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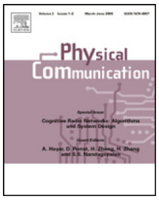

Full length article

OFDM symbol detection integrated with channel multipath gains estimation for doubly-selective fading channels

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ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) is a technique for wideband transmission that is commonly used in modern wireless communication systems because of its good performance over frequency selective channels. However OFDM systems are sensitive to channel time variations resulting in Inter-Carrier Interference (ICI), that without suitable detection methods can degrade performance significantly. Channel State Information (CSI) is essential to various OFDM detection schemes, and its acquisition is a critical factor over time varying channels. This work considers a Kalman filter channel multipath gains estimation technique for time varying environments, integrated with a novel detection scheme for OFDM based on a Sphere Decoding (SD) algorithm derived to exploit the banded structure of the channel matrix. This combined scheme employs decision–feedback from the SD requiring only a low pilot symbol density, and hence improves bandwidth efficiency. Three techniques for integrating the Kalman filter operating in decision–feedback mode, with SD data detection that produces these decisions, are considered in this paper. When compared with other competing schemes, this integrated symbol detection and channel multipath gains estimation approach for OFDM provides performance advantages over time varying channels. Furthermore, it is shown that for moderate Doppler shifts the degradation that carrier phase noise induces in this scheme is small.

1. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a commonly used transmission technique for frequency selective channels [1]. Over the years OFDM became a basic technology for broadband services that is used in Digital TV systems [2], WiMAX [3] and 4G LTE-Advanced [4]. Many OFDM systems operate in environments that can be characterized as doubly-selective channels, experiencing frequency selectivity as well as time variations [5,6]. Symbol detection in OFDM systems over doubly-selective channels is a challenging task, since orthogonality between sub-carriers is destroyed when the channel is time varying [7–9]. For example, at a carrier frequency of 1492 MHz and vehicle speed of 100 km/h the normalized Doppler shift in DVB-T/H (mode 8k) and DAB systems can be as high as 0.2 and 0.14 respectively [7]. Such systems can experience even higher normalized Doppler shifts when used in high speed trains. Hence suitable detection techniques are critical for successful use of OFDM in such applications.

In a static environment, the channel matrix of an OFDM system in frequency domain is diagonal, and hence data detection can be easily implemented by using a single tap equalizer [7]. Over a time varying channel, however, the OFDM system channel matrix becomes full and introduces Inter-Carrier Interference (ICI) [9], that without suitable detection techniques can cause significant performance losses [5,7,9]. Hence ICI cancellation based demodulation for OFDM systems has been a subject of continuous research over many years [10]. Other approaches for demodulation of OFDM signals include ICI whitening [11], and Minimum Mean Square Error (MMSE) techniques [9].

The ICI in OFDM is mainly contributed by adjacent sub-carriers, and hence the channel matrix can be modelled as banded [7,12]. Various techniques based on such banded approximation have been proposed to mitigate ICI effects while maintaining a moderate complexity. A serial Zero-Forcing (ZF) equalizer was proposed in [13], where based on a banded channel matrix approximation the original system is decomposed into several sub-systems allowing data detection with reasonable complexity. A similar approach based on the MMSE criterion was considered

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in [14], where it is integrated with decision–feedback. The banded approximation is also used in [15] to derive block linear and decision–feedback equalizers for demodulation in OFDM systems over time varying channels.

A high performance alternative to the ZF and MMSE approaches is Maximum Likelihood (ML) detection. However the complexity of ML detection, in its exhaustive search form, is exponential in the number of sub-carriers. Employing the banded channel matrix approximation, a Viterbi Algorithm (VA) operating in the frequency domain is considered in [16] for OFDM demodulation. The complexity of the VA is determined by the number of trellis states, that depends on the number of diagonals in the approximated channel matrix. For moderate Doppler rates, approximating the channel matrix by seven diagonals provides diversity gains with a reasonable complexity [16]. In [17] we proposed a data detector for OFDM based on a Sphere Decoding (SD) algorithm designed for a banded matrix approximation of the channel, making it as practical as the VA scheme of [16] while providing important performance gains over the latter. However, the detection techniques of [16,17], as well as many other demodulation schemes for OFDM, require Channel State Information (CSI).

The assumption that CSI is known perfectly at the receiver is not realistic, and in practice it has to be acquired. In OFDM systems direct estimation of time varying channel gains is complex because of the large number of sub-carriers [7,18]. To circumvent this problem, Basis Expansion (BE) techniques, that decompose the time varying channel into a linear combination of time basis functions with coefficients that vary between different OFDM symbols, are often employed [12]. Since the number of basis functions is usually small, the estimation of the BE coefficients is a more feasible task. In [18], a Least Square (LS) channel estimator based on the Karhunen–Loeve (KL) expansion is proposed, and a VA [16] is used for data detection. In [19], a polynomial BE is used with LS estimation of BE coefficients based on pilot symbols. The estimated channel is then used by a successive interference suppression technique for data detection. A BE method known as Generalized Complex Exponential (GCE) is used in [20], with LS, Kalman and Modified Recursive LS (MRLS) estimation based on pilot symbols. It is shown that the Kalman filter converges faster than the MRLS, and both provide good performance. The optimal position of pilot symbols for GCE-BE is studied in [21]. A Kalman filter based on a polynomial BE model is used to estimate the channel in [22]. Data is detected after the time update stage of the Kalman filter, and fed back to the measurement update stage. Another scheme where the state-space equations are derived based on pilot symbols only is presented in [23]. The unknown data is considered as noise, and hence no decision–feedback is required. The use of a Basis Expansion Model (BEM) for OFDM channel estimation employing a Kalman filter switched periodically to operate on pilot symbols and decision–feedback modes is considered in [24]. A joint channel estimation and data detection technique for OFDM over fast time varying channels, that is based on the Space Alternating Generalized Expectation Maximum A-Posterior Probability (SAGE-MAP) algorithm is considered in [25], where a BE technique employing discrete Legendre basis functions is used. Using complex exponentials, a BE model has been presented in [26,27] for estimating doubly selective channels in Multiple-Input Multiple-Output (MIMO) systems.

In this paper we introduce a joint data detection and channel multipath gains estimation scheme for OFDM systems based on integrating a Kalman filter, operating in decision–feedback mode, with a specially derived SD algorithm providing data decisions. For large Doppler, there is a need for a large pilot density in order to achieve good channel estimation, and hence the throughput is reduced. Employing decision–feedback reduces the number of pilot symbols required for channel tracking, and hence increases bandwidth efficiency. The large number of pilots is one of the main factors that limits the throughput in 3G/4G wireless systems, well below of what was envisaged [28]. Hence reducing the required number of pilots is an important improvement for future OFDM systems. We use a KL-BE as in [29] to model the time-varying channel, and employ our new SD algorithm of [17] based on a banded channel matrix approximation because of its good performance and its suitability for practical OFDM systems. Integrating such a detector with a Kalman filter operating in decision–feedback mode for channel tracking presents some intricate issues that are tackled in this paper. In [17] we compared our SD based technique with the VA detector of [16] in terms of performance and complexity assuming that CSI is perfectly known. In the present paper, the comparison is done with [18] where CSI is estimated based on pilot symbols, and also with [25] that considers joint channel estimation and data detection for OFDM over time varying channels. Performance results for LTE channels including effects of carrier phase noise are also presented.

In the continuation of this paper, Section 2 presents the OFDM system with KL-BE modelling of time varying channel multipath gains. Section 3 presents the state space model for KL-BE coefficients, and the associated Kalman filter. Section 4 presents our SD algorithm based on a banded matrix approximation of the channel, named Ordered Partial tree search Sphere Decoder (OPSD). Section 5, presents a joint data detection and channel multipath gains estimation scheme based on integrating Kalman filtering with the OPSD using three variations for deriving decision–feedback. Section 6 presents Monte-Carlo simulation results for the error rate, and also a comparison with [18,25]. Furthermore, error rate results over LTE channels with various normalized Doppler frequencies and carrier phase noise, are also presented. Finally, Section 7 presents the conclusions.

2. System model and basis expansion representation of the channel

In this work, the k, l component of matrix $\mathbf{A}$ is denoted as $[\mathbf{A}]_{k,l}$. Consider an OFDM symbol expressed in the continuous time domain as

$$s_m(t) = \frac{1}{\sqrt{K}} \sum_{l=0}^{K-1} d_m[l] \exp(j2\pi f_l t), \quad t \in [(m-1)T_{sym}, mT_{sym}],$$

where $d_m[l], l = 0, \dots, K-1$, denote transmitted data symbols on sub-carrier l during the mth OFDM symbol interval, $f_l, l = 0, \dots, K-1$ are sub-carrier frequencies satisfying $f_l = \frac{l}{T_{sym}}$ to preserve orthogonality, and T_{sym} is the duration of an OFDM symbol excluding the cyclic prefix. The data symbols $d_m[l]$ are generated with equal probability from a constellation set $\mathcal{A}$ (MPSK, MQAM, etc.) of size $N_{\mathcal{A}}$ and average energy E_s. After adding a cyclic prefix, the OFDM symbol is transmitted over a multipath channel of impulse response

$$h(t, \tau) = \sum_{p=0}^{P-1} h_p(t) \delta(\tau - \tau'_p)$$

where P is the number of multipath components, $h_p(t)$ is the time varying gain of path p and τ'_p is its delay. We assume that $h_p(t)$ are stationary zero mean circularly symmetric complex Gaussian random processes, that are independent for different p.

After sampling at rate K/T_{sym} and removing the cyclic prefix samples, the discrete time received signal in an OFDM system can be represented as

$$r_m[n] = \frac{1}{\sqrt{K}} \sum_{p=0}^{P-1} \sum_{l=0}^{K-1} h_{m,p}[n] d_m[l] \exp\left(\frac{j2\pi ln}{K}\right) \exp\left(\frac{-j2\pi l\tau_p}{K}\right) + v_m[n], \quad n = 0, \dots, K-1 \qquad (1)$$