Doppler Spread Estimation for Wireless OFDM Systems

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Abstract **In this paper, we present a method for estimating the Doppler spread in mobile orthogonal frequency division multiplexing (OFDM) systems. The estimation is based on nding the autocorrelation function of time domain channel estimates over several OFDM symbols. In OFDM systems channel estimation is popularly performed in frequency domain. Channel frequency response estimates are affected by noise and inter-carrier interference (ICI). As a result, Doppler estimates based on frequency domain channel estimates will be affected signi cantly. We show that use of channel estimates in time domain can greatly improve the performance of Doppler estimates. The channel impulse response (CIR) can be obtained by taking IDFT of the channel frequency response (CFR). Consequently the proposed method will reduce processing time and memory usage. Computer simulations support our claim for a broad range of Doppler spread and signal-to-noise ratio (SNR) values in Rayleigh fading channels.**

I. Introduction

OFDM has been applied for various wireless communication systems in the last decade. Because of its tremendous success in digital video broadcasting (DVB) and wireless local area networks (WLANs), it is now considered for broadband wireless systems for both fixed and mobile applications such as wireless metropolitan area networks (WMANs), mobile broadband wireless access (MBWA) and proposed fourth generation (4G) cellular systems [1]. Those systems however, should be capable of working efficiently in wide range of operating conditions, such as large range of mobile subscriber station (MSS) speeds, different carrier frequencies in licensed and licensed-exempt bands, 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. Adaptation aims to optimize wireless mobile radio systems performance, enhance its capacity and utilize available resources in an efficient manner. However, adaptation requires a form of accurate parameter measurements. One key parameter in adaptation of mobile radio systems is the maximum Doppler spread. It provides information about the fading rate of the channel. Knowing Doppler spread in mobile communication systems can improve detection and help to optimize transmission at the physical layer as well as higher levels of the protocol stack [2]. Specifically, knowing Doppler spread can decrease unnecessary handoffs, adjust interleaving lengths to reduce reception delays, update rate of power control algorithms, *etc*. In addition, in OFDM systems, if the channel varies considerably within one OFDM symbol because of high MSS mobility, orthogonality between subcarriers is lost, leading to inter-carrier interference (ICI) [3]. Doppler information can help in selection of appropriate transmission profiles that are immune to ICI and hence the overall system performance will be improved.

Various methods based on the auto-correlation function (ACF) have been used to estimate the Doppler spread f_d in single carrier systems [2]. In OFDM systems, the autocorrelation between the repeated parts of the symbol due to cyclic prefix (CP) is exploited in [4] to estimate the Doppler spread. However, adaptive OFDM systems employ a form of variable CP size selection according to the delay spread of the channel. The part of the CP that is undisturbed by the multipath channel may be small especially when the environment causes large delay spread. This will degrade estimation greatly. Moreover, the results presented shows that the algorithm is biased at low and medium Doppler values, and gives good estimates at very high velocities which is less likely to occur. The scheme is also sensitive to SNR variations. In OFDM systems, channel estimates are often obtained in frequency domain. By obtaining the ACF of a certain subcarrier over several symbols, f_d can also be estimated [5]. However, every subcarrier will have noise perturbation due to additive white Gaussian noise (AWGN) and ICI. In this paper, we overcome this bias by performing inverse fast Fourier transform (IFFT) to the channel estimates and then using the few obtained channel taps to get f_d.

The organization of this paper is as follows. In Section II, brief system and channel models are presented. Then, the Doppler spread estimation algorithm is discussed in Section III. Simulation results are presented and analyzed in Section IV. Finally, Section V concludes the paper.

II. System and Channel Models

Let us consider the well known OFDM modulation and demodulation using IFFT and fast Fourier transform (FFT) algorithms. A CP is added to suppress the effect of ISI. The transmitted OFDM symbols can be written as

$$x_m(n) = IFFT\{X_m\} \quad (1)$$

$$= \sqrt{\frac{1}{N}} \sum_{k=0}^{N-1} X_m(k) e^{\frac{j2\pi nk}{N}} \quad (2)$$

where $x_m(n)$ is the mth OFDM symbol at discrete time n, N is the FFT size, and $X_m(k)$ is the data symbol transmitted on the kth subcarrier of mth OFDM symbol. For the channel, we adopt the 2D channel model proposed by Clarke, where at a given instant, there exist L multipaths arriving at the receiver with distinct complex amplitudes, phases, Doppler shifts and delays. It was shown that with no line-of-sight path the envelope of each path fading is modelled by Rayleigh distribution [6]. The channel is assumed to be time-variant. Consequently, during an OFDM symbol period, the discrete time channel impulse response is given by

$$h(n,\tau) = \sum_{l=1}^{L} h_l(n)\delta(n-\tau_l) \tag{3}$$

where τ_l is the propagation delay associated with path l. The path gains $h_l(n)$ are zero-mean stochastic processes with normalized overall power, so that $E\left[(h_l(n))\right] = 0$ and $\sum_{l=1}^{L} E\left[|h_l(n)|^2\right] = 1$. Assuming wide sense stationary uncorrelated scattering (WSSUS) channel model, and with uniformly distributed angle of arrival (AOA), the autocorrelation function of the channel impulse response (CIR) for a certain tap l is given by

$$E\{h(n)h^*(n+\tau)\} = J_0\left(2\pi f_d \tau\right) \tag{4}$$

where $J_o(.)$ is the zeroth order Bessel function of the first kind. The maximum Doppler shift $f_d = \frac{v}{\lambda}$ is determined by the mobile velocity v and the wavelength λ. After passing through a radio channel, the mth received time-domain OFDM signal $y_m(n)$ can be written as a function of the transmitted signal, the channel transfer function, and AWGN as

$$y_m(n) = x_m(n) * h(n,\tau) + w_m(n), \quad 1 \le n \le N \tag{5}$$

where $*$ denotes convolution. After performing the FFT operation at receiver, the received frequency-domain signal $Y_m(k)$ can be expressed as [7]

$$Y_m(k) = X_m(k)H_m(k) + I_m(k) + W_m(k) \tag{6}$$

where $H_m(k)$ is the channel transfer function at the kth subcarrier, $I_m(k)$ is the ICI term, and $W_m(k)$ represents the AWGN. The interference term depends on transmitted symbols and the variation of the channel over an OFDM symbol. It can be formulated as

$$I_m(k) = \sum_{u=0,\ u\neq k}^{N-1} \sum_{l=0}^{L-1} X_m(u) \frac{1}{N} \sum_{d=0}^{N-1} h_l(d) e^{j2\pi d(u-k)/N} . \tag{7}$$

Note that the interference power increases with increasing variation in the channel response, *i.e* with increasing velocity or Doppler spread.

III. Doppler Spread Estimation

In OFDM systems, channel estimation is usually done in frequency domain either by sending pilots on specific subcarriers or using preambles and inserting frequent mid-ambles to capture channel variations. The latter case will be considered in this paper. The channel estimates at all subcarriers can be obtained by dividing (6) by the known transmitted symbols $X_m(k)$ as

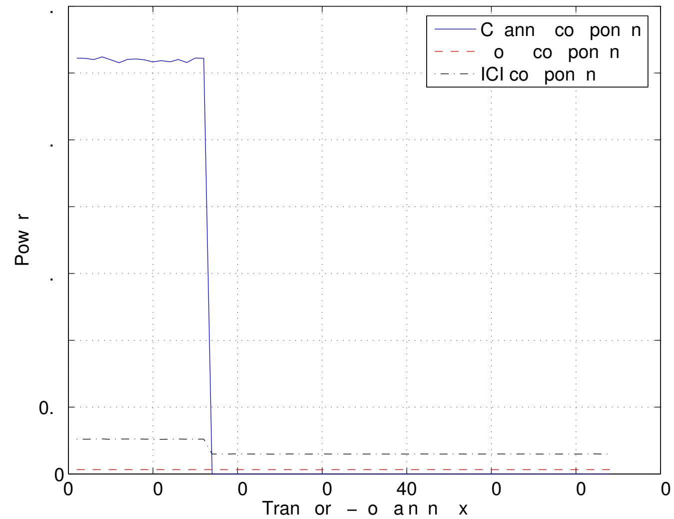

Fig. 1. Average powers of the channel components and disturbances in time-domain.

$$\hat{H}_m(k) = \frac{Y_m(k)}{X_m(k)} = H_m(k) + \frac{I_m(k)}{X_m(k)} + \frac{W_m(k)}{X_m(k)} . \tag{8}$$

The second term on the right hand side is the bias in the estimate due to ICI and can have an effect on the estimation if the Doppler frequency is relatively high. However, the ICI term depends on the signal values modulated on all the other subcarriers. Since, we are interested in the correlation of the channel estimate at kth subcarrier in time, ICI appears uncorrelated. Hence, it can be treated as additional noise. The last term in (8) represents the AWGN.

It is known that the channel in time domain is limited to the maximum excess delay of the channel. The data mapped into various subcarriers are zero-mean random variables. Thus ICI appears fast varying over subcarriers. The same holds true for the totally random AWGN samples in frequency domain which change very fast over OFDM subcarriers. Therefore, by transforming the frequency domain channel components, the true channel and noise components (ICI and AWGN) may be separated. When IFFT is applied to the channel frequency response (CFR), the channel impulse response (CIR) will be concentrated on the first few taps, while noise and ICI terms will be spread over all IFFT size. Fig. 1 illustrates this fact for a MSS with moderate vehicular speed. The average power levels of the components in the channel estimate is plotted for a uniform power delay profile (PDP).

In this paper, we propose to use time domain channel estimation instead of frequency domain estimation in order to increase the immunity to white noise and to ICI in the channel estimation. Similar approaches are used in OFDM literature for channel estimation, and are commonly referred to as transform-domain methods [8]. In the time-domain, the first few taps can be used to estimate the Doppler spread with lower estimation error. Besides, this can allow use of less number of symbols to find the autocorrelation and so we can reduce memory usage and computation time needed for fast adaptation. By using (4) and following the assumptions, we can obtain the autocorrelation of a CIR tap as

$$E\{\hat{h}(n)\hat{h}^*(n+sT_s)\} = J_0(2\pi f_d sT_s) + \sigma_r^2\delta(l) \qquad (9)$$

where $\hat{h}$ is the estimate of the time domain channel taps, s is the difference in OFDM symbol number and σ_r^2 is the combined reduced variance of ICI plus AWGN.

A. Computing f_d from Auto-correlation Function

Once the ACF is estimated, different methods can be used to calculate the Doppler spread (see references in [2]). We will use a similar method to that proposed in [9] to extract f_d from the calculated ACF. In this method, the best hypothesis that minimizes the mean-squared error (MSE) between the actual ACF and the Bessel function given by (4) is used. The whole Doppler range is divided into several bins depending on accuracy required. The ACF of few lags is then obtained and the estimate of Doppler spread which minimizes the MSE goal function is selected.

We note here that although the zero-crossing method used in [10] avoids the influence of noise on finding zero-crossing point if perfect match with Bessel function is assumed, this is unlikely to occur especially in relatively low Doppler values where the high lags are not reliable due to insufficient samples for correlation computation. The method will require very large number of symbols for ACF computation. On the contrary, here we assume use of less symbols to obtain the ACF.

B. Coherence Time versus Doppler Spread

The coherence time of the channel t_c is the duration over which the channel characteristics can be considered as time-invariant [11]. It is of utmost importance for evaluating and adapting the techniques that try to exploit time diversity of the channel or to compensate its time selectivity [12]. Time diversity can be exploited if the separation between time slots carrying the same information exceeds the coherence time. For an OFDM transmission system, the coherence time has a special significance because the symbol duration should be chosen to be much smaller than t_c to avoid ICI. Although, there is no specific definition for the coherence time, it is known to be inversely proportional to the maximum Doppler frequency [13], *i.e.*

$$t_C \approx \frac{1}{f_d} \ . \qquad (10)$$

The computation of the coherence time can be easily obtained from the ACF of the available channel estimates if a certain threshold is attained within an amount of time lags. Commonly, when the time elapsed for ACF to drop to half of its maximum zero lag value, this can be regarded as a measure of the coherence time. It is obvious that our proposed method will also allow a reliable estimate of the coherence time due to its immunity to noise and ICI perturbations.

C. Complexity of Proposed Method versus Gains

The proposed modification performs an added IFFT operation. In some cases this might be already implemented in order to perform reliable channel estimation. The added complexity of this is $O(N\log N)$. The complexity of computing ACF is $O(C^2)$, C is the number of samples used to estimate the ACF and can be regarded as the correlation length. For a fixed FFT size, by reducing C to ten folds, the proposed method will allow 100 folds complexity reduction in obtaining ACF but adds $N\log N$. As a numerical example, in [10], pilot carriers over 4096 symbols were used in a 2048 FFT size OFDM system to estimate ACF. In our proposed modification, we use only 200 symbols and even get gains in our results. Simple calculations show tremendous 350 times complexity reduction and at least 20 times reduction in processing time.

IV. Simulation Results

Computer simulations were performed to evaluate the performance of the proposed scheme. An OFDM system with 64 subcarriers is used for simulations. The carrier frequency is set to 3.5GHz and CP size of 16 is used. The available channel bandwidth is 1MHz and QPSK is used for mapping bits into data symbols. For a MSS speed of 55 mph, $f_d = 300$Hz. A 16-tap time-varying channel with exponentially decaying power profile, which is is generated according to [14], is used in simulations.

For obtaining the Doppler values, all of the subcarriers in the CFR based method and all of the taps in the CIR method are used. The correlations from different taps are added up to obtain maximum ratio combining.

Fig. 2 shows the normalized mean square error (NMSE) of Doppler estimation when estimation is done using CFR and when it is done using CIR as proposed. 300 OFDM symbols are used to obtain the correlation values and the Doppler spread was 300Hz. We can see a considerable gain achieved by the proposed method especially in low SNR (5-10 dB) conditions where the effect of noise is more visible.

The NMSE versus the correlation length is shown in Fig. 3. The Doppler spread is fixed to 300Hz and SNR is 15dB. It is evident that our method reduces the correlation length to many folds less than conventional method for same estimation performance. In general, the results obtained indicates robustness of this method for Doppler spread estimation in Rayleigh fading channels.

Finall, Fig. 4 shows the MSE as a function of the maximum Doppler frequency for a fixed SNR of 15dB. As this figure shows, the MSE increases for both time and frequency domain estimations with increasing Doppler frequency. This is caused by the increased ICI power due to larger Doppler frequencies.

V. Conclusion

In this paper, Doppler spread estimation for mobile OFDM systems in Rayleigh fading channels is presented. Doppler spread is estimated using the time domain channel estimates instead of frequency domain channel response. By using the

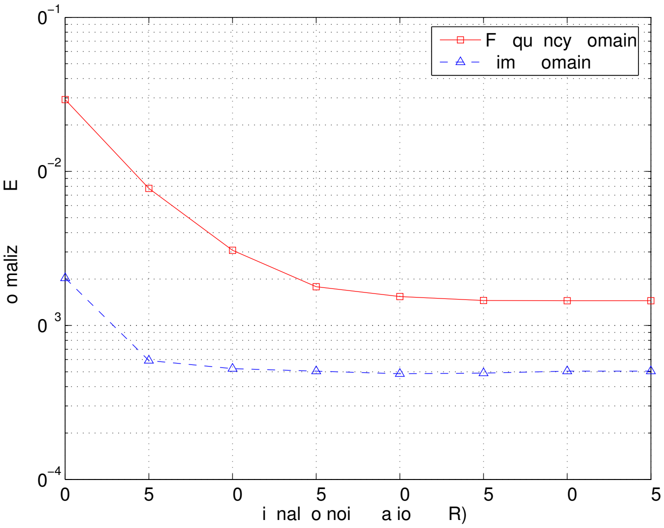

Fig. 2. Mean squared error as a function of singal to noise ratio for a fixed Dopper spread of 300Hz.

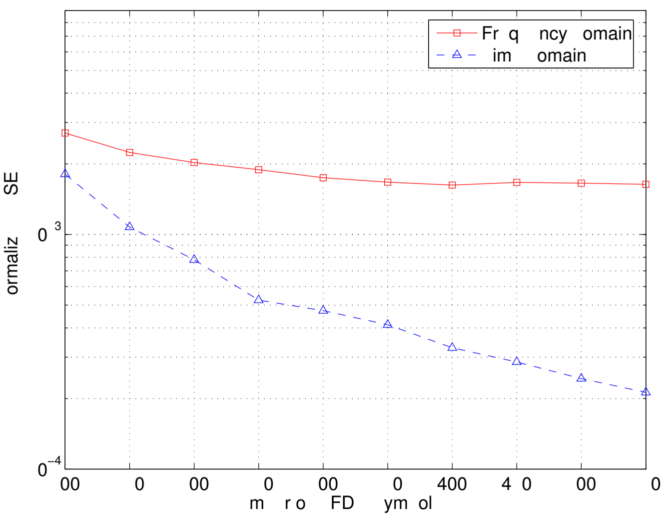

Fig. 3. Mean squared error as a function of averaging size for fixed Dopper spread of 300Hz and SNR value of 15dB.

CIR, the effect of the noise and ICI on the frequency-domain channel is reduced. Computer simulations are carried out for comparing the performance of time domain and frequency domain Doppler estimation methods. Our results show the validity and the robustness of proposed scheme in wide range of operating conditions.

Acknowledgment

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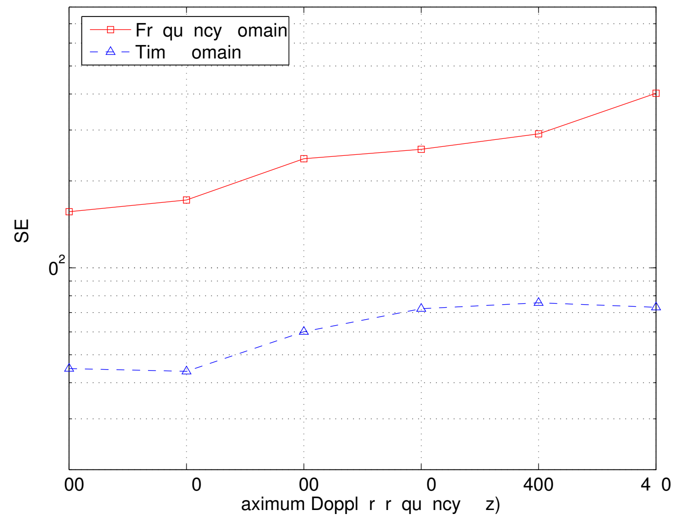

Fig. 4. Mean squared error as a function of the maximum Doppler frequency for SNR value of 15dB.

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