Adaptive Symbol Length for OFDM Systems in Doubly Selective Channels

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***Abstract*— Symbol length is an important factor that can affect the spectrum efficiency and the performance of Orthogonal Frequency Division Multiplexing OFDM system. However, the symbol length is usually fixed in conventional OFDM systems, which decreases the spectrum efficiency considerably, especially in a mobile environment. This paper introduces an adaptive OFDM system in which the delay spread and Doppler spread are estimated at the receiver and according to their estimated values, the transmitter vary the symbol length such that the Bit Error Rate BER is always around a certain predetermined value. The value of the BER is chosen according to the type of the transmitted information. Simulation has been implemented and the results show that the proposed adaptive algorithm gives an improvement in the total throughput of the system without significantly sacrificing the BER performance.**

I. INTRODUCTION

ORTHOGONAL frequency-division multiplexing (OFDM) has been successfully applied in various wireless communication systems in the last decade [1], [2], [3]. Those systems, however, should be capable of efficiently working in a wide range of operating conditions, such as a large range of mobile speeds, different carrier frequencies, various delay spreads, asymmetric traffic loads in downlink and uplink, and wide dynamic Signal-to-Noise Ratio (SNR) ranges. The aforementioned reasons motivated the use of adaptive algorithms in new-generation wireless communication systems [4]. Adaptation aims at optimizing the wireless mobile radio system performance, enhancing its capacity, and utilizing the available resources in an efficient manner. If adaptation is not used, the worst-case channel condition is used for system design. Many adaptive techniques have been investigated for the OFDM system in the previous research. One example of adaptive Variable modulation rate for Direct Sequence Code Division Multiple Access (DS-CDMA) is introduced in [5]. In [6] and [7], adaptive Orthogonal Frequency Division Multiplexing (OFDM) systems are proposed. The digital adaptive filters have also found their applications for equalization in modern communication systems as in [8] and [9]. Some examples of adaptive power control technique for cellular systems is studied in [10] and [11]. For short term time variations, the channel can be assumed wide since stationary uncorrelated scattering WSSUS [12], which means that, the channel statistical parameters such as Doppler and delay spreads can be assumed constant. However, the long term variations of the channel lead to changes in the channel statistical parameters during the transmission time. This variations degrade the performance of the conventional systems that use fixed symbol length , either by increasing the effect of Doppler spread for systems with long symbols in rabidly time-varying channels or by introducing Inter-Symbol Interference ISI for systems with short symbols in case of highly frequency selective channels. In this paper, a method for adapting OFDM symbol length is introduced, in which the estimation of the delay spread and Doppler spread at the receiver side is accomplished and fed back to the transmitter in order to adapt the symbol length by means of increasing or decreasing the padded zeros aiming at increasing the total throughput of the system as a subject of a BER target.

II. SYSTEM MODEL

Before formulating the system model, we define the notation used in this paper as follow: Bold uppercase letters ($\mathbf{H}$) denote matrices, bold uppercase underlined letters ($\underline{\mathbf{V}}$) denote frequency domain vectors, while time domain vectors are represented by bold lowercase underlined letters ($\underline{\mathbf{v}}$), variables in time are denoted by lowercase letters $v(n)$, and in frequency by uppercase letters $V(n)$. The operators $\{.\}^*, \{.\}^T, \{.\}^H, E\{.\}, \mathcal{D}\{.\}$, represent complex conjugate, matrix/vector transpose, Hermitian transpose, mathematical expectation, and the diagonal matrix composed of the elements of a vector, respectively. $\mathbf{I}$ denotes the identity matrix.

In the OFDM system, the source stream is first modulated using a common modulation scheme as Quadrature Amplitude Modulation QAM or Phase Shift Keying PSK before applying Fast Fourier Transform FFT operation. The multi-path time-variant channel can be expressed as

$$h(t,\tau) = \sum_{l=0}^{L-1} d_l(t)\delta(\tau - \tau_l(t)), \tag{1}$$

where $d_l(t)$ is the time-variant complex amplitude of the channel at the lth path and $\tau_l(t)$ is the corresponding time

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delay. In (1), we assume that not only the channel amplitudes are changing in time, but also the delays are changing in long-term sense. The n^{th} time sample of the transmitted OFDM symbol is written as

$$x(n) = \sum_{m=0}^{N-1} S(m) e^{j\frac{2\pi n m}{N}} \qquad 0 \leq n \leq N-1, \tag{2}$$

where $S(m)$ is the QAM/PSK symbol at the m^{th} sub-carrier. The transmitted signal is convolved with the channel to produce the received signal as

$$y(n) = \sum_{l=0}^{L-1} d(n,l) x(n-\tau_l) + v(n), \tag{3}$$

where $v(n)$ describes the additive white Gaussian noise and $d(n,l)$ represents the discrete complex amplitude of the channel at sample n. By performing FFT at the receiver, the kth unequalized frequency domain carrier becomes

$$Y(k) = \frac{1}{N} \sum_{n=0}^{N-1} \Big(\sum_{l=0}^{L-1} d(n,l) x(n-\tau_l) + v(n) \Big) e^{-j\frac{2\pi n k}{N}}. \tag{4}$$

Equation (4) can be simplified [13] to

$$Y(k) = S(k) H_{k,k} + \underbrace{\sum_{m \neq k} S(m) H_{m,k}}_{ICI} + V(k). \tag{5}$$

Writing (5) in vector form gives

$$\underline{\mathbf{Y}} = \mathbf{H}\underline{\mathbf{S}} + \underline{\mathbf{V}}, \tag{6}$$

where $\underline{\mathbf{S}}$ is the frequency domain transmitted OFDM symbol, $\mathbf{H}$ is the channel matrix, and $\underline{\mathbf{V}}$ is the noise vector in frequency domain. In time-invariant channels, $\mathbf{H}$ has a diagonal structure, and loses its diagonality in time-variant channels, thus the sub-diagonals represent Inter-Carrier Interference (ICI) strength between the sub-carriers which reflects the variation level of the channel caused by Doppler effect. If we define $U_k(n)$ as the time varying channel weights for each sub-carrier k and time sample n, $H_{k,m}$ can be expressed as

$$H_{k,m} = \frac{1}{N} \sum_{n=0}^{N-1} U_k(n) e^{-j\frac{2\pi}{N} n(k-m)}. \tag{7}$$

The adaptive system is working as following: In rabidly time-variant channels (high Doppler spread), the symbol length is reduced in order to cope with the resulting ICI. Whereas, for long channel impulse response (CIR), the symbol is increased to deal with the possible ISI.

A. Channel Matrix Estimation Using Numerical Approximation

In order to estimate the Doppler spread that is used for the adaptation, the channel matrix needs to be estimated, which contains information about Doppler spread. Firstly, the main diagonal of $\mathbf{H}$ is estimated using pilot-based one dimensional Wiener filter [14] . The delay spread can be estimated from the main diagonal of the matrix at the beginning of the transmission by sending pure pilots and then applying a super resolution scheme as Root-MUSIC [15]. For the payload data, the off-diagonals can be estimated by means of an approximation method over Q successive OFDM symbols [16]. From (7), the main diagonal of $\mathbf{H}$ is written as

$$\overline{U}_k = H_{k,k} = \frac{1}{N} \sum_{n=0}^{N-1} U_k(n) \tag{8}$$

which is in fact, the averaged value of $U_k(n)$ over n and located at the middle of the symbol. By considering a Taylor expansion one can write

$$U_k(n) = \overline{U}_k + \frac{(n - \frac{N-1}{2})\overline{U}'_k}{1!} + \frac{(n - \frac{N-1}{2})^2 \overline{U}''_k}{2!} + \ldots. \\ + \frac{(n - \frac{N-1}{2})^Q \overline{U}^{(Q)}_k}{Q!} + \ldots. \tag{9}$$

where $\overline{U}^{(Q)}_k$ is the q^{th} derivative of $\overline{U}_k$. If we define $\overline{U}^{(0)}_k$ and $\overline{U}^{(\pm i)}_k$ as $\overline{U}_k$ at the current symbol and the next and the previous symbols respectively, these derivatives can be expressed using the central difference formulas for $Q = 5$ as

$$\overline{U}'_k \approx \frac{\overline{U}^{(-2)}_k - 8\overline{U}^{(-1)}_k + 8\overline{U}^{(+1)}_k - \overline{U}^{(+2)}_k}{12 N_s}, \tag{10}$$

$$\overline{U}''_k \approx \frac{-\overline{U}^{(+2)}_k + 16\overline{U}^{(+1)}_k - 30\overline{U}^{(0)}_k + 16\overline{U}^{(-1)}_k - \overline{U}^{(-2)}_k}{12 N_s^2} \tag{11}$$

N_s is the total OFDM symbol duration. The more terms of Taylor equation are considered, the more accurate approximation is obtained. Once the approximated $U_k(n)$ is calculated, the channel matrix $\mathbf{H}$ is estimated relying on (7). Fig. 1 illustrates the adaptive OFDM system with the feedback signaling.

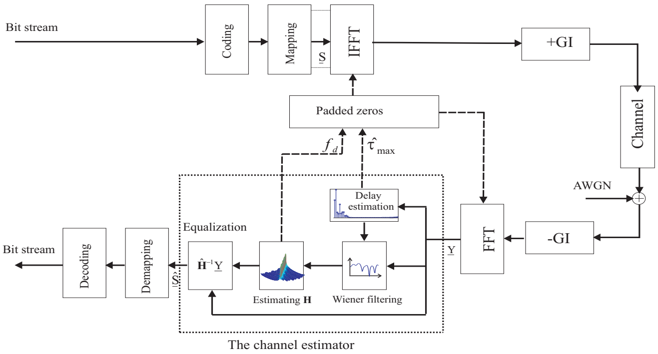

Fig. 1. Baseband adaptive OFDM system.

III. SIMULATION RESULTS

For simulation, an OFDM system with variant FFT length has been considered. The number of carriers was 91. The baseband bandwidth was 4.5 KHz and the sampling rate was 48 KHz. Uncoded Quadrature Phase Shift Keying QPSK scheme was used and OFDM symbols were transmitted through a

4-tap time-variant channel. We assume that the channel has variant maximum delay between .1 ms to 4.4 ms during the transmission time. The channel taps were generated as random processes with Rayleigh distribution and with variant Doppler spread between .1 to 12 Hz. According to the delay and Doppler spreads, a signal is fed back to the transmitter to change the number of padded zeros, which leads to change the total symbol length between 0.0107 ms to 0.0480 ms with assuming an ideal feedback channel without errors. Fig. 2 shows the BER performance of the system vs. both delay and Doppler spread. The adaptive behavior of the system is demonstrated in Fig. 3 by tracking the variation of the delay and Doppler spread. The figure shows a considerable gain in the throughput compared with the conventional one that has an FFT length of 1024. The aim of the adaptive system was to gain the maximum throughput without sacrificing the BER performance. Fig. 4 shows comparison of the BER performance between the conventional and the adaptive systems. It can be seen that the adaptive system reduces the peaks in the BER performance caused by the variations in the channel statistics. Both systems are performing approximately the same in terms of total BER performance over the transmission period.

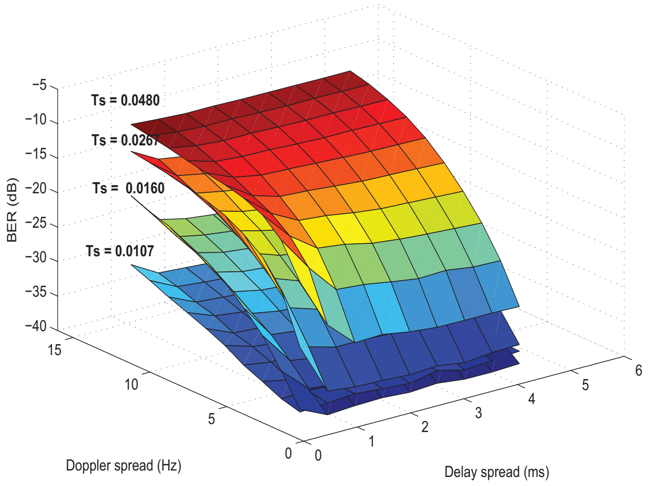

Fig. 2. BER vs. (Delay spread & Doppler spread).

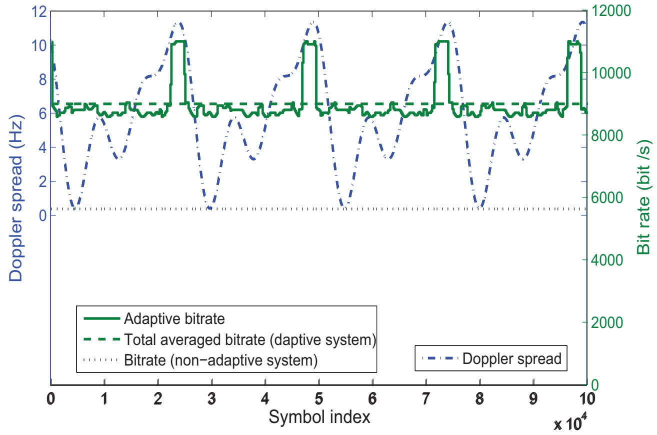

Fig. 3. Bitrate vs. Doppler spread.

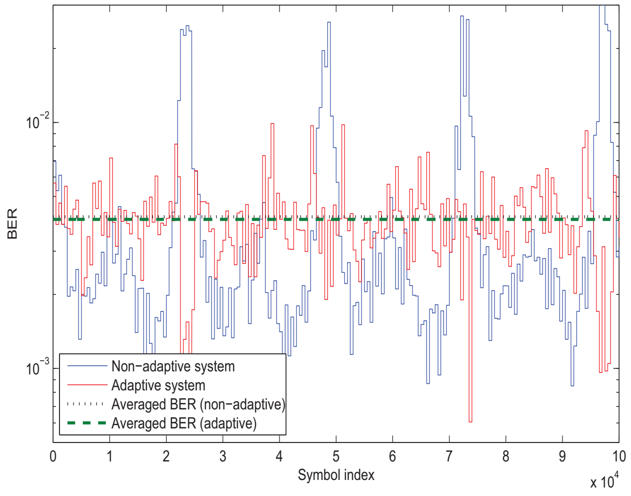

Fig. 4. Comparison of the BER performance between the conventional and the adaptive systems.

IV. CONCLUSION

This paper proposes an adaptive symbol length scheme for OFDM system. The scheme changes the symbol length according to the delay and Doppler spread of the channel. It has been shown from the simulation results that a considerable gain in the system throughput has been achieved without sacrificing the system performance in terms of BER. In order to reduce the effect of ICI, the off-diagonals of the channel matrix have been estimated using numerical approximation of the time-variant channel.

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