PERFORMANCE EVALUATION AND PARAMETERS SENSITIVITY OF THE OFDM MODULATION IN HF TRANSMISSION

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ABSTRACT

This study examines the transmission performance over high frequency (HF) channels when OFDM modulation is employed, taking into account influences of the modulation parameters. The channel estimation is done by using pilot subcarriers in the OFDM modulation. Whereas a least squares algorithm was applied to estimate the channel frequency response in the frequencies of the pilot carriers, an interpolation technique was used to obtain the response in other frequencies. Performance comparisons were made based on bit error rate (BER) measurements considering the following parameters: total number of subcarriers, the interval between the pilot subcarriers and the modulation schemes (BPSK, QPSK, 8PSK and 16 QAM). For the channel simulation, we adopted the standard specifications of the U. S. Department of Defense, MIL-STD-188-110/B, which sets performance standards for HF data modems. The results showed that the HF transmission performance depends directly on the channel conditions and on the chosen OFDM parameters, suggesting that, to improve the performance of OFDM modulation in HF channels, the proper parameters should be selected based on the channel characteristics, which might be done in cognitive radios.

1. INTRODUCTION

Every day more wireless devices make use of a scarce natural resource, the electromagnetic spectrum. Its efficient use is a big challenge to the telecommunications engineering. Haykin [1] suggests that its use can be optimized by sharing it with secondary users and that cognitive radios (CR) would be a possible solution to this problem, due to their abilities to exploit unused parts of the spectrum to provide new communications paths.

In order to meet the communications requirements of CR, the physical layer must be highly flexible and adaptable. The orthogonal frequency division multiplexing (OFDM) technique has the potential of fulfilling such requirements, either inherently or with some modifications [2]. The OFDM modulation consists on a parallel transmission data system, using orthogonal and overlapped pilot subcarriers. Employing overlapped modulation, there is a 50% reduction in the frequency bandwidth when compared to frequency division multiplexing (FDM). The nature of the OFDM modulation allows the use of simple channel estimation and equalization techniques which affords that the communication be kept even in time-varying and frequency selective channels. The channel estimation can be performed by inserting, periodically in time, reference values in all subcarriers, or by inserting pilot subcarriers, periodically in frequency.

Nowadays, OFDM modulation is mostly employed in the VHF, UHF and SHF bands, where several standards are already available, such as WiMAX, DVB, IEEE 802.11-b/g/n. On the other hand, for the HF band the OFDM modulation is not very effective. This band provides a communications channel that allows transferring beyond horizon. The terrestrial waves can be used for communication of a few hundreds of kilometers, whereas the spatial (ionospheric) can be used for long distance communications.

The radio waves refracted by the ionospheric layers suffer several disturbs such as multipath and time dispersion, dispersion in several frequency bands, high level atmospheric non-gaussian noise and co-channel interference generated by other HF spectrum users. The MIL-STD-188-110/B [3] defines the requirements of minimum performance for data modems in HF. From performance evaluation and sensitivity to the OFDM modulation parameters in HF channels, the cognitive radios can select the adequate parameters for each channel condition, in order to improve the performance for the OFDM modulation in the HF band.

2. SYSTEM DESCRIPTION

The operation of an OFDM system is detailed in the block diagram of Fig. 1.

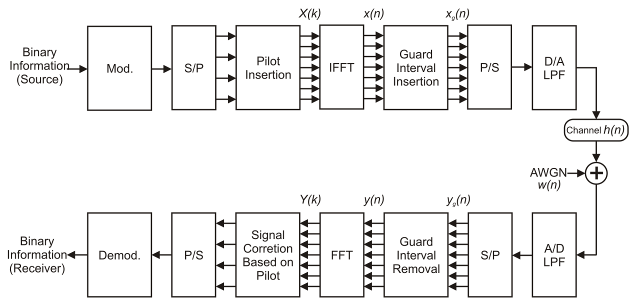

Figure 1: Block diagram of an OFDM with pilot subcarriers

In a channel affected by multipath and fading due to frequency selectivity, the subcarriers might be attenuated differently. The power of some subcarriers would suffer severe attenuation due to fast fading. Therefore, the bit error rate (BER) could be dominated by such reduced power subcarriers. To reduce the performance degradation of the system, the signal is coded before the bit modulation. The channel coding might reduce significantly the BER, according to the coding rate, decoder complexity and signal-to-noise ratio (SNR). The interlacing technique can also be used to enhance the system immunity to impulsive noise. The coded and interlaced signal is applied to the modulator, which will map it in the constellation points to produce the symbols to be transmitted. The pilot signals are added to such symbols using a combtype array, where the pilot subcarriers are evenly spaced in frequency. The data and pilot subcarriers are then combined in an N-symbol block, which is converted to time-domain symbols by means of an inverse discrete Fourier transform (IDFT), resulting in the time-domain symbols given by

$$s(n) = IDFT\{S(k)\} = \sum_{k=0}^{N-1} S(k)e^{j2\pi nk/N} \quad 0 \le n \le N-1 \quad (1)$$

where $S(k)$ corresponds to the transmitted symbol for the k-th subcarrier and N is the number of subcarriers. The signal is then serialized and a redundancy is added to the OFDM symbol, which might be a cyclic prefix (CP), that is, copies of the samples of s(n) for $n = N - v, \cdots, N-1$ are inserted in the beginning of each symbol. Such redundancy aims to reduce the intersymbol interference (ISI). Then, the baseband signal is applied to a digital-to-analog converter and then to the transmitter radio. The radio shifts the signal to a radio frequency using mixers and power amplifiers and transmits it through antennas.

The signal suffers the influence of the channels and noise. In the receptor, it is converted to baseband and digitized by an analog-to-digital converter. After synchronization, the cyclic prefix is removed and the data is grouped and transformed to the frequency-domain through a discrete Fourier transform (DFT). Assuming that the guard interval is larger than the length of the channel impulse response, that is, there is no ISI between OFDM symbols, then the demodulated signals $Y(k)$ can be represented by:

$$Y(k) = X(k)H(k) + I(k) + W(k), \quad k = 0, 1, \cdots, N-1 \quad (2)$$

where $H(k) = DFT\{h(n)\}$, $W(k) = DFT\{w(n)\}$ and $I(k)$ denotes the subcarrier interferences. The pilot subcarriers $Y_p(k)$ are extracted form $Y(k)$. The channel frequency response $H(k)$ can then be estimated by interpolation from $H_p(k)$. Knowing the channel response $H(k)$, one can recover the transmitted data $X(k)$ by

$$\hat{X}(k) = \frac{Y(k)}{\hat{H}(k)}, \quad k = 0, 1, \cdots, N-1 \quad (3)$$

where $\hat{H}(k)$ is an estimation of the channel response $H(k)$.

After the DFT, the symbols are demodulated, deinterlaced and decoded, thus generating the transmitted information.

2.1 Estimation of the Pilot Signals

For the combtype array, the N_p pilot signals $X_p(m)$, $m = 0, 1, \cdots, N_p - 1$, are inserted uniformly-spaced in $X(k)$. The N carriers are subdivided in N_p groups, each one with $L = N/N_p$ adjacent subcarriers. In each group, the first subcarrier is used to send the pilot signal. The OFDM modulated signal in the k-th subcarrier can be expressed as

$$X(k) = X(mL + l) = \begin{cases} X_p(m), & l = 0 \\ data, & l = 1, 2, \cdots, L-1 \end{cases} \quad (4)$$

The pilot subcarriers $X_p(k)$ might have the same complex value c in order to reduce the computational complexity.

Let $\boldsymbol{H_p}$ be the vector with samples of the channel frequency response in the pilot subcarriers frequencies,

$$\begin{aligned} \boldsymbol{H_p} &= [H_p(0) \quad H_p(1) \quad \cdots \quad H_p(N_p-1)]^T \quad (5) \\ &= [H(0) \quad H(L-1) \quad \cdots \quad H((N_p-1)(L-1))]^T \end{aligned}$$

and $\boldsymbol{Y_p} = [Y_p(0) \quad Y_p(1) \quad \cdots \quad Y_p(N_p-1)]^T$ be the vector with the received subcarriers, which can be written as

$$\boldsymbol{Y_p} = \boldsymbol{X_p H_p} + \boldsymbol{I_p} + \boldsymbol{W_p} \quad (6)$$

where $\boldsymbol{I_p}$ contains the subcarriers interferences, $\boldsymbol{W_p}$ contains the added gaussian noise and

$$\boldsymbol{X_p} = \begin{bmatrix} X_p(0) & & 0 \\ & \ddots & \\ 0 & & X_p(N_p-1) \end{bmatrix} \quad (7)$$

Then the pilot subcarriers are estimated by the Least Squares (LS) method:

$$\begin{aligned} \boldsymbol{\hat{H}_{p,ls}} &= [H_{p,ls}(0) \quad H_{p,ls}(1) \quad \cdots \quad H_{p,ls}(N_p-1)]^T \quad (8) \\ &= \boldsymbol{X_p}^{-1}\boldsymbol{Y_p} \quad (9) \\ &= \left[\frac{Y_p(0)}{X_p(0)} \quad \frac{Y_p(1)}{X_p(1)} \quad \cdots \quad \frac{Y_p(N_p-1)}{X_p(N_p-1)}\right]^T \quad (10) \end{aligned}$$

In [4], in order to obtain a general result, the frequency coherence of the channel $(\Delta f)_c$ is related to the spacing between pilot subcarriers $(\Delta f)_p$ through the parameter:

$$\mu = \frac{(\Delta f)_p}{(\Delta f)_c} \quad (11)$$

where $(\Delta f)_c$ is inversely proportional to the time spread of the channel, that is, $(\Delta f)_c = \frac{1}{\tau_m}$. To obtain an appropriate channel estimate, the spacing between pilot subcarriers should be considerably smaller than the frequency coherence of the channel. Thus, the following condition must be satisfied:

$$0 < \mu << 1 \quad (12)$$

It is not possible to use a value of μ close to the lower bound, since the system efficient would be very low. An adequate value of μ would allow the correct estimation of the channel without degrading the channel efficiency. Values of μ between 0.01 and 0.1 are used in [4]. In Zhao [5], the the best results are obtained with $(\Delta f)_p \approx (\Delta f)_c/8$ or $\mu \approx 0.125$.

After estimating the channel response in the pilot subcarriers frequencies, it is necessary to apply an interpolation technique in order to estimate the complete response. The linear interpolation method described in [4] presented better results than the constant interpolation one. In such method, two consecutive pilot subcarriers are used to estimate the frequency response in between the pilot frequencies.

For the k-th data subcarrier, $mL \le k < (m+1)L$, the estimated channel response is given by:

$$\begin{aligned} \hat{H}(k) &= \hat{H}(mL+l) = \left(1 - \frac{l}{L}\right)\hat{H}_p(m) + \frac{l}{L}\hat{H}_p(m+1) \quad (13) \\ &= \hat{H}_p(m) + \frac{l}{L}\left(\hat{H}_p(m+1) - \hat{H}_p(m)\right), 0 \le l < L \end{aligned}$$

3. SIMULATION RESULTS

In the simulations, the HF channel specifications given in the MIL-STD-110/B norm were adopted. Two HF channels, the ITU-R F.1487 Mid Latitude Disturbed Conditions

(ITU-R Poor) and the same channel with Doppler frequency of 2 Hz (ITU-R Poor with Doppler of 2 Hz), were tested. According to the MIL-STD, the signal was applied to a nominal speech channel of 3kHz allocated to a simple radio channel, in which frequencies above 3.4kHz are to be attenuated by at least 40dB. The HF channel is simulated using the Watterson model implemented according to the standard recommended by ITU-R F.1487 [6].

3.1 Simulations Parameters

The parameters and their values employed in the simulations are presented in Table 1.

Parameter	Description	Values
N	Number of OFDM subcarriers	128, 256, 512 and 1024
M	Modulation	B/Q/8-PSK and 16-QAM
L	Distance between Pilot subcarriers	2, 4, 8 and 16
GI	Guard interval	N/8
R	Coder effective rate	1/2
Fs	Symbol rate	4800 baud

Table 1: Parameters values employed in the simulations

The effective bit rate per second varies according to the selected parameters. Such rate is directly proportional to the symbol rate (F_s), and to the coder rate (R). It is proportional to $\log_2 M$, since as the number of bits per symbol due to the modulation scheme (M) increases, so does the effective rate. The effective rate is proportional to $\frac{L-1}{L}$, since the distance between the pilot subcarriers (L) determines the number of subcarriers ($L-1$) used to transmit data. The effective rate also depends on the guard interval (GI), since as the length of the cyclic code increases, more time is needed to transmit the redundant symbols

The effective bit rate per second can be expressed as

$$Rate = F_s \cdot R \cdot \log_2 M \cdot \frac{L-1}{L} \cdot \frac{N}{N+GI} \qquad (14)$$

The effective bit rates per second, obtained from Eq. (14) with the values of M and L used in the following simulations, are given in Table 2.

M	L	Rate bits/s	M	L	Rate bits/s
2(BPSK)	2	1067	4(QPSK)	8	3733
2(BPSK)	4	1600	8(8PSK)	2	3200
2(BPSK)	8	1867	8(8PSK)	4	4800
4(QPSK)	2	2133	16(16-QAM)	2	4267
4(QPSK)	4	3200			

Table 2: Effective rates for the simulations

Table 3 presents the μ values obtained from Eq. (11) for a channel with time spread $\tau_m = 2ms$, and the values of N and L used in the simulations.

4. RESULTS AND DISCUSSION

In Figs. 2 through 9 the graphs that relate the BER and the SNR measured in a 3kHz channel for different effective bit rate per second are presented.

In all simulations, it can be observed that for $\mu \geq 0.3$ the channel was not correctly estimated. For these μ values the error rate was 0.5 regardless of the SNR level. This result is

N	L	μ	L	μ	L	μ
64	2	0.300	4	0.600	8	1.2
128	2	0.150	4	0.300	8	0.600
256	2	0.075	4	0.150	8	0.300
512	2	0.0375	4	0.075	8	0.150
1024	2	0.01875	4	0.0375	8	0.075

Table 3: Spacing between the pilot subcarriers for the simulations

in agreement with [5], which suggests $\mu \leq 0.25$ as a general rule.

The best performance for the majority of the simulated bit rates and for $L = 2$ and $L = 4$ was obtained with $\mu = 0.075$. For rates of 1867 bps (Fig. 4) and 3733 bps (Fig. 7), where $L = 8$, the value $\mu = 0.15$ yielded the smallest error rates. These results suggest that for a determined quantity of data subcarriers between pilot subcarriers (L) there is an optimal value for μ that defines the total number of subcarriers (N). The 3200 bps rate was simulated with parameters ($M = 4$, $L = 4$) and ($M = 8$, $L = 2$). The results for this rate (Fig. 6) show that the best performance was obtained with ($M = 4$, $L = 4$). Such analysis suggests that for a given amount of transmitted information, a reduced modulation scheme with larger space between subcarriers is more efficient than a modulation scheme with a larger number of symbols in its constellation and a smaller number of pilot subcarriers.

5. CONCLUSION

The HF channel estimation with the use of pilot subcarriers in OFDM modulation proved very efficient when adequate parameter values for a given channel condition are employed. In its learning period, cognitive radios might analyze the channel conditions in order to select the optimal parameters in each circumstance.

6. REFERENCES

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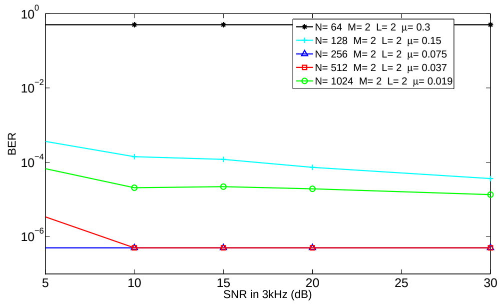
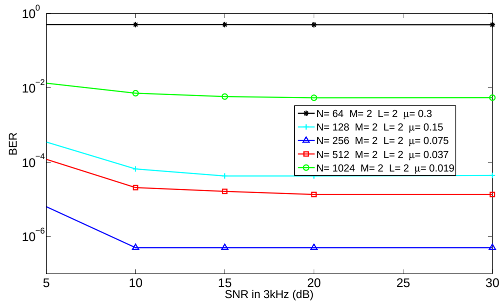
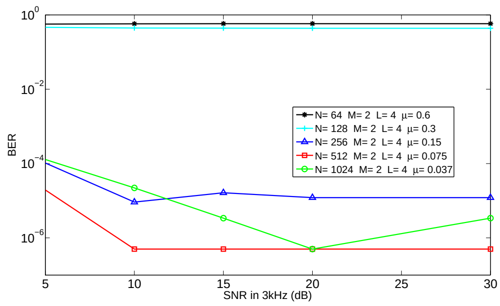


(a) ITU-R Poor

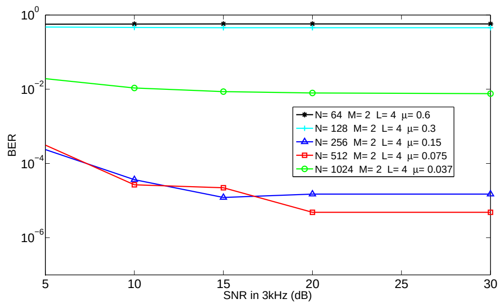


(b) ITU-R Poor with Doppler of 2 Hz

Figure 2: Performance comparisons for different numbers of subcarriers in two HF channels with rate of 1067 bps

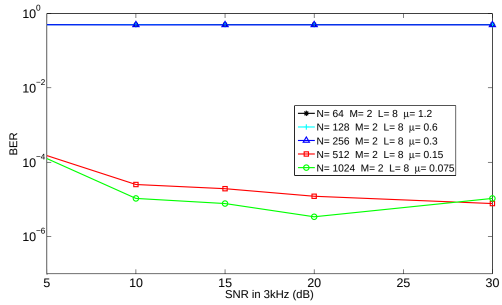


(a) ITU-R Poor

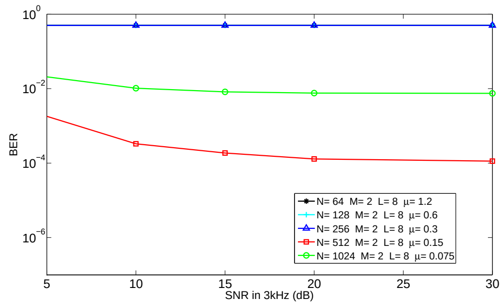


(b) ITU-R Poor with Doppler of 2 Hz

Figure 3: Performance comparisons for different numbers of subcarriers in two HF channels with rate of 1600 bps

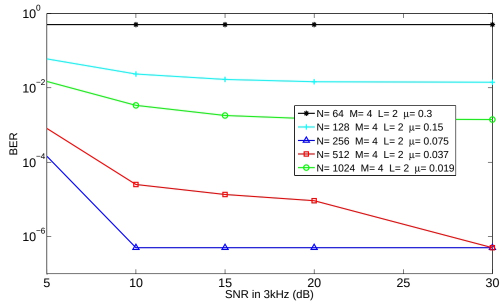


(a) ITU-R Poor

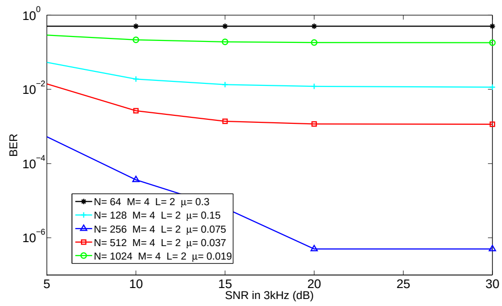


(b) ITU-R Poor with Doppler of 2 Hz

Figure 4: Performance comparisons for different numbers of subcarriers in two HF channels with rate of 1867 bps

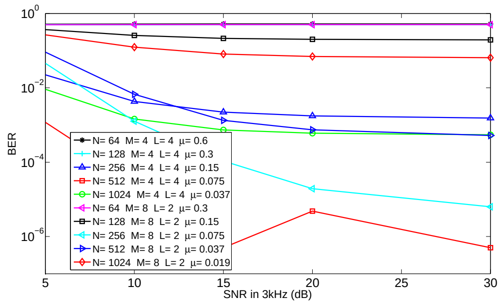


(a) ITU-R Poor

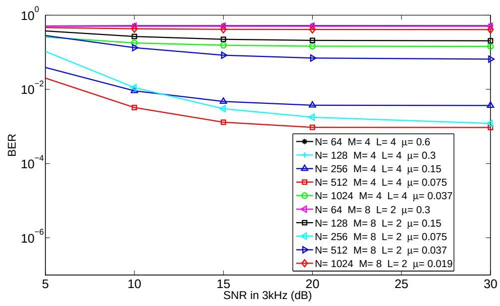


(b) ITU-R Poor with Doppler of 2 Hz

Figure 5: Performance comparisons for different numbers of subcarriers for two HF channels with rate of 2133 bps

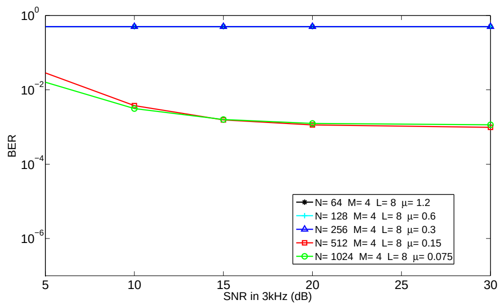


(a) ITU-R Poor

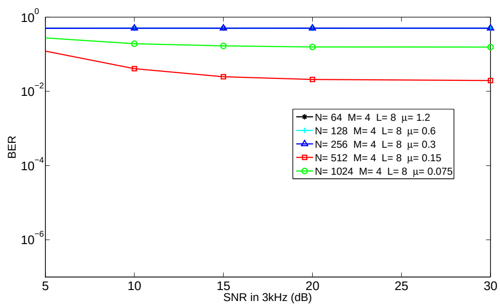


(b) ITU-R Poor with Doppler of 2 Hz

Figure 6: Performance comparisons for different numbers of subcarriers for two HF channels with rate of 3200 bps

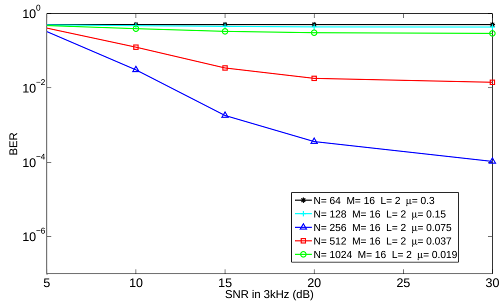


(a) ITU-R Poor

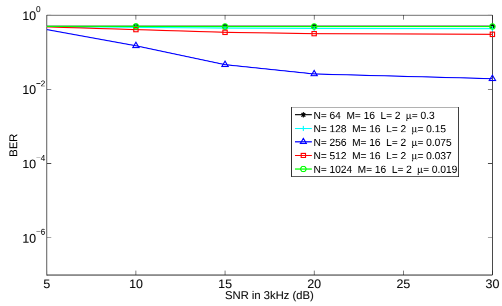


(b) ITU-R Poor with Doppler of 2 Hz

Figure 7: Performance comparisons for different numbers of subcarriers for two HF channels with rate of 3733 bps

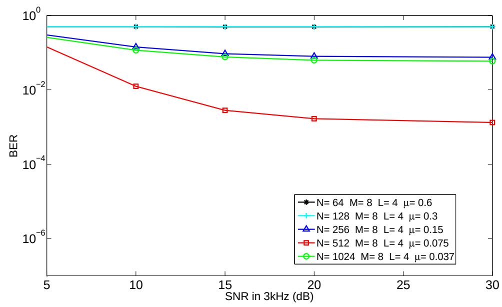


(a) ITU-R Poor

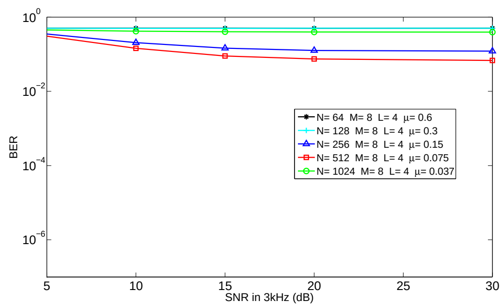


(b) ITU-R Poor with Doppler of 2 Hz

Figure 8: Performance comparisons for different numbers of subcarriers for two HF channels with rate of 4267 bps



(a) ITU-R Poor



(b) ITU-R Poor with Doppler of 2 Hz

Figure 9: Performance comparisons for different numbers of subcarriers for two HF channels with rate of 4800 bps