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Impact of phase noise on single-tap equalization for fast–OFDM signals under generic linear fading channels

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ABSTRACT

In this correspondence, we present the performance evaluation of a low-complexity fast – orthogonal–frequency–division–multiplexing (F–OFDM) scheme, in the presence of phase-noise (PHN), working under the generic linear fading channels (like two-wave-with-diffuse-power (TWDP) multipath fading and modal dispersion in multi-mode-fiber optic channel). Here, a single-tap zero-forcing (ZF) equalizer is utilized to compensate the channel-impulse-response (CIR) without sacrificing data-rate, in which the discrete-cosine-transform (DCT) operation is replaced by the discrete-Fourier-transform (DFT) operation at the receiver. The phase noise variations are modelled by utilizing the random–walk paradigm, in which PHN is dependent on the model parameters/statistics. Therefore, main focus is on the impact of PHN on the performance of single-tap ZF equalization for F–OFDM signals. Simulation results are presented to illustrate efficiency and efficacy of underlying F–OFDM system, while working under TWDP, Rician and Rayleigh multipath fading linear channels. It can be inferred from results that the PHN severely affects/deteriorates the performance of F–OFDM based communication systems in terms of high bit-error-rate (BER), when the PHN variations are large. Moreover, the TWDP fading model is found to be quite appropriate for analyzing/investigating the BER performance of communication systems using the binary-shift-keying modulation technique.

1. Introduction

Fast–orthogonal–frequency–division–multiplexing (F–OFDM) system has emerged as a proficient multicarrier (MC) transmission scheme, in which the subcarrier spacing is half of that of the traditional OFDM scheme [1–3]. In the domain of fiber optic communication systems, the discrete–cosine–transform (DCT) is usually preferred over the discrete–Fourier–transform (DFT) in F–OFDM systems for the information symbol multiplexing onto the subcarriers [4–6]. Exclusively, F–OFDM possesses enhanced tolerance, to the carrier frequency offset in optical coherent detection, as well as to the Doppler shift in wireless communication [7,8]. However, F–OFDM exhibits better receiver sensitivity in optical full field detection [9]. These striking features make the F–OFDM technique an efficient and suitable technique for MC transmission. But, one of the key challenges in optical communication systems utilizing the DCT based F–OFDM technique is that the DCT exhibits symmetric convolution property [10], in which two sequences must be symmetrically extended to make the DCT of convolution equal to the product of their individual DCTs. It imposes a stringent condition that the symmetric prefix and suffix are needed as guard-interval (GI) for F–OFDM signaling in addition to the inherently symmetric channel–impulse–response (CIR). Here, single-tap equalization in the cosine–domain for F–OFDM signaling for the

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symmetric channels is promising only under a few typical cases like chromatic dispersion in the single-mode-fiber (SMF) optic channel [11].

On the contrary, under generic linear fading channel conditions (like modal dispersion in multi-mode-fibers (MMF) optic channel and multipath fading in wireless channel), the condition for symmetric convolution is not fulfilled, and it precludes the usage of traditional single-tap equalizers for CIR compensation. The condition of symmetric convolution can be met by symmetrically extending the F–OFDM signal, but it is possible at the cost of reduced data-rate [12]. Subsequently, the minimum-mean-square-error (MMSE) criterion based time-domain pre-filtering at the receiver is suggested in [13] to improve the data-rate under similar conditions. But, its major limitation is computational complexity. Further, in frequency-domain-equalization (FDE) [14], the CIR impairments are compensated at the receiver (using DFT operations) before the signal is transformed to the cosine-domain by using DCT operation. However, it is observed that noise in the frequency-domain is getting amplified, and it is found to spread over the subcarriers after DCT operation. Though the MMSE criterion based equalizer performs well as compared to the zero-forcing (ZF) equalizer in controlling this noise amplification, but the underlying F–OFDM system still appears to be vulnerable to the noise at spectral nulls [15].

Ouyang et al. [16] have reported a low complexity F–OFDM scheme for generic linear fading channels (like modal dispersion in MMF optic channel [17] and multipath fading in wireless channel), which can be employed for the single-tap equalization irrespective of the requirement of symmetric channel characteristics. This technique outperforms the FDE based F–OFDM scheme working under the frequency–selective channels. It compensates generic linear-time-invariant (LTI) channels by utilizing a single-tap equalizer without compromising the data-rate. In addition to zero-padded (ZP) GI, the DFT of double length (*i.e.*, 2N–point) has been incorporated at the receiver instead of the conventional N–point DCT approach; where N is the number of demultiplexed subcarriers. However, the MC modulation exhibits a substantial sensitivity to the phase-noise (PHN) of the oscillator utilized for frequency down-conversion at receiver [18], which causes interbin interference (depending on the information data from all of the different sub-channels).

Moreover, OFDM systems are sensitive to phase noise and to carrier-frequency-offset (CFO), respectively, caused by the oscillator imperfections and Doppler shifts [19–21]. Indeed, these phase distortions disturb the orthogonality of OFDM subcarriers and it results both in rotation of every subcarrier by a random phase, called common-phase-error (CPE) [22], and to inter-carrier-interference (ICI). The performance of underlying OFDM system gets deteriorated due to the presence of this random Wiener phase noise, which also significantly degrades the efficiency of channel estimator [23]. The effect of Wiener phase noise has been examined by Pollet et al. in [19], which has been found to be a much more complex phenomenon as compared to CFO. The PHN generated by the fluctuations of receiver as well as transmitter oscillators causes leakage of DFT [24]. The CPE causes subcarrier phase rotation, which doesn't change within OFDM symbol duration; while ICI introduces interference to any subcarrier of a certain symbol from all the other subcarriers of that symbol, and therefore it possesses noise-like features. However, the higher PHN levels are catastrophic, as it makes ICI dominant over the transmitted signal [25]; but the lower phase noise levels can be tackled by estimating and compensating for CPE, only by minimizing mean-squared-error (MSE) [26,27]. To better characterize PHN, Demir et al. [28] developed a unifying theory by utilizing a nonlinear method, which proves to be more accurate as per its description. Here, the phase noise $\phi(t)$ is illustrated to become (asymptotically in time) a Gaussian random process having a constant mean, a variance increasing linearly with time and the correlation function that satisfies $E[\phi(t)\phi(t+\tau)] = Min[E\{\phi^2(t)\}, E\{\phi^2(t+\tau)\}]$. Nikitopoulos et al. have indicated in [29] that a discrete Markov-process is an appropriate model to illustrate PHN.

The small scale fading experienced by the narrowband receivers has been extensively explored by characterizing fading channels while utilizing the Rayleigh, Rician or Nakagami-m probability density functions (PDFs) [30–32], where the complexity of analysis is quite lower than that of the two-wave-with-diffuse-power (TWDP) fading for the phase modulation schemes. Actually, TWDP is characterized by the presence of multiple scattered waves and two line-of-sight components with constant amplitudes and uniformly as well as independently distributed phases [32,33], which can also be represented as an infinite mixture of gamma distributions [34]. The recent studies in this field quantitatively reveal that TWDP fading can give rise to a link worse than Rayleigh fading, when two direct waves are equal in strength, but opposite in phase, and have a combined power of ≥ 6 dB higher than diffused power. This inference points towards the utilization of TWDP fading rather than Rayleigh fading as a worst case scenario in designing and evaluating the communication systems [35]. To address this issue in the domain of F–OFDM signal transmission and reception, the performance of single-tap ZF equalization technique needs to be investigated further.

In this research work, we emphasis on the performance evaluation of an efficient F–OFDM technique using the IDCT operation at transmitter and the DFT operation at receiver [16], in the presence of phase noise [23,25], while working under the generic linear fading channels (like TWDP fading channels [30,32,34,35], in which the requirement for symmetric condition is not satisfied in underlying system). In Section 2, we describe the F–OFDM communication system affected by PHN, which uses a ZF equalization based approach for the CIR compensation. The details about phase noise attributes are provided in Section 3. Simulation results are presented in Section 4 to demonstrate the average BER performance of F–OFDM system under the influence of PHN, and to analyze the adverse impact of PHN variations on its BER at the different values of signal-to-noise-ratio (SNR). Section 5 includes concluding remarks and future scope.

2. F–OFDM system working under linear fading channel and phase noise

A paradigm for the F–OFDM system working under the linear generic fading channel, in the presence of phase noise, is illustrated in Fig. 1. The kth subcarrier is modulated by the information symbols $q[k]$, when there are N subcarriers with $k = 0, 1, \ldots, N-1$. The related time-domain signal samples $x(n)$ are generated by using the inverse-DCT (IDCT) operation [36], it follows that