PERFORMANCE OF CHAOTIC MODULATION OVER RAYLEIGH FADING CHANNELS USING FFT-OFDM AND DWT-OFDM

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ABSTRACT

A study on the performance of Symbolic Dynamics Chaotic OFDM signals over Rayleigh fading channels is presented. Both Fourier OFDM and Wavelet OFDM are considered and compared with each other. First, it was found that traditional non-OFDM chaotic communications do not perform well in a multipath environment. Then, the conjugation of Symbolic Dynamics and OFDM techniques was simulated and considered to present a better BER performance comparable to non chaotic modulation schemes in the same realistic wireless environment. It was also found that Chaotic Wavelet OFDM outperforms Chaotic Fourier OFDM systems in a multipath environment.

Index Terms— OFDM;Chaos;Fourier;Wavelet;

1. INTRODUCTION

Mobile computing and communication became a key factor in our modern society. An increasing number of portable devices are being produced in order to fulfill consumer's expectations, implying in a crescent demand for high speed data connections to support the integration of voice, data and video services.

In this context, it is important to consider the characteristics of wireless channels, namely frequency bandwidth limitations, fading due to multipath propagation and Doppler effects.

Several technologies have been studied and used in order to maximize the frequency bandwidth availability and the demanded high data rates. One of them is OFDM (Orthogonal Frequency Division Multiplex), that was first introduced by Chang [1] in 1966, and is being pervasively used in high traffic demand wireless systems as IEEE standard on 802.11g ; 802.11a, Wimax, etc. OFDM is also employed due to its inherent resilience regarding fading effects in wireless channels. However, OFDM signals can be readily detected and decoded by an unauthorized part.

Other line of study is the use of alternative technologies as chaotic signals to improve security at physical layer. Several articles have been published explaining the concept of using chaotic signals in telecommunications since Pecora and Carroll [2] showed that was possible to synchronize chaotic systems. Although the performance of chaotic modulations schemes over wireless channels has not been demonstrated to be comparable to the more traditional modulation techniques, there is an ongoing research activity in applications of Chaos in Telecommunications [3].

Recently, Luengo et al [4] have presented a novel technique of digital transmission of information that conjugates the use of chaotic signals with orthogonal frequency division multiplex. The underlying concept is to take advantage of OFDM resilience to fading effects as well as the inherent security of chaotic signals. For this purpose, an alternative chaotic signal modulation that uses symbolic dynamics is used in a Fourier OFDM scheme. The simulated results in that article indicate that this technique has very good potential regarding its performance in AWGN channels.

The above mentioned article, nonetheless, did not present a thorough study of the performance of this novel technique in terms of BER (bit error rate), when submitted to different OFDM schemes and a Rayleigh channel with both Doppler and fading effects.

The purpose of this article is to close this gap by investigating the performance of the technique when applied to a more realistic Rayleigh channel model and two different implementations, namely the Fourier and Wavelet OFDM modulation.

To achieve this goal, this work is partitioned in the following way. First, the chaotic OFDM scheme is presented in section 2. The channel model is described in section 3. The results of mathematical simulations are reported in section 4 as well as their analytical interpretation. Finally, conclusions remarks close this article in section 5.

2. SYMBOLIC DYNAMICS CHAOTIC OFDM MODEL

2.1 Symbolic Dynamics Chaotic Modulation

Symbolic dynamics modulation relies on the representation of the trajectory of a dynamical system through symbols derived from a chaotic map based on the data to be transmitted. The symbols are generated by means of iterations of a nonlinear chaotic map, f(x), beginning at an initial condition x[0]. Thus, the sequence of symbols is given by:

$$x[0]\ ;\ x[1] = f(x[0])\ ;\ x[2]=f(x[1])\ ;\ \ldots;\ x[n] = f(x[n-1]) \quad (1)$$

or, for the k^{th} sample:

$$x[n+k]=f^{k}(x[n]) \quad (2)$$

In [4], Luengo et al. proposed a modulator based on the following chaotic map:

$$f(x) = \begin{cases} [2x+(1+p)]/(1-p), & -1 \le x \le -p \\ x/p, & -p < x < p \\ [2x-(1+p)]/(1-p), & p \le x \le 1 \end{cases} \quad (3)$$

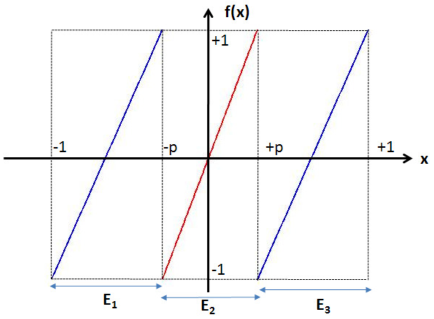

Figure 1: f (x) and the map with regions E_1, E_2 and E_3.

The graphical representation of this map is shown in Figure 1. Clearly, the domain and image of this map, namely its phase space, is the subset of real numbers with absolute value less or equal to one. Moreover, this real segment is divided into 3 regions E_1, E_2 and E_3 according to a control parameter p ($0 \le p \le 1$), such that:

$$E_{1=}\{x|x \in [-1,-p]\};\ E_{2=}\{x|x \in [-p,p]\}\ ;\ E_{3=}\{x|x \in [p,1]\} \quad (4)$$

The value of control parameter p defines the chaotic behavior of the generated sequence by controlling the length of each partition E_1, E_2 and E_3. This partitioning of the map domain has an effect on the chaotic nature of the numbers generated through this mapping. Nonetheless, the value of the parameter p can be used to set up a compromise between performance and security in the transmission as it will be shortly seen.

The symbols to be transmitted belong to one of the partitions placed at the extremes of the phase space, according to the information bit to be represented. The central partition is left as a buffering zone intended to provide a Euclidian distance between symbols in the 2 partitions used for symbolic dynamics modulation. This distance guarantees a minimum separation between symbols representing the binary information bits and simplifies the estimation of the transmitted symbol at the receiver.

Considering that b[n] is an incoming serial bit string composed of 0's and 1's, the symbolic dynamic modulation must associate it to a stream of symbols s[n] generated through the map in eq. 3, but preventing any symbol to fall into partition E2. For this matter, the following transformation is used before modulation**:**

$$s[n]= 2^{*}\, b[n]+1 \qquad 1 \le n < N \quad (5)$$

.

Then, the stream s[n] is applied to the inverse mapping given by:

$$f^{-1}(x) = \begin{cases} \dfrac{(1-p)x-(1+p)}{2}, & s=1 \\ px, & s=2 \\ \dfrac{(1-p)x+(1+p)}{2}, & s=3 \end{cases} \quad (6)$$

So, when b[j]=0, s[j]=1 and region E_1 is used. On the other hand, when b[j]=1, s[j]=3, region E_3 is used.

The transmitted signal, x[n], is generated using forward iterations from x[0] till the final condition x [N] on the inverse mapping $f^{-1}(x)$.

The signals used in this process are illustrated in Fig. 2.

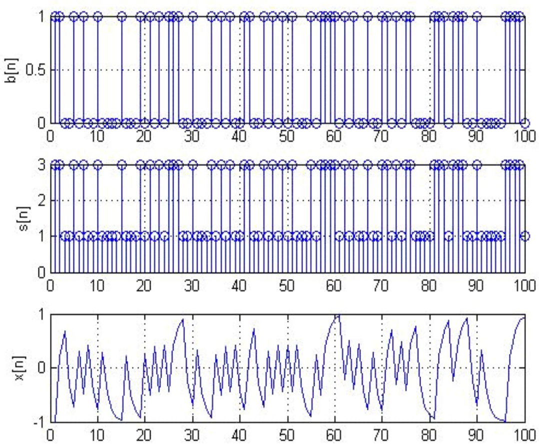

Figure 2: Input bits $b_{[n]}$, symbolic sequence $s_{[n]}$ and the chaotic sequence $x_{[n]}$

2.2 Symbolic Dynamics Chaotic Demodulation

One of the main characteristics of chaotic signals is its dependence on the initial conditions, that is, even a very small difference on the initial condition lead to trajectories that diverges between them. In addition, round off errors in algebraic computations contribute to deteriorate the performance of traditional chaotic modulators implemented digitally.

For this reason, the demodulator used in [4] employs a backward iteration in which the sequence is reconstructed beginning from a known final condition. The estimation process shall converge to the initial condition. This is achieved using a Viterbi algorithm with two state memory.

Hence, the sequence of recovered symbols is given by:

$x[n-1] = f^{-1}(x[n])$; $x[n-2] = f^{-1}(x[n-1])$; …; $x[1] = f^{-1}(x[0])$ (7)

or for the k^{th} sample :

$$x[n-1]=f^{-k}(x[n]) \quad (8)$$

Fortunately, the chosen map is piece-wise invertible and the resulting map is shown in figure 3:

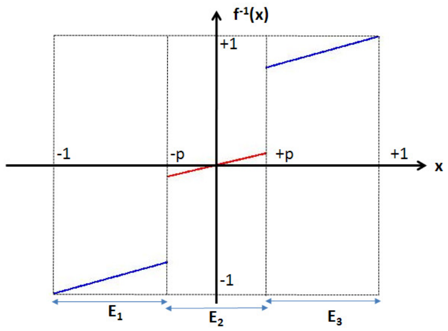

Figure 3: The invertible map $f^{-1}(x)$.

In order to promote the estimation, the signal is fed into a Viterbi module with two stage memory. Since the symbolic dynamic, as was chosen in eq. 5 , guarantees that no signal will be falling in the inner region E_2, a simple cost function (eq. 9) is used to estimate the state in the node under evaluation in the Viterbi algorithm:

$$C_{ij} = | y(n+1) - f_j^{-1}(x(n)) | \quad (9)$$

in which y(n+1) is the signal received at the $(n+1)^{th}$ instance and $f_j^{-1}(x(n))$ represents the backward iteration starting from $x(n)$.

2.3 Chaotic OFDM

OFDM - Orthogonal Frequency Division Multiplex is a consolidated technique that uses a set of orthogonal carriers to offer more traffic allocation capacity in physical channels within a limited bandwidth, but at the same time providing an increased robustness against wireless channel effects such as multipath fading, Doppler shift, etc [5].

Usually, each of the carriers is modulated using either BPSK or QAM modulation [6]. In this article, the chaotic signal described in section 2.1 will be used instead, as depicted in Fig. 4 which will be used to explain the process of transmitting and receiving the Chaotic OFDM signal.

The chaotic modulated signal is converted from serial to parallel and applied to the block that will perform either an IFFT (Inverse Fast Fourier Transform) or an IDWT (Inverse Discrete Wavelet Transform) operation in order to move the signals at each sub channel to its proper domain (either in frequency or resolution scale). Then, a guard interval (GI) is added at beginning and end of each symbol. A cycle prefix (CP) is also added by copying the last samples of the OFDM symbol and placing them at the beginning of the symbol. Pilots are finally inserted in order to allow the estimation of the channel conditions at reception. The resulting signal s(t) is converted from parallel to serial in order to be transmitted.

At the receiver, a reverse set of operations is performed to convert the received signal from serial to parallel, to remove GI and CP and either a FFT or DWT performed. Lastly, after estimating the channel, proper demodulation in individual sub channels is executed. All the sub channels data are converted from parallel and multiplexed into a serial bit stream. BER (Bit error rate) is calculated at the aggregated bit stream.

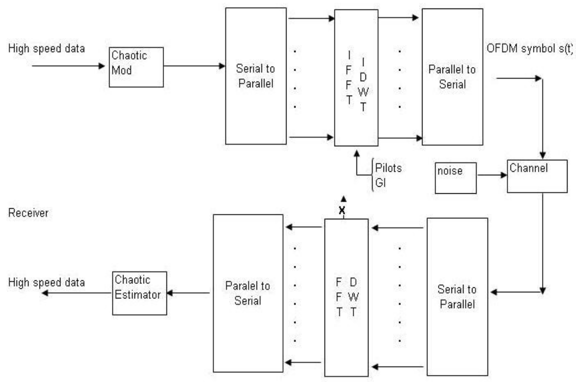

Figure 4: Block diagram of the OFDM system.

3. CHANNEL MODEL

As the objective of this research is to investigate the performance of the proposed Chaotic OFDM modulation in realistic channels, the channel model used reflected simultaneously white Gaussian noise, Rayleigh fading and Doppler effect, similar to one discussed in [7].

As for OFDM, a system similar to the IEEE 802.11a standard was simulated, leading to the following basic simulation parameters:

- Number of data carriers :48
- Number of Pilots :4

- Guard Interval: 6 at the beginning and 5 at the end
- IFFT/FFT Size : 64
- IDWT/DWT Size:124
- Wavelet db3.
- Cycle Prefix (CP) :16 samples only for IFFT/FFT
- p (chaotic map parameter) = 0.2, 0.5 and 0.9
- SNR: from 0 to 20 dB
- TS (Sample Time of input signal) = 10-4 sec
- FD (Doppler Frequency) =1 Hz
- TAU (path delays) =0; 10-7 sec
- PDB (Average path gains) = 0 ; -5 db

The channel estimation for the Rayleigh channel was performed by using 4 pilots [5]. This channel estimation is important as the signals were observed to suffer severe rotation due to the channel effect. So, the signal applied to the structure in Fig. 4 is given by:

$$Y(e^{j\omega}) = X(e^{j\omega})/H_{cn}(e^{j\omega}) \tag{10}$$

in which $X(e^{jw})$ is the transmitted signal and $H_{cn}(e^{jw})$, the channel response matrix, was obtained through an estimation algorithm based on the pilot tones [5].

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4. SIMULATION RESULTS

The purely chaotic modulator signal (without OFDM) was first transmitted through the channel, but it wasn't possible to recover it at the receiver due to the effect of the Rayleigh channel. The scattered plotter of the received signal is shown in Fig. 5. Hence, the purely chaotic system was considered to be limited to AWGN channels with neither multipath nor Doppler effects.

In the Chaotic OFDM system simulation, parameter p plays an important role in the estimation of the transmitted signal, as it sustains the distance between the E_1 and E_3 regions. This is clearly observed in the scatter plots shown in fig, 6 for Chaos OFDM based in Fourier transform and fig. 7 for Chaos OFDM based in Wavelet transform.

In both Fig. 6 and 7, it is possible to see the gap that the parameter p generates, clearly separating the points in two different regions E_1 and E_3 and none in the central region E_2. This will guarantee that the Viterbi estimation can be done with low computational cost and with few states.

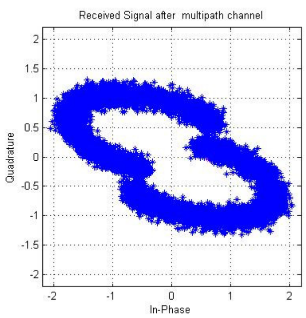
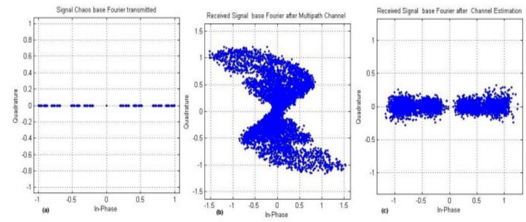
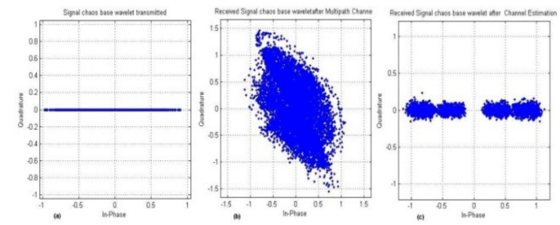


Figure 5: Received chaotic signal over Rayleigh channel.



(a) (b) (c)

Figure 6: Chaos OFDM system using Fourier Transform (a) Transmitted signal ;(b) Received signal over Rayleigh Channel ;(c) Signal after Pilot Channel Estimation correction , for p=0.2.



(a) (b) (c)

Figure 7: Chaos OFDM system using Wavelet Transform (a) Transmitted signal ;(b) Received signal over Rayleigh Channel ;(c) Signal after Pilot Channel Estimation correction , for p=0.2.

Next, the bit error rate (BER) of both Fourier and Wavelet systems was computed for both Rayleigh and AWGN channel, varying the level of noise. The results are shown in figs. 8 to 10 for different values of the parameter p.

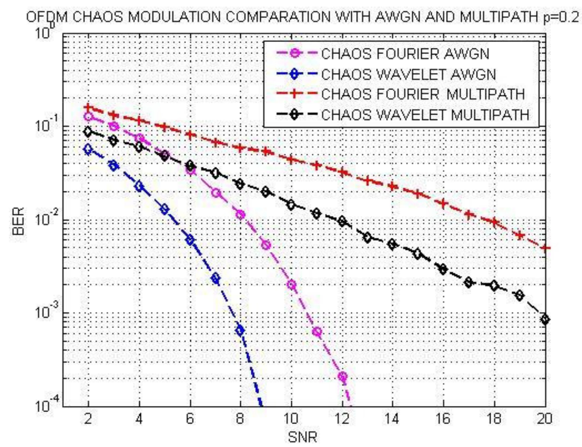


Figure 8: BER for Chaos OFDM based on IFFT/FFT and IDWT/DWT (p=0.2)

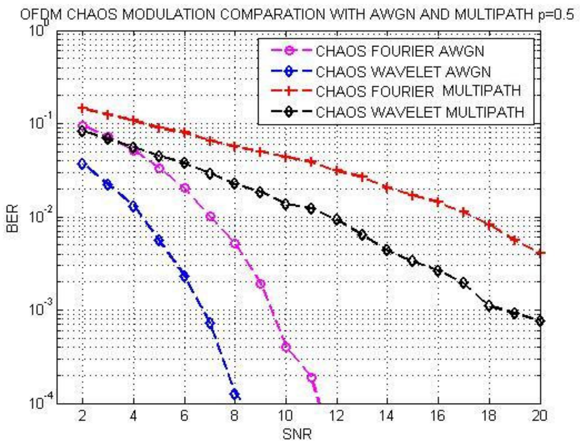


Figure 9: BER for Chaos OFDM based on IFFT/FFT and IDWT/DWT (p=0.5)

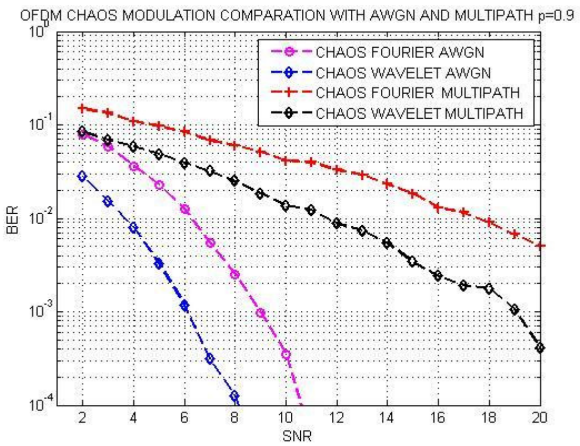


Figure 10: BER for Chaos OFDM based on IFFT/FFT and IDWT/DWT (p=0.9)

In general, the BER curves for Chaotic OFDM using Wavelet showed a 3 dB improvement in comparison to the Chaotic OFDM using Fourier on the AWGN channel. This difference rose to 6 dB in a multipath environment.

This result is in accordance to the results previously reported for non chaotic OFDM [8-10]. The out of band rejection and pulse shaping along with the time positioning and frequency localization (scale) provided by the wavelet pulse contribute to the better performance of wavelet based in comparison to the Fourier OFDM.

As the value of the parameter p was increased, the BER performance improved as well, according to the predicted as the Euclidean distance between the E_1 and E_3 regions also increased. In the limit, as p goes towards 1, the system behaves as a BPSK

From the above results, it can be seen that Chaotic OFDM based on Wavelet Transform outperforms the one based on Fourier. Even more important, the BER performance of the Chaotic OFDM system in a Rayleigh channel compares well to the performance reported in [8], for conventional OFDM systems in AWGN channels. Clearly, this indicates the feasibility of using this novel technique in practical radio systems.

5. CONCLUSIONS

Simulations of the behavior of Chaotic OFDM system over Rayleigh channels were presented for both Fourier and Wavelet implementations. A detailed analysis of the results indicates that BER performance of such systems approaches the performance of traditional non chaotic system. This indicates the suitability of using this technique in practical wireless system.

The results also indicate the superiority of the wavelet based system in comparison to the Fourier OFDM. This effect has been pointed out before for traditional OFDM. The time positioning and frequency localization of the wavelets are the main causes for this.

6. REFERENCES

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