Channel Aware Unequal Error Protection for Image Transmission over Broadband Wireless LAN

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Abstract—**Orthogonal Frequency Division Multiplexing (OFDM) has been adopted in many broadband wireless communication standards. In OFDM systems, channel estimation is a crucial module in coherent signal detection and receiver diversity combining. In this paper, we investigate the leakage effect of pilot-symbol-assisted channel estimation techniques and propose a channel-aware Unequal Error Protection (UEP) scheme for multimedia communications in OFDM systems. The proposed method exploits the variations of the bit error rate in different OFDM subchannels caused by the leakage effect, and provides UEP by transmitting the more important data through the subchannels experiencing lower channel estimation error. Compared with the systems that do not jointly consider the channel estimation in the transmission of multimedia data, the proposed scheme can improve the Peak-Signal-to-Noise-Ratio (PSNR) of reconstructed images by up to 3dB.**

I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) has been known for its ability of transforming frequency selective fading channel into a set of parallel flat fading subchannels , which facilitates high data rate transmission over wireless channels without employing complicated channel equalization techniques [1]. OFDM has been adopted by many wireless multimedia transmission standards such as digital audio broadcasting (DAB)[2], digital video broadcasting (DVB-T)[3], and broadband wireless LAN standards IEEE 802.11a [4].

Channel estimation, required by coherent signal detection and receiver diversity combining [5], has a significant impact on the performance of the entire OFDM communication systems. Practical Channel estimation methods in OFDM systems utilize FFT and IFFT to perform interpolation along frequency (across subchannels in one OFDM block) and along time (across different OFDM blocks) [6][5][7]. In these schemes, there exists the variation of channel estimation error across different subchannels, which is refered to as the *leakage effect*, when the delay profile of the multipath fading is not an integer multiple of the sampling period [6] [5]. In realistic wireless environment, the multipath delay is usually not an integer multiple of sampling period and the leakage effect causes severe performance degradation [6]. To reduce the damage of the leakage effect, we proposed to utilize this effect to provide UEP in multimedia communications.

It is well-known that the unequal error protection can be employed to enhance error resilience in multimedia communications. For example, forward error correcting (FEC) codes with different correcting capabilities and bitstream reordering were proposed to provide the UEP for SPIHT coded images [8][9]. However, channel estimation has not been exploited for the transmission of multimedia data.

In this paper, we investigate the leakage effect of pilot-symbol-assisted channel estimation techniques [7] and propose a *Priority Transmission*(PT) scheme. The proposed scheme exploits the variations of the bit error rate in different OFDM subchannels and provides UEP for multimedia communications by rearranging the transmission order in such a way that the more important data are transmitted through the subchannels experiencing lower channel estimation error. In addition, the effects of different training data/pilots patterns used in the channel estimation algorithms are studied.

The rest of the paper is organized as follows. In Section II, we introduce the OFDM system and briefly review the pilot-symbol-assisted channel estimation. In Section III, popular training pilot patterns are introduced and the mean square channel estimation error (MSE) of different OFDM subchannels is derived. Furthermore, we propose the Priority Transmission (PT) scheme, which provides unequal error protection for multimedia transmission by matching the importance of the data to the error variation in OFDM subchannels due to imperfectness in channel estimation algorithm. The PT scheme for SPIHT [11] coded images is investigated through simulations in Section IV, followed by the conclusion in Section V.

II. OFDM Systems and Pilot-Symbol-Aided Channel Estimation

As illustrated in Figure 1, we study the OFDM systems with one transmitter antenna and multiple receiver antennas. At the transmitter, the input data are arranged into blocks by a serial-to-parallel (S/P) converter and mapped to a set of complex constellation points, $\{X[1,k], \cdots, X[N,k]\}$, which is called as one OFDM block, where k is the index of the OFDM blocks and N is the total number of subchannels. After the signal mapping, modulation is implemented using inverse Fast Fourier Transform (IFFT). Cyclic prefix is appended to the OFDM blocks to eliminate Inter Symbol Interference (ISI). Then, data are sent out after a parallel to serial (P/S) converter.

The structure of the OFDM receiver with m receiver antennas is illustrated in Figure 1(b). The signal received at the m^{th} antenna can be represented as:

$$Y_m[n,k] = H_m[n,k]X[n,k] + w_m[n,k], \qquad n = 1,\ldots,N. \tag{1}$$

where $X[n,k]$ is the transmitted signal, $H_m[n,k]$, $w_m[n,k]$ are the subchannel gain and additive Gaussian noise at the n^{th} subchannel in the k^{th} block corresponding to the m^{th} antenna. In addition, we assume that $w_m[n,k]$ is independent for different m's, n's or k's and has zeros mean and variance σ^2. $H_m[n,k]$ for different $m's$ are independent but follow the same distribution

The goal of the channel estimation is to estimate the subchannel gain, $H_m[n,k]$, which is critical for both coherent signal detection and diversity combining [5]. In the OFDM receiver, the one-tap equalizer takes the estimated channel parameters, denoted by

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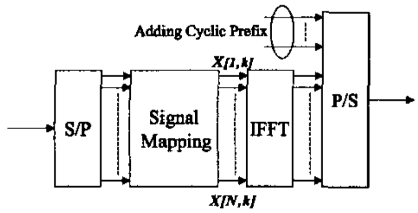
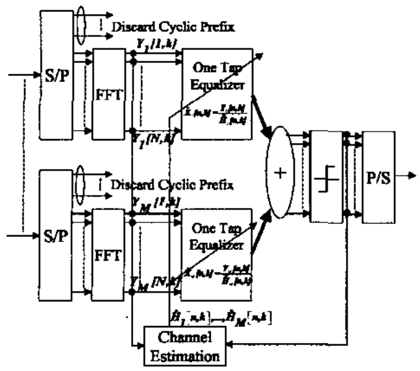


(a) Transmitter



(b) Receiver with with multiple antennas

Fig. 1. High level diagram of OFDM systems

$\hat{H}_m[n,k]$, and the received signals $Y_m[n,k]$ from each receiver antenna, and produces the estimates of the transmitted signals, denoted by $\hat{X}[n,k]$, using MMSE combining, as

$$\begin{aligned}\hat{X}[n,k] &= \frac{\sum_{m=1}^{M}\hat{H}_m^*[n,k]Y_m[n,k]}{\sum_{m=1}^{M}|\hat{H}_m[n,k]|^2} \\ &= \frac{\sum_{m=1}^{M}\hat{H}_m^*[n,k]H_m[n,k]}{\sum_{m=1}^{M}|\hat{H}_m[n,k]|^2}X[n,k] + \\ &\quad \frac{\sum_{m=1}^{M}\hat{H}_m^*[n,k]w_m[n,k]}{\sum_{m=1}^{M}|\hat{H}_m[n,k]|^2}. \end{aligned} \tag{2}$$

It is obvious that the imprecision of the channel estimation, as well as channel noise cause decoding errors.

In order to estimate the channel parameters, training symbols that are known by both transmitter and receiver are transmitted periodically. These methods are usually referred to as pilot-symbol-assisted channel estimation. The general structure of the channel estimation [5],[7] is illustrated in Figure 2. The IFFT and FFT perform the interpolation/filtering of channel response along different OFDM subchannels in one OFDM block by retaining $K0$ components of IFFT output and the filter $\Phi(\omega)$ performs filtering along different OFDM blocks. Particularly, we assume that the pilot symbols are transmitted in $i \in \{0, p, 2p, \cdots, N\}^{th}$ subchannels, where p denotes the spacing between pilot symbols. Then, the temporal estimation of the channel response in pilot locations is obtained as:

$$\tilde{H}_m[i,k] = \frac{Y_m[i,k]}{X[i,k]} \tag{3}$$

The temporal estimation for the non-pilot locations are filled with

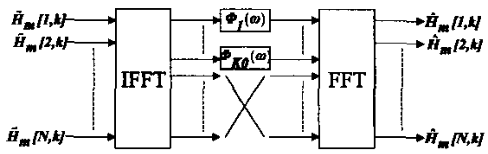


Fig. 2. Channel estimator in OFDM systems

zeros, i.e.: $\tilde{H}_m[n,k] = 0$, for $n \notin \{0, p, 2p, \ldots, N\}$. Given the pilot spacing p, the number of pilot in one OFDM block denoted by L is calculated as $L = \lceil \frac{N}{p} \rceil$.

III. Priority Transmission

In this section, we derive the mean square channel estimation error for different pilot patterns in pilot-symbol-assisted channel estimation techniques, and introduce the Priority Transmission scheme for the transmission of multimedia data in OFDM systems.

In wireless scenarios, delay profile and fading doppler frequency are used to describe the frequency selective fading channel [10], particularly the channel impulse response can be described by $h(t,\tau) = \sum_i \gamma_i(t)\delta(\tau - \tau_i)$ where τ_i is the delay of i^{th} path and $\gamma_i(t)$ is its corresponding complex amplitude. In this paper, we adopt the Typical Urban (TU) delay profile shown in Figure 3. In practice, the delay path, τ_i is not the integer multiple of the sampling period in the OFDM systems. In this case, the FFT based channel estimation technique [6],[5] described in the previous section experiences the leakage effect, which depends on the arrangement of pilot symbols as well as the delay profile. Two typical pilot patterns are shown in Figure 4. In both patterns, p is equal to 8 and the pilots are sent periodically every OFDM block. The shifted pilot similar to Figure 4(b) is recommended in some standard [3] to better interpolate the channel.

Let $\hat{\mathbf{H}}$ denotes the estimated channel parameters and $\tilde{\mathbf{H}}_\mathbf{p}$ denotes the temporal estimates obtained through pilot symbols, where $\hat{\mathbf{H}}$ is a N by 1 vector, $\tilde{\mathbf{H}}_\mathbf{p}$ is a L by 1 vector. The estimated channel response across different OFDM subchannels is:

$$\hat{\mathbf{H}} = \mathbf{W}^\mathbf{H}\begin{pmatrix} \mathbf{I}_{K0} & \mathbf{0}_{K0\times(N-K0)} \\ \mathbf{0}_{(N-K0)\times K0} & \mathbf{0}_{(N-K0)\times(N-K0)} \end{pmatrix}\mathbf{W}_\mathbf{p}\tilde{\mathbf{H}}_\mathbf{p} \tag{4}$$

where $\mathbf{W}$ is N by N DFT matrix, $\mathbf{I}_{K0}$ is the identity matrix of size $K0$ by $K0$, $\mathbf{0}_{a\times b}$ is the all zero matrix with size a by b, $K0$, equals to $\lceil B_d \cdot \tau_{max} \rceil$ describes the number of IFFT output to be retained in filtering the channel [5], B_d is the total bandwidth and τ_{max} is the maximum delay path in the channel. $\mathbf{W}_\mathbf{p}$ is the N by L matrix obtained from $\mathbf{W}$ by retaining columns where pilots are sent. For instance, if the pilots are transmitted in $i \in \{0, p, 2p, \cdots, N\}^{th}$ *subchannels, then* $\mathbf{W}_\mathbf{p}$ *is represented by*

$$\mathbf{W}_\mathbf{p} = \frac{1}{\sqrt{N}}\begin{pmatrix} 1 & 1 & 1 & \cdots \\ 1 & e^{\frac{j(2\pi p)}{N}} & e^{\frac{j(2\pi 2p)}{N}} & \cdots \\ \vdots & \vdots & \cdots & \cdots \\ 1 & e^{\frac{j(2\pi(N-1)p)}{N}} & e^{\frac{j(2\pi(N-1)2p)}{N}} & \cdots \end{pmatrix} \tag{5}$$

We also define

$$\mathbf{W}_\mathbf{tot} = \mathbf{W}^\mathbf{H}\begin{pmatrix} \mathbf{I}_{K0} & \mathbf{0}_{K0\times(N-K0)} \\ \mathbf{0}_{(N-K0)\times K0} & \mathbf{0}_{(N-K0)\times(N-K0)} \end{pmatrix}\mathbf{W}_\mathbf{p}. \tag{6}$$

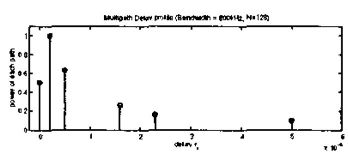


Fig. 3. Typical Urban (TU) Delay profile, where τ_i is the delay of the ith path in Multipath Rayleigh fading channel model.

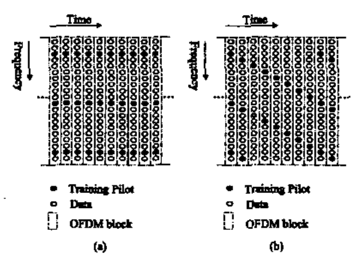


Fig. 4. Typical training patterns for coherent channel estimation ((a) Non Time Shifted pilot (b) Time shifted pilot). Both patterns contain 12.5% training pilots and 87.5% data.

Given the channel correlation function , the channel estimation MSE of different subchannels in one OFDM block can be calculated as

$$\begin{aligned} \mathbf{MSE} &= diag(E[(\hat{\mathbf{H}} - \mathbf{H})(\hat{\mathbf{H}} - \mathbf{H})^{\mathrm{H}}]) \\ &= diag(\mathbf{W}_{\mathrm{tot}} E[\tilde{\mathbf{H}}_{\mathrm{p}} \tilde{\mathbf{H}}_{\mathrm{p}}^{\mathrm{H}}] \mathbf{W}_{\mathrm{tot}}^{\mathrm{H}} - \mathbf{W}_{\mathrm{tot}} E[\tilde{\mathbf{H}}_{\mathrm{p}} \mathbf{H}^{\mathrm{H}}] - \\ &\quad E[\mathbf{H} \tilde{\mathbf{H}}_{\mathrm{p}}^{\mathrm{H}}] \mathbf{W}_{\mathrm{tot}}^{\mathrm{H}} + E[\mathbf{H}\mathbf{H}^{\mathrm{H}}]) \end{aligned} \quad (7)$$

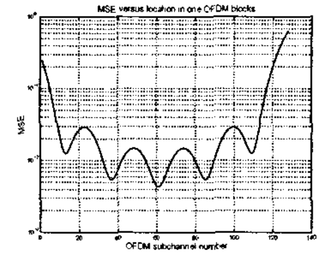
It is obvious that the channel estimation error is influenced by the delay profile, fading doppler frequency and pilot pattern. The estimation error for Typical Urban (TU) delay profile using two pilot patterns Figure 4 are shown in Figure 5. When using non-shifted pilot (see Figure 4(a)), average estimation error is the same for every OFDM block. In shifted pilot (see Figure 4(b)), the average estimation error in particular OFDM block is the shifted version of its neighboring blocks. Due to the arrangement in shifted pilot, the channel estimation MSE in one particular OFDM block will repeat periodically, for instance if the pilot spacing $p = 8$, then the MSE in each block will repeat itself in every 8 OFDM blocks.

As illustrated in Figure 5, different subchannels experience different estimation error and the estimation error is generally larger in the boundary than in the middle. In practice, subchannels located in the edge are used as guard tones instead of transmitting data [5]. Even after discarding the boundary subchannels, the range of the variation of channel estimation error in different subchannels is still significant. According to equation (2), the decoding bit error rate (BER) will also vary accordingly. This motivates us to design the PT scheme that rearranges the transmission order of the multimedia data such that the more important data are sent through the OFDM subchannels that experience less estimation error. In order to bound the decoding delay caused by PT, we introduce the delay parameter D and the rearrangement of transmission order can only take place in D consecutive OFDM blocks. Particularly, PT is performed before the IFFT at the OFDM transmitter (Figure 1) in 3 steps:

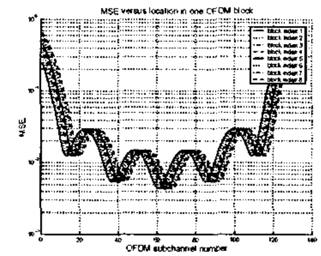
Step 1. Given the channel correlation function, compute the MSE of channel estimation of all subchannels in consecutive D OFDM blocks using equation (7). Then, sort the subchannels within D OFDM blocks in the increase order of the MSE.

Step 2. For progressively encoded multimedia data, rearrange the bitstream in the decreasing order of the importance.

Step 3. Match the reordered multimedia data into the sorted subchannels, such that the more important data are transmitted over subchannel with lower MSE.



(a). Non-shifted Pilot



(b). Shifted Pilot

Fig. 5. MSE of channel estimation of subchannels in OFDM blocks at high SNR for Typical Urban delay profile

Priority Transmission (PT) can be used in any general multimedia transmission framework. To illustrate the effectiveness of the PT, we used the SPIHT [11] coded images as the multimedia source. One of the important characteristic of SPIHT is its progressive property, i.e.: the decoder can correctly decode the received data whenever the transmission stops or an unrecoverable error occurs. The more data received correctly, the higher quality of image can be obtained. Since the SPIHT coded bitstream virtually has been sorted in decreasing important, we may skip the step 2 in the above procedure. In contrast to the PT scheme, regular transmission directly allocates the multimedia bitstream to the subchannels and treats each subchannels equally. Hence, the property arised from channel estimation is not exploited.

There are many other ways to provide UEP to the transmission of progressive images. One of the most popular methods is to apply forward error correction (FEC) codes with different coding rates according to the importance of data [8][9]. Compared with the FEC based methods, the proposed scheme has the advantages of not introducing additional redundancy to transmission and easy implementation. The major drawback in the Priority Transmission is the decoding delay. It will be shown through simulations that large performance gain can be obtained at the expense of a small amount of decoding delay. In addition, the proposed scheme can work together with the existing FEC based methods when the coding rates are chosen considering both the variation of channel error and the

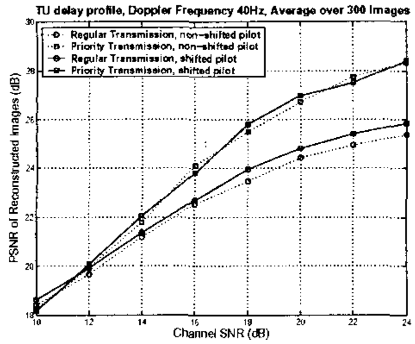


Fig. 6. Performance comparison for Doppler frequency 40Hz

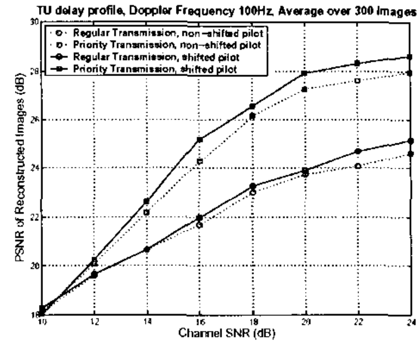


Fig. 7. Performance comparison for Doppler frequency 100Hz

importance of multimedia data.

IV. Simulation Results

The transmission of SPIHT encoded images is simulated in OFDM systems for different channel SNRs. The input is the 512 by 512 Lena image encoded at the data rate of 1 bit per pixel (bpp). The OFDM system consists of 128 subchannels with a 32 symbol long cyclic prefix, and the total bandwidth is 800kHz. Four boundary subchannels on each end are used as guard tones and the rest 120 subchannels are used to transmit data. QPSK modulation is used for all subchannels. The channel coding is chosen to be a (10,8) punctured/shortened Reed-Solomon code over Galois Field GF(2^6). Hence, the transmission data rate is 960kbits/s. Typical urban (TU) delay profile (Figure 3) with Doppler frequency of 40Hz and 100Hz is used to model the multi-path fading channel. The receiver used 2 receiver antennas and MMSE combining to decode the transmitted images.

Regular transmission and Priority Transmission with non-shifted and shifted pilot arrangement are simulated. Both regular and PT scheme use the same RS code and the same training pattern. One pilot symbol is inserted in every 8 data symbols. The delay parameter in PT is chosen to be $D = 128$, i.e.: the input multimedia data is rearranged within 128 OFDM blocks according to the channel estimation error.

The average peak-signal-to-noise-ratio (PSNR) of the reconstructed images for different channel SNR averaged over 300 images transmission is shown in Figure 6 and Figure 7. The performance curves show that the proposed system can achieve performance gain more than 3dB in the moderate and high channel SNR region, where the most practical wireless systems operate. For all cases, the shifted pilot outperforms or at least as good as the non-shifted pilot arrangement due to its better ability to track the channel variation. In both pilot patterns, PT scheme is shown to be effective in improving the PSNR of the reconstructed images. The performance gain in PT results from the fact that by rearranging the multimedia data accordingly, the average received SPIHT bitstream length before an unrecoverable error for PT scheme is effectively longer than for regular transmission.

The delay constraint $D = 128$ in this simulation is equivalent to 32 ms. Since the whole images has $\frac{512\times512\times10}{8}$ bits, which required 1366 OFDM blocks for transmission. This means the decoding delay is less than 9% of the overall time to transmit the whole image. The performance gain in our proposed scheme is achieved at the expense of sacrificing a little progressiveness.

V. Conclusion

This paper proposed a scheme to exploit the error rate variation of the pilot-symbol-assisted estimation methods to provide UEP for multimedia transmission. The advantage of this scheme is that it does not require any additional redundancy (different correcting capabilities of FEC) to achieve UEP. Furthermore, existing UEP methods can be used along with the proposed scheme. Given any types of pilot arrangement and multimedia data, PT scheme can be applied to improve the performance at the expense of a small decoding delay. A performance gain of more than 3dB in the PSNR of the reconstructed images is achieved at the moderate and high channel SNR region.

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