On the Time-Varying Non-Linearity Effects Over the Spectrum of MIMO-OFDM Wireless Communications Systems

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ABSTRACT

This article presents analytical expressions that can be used in the evaluation of the effects of a non-linear mobile (multi-path) channel on the spectrum of MIMO-OFDM communications systems, such as 4G systems (LTE, WiMax) and probably the future 5G systems. The channel is modeled by a time-varying Volterra Series and the MIMO-OFDM signal by a complex, proper, wide-sense stationary Gaussian random process with zero mean. The resulting mathematical expressions are applied to a specific situation, allowing a quantitative evaluation of the out-band spectrum regrowth of MIMO-OFDM wireless communications systems produced by the use of non-linear devices in mobile channels.

KEYWORDS

MIMO-OFDM, Multi-Path Channels, Non-Linearity, Spectrum Regrowth, Wireless Systems

1. INTRODUCTION

In the recent years, the wireless communications industry has been very successful in providing high-speed data link that allow for a multitude of multimedia applications. These successes include, among others, DAB (European Telecommunications Standards Institute [ETSI], 2016) (Digital Audio Broadcasting) digital audio and digital video DVB (ETSI, 2015) (Digital Video Broadcasting) systems. Many of these technologies are intended for the use of fixed or portable devices, and do not support full mobility. Much of the recent academic research and industrial development in wireless communications has focused on migrating these technologies to a fully mobile environment. Multiple Input - Multiple Output systems using Orthogonal Frequency Division Multiplexing (MIMO-OFDM) have come forward as a good candidate to meet the goals of high data rate wireless communications for fixed, portable, as well as fully mobile devices and are currently used in the latest generation wireless communication systems such as Wi-Fi, WiMAX, LTE (Jamil, Shaikh, Shahzad & Awais, 2008) and probably in the future 5G systems (Andrews, Choi, Hanly, Lozano, Soong & Zhang, 2014; Li, Zhu & Liang, 2015; Kim, Choi, Lee & Kim, 2015). Wireless communications systems using MIMO-OFDM are multicarrier communications systems, therefore, these systems present a considerable loss of performance caused by distortions created by non-linear devices such as high-power amplifiers. Likewise, the multicarrier systems have increased the duration of the transmitted symbols, which also generates a performance loss mainly caused by time variations typical of mobile channels. To assess all the effects generated by non-linear devices, the memory effects of these devices must be studied, basically because these effects are more important the higher the bandwidth. With respect to mobile channels, a feature to consider is

DOI: 10.4018/IJITN.2018040103

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the Doppler effect as it tends to destroy the orthogonality in MIMO-OFDM systems generating an interference between sub-carriers. At present, there are few jobs that can be found in the literature assessing the effects of non-linear (Munoz & Eslava, 2014) or time-varying channels (Pan, Xu, Yang & Chen, 2015; Yang, Ye, Si, Sun & Zhang, 2015) in MIMO-OFDM communications systems, and there are no studies that evaluate the joint effect of these two types channels. Thus, in this paper mathematical expressions will be developed to characterize the effect of non-linear time-varying channels in wireless communications systems using MIMO-OFDM. Basically, this paper is focused on characterizing the combined effects of these channels to evaluate the out-band spectrum regrowth of the MIMO-OFDM signal.

The rest of the paper is organized as follows: the characterization of MIMO-OFDM signals is presented in Section 2. Section 3 describes the representation by Volterra Series of time-varying non-linear systems with memory. In order to analyze the out-band spectrum regrown, mathematical expressions are developed and presented in Section 4. Using theses expressions, numerical results for a specific case, involving a non-linearity of third order are presented in Section 5 and finally some conclusions are presented in Section 6.

2. CHARACTERIZATION OF MIMO-OFDM SIGNALS

The mathematical model of the \( i \)-th transmitted MIMO-OFDM signal \( x_i(t) \) can be written as

\[
x_i(t) = Re\left\{ \tilde{x}i(t) e^{j2\pi f_i t} \right\}
\]  

with \( f_i \) denoting the frequency of its first sub-carrier and \( \tilde{x}i(t) \) denoting the complex envelope of the \( i \)-th transmitted MIMO-OFDM signal, given by

\[
\tilde{x}i(t) = \sum_{k=-\infty}^{\infty} \sum_{n=0}^{N-1} X_{i,k,n} p\left(t + \epsilon - kT \right) e^{j2\pi \left( t - T_{cp} \right) \left( -kT - T_{cp} + \epsilon \right)}
\]  

where \( X_{i,k,n} \) is the complex symbol transmitted in the antenna \( i \), subcarrier \( n \) on the \( k \)-th time interval, \( N \) is the number of OFDM sub-carriers, \( T \) is the length of the OFDM symbol, \( \theta \) and \( \epsilon \) are random variables modeling the phase of the oscillator and the error of synchronization respectively, \( p(\cdot) \) denote the modulation shaping pulse and \( T_{cp} \) denote the duration of the cyclic prefix of the OFDM signal. The random variables \( \theta \) and \( \epsilon \) are considered statistically independent and uniformly distributed on \((0,2\pi)\) and \((-T/2,T/2)\) respectively.

The mean of the complex envelope \( \tilde{x}i(t) \) is given by

\[
m_{\tilde{x}i} = \sum_{k=-\infty}^{\infty} \sum_{n=0}^{N-1} E\left[ X_{i,k,n} \right] E\left[ p\left(t + \epsilon - kT \right) e^{j2\pi \left( t - T_{cp} \right) \left( -kT - T_{cp} + \epsilon \right)} \right] E\left[ e^{j\theta} \right]
\]  

note that, since \( \theta \) is uniformly distributed on \((0,2\pi)\), \( E\left[ e^{j\theta} \right] = 0 \) and consequently
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