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# Time-domain clustered transmit power adaptation for OFDM system in fading channels*

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**Abstract:** This paper proposes a time-domain clustered transmitter power adaptation scheme for orthogonal frequency division multiplexing (OFDM) system, which can significantly reduce the feedback amount during power adaptation comparison with conventional frequency-domain adaptation schemes. It was found that the cluster size plays an important role on the adaptation performance, especially for the vehicular environment. Simulation results showed that using Lagrange interpolation to obtain an explicit curve of Doppler frequency vs cluster size yields good trade-off between the resulted bit error rate (BER) and the amount of feedback.

**Key words:** Power adaptation, Orthogonal frequency division multiplexing (OFDM), Time-domain cluster, Coherence time
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## INTRODUCTION

The growing demand for wireless multimedia services requires reliable and high data rate communications over a wireless channel. However, the reliability is significantly limited by the ability of combating the intersymbol interference (ISI) introduced by the time dispersive nature of the wireless channel. Multicarrier transmission systems, especially OFDM systems, have aroused great interest in recent years as a potential solution to overcome ISI (Hanzo *et al*., 2002; Jang and Lee, 2003; Cheong *et al*., 1999). The ISI can be almost completely eliminated by introducing a cyclic extension of the OFDM symbol.

Adaptive allocation schemes (Chen *et al*., 2002) have already been applied in wideband CDMA systems, where the total bandwidth resources are divided into several subchannels in frequency domain and time slots in time domain. In OFDM system, subcarriers are divided originally according to the parallel process and when the channel state information (CSI) of a time dispersive channel is available at the transmitter, the transmitter power distribution and modulation modes on each subcarrier can also be adapted to maximize the transmission data-rate. Several algorithms, such as water-fill and greedy allocation (Jang and Lee, 2003; Cheong *et al*., 1999; Kivanc *et al*., 2003), have been developed to maximize the data-rate. These schemes are mainly carried out in frequency domain and the transmitter power is adapted under the constraint of total transmit power. To obtain transmission reliability, bit error rate (BER) constraint is added to those schemes (Jang and Lee, 2003).

In these papers, it is assumed that the perfect CSI is known at the transmitter, but CSI estimation is applied at the receiver and the CSI feedback will definitely introduce system overhead. How to make a compromise between the overhead and the adaptation performance is quite essential to the design of adaptation schemes. Conventional adaptation schemes are carried out in frequency domain, where the power

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distribution and modulation modes are calculated at each OFDM symbol, namely symbol-wise adaptation. In such case, the CSI feedback from the receiver to transmitter will significantly increase with the number of transmission OFDM symbols. To reduce the amount of CSI feedback, frequency-time domain transmit power adaptation (Jang *et al*., 2002) was introduced, where the transmit power is distributed according to the probability distribution function (PDF) of CSI on each subcarrier, namely the average power over all transmitted symbols is regarded as the power constraint. However, the CSI PDF can only be achieved by long time statistics and the maximized data-rate of frequency-time domain adaptation is obtained according to statistical analysis, namely long time average. These two necessary conditions are infeasible for mobile system, whose channels and resource allocation are both instantaneously variable. Therefore, a modified scheme which is combined with frequency-time domain scheme and symbol-wise scheme should be considered. The simulation results in (Jang *et al*., 2002) showed that the maximized data-rate of symbol-wise adaptation will closely approach that of the frequency-time domain adaptation when the subcarrier number exceeds 16, which is essentially achieved in almost all OFMD systems. Hence, in the following section, to simplify the calculation, the performance of symbol-wise adaptation scheme is regarded as the benchmark.

For wireless channels, coherent time is a key parameter for evaluating the channel coherence in time domain. On the same subcarrier, namely the same frequency point, there is great coherence among the channel gains of neighboring OFDM symbols within the coherent time. Such assumption has been applied in Maeda *et al*.(2003), where spread in time domain had been developed and proved to have good performance. Due to the similarities of the time-coherence process, subcarrier cluster in time domain, which combines the symbol-wise scheme with the frequency-time domain scheme, may have close relation to the maximized data-rate acquired by conventional symbol-wise adaptation schemes.

This paper proposes a time-domain clustered transmit power adaptation scheme, in which real-time feedback is adopted but the amount of feedback is significantly reduced. Subcarriers are clustered in time domain on the same subcarrier, with the cluster size being proportional to the feedback reduction ratio. The reduction of feedback is mainly due to the high correlation of channel impulse response between neighboring symbols in time domain. Simulation results showed that the performance of cluster in time domain has close relation to the maximized data-rate and resulting BER acquired by the symbol-wise adaptation schemes. In addition, through Lagrange interpolation, an explicit curve of Doppler frequency vs cluster size is obtained, which makes a good trade-off between the resulted BER and the amount of feedback.

## SYMBOL-WISE POWER ADAPTATION

Downlink transmission of the OFDM system is considered in this paper. We assume that the CSI is perfectly estimated by the receiver and fed back to the transmitter with no delay. Letting $H_m[i]$ denote the frequency domain channel impulse response on the $m$th subcarrier at time $i$, the parallel equivalent model of OFDM system is expressed by the equation

$$r_m[i]=\sqrt{P_m[i]}\times H_m[i]\times s_m[i]+\eta_m[i]\,, \tag{1}$$

where $s_m[i]$ is the transmitted sample on the $m$th subcarrier and $\eta_m[i]$ denotes the additive white Gaussian noise (AWGN) with mean zero and variance $\sigma^2$. $P_m[i]$ is the power distribution on the transmitter side with power constraint

$$\sum_{m=1,\ldots,M} P_m[i]=\bar{S}\,. \tag{2}$$

The signal to noise ratio (SNR) on each subcarrier can be written as

$$SNR_m[i]=\frac{P_m[i]\,|\,H_m[i]\,|^2}{\sigma^2}\,. \tag{3}$$

In order to formulate the capacity maximization problems, we use the equation in (Jang and Lee, 2003) that

$$q_m[i]=\log_2\left(1+\frac{SNR_m[i]}{-\ln(5BER_\mathrm{t})/1.5}\right), \tag{4}$$

where $q_m[i]$ is the number of transmitter bits on each subcarrier and $BER_\mathrm{t}$ denotes the target BER. Accordingly, the total bits in an OFDM symbol are represented as

$$R[i]=\sum_{m=1,\dots,M} q_m[i]=\sum_{m=1,\dots,M}\log_2\left(1+\frac{SNR_m[i]}{-\ln(5BER_t)/1.5}\right). \quad (5)$$

The aim of the symbol-wise transmitter power adaptation is to maximize the data-rate at the entire transmission time *i*, namely for each OFDM symbol, with power constraint Eq.(2). The overall data-rate can be evaluated by averaging Eq.(5) over all transmission time, but may not be explicitly expressed in a closed form equation.

## TIME-DOMAIN CLUSTERED POWER ADAPTATION

According to the analysis in the last section, CSI feedback is required at each time *i* for the symbol-wise adaptation schemes, which will introduce heavy system overhead. However, the coherence in time domain for wireless channels can be used to reduce the amount of CSI feedback. The definition of coherent time is expressed first and then the corresponding schemes will be explained.

### Coherent time

Coherent time can be deduced from the time correlation function (Sandell *et al*., 1996) as follows

$$R_t(\Delta t)=J_0(2\pi f_D\Delta t), \quad (6)$$

where $\Delta t$ is a time separation and $f_D$ is the maximum Doppler frequency. In OFDM systems, the time separation between OFDM symbols on the same subcarrier is $\Delta t=m\times L\times T_s$, where $L$ is the length of samples during an OFDM symbol; $m$ is the number of OFDM symbols; $T_s$ is the sampling period of the system; $J_0(\cdot)$ is the zeroth order Bessel function of the first kind.

Fig.1 shows the unified time correlation function for channels with different Doppler frequency (1024-FFT 216-cyclic prefix). The correlation value, which indicates the coherence between the adjacent OFDM symbols, is found to rapidly fluctuate with increasing Doppler frequency. For a certain value $m$ on the *X*-label, large correlation value on the corresponding *Y*-label means that there is full coherence within $m$ adjacent OFDM symbols. On the contrary, low correlation value on the corresponding *Y*-label means that the coherence within $m$ adjacent OFDM symbols is weak.

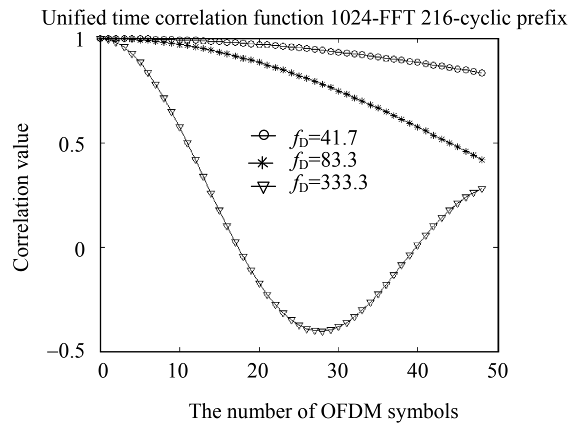


**Fig.1 Unified time correlation function for channels with different Doppler frequency**

Coherent time $T_{coh}$, which can be obtained by the equation $R_t(T_{coh})=Val_{coh}$, is a criterion to evaluate coherence between adjacent OFDM symbols, where $Val_{coh}$ determines the unified coherence level. In addition, the number of OFDM symbols within $T_{coh}$ is

$$N_{coh}=\lfloor T_{coh}/(L\times T_s)\rfloor,$$

where $\lfloor x\rfloor$ denotes the maximum integer less than $x$. In this paper, $Val_{coh}$ is chosen according to the simulation results and the analysis is explained in Section 4.

### Time-domain clustered power adaptation

According to the analysis in the last section, there is full coherence between adjacent OFDM symbols within coherent time $T_{coh}$. Due to this assumption, a reliable scheme is to choose a characteristic value to represent the channel gains, on the same subcarrier of the adjacent OFDM symbols, within $N_{coh}$ symbols. The number of adjacent OFDM symbols is defined as the cluster size $N$, with the characteristic value $Hc_m[j]$ of each cluster on the $m$th subcarrier being

$$Hc_m[j]=\frac{1}{N}\sum_{i=1}^{N}H_m[(j-1)\times N+i],\quad j\in\mathbb{Z}^+. \quad (7)$$

Therefore, the symbol-wise power adaptation can be rewritten as cluster-wise power adaptation and only the feedback of $Hc_m[j]$ is necessary, which means that both the amount of feedback and the computational complexity will reduce to $1/N$ of those obtained by symbol-wise adaptation. The power constraint and the modified data-rate expression is as follows

$$\sum_{m=1,\ldots,M} Pc_m[j] = \overline{S}, \quad SNRc_m[j] = \frac{Pc_m[j]\,|\,Hc_m[j]\,|^2}{\sigma^2},$$

$$Rc[j] = \sum_{m=1,\ldots,M} \log_2\left(1 + \frac{SNRc_m[j]}{-\ln(5BER_{\mathrm{t}})/1.5}\right), \tag{8}$$

where $Pc_m[j]$ is the power distribution allocated on the $j$th cluster, namely the same power distribution is allocated for all OFDM symbols within the $j$th cluster.

The feedback reduction introduced by time-domain subcarrier cluster has been discussed in this section. However, the implicit variance of channel gains within a cluster will result in difference of resulting BER and maximized data-rate between symbol-wise and cluster-wise schemes. The analysis of cluster size and the induced difference is presented in Section 4 and an expression for the relation between the Doppler frequency and the cluster size is given. It was found that if cluster size is designed according to the expression in Section 4, the resulting BER and maximized data-rate for cluster-wise adaptation have close correlation to those for symbol-wise adaptation.

## CLUSTER SIZE AND DOPPLER FREQUENCY

There are two kinds of criteria, maximized data-rate and resulting BER, for the evaluation of cluster adaptation schemes. It is emphasized in Eq.(8) that target BER is a pre-set constraint of the optimization problem, hence, the difference between target BER and resulting BER is considered as a key criterion in this paper. To reduce the computational complexity, instead of Mean Square Error (MSE), mean absolute difference (MAD) is used to evaluate the difference. The MAD is expressed as

$$MAD_{BER} = \frac{1}{K} \sum_{i=1,\ldots,K} \left| BER_{\mathrm{t}}(i) - BER_{\mathrm{r}}(i) \right|, \tag{9}$$

where $BER_{\mathrm{r}}$ denotes the resulting $BER$ and $K$ is the number of total clusters. The relationship among $MAD_{BER}$, $f_{\mathrm{D}}$ and $N_{\mathrm{coh}}$ ($SNR$=12 dB) is shown in Fig.2. The three curves correspond to the three $f_{\mathrm{D}}$ values and $MAD_{BER}$ increases with the increasing cluster size ($N_{\mathrm{coh}}$).

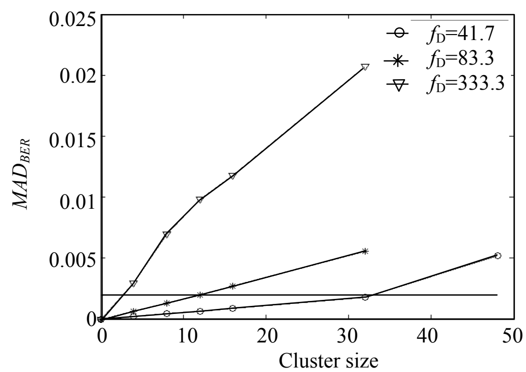


**Fig.2 $MAD_{BER}$ for different $f_{\mathrm{D}}$**

Take the condition that $MAD_{BER} \le 20\% \times BER_{\mathrm{t}}$ ($MAD_{BER} \le 0.002$) as an example, referring to Figs.1~2, the corresponding ($N_{\mathrm{coh}}$, $Val_{\mathrm{coh}}$) for each $f_{\mathrm{D}}$ (41.7, 83.3, 333.3) is (33, 0.92), (12, 0.964) and (2, 0.995). Lagrange polynomial fits are used to interpolate the intermediate ($N_{\mathrm{coh}}$, $Val_{\mathrm{coh}}$). The Lagrange interpolation formula is

$$f(x) = \sum_{i=1}^{3} f(x_i) \frac{\prod_{j \ne i}(x - x_j)}{\prod_{j \ne i}(x_i - x_j)}, \tag{10}$$

where $[x_i, f(x_i)]$ comprise the upper three experimental results ($N_{\mathrm{coh}}$, $Val_{\mathrm{coh}}$). The interpolated threshold curve $N_{\mathrm{coh}}$ vs $Val_{\mathrm{coh}}$ is shown in Fig.3, which indicates the coherence threshold in clustered power adaptation. In conclusion, the expression for the relation between cluster size $N_{\mathrm{coh}}$ and $Val_{\mathrm{coh}}$ is

$$J_0(2\pi f_{\mathrm{D}} \times N_{\mathrm{coh}} \times L \times T_{\mathrm{s}}) \le Val_{\mathrm{coh}}. \tag{11}$$

To obtain the $N_{\mathrm{coh}}$ value for any $f_{\mathrm{D}}$, the crossing point between the corresponding Bessel curve and the $Val_{\mathrm{coh}}$ threshold curve is first marked. Then the $x$-coordinate value of the crossing point is taken as $N_{\mathrm{coh}}$. Simulation result to evaluate this criterion is given in the next section.

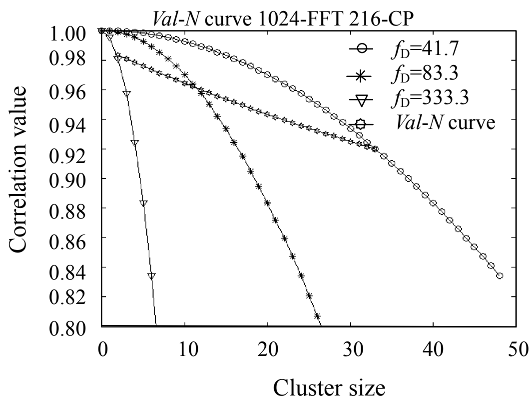


**Fig.3 $N_{coh}$ vs $Val_{coh}$ curve**

## SIMULATION RESULTS

In this section, we evaluate the proposed clustered transmit power adaptation scheme in Eq.(8) and the $Val_{coh}$ curve in Eq.(10) in terms of the average maximized data-rate and resulting BER by computer simulation. It is assumed that channel response is unchanged during one OFDM symbol and that its delay power profile is exponential attenuation $P(\tau)=\exp(-\tau/\tau_0)$, where $\tau_0$ is a constant. Greedy algorithm (Campello, 1998) with even bit loading and1024-FFT is applied in this paper for comparison. The target BER (uncoded) is set to $1\times10^{-2}$, which is the waterfall threshold of turbo product code (Xu, 2003).

Referring to the $N_{coh}$ vs $Val_{coh}$ curve in Fig.3, the $N_{coh}$ values for $f_D$= 68.22 Hz, 166.7 Hz, 250 Hz are 17, 4, 2, respectively. Accordingly, the cluster sizes are set as 17, 4 and 2 for the transmit power adaptation scheme. The resulting BER are shown in Fig.4. For a benchmark, the target BER is also included.

It was found that the resulting BER of time-domain clustered power adaptation schemes have close correlation to the target BER. The variance range accords with pre-set condition that $MAD_{BER} \leq 20\%\times BER_t$ ($MAD_{BER}\leq 0.002$). In addition, it is shown in Fig.5 that the maximized bits per subcarrier of the cluster-wise power adaptation scheme has close correlation to the symbol-wise power adaptation scheme. The differences between these curve-couples are all less then 0.005 bits per subcarrier. Simulation results indicated that the cluster size, which was determined according to the Doppler analysis in the last section, is efficient in reducing the amount of feedback and in keeping superior resulting performance. For the system with carrier frequency of 3.5 GHz and speed of 15 km/h, cluster size is choose to be 33 and the corresponding feedback is reduced to one 33th that of the original feedback amount. Furthermore, the performance of cluster-wise power adaptation almost perfectly accorded with to that of symbol-wise adaptation.

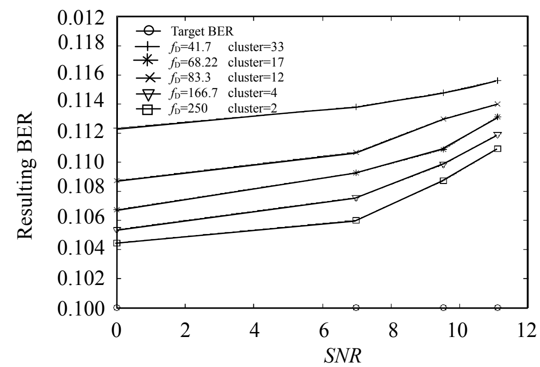


**Fig.4 Resulting BER for clustered adaptation**

## CONCLUSION

The time-domain clustered transmitter power adaptation scheme proposed in this paper, which greatly reduces the amount of feedback compared to that of the conventional frequency-domain symbol-wise scheme. The cluster size is proportional to the feedback reduction ratio. In addition, the relationship between cluster size and the Doppler frequency is expressed by a coherence threshold curve, which is regarded as a design criterion for choosing the proper cluster size at different moving speed. Simulation results showed that the resulting BER and the maximized data-rate of the clustered power adaptation scheme have close correlation to those of the symbol-wise adaptation scheme. The cluster-wise adaptation scheme was proven to be a good trade-off between capacity performance and the amount of feedback overhead.

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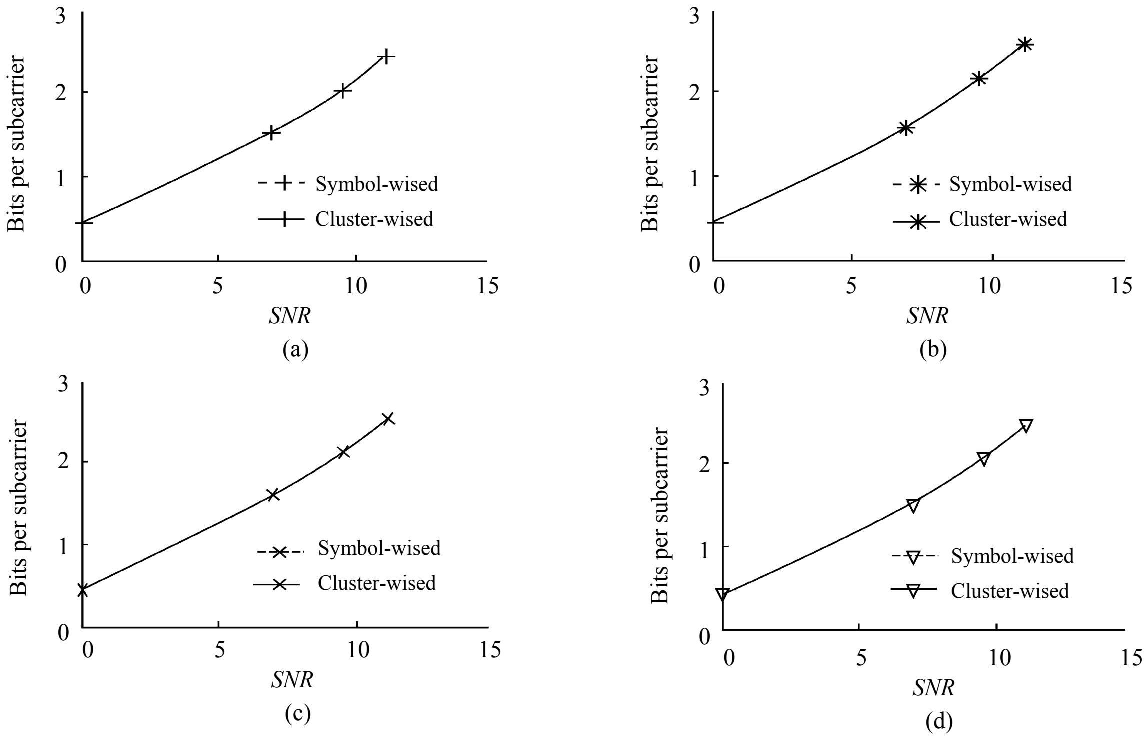


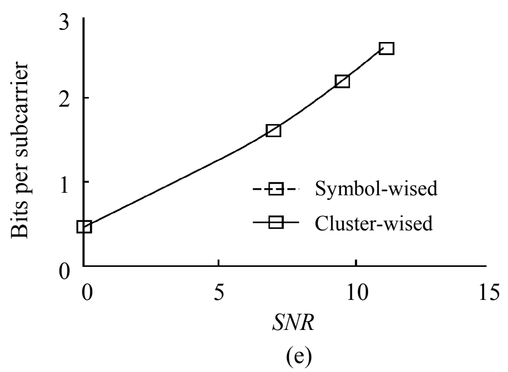


**Fig.5 Bits per subcarrier for clustered adaptation**
(a) $f_D$=41.7, cluster=33; (b) $f_D$=68.22, cluster=17; (c) $f_D$=83.3, cluster=12; (d) $f_D$=166.7, cluster=4; (e) $f_D$=250, cluster=2

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