 a 4-channel wavelet packed based transmultiplexer is illustrated. The upsampling and downsampling operations by a factor 2 are represented by ↑2 and ↓2 respectively, while filter G stands for high-pass wavelet filter and filter H is corresponding low-pass scaling filter.

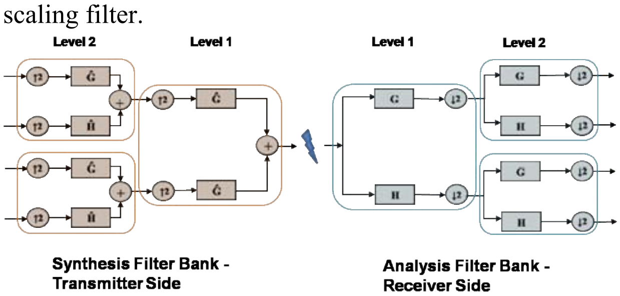

Figure 5. Wavelet Packed based Transmultiplexer
Left: Synthesis tree, Right: Analysis tree

The wavelet packet analysis and synthesis trees can be efficiently constructed by iteration of corresponding 2-channel filter bank. Therefore we can calculate the wavelet packet waveforms in a recursive manner using the following algorithm

$$\begin{aligned} \xi_{l+1}^{2p}(t) &= \sqrt{2}\sum_n h(n)\xi_l^p(t-2^l n) \\ \xi_{l+1}^{2p+1}(t) &= \sqrt{2}\sum_n g(n)\xi_l^p(t-2^l n) \end{aligned} \quad (3)$$

In (3) the wavelet packet waveforms are denoted by ξ while superscript p can be seen as subcarrier index at a given tree depth (level l). The scaling and wavelet filter coefficients in (3) are represented by $h(n)$ and $g(n)$, respectively.

Because WPMCM transceivers are realized by an iterative method we can easily change the number of subcarriers and their bandwidth. By performing an additional iteration of 2-channel filter bank at all outputs the subcarriers number is doubled or more generally the number of subcarriers is given by

$$N = 2^l \quad (4)$$

The subcarriers in WPMCM transceivers are completely determined by filters H and G and therefore by applying different set of filters we get different subcarriers which in turn lead to different transmission system characteristics. References [20]–[25] have shown that by just altering the filter coefficients the WPMCM transceivers are capable to achieve different values for bandwidth efficiency, frequency concentration of subcarriers, sensitivity to synchronization errors, PAPR, etc.

Filters in WPMCM cannot be arbitrary chosen and not all scaling and wavelet filters will fit the requirements for a communication system. First of all, we will only consider Finite Impulse Response (FIR) filters because they allow wavelet packet transformation to be implemented by described fast recursive algorithm. Furthermore, we require perfect reconstruction and hence the orthogonal subcarriers. These can only be generated by filters that fulfill the double shift orthogonality constraint [26]. The WPMCM's waveforms are mutually orthogonal if they satisfy the following condition

$$\left\langle \xi_l^p(t), \xi_l^i(t) \right\rangle = \sum_k \xi_l^p(t)\xi_l^i(t) = \delta(p-i) \quad (5)$$

In (5) the angle brackets stand for the inner product between two waveforms.

The WPMCM signal consists of compartmentalized frames which in turn contain multicarrier symbols obtained by summing modulated subcarriers. Since the filters used to derive the waveforms are than one multicarrier symbol period, the whole WPMCM frame has to be processed at once. The WPMCM transmitted signal in the discrete time domain can be expressed as

$$S(n) = \sum_u \sum_{k=0}^{N-1} a_{u,k}\xi_{2^{\log(N)}}^k(n-uN) \quad (6)$$

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In (6) k denotes the subcarrier index and u denotes the WPMCM symbol index. The constellation symbol modulating k^{th} subcarrier in u^{th} WPMCM symbol is represented by $a_{u,k}$.

The receiver demodulates the data by employing time reversed version of waveforms used by the transmitter. If we assume that the WPMCM transmitter and receiver are perfectly synchronized and that the channel is ideal, the detected data at the receiver output can be expressed as

$$\begin{aligned}\hat{a}_{u',k'} &= \sum_n R(n)\xi^{k'}_{2^{\log(N)}}(u'N-n)\\ &= \sum_n\sum_u\sum_{k=0}^{N-1} a_{u,k}\xi^{k}_{2^{\log(N)}}(n-uN)\xi^{k'}_{2^{\log(N)}}(u'N-n)\\ &= \sum_u\sum_{k=0}^{N-1} a_{u,k}\left(\sum_n \xi^{k}_{2^{\log(N)}}(n-uN)\xi^{k'}_{2^{\log(N)}}(u'N-n)\right)\\ &= \sum_u\sum_{k=0}^{N-1} a_{u,k}\delta(k-k')\\ &= a_{u',k'}\end{aligned} \tag{7}$$

In Fig.6 and Fig.7 the transmitter and receiver blocks of a WPMCM communication system are illustrated.

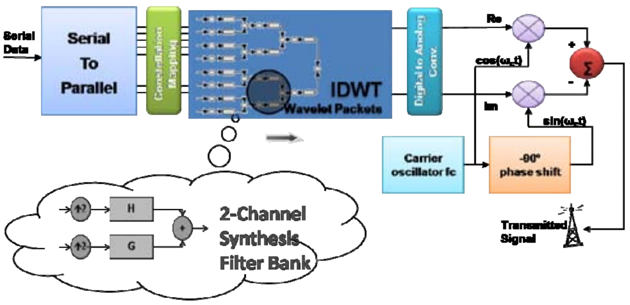

Figure 6. WPMCM Transmitter

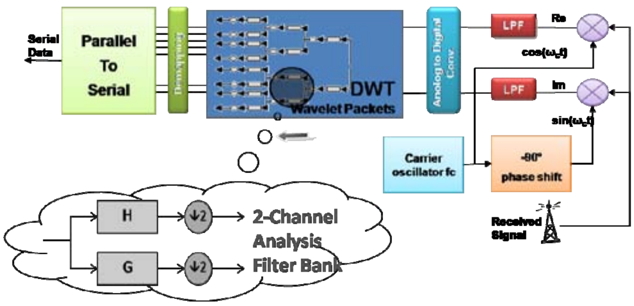

Figure 7. WPMCM Receiver

III. Carrier Frequency Offset in Multicarrier Modulation

The orthogonality between the subcarriers is maintained at the receiver only if the transmitter and receiver have the same reference frequency. Any offset in the frequency will result in loss of orthogonality and hence in generation of interference. The interference is the most severe consequence of frequency offset but not the only one. Besides the interference term, frequency offsets initiates attenuation and phase rotation of each subcarrier. Generally frequency offset can be caused by misalignment between receiver and transmitter local oscillator frequencies or due to Doppler shift.

The frequency offset can be modeled at the receiver by multiplying received time-domain signal by a complex exponential whose frequency component is equal to frequency offset value. If we assume that transmitted signal is given by $S(n)$, the received signal $R(n)$ can be written as

$$R(n) = S(n)e^{j2\pi f_\varepsilon n/N+\phi_0} + w(n) \tag{8}$$

In (8) f_ε denotes the relative frequency offset due to local oscillator mismatch or due to Doppler shift or due to combination of both. ϕ_0 is initial phase and w denotes additive white Gaussian noise (AWGN). Without loss of generality, we assume for the moment that $w(n) = 0$ and $\phi_0 = 0$.

A. Carrier Frequency Offset in OFDM

In OFDM the frequency offset prevents the perfect alignment of FFT bins with the peaks of the sinc pulses i.e. subcarriers. The FFT output corresponding to the k^{th} subcarrier can be written in this case as:

$$\begin{aligned}\hat{a}_{k'} &= \frac{1}{N}\sum_{n=0}^{N-1} R(n)e^{-j2\pi\frac{k'n}{N}}\\ &= \frac{1}{N}\sum_{k=0}^{N-1} a_k \sum_{n=0}^{N-1} e^{j2\pi\frac{kn}{N}}e^{j2\pi f_\varepsilon\frac{n}{N}}e^{-j2\pi\frac{k'n}{N}}\\ &= \frac{1}{N}\sum_{k=0}^{N-1} a_k \sum_{n=0}^{N-1} e^{j2\pi\frac{(k-k'+f_\varepsilon)n}{N}}\end{aligned} \tag{9}$$

Using the geometric series properties (9) can also be expressed as [10], [12]:

$$\hat{a}_{k'} = \frac{1}{N}\sum_{k=0}^{N-1} a_k \frac{\sin(\pi(k-k'+f_\varepsilon))}{\sin\left(\frac{\pi(k-k'+f_\varepsilon)}{N}\right)} e^{j\pi\left(\frac{N-1}{N}\right)(k-k'+f_\varepsilon)} \tag{10}$$

We can split (10) into two distinct parts

$$\begin{aligned}\hat{a}_{k'} &= a_{k'}\frac{\sin(\pi f_\varepsilon)}{N\sin\left(\frac{\pi f_\varepsilon}{N}\right)}e^{j\pi\left(\frac{N-1}{N}\right)f_\varepsilon}\\ &+\frac{1}{N}\sum_{k=0;k\neq k'}^{N-1} a_k \frac{\sin(\pi(k-k'+f_\varepsilon))}{\sin\left(\frac{\pi(k-k'+f_\varepsilon)}{N}\right)} e^{j\pi\left(\frac{N-1}{N}\right)(k-k'+f_\varepsilon)}\end{aligned} \tag{11}$$

The first component of (11) stands for useful demodulated signal, which has been attenuated and phase shifted due to frequency offset. The second part of (10) contains the ICI term, in which contribute all other subcarriers.

B. Carrier Frequency Offset in WPMCM

The presence of the frequency offset in WPMCM transceiver cause the frequency misalignment between the waveforms of the transmitter and receiver. The detected data at the WPMCM receiver in case of the frequency offset can be written for the k^{th} subcarrier and u^{th} symbol as

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$$\begin{aligned}\hat{a}_{u',k'} &= \sum_n R(n)\xi^{k'}_{{}^2\log(N)}(u'N-n) \\ &= \sum_n \sum_u \sum_{k=0}^{N-1} a_{f,k}\xi^{k}_{{}^2\log(N)}(n-uN)e^{j2\pi f_e \frac{n}{N}}\xi^{k'}_{{}^2\log(N)}(u'N-n) \\ &= \sum_u \sum_{k=0}^{N-1} a_{f,k}\left(\sum_n \xi^{k}_{{}^2\log(N)}(n-uN)e^{j2\pi f_e \frac{n}{N}}\xi^{k'}_{{}^2\log(N)}(u'N-n)\right)\end{aligned} \quad (12)$$

In order to shorten the derivation we are going to use different notation, first we define

$$\Omega^{u,u'}_{k,k'} = \sum_n e^{j2\pi f_e \frac{n}{N}}\xi^{k}_{{}^2\log(N)}(n-uN)\xi^{k'}_{{}^2\log(N)}(u'N-n) \quad (13)$$

Using equation (12) and (13) we can now express the output of the WPMCM receiver for the k^{th} subcarrier and u^{th} WPMCM symbol as

$$\hat{a}_{u',k'} = a_{u',k'}\Omega^{u',u'}_{k',k'} + \sum_{u;u\neq u'} a_{u,k'}\Omega^{u,u'}_{k',k'} + \sum_u \sum_{k=0;k\neq k'}^{N-1} a_{u,k}\Omega^{u,u'}_{k,k'} \quad (14)$$

In (14) the first term stands for attenuated and rotated useful signal. The second term gives the ISI due to symbols transmitted on the same subchannel and the third term denotes ICI measured over the whole frame.

IV. Numerical Results for Carrier Frequency Offset

The performance of WPMCM with frequency offset has been investigated by means of computer simulations and compared to the well-known OFDM. The WPMCM transceiver is simulated with different standard wavelets that are available today, an enumeration of tested wavelets and their properties is shown in table 1.

TABLE I.
Wavelet Specifications

Name	Length	*K*-Regularity	Orthogonality
Haar	2	1	Yes
Daubechies	20	10	Yes
Symlets	20	10	Yes
Coiflet	24	3	Yes
Discrete Meyer	102	1	Yes
Biorthogonal	(12, 4)	(6,2)	No

To simplify the analysis, the channel is taken to be additive white Gaussian noise (AWGN) and no other distortions except frequency offset is introduced. QPSK is the modulation of choice and frame size is set to 100 multicarrier symbols, each consisting of 128 subcarriers. Furthermore, the simulated system has no error estimation or correction capabilities and nor are guard intervals or guard bands used.

Fig.8 illustrates the Bit Error Rate (BER) of OFDM and WPMCM transceivers with relative frequency offset of 5% with regard to $^1/_T$ spacing. BER curves of different wavelets and OFDM show similar performance but due to frequency offset they all lie far from theoretical curve. The biorthogonal wavelet is the exception with a very poor performance compared to the other systems. This is due to the fact that the biorthogonal wavelet does not fulfill orthogonality condition (5) and therefore even without frequency offset it suffers from ICI and ISI.

In Fig.9 BER is shown for different values of relative frequency offset varying from 0 to 40 %. During this simulation we kept SNR constant at 16 dB. Again we can see that the performances of majority of the wavelets are very similar to that of OFDM. The biorthogonal wavelet has obviously a poor performance, while Haar wavelet slightly outperforms other wavelets and OFDM. Fig.9 implies that WPMCM and OFDM are both very sensitive to the frequency offset, since small variations of frequency offset degrade the system performance significantly.

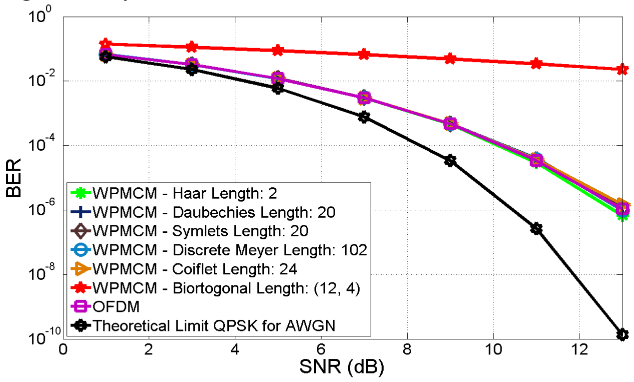

Figure 8. BER for WPMCM with Different Wavelets and OFDM under Relative Frequency Offset of 5%

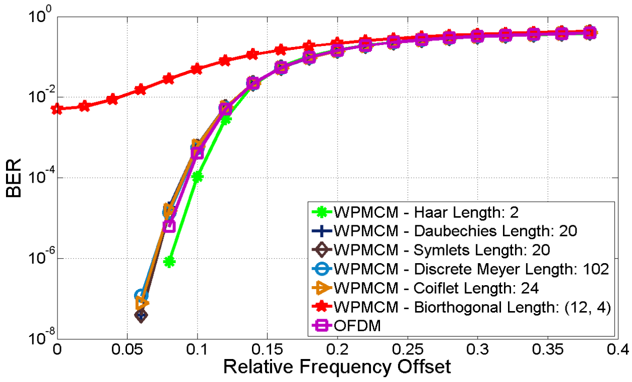

Figure 9. BER vs. Relative Frequency Offset for WPMCM and OFDM in AWGN Channel (SNR 16 dB)

Fig.10 illustrates the influence of the number of subcarriers in combination with frequency offset on the BER. All WPMCM transceivers are now simulated with the same wavelet but with different number of subcarriers. We arbitrarily chose the Daubechies wavelet with 20 coefficients. Furthermore the relative frequency offset is set to 10% and we use AWGN channel.

The degradation of WPMCM's BER in the presence of frequency offset is dependent on the number of subcarriers. This is straightforward when the absolute frequency offset is fixed [4], since more the subcarriers in a given bandwidth the subcarrier spacing decreases and hence the relative frequency offset increases. However, in the Fig.10 the relative frequency offset with respect to inter-carrier spacing is kept constant and there are still noticeable differences in the number of subcarriers used. WPMCM configurations with more subcarriers are more susceptible to the frequency offset (e.g. compare cases with 4, 8 and 16 carriers). However, beyond a point the

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impact plateaus and the number of carriers do not influence the frequency offset sensitivity (e.g. for 32 carriers and more).

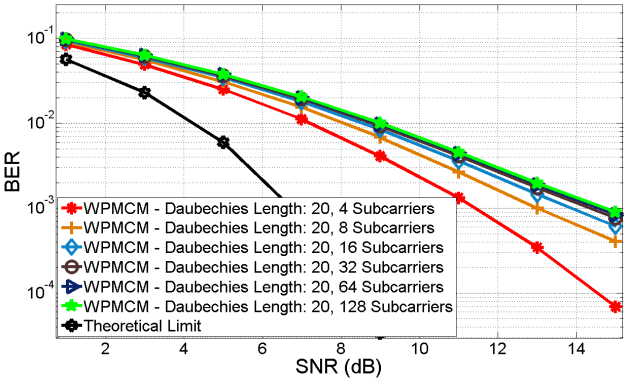

Figure 10. BER for WPMCM with Different Number of Subcarriers, Relative Frequency Offset 10 %

Frequency offset in WPMCM does not only lead to ICI inside one symbol but across the whole frame. Therefore, it is important to see the effect of the frame size in combination with the frequency offset. These results are illustrated in Fig.11. This figure shows that the amount of multicarrier symbols in a frame does not affect the performance of WPMCM in the presence of frequency offset. The extraordinarily bad performance of WPMCM transceiver that uses frame size of just 5 multicarrier symbols is caused by the relatively long filter. We make use of periodic extension in order to deal with excessive length caused by the convolution. The problem occurs when the filter is longer than the frame. Accordingly the filtered data does not fit anymore in the available space and a part of the samples has to be discarded.

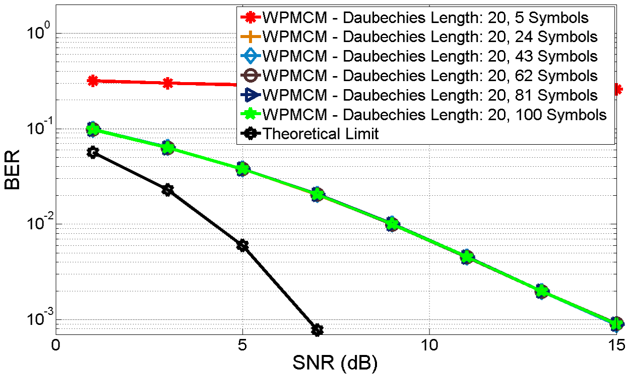

Figure 11. BER for WPMCM with Different Number of Multicarrier Symbols/Frame, Relative Frequency Offset 10 %

The influence of the filter's length in combination with the frequency offset on the BER is illustrated in Fig.12. This simulation is performed for AWGN channel and the relative frequency offset of 10%. For a second time, we arbitrary choose for Daubechies wavelet but now we alter the number of filter's coefficients and fix the number of subcarriers to 128. In case of Daubechies wavelet the amount of wavelet zero moments is indisputably related to the length of the filter, and hence for each doubling of filters' coefficients we also double the number of wavelet zero moments. The BER curves shown in Fig.12 are all superimposed one over another, suggesting that the filter's length and number of wavelet's zero moments have no noticeable influence on the system performance in the case of frequency offset.

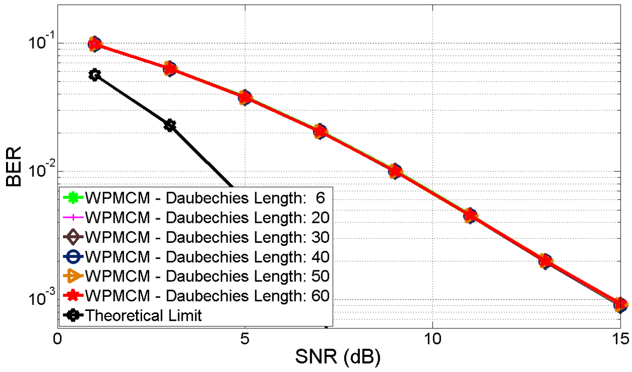

Figure 12. BER for WPMCM using Daubechies Wavelets of Different Lengths, Relative Frequency Offset 10 %

The effect of frequency misalignment between transmitter and receiver on the constellation points is depicted in the Fig.13, for the relative frequency offset of 5%. In order to highlight the effect of frequency offset we assumed for the moment an ideal channel without any noise. The main consequence of the frequency offset is the scattering of the constellation points around reference positions due to interference. Other consequences are the anti-clockwise rotation of all constellation points and almost negligible attenuation.

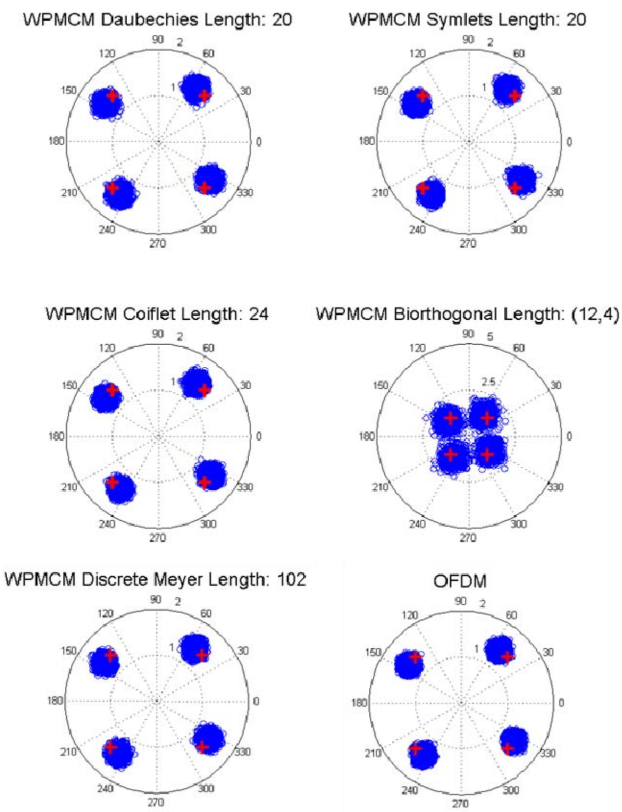

Figure 13. Constellation Points in Presence of Relative Frequency Offset of 5%

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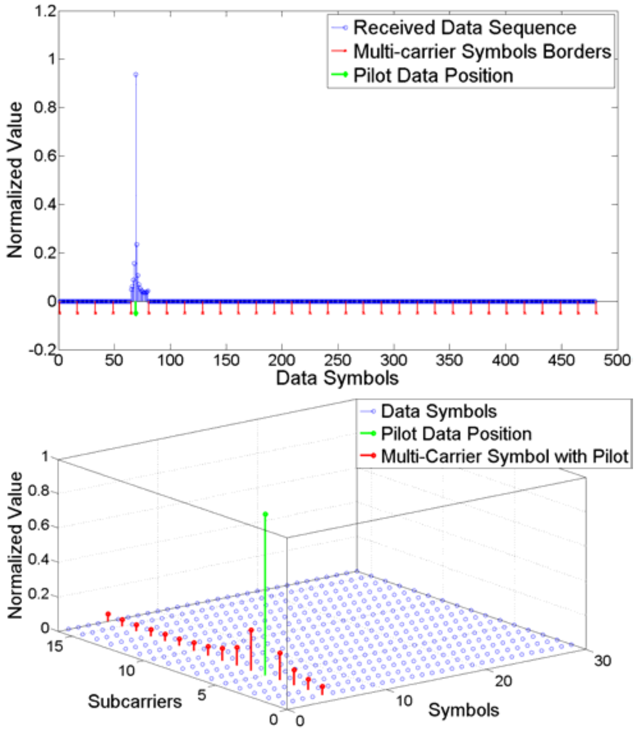

Figure 14. Received OFDM Subcarriers Spectral Energy in a Frame in Presence of the Frequency Offset; Top: 2D view, Bottom: 3D View

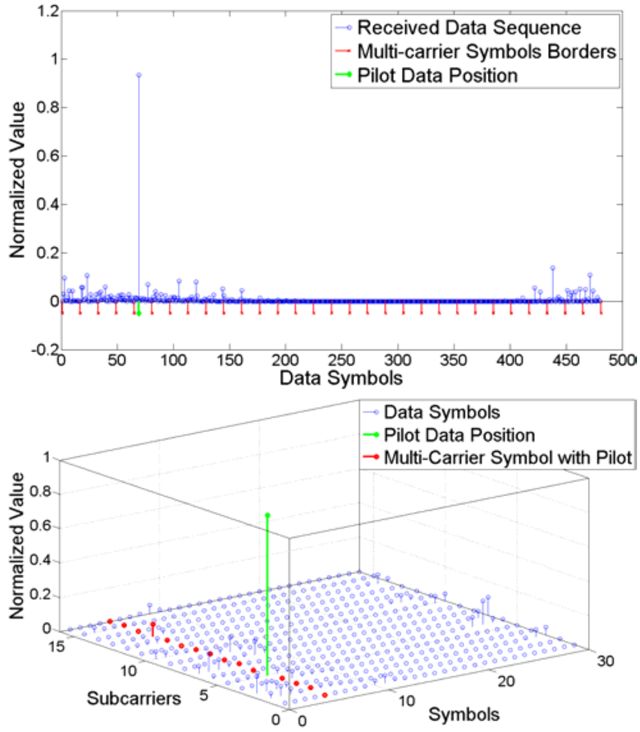

Figure 15. Received WPMCM Subcarriers Spectral Energy in a Frame in Presence of the Frequency Offset; Top: 2D view, Bottom: 3D View

The last set of figures in this section show the dispersion of the subcarriers energy due to a frequency offset. For clarity we limited the number of subcarriers to 16 and the frame size to 30 multicarrier symbols. The channel is assumed to be ideal so that all exposed disturbance of the subcarriers is a consequence of the frequency offset.

Fig.14 and Fig.15 are obtained by transmission of just one non-zero pilot subcarrier while all other subcarriers in the frame are set to zero. In an ideal situation, without any frequency offset, the only subcarrier with non-zero value will be the pilot subcarrier regardless of which system we use: WPMCM or OFDM. However, the frequency offset results in loss of orthogonality and subcarriers begin to interfere one with another. Fig.14 shows that in OFDM the interference due to frequency offset is limited to inside the multicarrier symbol where ICI occurs. The other OFDM symbols in this case are not affected. The WPMCM, on the other hand, has overlapping symbols and an offset in reference frequency results in both ICI and ISI. In Fig.15 we therefore observe that the energy of the pilot subcarrier located in the 5th subcarrier and 5th symbol is spread almost across the whole frame. This is in agreement with the theoretical derivation carried out in the previous section.

V. Phase Noise in Multicarrier Modulation

The ideal local oscillator would have a single carrier with constant amplitude and frequency. However, the outputs of practical local oscillators are degraded due to factors such as noise, jitter, etc. [27] causing the oscillator's central frequency to fluctuate a bit. This uncertainty in the actual frequency or the phase of the signal is referred to as phase noise.

Multicarrier transmission is very vulnerable to phase noise since phase noise can cause the loss of orthogonality between subcarriers. The influence of the phase noise on multicarrier transmission can be divided into two parts:

- Common Phase Error (CPE): Attenuates and rotates all constellation symbols by the same angle.
- Interference: Contribution of all other subcarriers.

Phase noise can be represented as a parasitic phase modulation of the oscillator's signal. In the literature there are different models used for the phase noise. Majority of these models are described in terms of power spectral density (PSD). In ideal case the PSD of the phase of local oscillator would be a single pulse (delta function) at the central frequency. Due to imperfections of oscillator, the PSD of the practical oscillator is distributed over a wider frequency band with highest concentration around oscillator's central frequency. The single side band PSD of free running oscillator can be estimated by the Lorentzian function [28].

In this paper we model the phase noise as a zero mean white Gaussian process ϕ_w with finite variance σ_w^2 [5]. The autocorrelation function of the phase noise is given by

$$R_{\phi_w}(\tau) = \sigma_w^2 \tag{15}$$

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Using (15) and Wiener-Khinchin theorem we can express the power spectral density of phase noise as

$$S_{\phi_w}(f) = \int_{-\infty}^{\infty} R_{\phi_w}(\tau) e^{-j2\pi f\tau} d\tau \tag{16}$$

In order to get the desired phase noise bandwidth we perform low pass filtering with filter F_ϕ. The PSD from (16) now becomes

$$S_{\phi b}(f) = S_{\phi_w}(f) \left| F_\phi(f) \right|^2 \tag{17}$$

By changing the corner frequency $f_{c\phi}$ of the filter used we can adjust the phase noise bandwidth. Low value of corner frequency results in narrow bandwidth while higher values spread the phase noise.

In the last stage of the model we add phase noise floor to the signal. Similarly to the main phase noise contribution, the phase noise floor is also modeled as a zero mean Gaussian process with finite variance σ_{wn}^2, which is relatively low compared to σ_w^2. The phase noise floor is not correlated so that it spans the whole available bandwidth and has flat PSD.

The total phase noise can now be expressed as a sum of bandwidth limited main noise contribution ϕ_b and phase noise floor ϕ_{wn} as

$$\phi(n) = \phi_b(n) + \phi_{wn}(n) \tag{18}$$

Using the phase noise model given in (15)–(18) we can write the received signal $R(n)$ that has been affected by phase noise and AWGN channel as

$$R(n) = S(n) e^{j\phi(n)} + w(n) \tag{19}$$

Without loss of generality, we assume for the moment that $w(n) = 0$.

A. Phase Noise in OFDM

When an OFDM transceiver experiences some phase noise, we can express the demodulated signal at the receiver's output as

$$\begin{aligned} \hat{a}_{k'} &= \frac{1}{N} \sum_{n=0}^{N-1} R(n) e^{-j2\pi \frac{k'}{N} n} \\ &= \frac{1}{N} \sum_{k=0}^{N-1} a_k \sum_{n=0}^{N-1} e^{j2\pi \frac{k}{N} n} e^{j\phi(n)} e^{-j2\pi \frac{k'}{N} n} \\ &= \frac{1}{N} \sum_{k=0}^{N-1} a_k \sum_{n=0}^{N-1} e^{j\phi(n)} e^{j2\pi \frac{(k-k')n}{N}} \end{aligned} \tag{20}$$

We can simplify the analysis for phase noise by splitting the demultiplexed signal in useful part and disturbance part. In order to do this we will assume that phase noise is sufficiently small so that it can be approximated by [5]

$$e^{j\phi(n)} \approx 1 + j\phi(n) \tag{21}$$

Using approximation (21) we can express the demodulated OFDM signal (20) for the k^{th} carrier as

$$\begin{aligned} \hat{a}_{k'} &\approx \frac{1}{N} \sum_{k=0}^{N-1} a_k \sum_{n=0}^{N-1} e^{j2\pi \frac{(k-k')n}{N}} \\ &\quad + \frac{j}{N} \sum_{k=0}^{N-1} a_k \sum_{n=0}^{N-1} \phi(n) e^{j2\pi \frac{(k-k')n}{N}} \\ &\approx a_{k'} + \frac{j}{N} \sum_{k=0}^{N-1} a_k \sum_{n=0}^{N-1} \phi(n) e^{j2\pi \frac{(k-k')n}{N}} \\ &\approx a_{k'} + I_\phi(k') \end{aligned} \tag{22}$$

The first component of (22) stands for correctly demodulated symbol and second term I_ϕ stands for disturbance which is added to the each subcarrier. Two distinct scenarios are possible with the phase noise.

A.1. If k = k': Common Phase Error (CPE)

The disturbance term from (22) can now be written as

$$\begin{aligned} I_\phi(k') &= \frac{j}{N} a_{k'} \sum_{n=0}^{N-1} \phi(n) \\ &= j \;\; \Phi \;\; a_{k'} \end{aligned} \tag{23}$$

The error, given in (23), causes the constellation points to be rotated by an angle Φ. This angle is common for all subcarriers so that all constellation points will be rotated by the same angle. Here, the rotation angle Φ is defined by the average phase noise which can be expressed as

$$\Phi = \frac{1}{N} \sum_{n=0}^{N-1} \phi(n) \tag{24}$$

The common phase error (CPE) is only dependent on low frequencies of the phase noise spectrum up to the frequency of the inter-carrier spacing.

A.2. If k ≠ k': Inter Carrier Interference (ICI)

The disturbance term from (22) can now be written as

$$I_\phi(k) = \frac{j}{N} \sum_{k=0;k\neq k'}^{N-1} a_k \sum_{n=0}^{N-1} \phi(n) e^{j2\pi \frac{(k-k')n}{N}} \tag{25}$$

The error in (25) consists of contribution from all other subcarriers in an OFDM symbol, and it is known as ICI. The magnitude of ICI as a result of phase noise is dependent only at the phase noise components that have high frequencies. In general, the phase noise that causes ICI has bandwidth which is larger than inter-carrier spacing frequency.

B. Phase Noise in WPMCM

The detected data at the WPMCM receiver in presence of the phase noise can be written for the k^{th} subcarrier and u^{th} symbol as

$$\begin{aligned} \hat{a}_{u',k'} &= \sum_n R(n) \xi^{k'}_{2^{\log(N)}}(u'N - n) \\ &= \sum_n \sum_u \sum_{k=0}^{N-1} a_{u,k} \xi^{k}_{2^{\log(N)}}(n - uN) e^{j\phi(n)} \xi^{k'}_{2^{\log(N)}}(u'N - n) \\ &= \sum_u \sum_{k=0}^{N-1} a_{u,k} \left(\sum_n \xi^{k}_{2^{\log(N)}}(n - uN) e^{j\phi(n)} \xi^{k'}_{2^{\log(N)}}(u'N - n) \right) \end{aligned} \tag{26}$$

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Using same assumption like we have done for phase noise analysis in OFDM (21), we can approximate the (26) by

$$\begin{aligned}\hat{a}_{u',k'} &\approx \sum_{u}\sum_{k=0}^{N-1} a_{u,k}\left(\sum_{n}\xi^{k}_{2^{\log(N)}}(n-uN)\,\xi^{k'}_{2^{\log(N)}}(u'N-n)\right)+\\ &\quad j\sum_{u}\sum_{k=0}^{N-1} a_{u,k}\left(\sum_{n}\xi^{k}_{2^{\log(N)}}(n-uN)\,\phi(m)\,\xi^{k'}_{2^{\log(N)}}(u'N-n)\right)\\ &\approx a_{u',k'} + j\sum_{u}\sum_{k=0}^{N-1} a_{u,k}\left(\sum_{n}\xi^{k}_{2^{\log(N)}}(n-uN)\,\phi(m)\,\xi^{k'}_{2^{\log(N)}}(u'N-n)\right)\\ &\approx a_{u',k'} + I_{\phi}(u',k')\end{aligned} \quad (27)$$

The first component of (27) stands for correctly demodulated symbol and second term I_ϕ stands for disturbance which is added to the each subcarrier. Similarly to the OFDM, we can also in WPMCM indicate two distinct situations in presence of phase noise.

B.1. If k = k' and f = f': Common Phase Error (CPE)

The disturbance term from (27) can now be written as

$$\begin{aligned} I_{\phi}(u',k') &= \frac{j}{N}\, a_{u',k'} \sum_{n=0}^{N-1} \phi(n) \\ &= j \;\; \Phi \;\; a_{u',k'} \end{aligned} \quad (28)$$

The equation (28) describes the rotation of constellation points by an angle *Φ*, which is common for all subcarriers. Rotation angle *Φ* is dependent on the average value of phase noise sequence and it is given in (24).

B.2. If k ≠ k' or/and f ≠ f': Inter Carrier Interference and Inter Symbol Interference (ICI/ISI)

The disturbance term from (27) can now be written as

$$I_{\phi}(u,k) = j \sum_{u;u\neq u'} \sum_{k=0;k\neq k'}^{N-1} a_{u,k}\left(\sum_{n}\xi^{k}_{2^{\log(N)}}(n-uN)\,\phi(m)\,\xi^{k'}_{2^{\log(N)}}(u'N-n)\right) \quad (29)$$

The equation (29) stands for the interference, caused by the phase noise. In contrary to the OFDM, the phase noise in WPMCM raises the ICI and ISI levels. This is due to overlapping nature of the wavelet transform.

Different frequency components of the phase noise have different impacts on the CPE and ICI/ISI terms. If the phase noise bandwidth is very concentrated near the central frequency the CPE term will dominate, but when the phase noise bandwidth is somewhat more spread the ICI/ISI term will soon take over. Using already defined model for phase noise (15)–(18), we can control the phase noise bandwidth by the corner frequency of the filter.

VI. Numerical Results for Carrier Frequency Offset

The performance degradation associated with phase noise has been evaluated by the computer simulations using almost identical set-up as for the frequency offset. More details on the set-up can be found in the section IV.

The different effects of the phase noise on the WPMCM and OFDM are best illustrated by the constellation points' diagram and the PSD of the phase noise.

In the upper part of the Fig.16 we can see the PSD of the phase noise which has relatively low corner frequency. The dominant effect of such phase noise is the common phase error, which results in the rotation of constellation points.

The PSD of the phase noise with relatively high corner frequency is illustrated in the Fig.17. Now the rotation behavior is not more visible but the interference between subcarriers is much more pronounced.

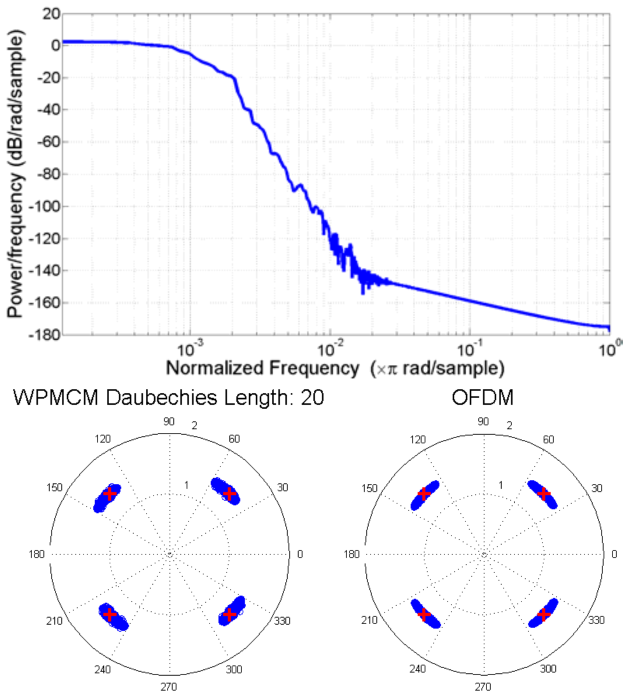

Figure 16. Phase Noise (Narrow Band);
Up: PSD, Down Left: WPMCM, Right: OFDM Constellation Points

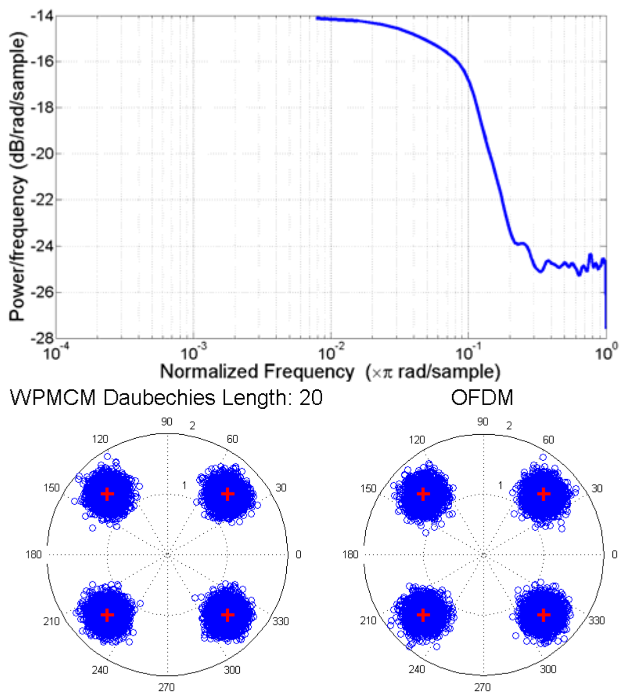

Figure 17. Phase Noise (Wide Band);
Up: PSD, Down Left: WPMCM, Right: OFDM Constellation Points

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Both effects of the phase noise are important and depending on the system one or the other can be the limiting factor for the system performance. In the literature there are many adequate correction approaches available for the CPE [29], [30] but the estimation and correction of the interference is much harder to realize. Therefore, we will limit the following part of this section to the performance analysis of the WPMCM and OFDM in the presence of phase noise interference. In order to achieve this, we have set the phase noise bandwidth to 10% of the total available bandwidth and the variance to -10 dB. The PSD of the phase noise will look similar to one illustrated in the Fig.17.

Fig.18 shows the BER of WPMCM and OFDM in presence of phase noise. The illustrated behaviors of BER curves are similar to each other with exception of biorthogonal wavelet. The poor performance of biorthogonal wavelet, as already mentioned, is due to the unfulfilled perfect reconstruction constraint.

Fig.19 illustrates the effect of the phase noise variance on the BER. This figure is obtained using an AWGN channel with 16 dB SNR while phase noise variance is varied from -10 to 20 dB with step-size of 5 dB. It is natural that the phase noise variance and the performance degradation are closely related. The sensitivity of WPMCM and OFDM to the variance of the phase noise is confirmed by Fig.19.

Fig.20 and Fig.21 show the performance of the WPMCM transceivers with phase noise when the number of subcarriers and symbols in the frame is altered. The simulation results haven't shown any essential connection between performance degradation and the number of subcarriers nor the number of symbols per frame. The results would be different if we set the corner-frequency to a smaller value. Because the inter-carrier spacing depends on the number of subcarriers, for low number of subcarriers the CPE term will dominate while for high number of subcarriers the interference will be the major term [5], [31].

Fig.22 illustrates the influence of filter's length and number of zero wavelet moments in combination with the phase noise on the BER. Similar to the frequency offset case there are no noticeable influences found in the system performance when length of the filter and number of wavelets' zero moments are altered.

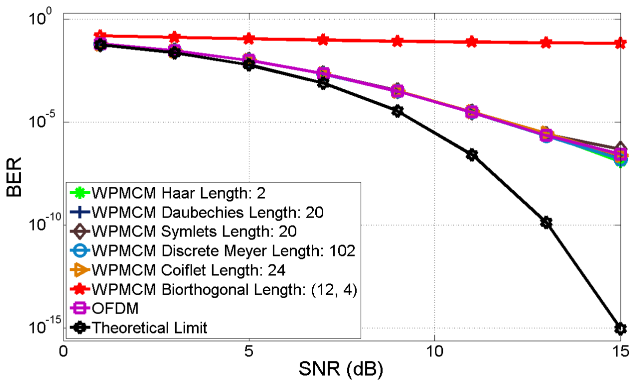

Figure 18. BER for WPMCM with Different Wavelets and OFDM, Phase Noise Bandwidth 10 % and Variance -10 dB

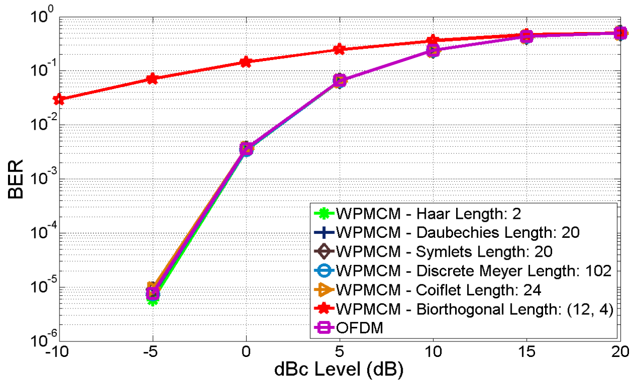

Figure 19. BER vs. Phase Noise Variance for WPMCM in AWGN Channel (SNR 16 dB)

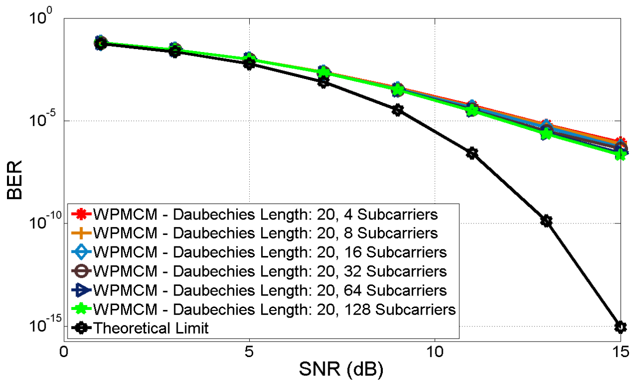

Figure 20. BER for WPMCM with Different Number of Subcarriers in Presence of Phase Noise

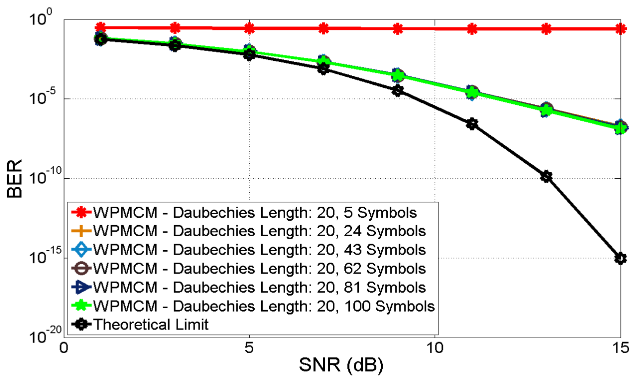

Figure 21. BER for WPMCM with Different Number of Symbols in Presence of Phase Noise

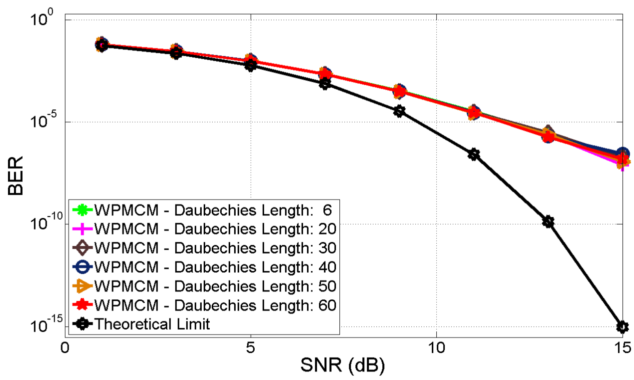

Figure 22. BER for WPMCM using Daubechies Wavelets of Different Lengths under Influence of Phase Noise

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For the completeness of the analysis we show in Fig.23 the effect of the phase noise on the constellation points, but now for all discussed wavelets and OFDM. The clearly visible scattering of the constellation points around the reference positions is caused by the phase noise, as the channel is assumed to be ideal and no other disturbances were introduced.

The spreading of subcarrier energy due to phase noise is illustrated in Fig.24 and Fig.25 for the OFDM and WPMCM transceiver, respectively. In this simulation we limited the number of subcarriers to 16 and the frame size to 30 multicarrier symbols. The channel is assumed to be ideal so that all exposed disturbance of the subcarriers is the consequence of phase noise.

Phase noise results in loss of orthogonality and subcarriers begin to interfere with each other. In OFDM interference due to phase noise is limited to the multicarrier symbol where ICI occurs. The other OFDM symbols in this case are not affected as can be seen in Fig.24. The WPMCM, on the other hand, has overlapping symbols and phase noise, besides ICI, also results in ISI. In Fig.25 we therefore observe that energy of the pilot subcarrier located at the 5th subcarrier and 5th symbol is spread almost across the whole frame. This is in agreement with the theoretical derivation carried out in previous section.

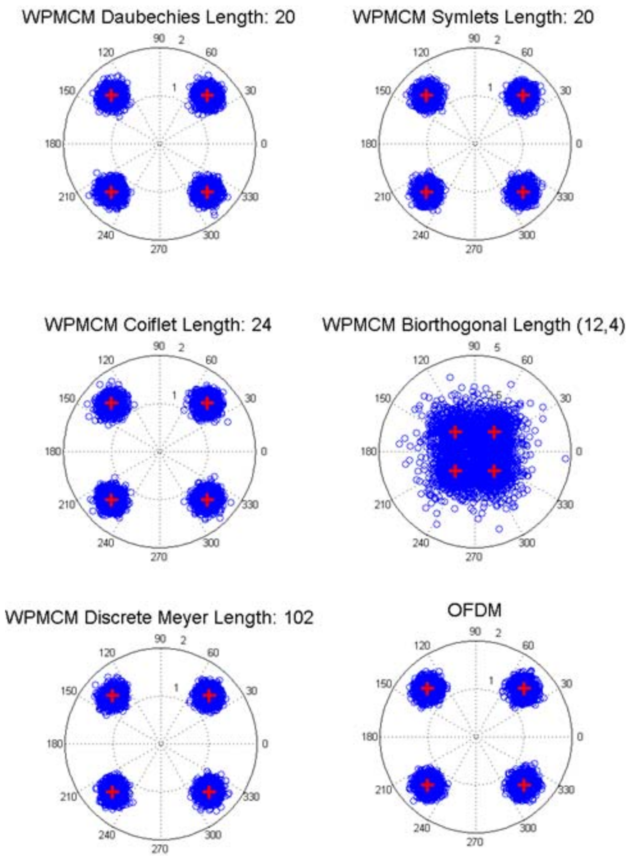

Figure 23. Constellation Points of WPMCM and OFDM Transceivers in the Presence of Phase Noise

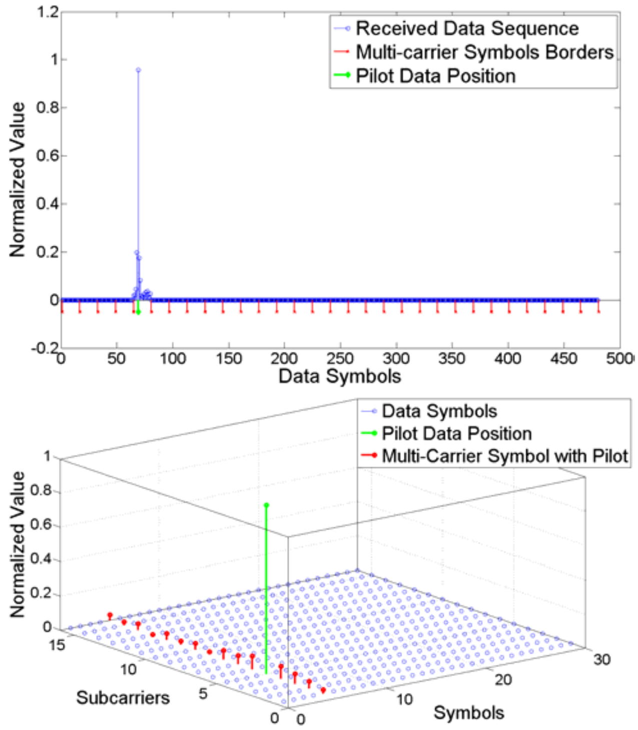

Figure 24. Received OFDM Subcarriers Spectral Energy in a Frame in Presence of the Phase Noise; Top: 2D view, Bottom: 3D View

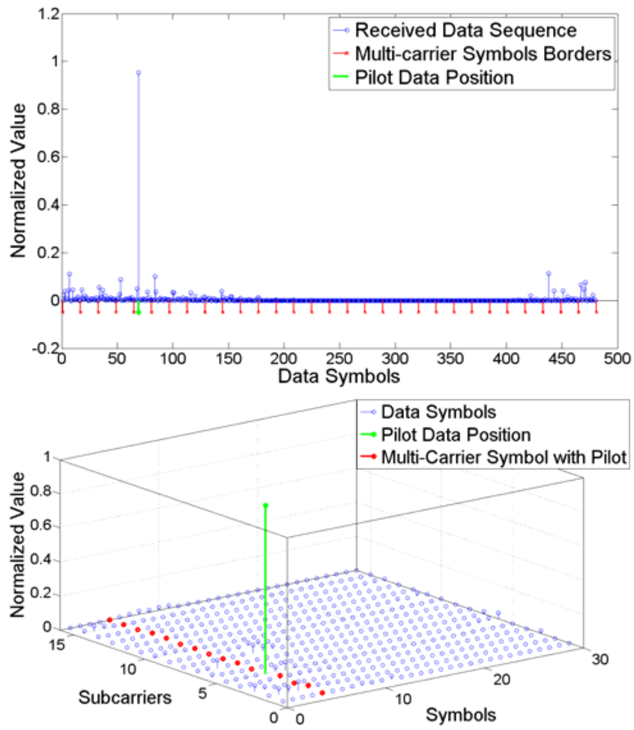

Figure 25. Received WPMCM Subcarriers Spectral Energy in a Frame in Presence of the Phase Noise; Top: 2D view, Bottom: 3D View

VII. Conclusions

WPMCM is a relatively young and promising communication concept which shares most of characteristics of an orthogonal multi carrier system and in addition offers the advantage of flexibility and adaptability. These properties can make it a suitable

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technology for the design and development of future wireless communication systems.

In this paper we have addressed the sensitivity of novel WPMCM transmission scheme to the carrier frequency offset and phase noise. Akin to OFDM, the WPMCM transceivers are found to be vulnerable to the radio front-end induced impairments. Carrier frequency offset and phase noise lead to the loss of orthogonality and consequently subcarriers begin to interfere with each other. In OFDM the performance degradation due to frequency offset and phase noise is limited to the interference among the subcarriers within one OFDM symbol (ICI), while in WPMCM subcarriers from multiple symbols interfere with each other (causing ICI + ISI). This dissimilarity in the interference behavior is due to the manner in which the subcarriers in wavelet and Fourier based systems are created. The signals generated by OFDM overlap only in frequency domain while WPMCM generated signals overlap in both frequency and time domain. However, simulations results have shown that the performance of WPMCM transceivers in presence of carrier frequency offset and phase noise is not inferior to the performance of OFDM under similar circumstances. Both transmission schemes are found to be equally affected by radio front-end induced impairments.

In OFDM there exist several synchronization techniques which can be used to estimate and reduce phase and frequency offsets at the cost of bandwidth/power efficiency [12]-[13], [15]-[17]. WPMCM on the other hand is a relatively new transmission technique and such synchronization algorithms are not available yet. Fortunately, WPMCM provides other benefits such as the possibility of altering the shape and properties of the wavelets according to a requirement. In this paper 'standard' wavelets are used which are designed for image and signal processing. Although some variations in BER performance have been found when different wavelets are employed, none of the wavelets considered showed any improvement. Future work should consider therefore design of new optimized wavelets which are more robust to imperfections such as frequency offset and phase noise. Additionally, the performance evaluation of WPMCM transceivers in different channel conditions is advisable.

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