Practical Feedback Design based OFDM Link Adaptive Communications over Frequency Selective Channels

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***Abstract*— In ideal OFDM adaptive transmissions, each subcarrier can get an independent adaptive mode according to the Channel State Information (CSI). The awfully large amount of CSI feedback and signalling transmissions will be a serious problem in adaptive OFDM systems. This paper focuses on the practical feedback and adaptive signalling designs of adaptive OFDM systems. Based on the characteristics of frequency selective channels, a Dynamic Neighboring Subcarrier Grouping Scheme (DNSGS) is proposed to cut down the feedback and adaptive signalling overhead, and to simplify the implementation of adaptive OFDM systems. Then the capacity of DNSGS based OFDM systems is also given. The simulation results powerfully show that the scheme designed in this paper is flexible enough for different kinds of communication environments, and can effectively cut down the feedback and signalling overhead with rather limited performance penalty. Besides, DNSGS outperforms the existing grouping schemes greatly.**

I. Introduction

In adaptive Orthogonal frequency-division multiplexing(OFDM) systems, due to the multi-path effect, different subchannels suffer different fading. Many link adaptive techniques are proposed to combat frequency selective fading. Adaptive techniques are suitable for duplex communications between two stations. When the forward and reverse channels are not reciprocal, e.g. frequency division duplexing systems, the adaptive transmission requires the feedback of CSI. When the forward and reverse channels are reciprocal, e.g. time division duplexing systems, though the forward channel state can be estimated through the reverse channel signals received at the transmitter, the transmitter still needs to inform the receiver of the adaptive mode each subcarrier uses. Besides, most traffics are asymmetrically distributed, and the transmitter may not receive any signal from the reverse channel for a long time before it wants to transmit something. Even for near symmetrical traffics, both the forward and reverse channels need to be OFDM channels. However, the downward channel can be an OFDM channel while the upward channel can not be an OFDM channel, since continuous uplink transmission of pilots over a large band would risk draining terminal batteries. Besides, the transmissions from all terminal to the base station would have to be well synchronized in frequency to avoid significant inter-carrier interference, which makes the frequency synchronization at the bast station rather difficult. Hence, an independent feedback is always needed. The awfully large amount of CSI feedback and signalling overhead will be a serious problem in adaptive OFDM systems.

Recent researches have payed much attention to this problem. [5] proposed to use one-bit channel state feedback for each subcarrier, and this one bit is used to indicate the subcarrier selection or threshold based power allocation, e.g. 1 for a power level and 0 for another. This method provides very limited adaptive capability and works well for excluding deep faded subcarriers. As compared with subcarrier-to-subcarrier adaptation mode, i.e. each subcarrier with one independent adaptation mode and signalling loop, grouping is proved to be effective in reducing transceiver complexity, CSI feedback and signalling overhead, since the same adaptive mode will be used in all member subcarriers of a group instead of one mode for one subcarrier. Besides, only minor modifications of traditional adaptive techniques need to be done for transmissions based on this kind of feedback. [6] has proposed a grouping adaptive modulation OFDM system, which separates subcarriers into groups for the same modulation. [8] proposed to process subband bit and power loading based on grouping the subcarriers according to the ascending order of subcarrier channel gains. However these methods either do not consider the characteristics of transmission channels or can not effectively cut down the adaptive signalling overhead.

This paper investigates the characteristics of frequency selective channels, based on which a Dynamic Neighboring Subcarrier Grouping Scheme (DNSGS) is proposed to cut down the signalling overhead, and to simplify the implementations of adaptive OFDM systems. Then the capacity of DNSGS based OFDM systems is also given.

II. System Model

Consider OFDM transmissions over frequency selective fading channels in the point to point cellular communication scenario, where both the transmitter and the receiver have one antenna. Assume that the symbol duration T satisfies $T \gg \delta$, where δ is the delay spread of the channel. Assume that the fading is slow compared to the transmission rate, i.e., $f_D T \ll 1$, in which f_D is the maximum Doppler shift , so that the channel state keeps near static during one symbol period. The finite impulse response(FIR) channel model with L time-varying taps is considered. The mth $(m = 1, 2, ..., L)$

propagation path is characterized by a delay τ_m and complex fading gain h_m, where all path gains are assumed to be independent complex Gaussian random variables with zero mean and variance σ_l^2. By adding cyclic prefix whose length is longer than τ_L, the OFDM system with N subcarriers converts the frequency selective fading channel into N parallel flat fading channels([1]), each of which has channel gain g_n:

$$g_n = \sum_{l=1}^{L} h_l \exp\left(-\frac{j2\pi n\tau_l}{NT}\right), \qquad n = 1, ..., N \tag{1}$$

It is easy to prove that g_n is a zero mean complex Gaussian random variable with variance $\sigma^2 = \sum_{l=1}^{L} \sigma_l^2$, and all g_n for $n = 1, \cdots, N$ have identical Gaussian distribution. Then the envelope of g_n is Rayleigh distributed with PDF:

$$\mathcal{F}(|g_n|) = \frac{|g_n|}{\sigma^2} \exp\left\{-\frac{|g_n|^2}{2\sigma^2}\right\}. \tag{2}$$

The OFDM system can be modelled in frequency domain as:

$$\mathbf{r} = \mathbf{G}\mathbf{P}^{1/2}\mathbf{s} + \mathbf{n} \tag{3}$$

where $\mathbf{s} = [s(1), \cdots, s(N)]$ is the transmitted symbols for one transmission time, $\mathbf{P} = diag(p_1, \cdots, p_N)$ represents the power allocation of all subcarriers, $\mathbf{G} = diag(g_1, \cdots, g_N)$ is the channel matrix, $\mathbf{n} = [n(1), \cdots, n(N)]$ is additive white Gaussian noise and each member is i.i.d. complex Gaussian variable with zero mean and ε_0 variance. $r = [r(1), \cdots, r(N)]$ is the received OFDM symbols.

Based on $\mathbf{G}$, different $\mathbf{P}$ and s can be designed to achieve the best transmission performance. This is realized specifically by all kinds of adaptive power allocation techniques, adaptive bit allocation techniques, adaptive coding techniques, etc.

III. Dynamic Neighbor Subcarrier Grouping Scheme

All subcarriers in one group have the same power allocation and modulation level. Each group has one signalling loop for CSI feedback and adaptive modulation negotiations. Besides, the grouping information, i.e. the members contained in each group, should also be exchanged.

A. Summary of Existing Subcarrier Grouping Scheme

1) Equal Size Continuous Grouping : Most recent researches on grouping OFDM systems ([6], [7], etc.) proposed to divide all N subcarriers into N_s groups with the same size simply. The ith group contains subcarriers with indices: $\mathbb{G}_i = \left\{(i-1)\frac{N}{N_s} + 1, \cdots, i\frac{N}{N_s}\right\}$. This is a pure mathematical subset division, and does not consider the channel characteristics at all.

2) Sorted Subcarrier Grouping: [8] proposed to group subcarriers according to the ascending order of channel gains. First reorder all subcarriers so that $|g_{I_1}|' \leq |g_{I_2}|' \leq \cdots \leq |g_{I_N}|'$, where $I_1, \cdots, I_N$ are reordered indices. Then divide all subcarriers into N_s groups with the same size. The jth group is: $\mathbb{G}_j = \left\{I_{(j-1)\frac{N}{N_s}+1}, \cdots, I_{j\frac{N}{N_s}}\right\}$. This method performs much better than the above one. However, it needs to exchange the reordering information of all subcarriers between the transmitter and receiver, which requires a large quantity of information transmission.

B. Channel Characteristics Analysis

Though many researches have assumed that all subcarriers have independent fading, this does not hold for general cases. Based on the model proposed in [2], the correlations of subchannel gains are:

$$\begin{aligned}\mathcal{R}_c(\triangle n) &= \mathcal{E}[g_n g_{n+\triangle n}^*] \\ &= \frac{J_0(0)}{1 + \frac{[2\pi(\triangle n)]^2}{T^2}\delta^2}\left[1 - j\frac{2\pi\triangle n}{T}\delta\right],\end{aligned} \tag{4}$$

where * denotes the complex conjugate, and $J_0(\cdot)$ is the Bessel function of order 0. The autocorrelation matrix of $\{g_n | n = 1, \cdots, N\}$ is R_c, in which the (j,k)th entry is $\mathcal{R}_c(|j-k|)$. The power gain of subchannel i is $\rho_i = |g_n|^2$. The power gain autocorrelation is:

$$\mathcal{E}[\rho_n \rho_{n+\triangle n}] = \mathcal{E}[|g_n|^2 |g_{n+\triangle n}|^2]. \tag{5}$$

According to eq.6 of [9], for zero-mean complex Gaussian variables: $\mathcal{E}[|x_1|^2|x_2|^2] = \mathcal{E}[|x_1|^2]\mathcal{E}[|x_2|^2] + |\mathcal{E}[x_1 x_2^*]|^2$. Hence,

$$\begin{aligned}\mathcal{E}[\rho_n \rho_{n+\triangle n}] &= \mathcal{E}[|g_n|^2]\mathcal{E}[|g_{n+\triangle n}|^2] + |\mathcal{E}[g_n g_{n+\triangle n}^*]|^2 \\ &= \sigma^4 + |\mathcal{R}_c(\triangle n)|^2.\end{aligned} \tag{6}$$

For neighboring subchannels, which means $\triangle n$ is small enough, since $T \gg \delta$, $\frac{\triangle n}{T}\delta \to 0$, $\mathcal{R}_c(\triangle n) = \mathcal{E}\{g_n g_{n+\triangle n}^*\} \to J_0(0) = 1$. Hence, when the symbol duration T satisfies $T \gg \delta$, neighboring subchannels are significantly correlated.

C. Dynamic Neighbor Subcarrier Grouping Scheme

The adaptive modulation, i.e. Modulation Constellation (MC) selection, is decided by the signal to noise ratio (SNR) of each subcarrier to achieve a certain BER requirement. The SNR of subcarrier n is $\gamma_n = \frac{|g_n|^2 p_n}{\varepsilon_0}$. K modulation levels are available, and the kth MC with constellation size $\mathcal{M}(k)$ is used at the nth subcarrier, then this subcarrier has SNR-BER property $\mathcal{P}_k(\gamma_n)$. Suppose all available MCs are ordered so that for a given SNR γ, $\mathcal{P}_1(\gamma) < \cdots < \mathcal{P}_K(\gamma)$, and the spectral efficiency, i.e. the number of bits per symbol, satisfies $\log_2 \mathcal{M}(1) \leq \cdots \leq \log_2 \mathcal{M}(K)$. Then to achieve a certain BER requirement, the basic SNRs of all modulation constellations are: $\Gamma_1, \Gamma_2, \cdots, \Gamma_K$.

If M-QAM modulation is used, the BER for coherently detected M-QAM with Gray bit mapping is approximately given by ([10])

$$\mathcal{P}_k(\gamma) \approx 0.2 \exp\left(-1.6\frac{\gamma}{\mathcal{M}(k) - 1}\right), \tag{7}$$

which is tight within 1dB when $\mathcal{M} \geq 4$ and $BER \leq 10^{-3}$. Based on (7) and given BER requirement P_{BER}, Γ_k is given by

$$\Gamma_k = 0.625(1 - \mathcal{M}(k)) \ln(5P_{BER}), \tag{8}$$

The MC selection is based on the SNR and BER requirement. Given SNR γ, if $\gamma < \Gamma_1$: this subcarrier is deep faded, and is excluded for data transmission. Otherwise, find k so that $\gamma \geq \Gamma_k$, and $\gamma_i < \Gamma_{k+1}$ when $k < K$. Select the kth MC.

The above shows how to adaptively modulate a single subcarrier. Since our scheme is group based, a measure is needed to decide the selection of modulation for a group of subcarriers. The effective SNR(ESNR) $\overline{\gamma}$ is defined for this purpose. For a given MC, ESNR should be able to represent the BER property of all subcarriers in the group. Intuitively, ESNR can be approximated by the average SNR of all subcarriers in one group.

Since the channel gains of neighboring subcarriers are significantly correlated, we propose to group the subcarriers continuously according to the channel gain distributions and the SNR requirements of different modulation constellations. The basic idea is to expand a basic group to include as many neighboring subcarriers as possible. In order to avoid groups with too small size and limit the feedback information, the basic group contains at least N_T neighboring subcarriers. Assume that one basic group has finished its expansion at subcarrier i. Then a new basic group with size N_T is formed. The ESNR is the average SNR of the new group. The kth MC is selected based on the ESNR: $\Gamma_k \leq \overline{\gamma} < \Gamma_{k+1}$. The group expansion should not change the MC selection. However, the expansion should not be interrupted by a subcarrier that has SNR slightly lower than Γ_k or higher than Γ_{k+1}. Because probably the expansion only meets a small number of subcarriers with sinking or spurting SNR, and these subcarriers should also be grouped together with neighboring subcarriers to avoid additional signalling overhead for only a slight performance improvement. Hence, these kinds of subcarriers will also be included, but some penalty should be exerted to avoid the inclusion of too many these neighboring sinking or spurting subcarriers. This penalty is expressed in the form of different weights when calculating ESNR, and it depends on the distance between the newly considered subcarrier and the most recent subcarrier in the group that satisfying $\Gamma_k \leq \gamma < \Gamma_{k+1}$. Suppose the existing group is $\mathbb{G}$ with ESNR $\overline{\gamma}$ and MC k, the candidate expanded group is $\mathbb{G}' = \mathbb{G} \bigcup \{s\}$, where $s = 1 + \max(i : i \in \mathbb{G})$. The ESNR of $\mathbb{G}'$ is given by

$$\overline{\gamma}' = \begin{cases} \frac{|\mathbb{G}|\overline{\gamma}+\gamma_s}{|\mathbb{G}|+1} & \Gamma_k \leq \gamma_s < \Gamma_{k+1} \\ \frac{|\mathbb{G}|\overline{\gamma}+(s-r)^2\gamma_s}{|\mathbb{G}|+(s-r)^2} & otherwise \end{cases}, \tag{9}$$

where $r = \max(i : i \in \mathbb{G}, \Gamma_k \leq \gamma_i < \Gamma_{k+1})$. The MC selection for $\mathbb{G}'$ is based on $\overline{\gamma}'$. If it is still k, subcarrier s is included, and the expansion continues. Otherwise, the group is big enough and a new group is to be formed. The detailed Dynamic Neighbor Subcarrier Grouping Scheme (DNSGS) is described as follows:

Step1 Based on channel estimation, the SNR of all subcarriers: $\gamma_1, \gamma_2, \cdots, \gamma_N$. According to BER requirement, get the SNR requirement for each MC. Set group counter $i = 0$, and position counter $j = 0$.

Step2 If $j \geq N$, $N_s = i$, grouping finished. Otherwise, set $\mathbb{G} = \{j+1, j+2, \cdots, \min(j+N_T, N)\}$. If these N_T subcarriers are deep faded, discard them, set $j = j + N_T$, do Step 2 again. Otherwise, determine the modulation for $\mathbb{G}$: the mth MC; If no discarded subcarriers exist between $\mathbb{G}$ and $\mathbb{G}_i$ and both $\mathbb{G}$ and $\mathbb{G}_i$ have the same MC, then $\mathbb{G}_i = \mathbb{G}_i \bigcup \mathbb{G}$; Otherwise, $i = i + 1$, $\mathbb{G}_i = \mathbb{G}$, $m_i = m$. Set $j = j + N_T$, go to Step 3 to expand $\mathbb{G}_i$.

Step3 If $j \geq N$, $N_s = i$, grouping finished. Otherwise, if $\mathbb{G}_i \bigcup \{j+1\}$ and $\mathbb{G}_i$ have the same MC, then $\mathbb{G}_i = \mathbb{G}_i \bigcup \{j+1\}$, $j = j + 1$, repeat Step 3. For other cases, go to Step 2 to begin a new group search .

DNSGS has time complexity $O(N)$. Since DNSGS is based on equal power allocation at the transmitter, the grouping and MC selection effectively reveal channel characteristics. Based on DNSGS, most deep faded subcarriers are excluded and all effective subcarriers are divided into groups $\{\mathbb{G}_i, \overline{\gamma}_i^{(o)} : i = 1, \cdots, N_s\}$, in which $\overline{\gamma}_i^{(o)}$ is the ESNR for $\mathbb{G}_i$ estimated under equal power allocation over all subcarriers. The receiver then sends these information to the transmitter for transmission optimizations.

The measure to group subcarriers is the basic SNRs of all modulation constellations to achieve the BER requirement: $\Gamma_1, \Gamma_2, \cdots, \Gamma_K$. This measure can be more general, e.g. the basic SNRs of different adaptive levels to achieve the BER requirement. Different adaptive levels correspond to different adaptive modulations, different coding schemes, different combinations of modulations and coding schemes, etc. In the following part, we consider only adaptive modulation and power allocation. Other kinds of adaptive techniques can be analyzed in a similar way.

D. *DNSGS based OFDM Channel Capacity*

Each subcarrier experiences AWGN flat channel, and the capacity is given by [11]:

$$C_i = \log_2(1+\gamma_i) = \log_2\left(1 + \frac{|g_i|^2 p_i}{\varepsilon_0}\right) \tag{10}$$

The channel capacity based on DNSGS is

$$\begin{aligned} C_G &= \max_{P_i : \sum_{i=1}^{N_s} |\mathbb{G}_i| \cdot P_i = P_T} \sum_{i=1}^{N_s} \sum_{j \in \mathbb{G}_i} C_j \\ &= \max_{P_i : \sum_{i=1}^{N_s} |\mathbb{G}_i| \cdot P_i = P_T} \sum_{i=1}^{N_s} \sum_{j \in \mathbb{G}_i} \log_2\left(1 + \frac{|g_j|^2 P_i}{\varepsilon_0}\right) \end{aligned} \tag{11}$$

where P_i is the power of each subcarrier in group $\mathbb{G}_i$, and P_T is the total transmit power.

The transmitter has no CSI of each subcarrier but ESNR in a group. Then the same CSI is assumed in each group: $\frac{|g_j|^2}{\varepsilon_0} = \frac{\overline{\gamma}_k^{(o)} N}{P_T}$, for $\forall j \in \mathbb{G}_k, k = 1, \cdots, N_s$. Via the Lagrangian technique, the optimal power allocation is found to be the water-filling allocation

$$P_k = \quad \mu_0 - \frac{P_T}{N\overline{\gamma}_k^{(o)}} \Big)^+, \qquad k = 1, \cdots, N_s, \tag{12}$$

and $(x)^+ = \max(0,x)$. The "water level" μ_0 is given by the power constraint: $\sum_{k=1}^{N_s}|\mathbb{G}_i|P_k = P_T$. Then based on DNSGS, the channel capacity is:

$$C_G = \sum_{i:N\overline{\gamma}_i^{(o)}\mu_0 \geqslant P_T} \sum_{j\in\mathbb{G}_i} \log_2(1+\frac{P_T\mu_0|g_j|^2}{\varepsilon_0} - \frac{P_T|g_j|^2}{\varepsilon_0 N\overline{\gamma}_i^{(o)}}). \quad (13)$$

IV. Adaptive Communication Based on DNSGS

Though a certain MC has been selected for each group, the power allocation and MC of each group can be adjusted to further improve the system performance. These adaptive techniques are names as Group Adaptive Techniques(GATs). GAT is different with traditional adaptive techniques, since traditional techniques focus on single subcarrier based resource allocation, while GAT group characteristics based. The MC selection and power allocation of all groups are denoted by $\mathbf{m} = [m_1,\cdots,m_{N_s}]$ and $\mathbf{P}_g = [P_1,\cdots,P_{N_s}]$, in which P_i is the the power of each subcarrier in $\mathbb{G}_i$.

A. Transmit Power Saving Oriented Adaptive Bit and Power Loading

Assume a constant bit rate and basic BER requirement. The transmit power needs to be minimized for power saving. The MC selection and power allocation is given by

$$\begin{aligned} &\min Power(\mathbf{m},\mathbf{P}_g) = \min\sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot P_i,\\ &s.t.\ \begin{cases} R=\sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot\log_2\mathcal{M}(m_i)\\ \mathcal{P}_{m_i}(\frac{P_i\overline{\gamma}_i^{(o)}N}{P_T}) = P_{BER}, i=1,\cdots,N_s \end{cases}, \end{aligned} \quad (14)$$

where R is the number of bits to be sent in one OFDM symbol time, P_{BER} is the BER requirement and $\frac{\overline{\gamma_i}P_iN}{P_T}$ is the ESNR of $\mathbb{G}_i$ after power allocation. Assume M-QAM modulations and BER is given by (7) (this is reasonable, since most deep faded subcarriers have been excluded by DNSGS), the problem can be converted into

$$\begin{aligned} &\min Power(\mathbf{m},\mathbf{P}_g) = \min\sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot P_i,\\ &s.t.\quad R=\sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot\log_2(P_i\overline{\gamma}_i^{(o)}S+1) \end{aligned} \quad (15)$$

where $S=\frac{N}{P_T[-\frac{5}{8}\ln(5P_{BER})]}$. Assuming an infinite continuous MC set, the power allocation is given by

$$P_k = \left(\mu_0 - \frac{1}{S\overline{\gamma}_k^{(o)}}\right)^+, k=1,\cdots,N_s. \quad (16)$$

via the Lagrangian technique. The MC for each group should guarantee the BER no more than P_{BER}. Among the available MCs, the MC selection for each group is given by

$$\begin{aligned} m_i = \arg_k\max\{\mathcal{M}(k):\mathcal{M}(k)\le P_i\overline{\gamma}_i^{(o)}S+1,\\ k=1,\cdots,K\}, i=1,\cdots,N_s. \end{aligned} \quad (17)$$

μ_0 is given by constant bit rate constraint: $\sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot\log_2\mathcal{M}(m_i) = R$. The minimum power needed is:

$$\min Power = \sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot\left(\mu_0 - \frac{1}{S\overline{\gamma}_i^{(o)}}\right)^+ \quad (18)$$

B. Throughput Maximization Oriented Adaptive Bit and Power Loading

Assume basic BER requirement and a total power limit. The data throughput is to be maximized. The MC selection and power allocation is given by

$$\begin{aligned} &\max R(\mathbf{m},\mathbf{P}_g) = \max\sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot\log_2\mathcal{M}(m_i),\\ &s.t.\ \begin{cases} \sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot P_i = P_T\\ \mathcal{P}_{m_i}(\frac{P_i\overline{\gamma}_i^{(o)}N}{P_T}) = P_{BER}, i=1,\cdots,N_s \end{cases}. \end{aligned} \quad (19)$$

With M-QAM modulations, the problem is formulated as

$$\begin{aligned} &\max R(\mathbf{m},\mathbf{P}_g) = \max\sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot\log_2(P_i\overline{\gamma}_i^{(o)}S+1),\\ &s.t.\sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot P_i = P_T. \end{aligned} \quad (20)$$

The power allocation and MC selection are also given by (16) and (17) respectively, in which μ_0 is given by power constraint: $\sum_{i=1}^{N_s}|\mathbb{G}_i|P_i = P_T$.

C. BER Minimization Oriented Adaptive Bit and Power Loading

Assume a constant transmit power and target bit rate. The average BER at the receiver is to be minimized. The MC selection and power allocation is given by

$$\begin{aligned} &\min\overline{BER}(\mathbf{m},\mathbf{P}_g) = \min\tfrac{1}{R}\textstyle\sum_{i=1}^{N_s}|\mathbb{G}_i|\log_2\mathcal{M}(m_i)\mathcal{P}_{m_i}(\frac{P_i\overline{\gamma}_i^{(o)}N}{P_T}),\\ &s.t.\ \begin{cases} \sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot\log_2\mathcal{M}(m_i)=R\\ \sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot P_i = P_T \end{cases}, \end{aligned} \quad (21)$$

The problem can be reformulated to minimize the Lagrange cost function

$$\begin{aligned} J(r_i,P_i,\mu_1,\mu_2) = \frac{1}{R}\sum_{i=1}^{N_s}|\mathbb{G}_i|r_i\mathcal{P}_{m_i}(\frac{P_i\overline{\gamma}_i^{(o)}N}{P_T})+\\ \mu_1(\sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot r_i - R)+\mu_2(\sum_{i=1}^{N_s}|\mathbb{G}_i|\cdot P_i - P_T), \end{aligned} \quad (22)$$

where $r_i = \log_2\mathcal{M}(m_i)$, μ_1 and μ_2 are the two Lagrange multipliers. Eq.(22) is minimized by fulfilling

$$\frac{\partial J}{\partial r_k} = 0 \qquad \text{and} \qquad \frac{\partial J}{\partial P_k} = 0 \qquad k=1,\cdots,N_s \quad (23)$$

Assume that M-QAM modulations are used and an infinite continuous MC set is available. Solving the partial derivatives

TABLE I

SIMULATION PARAMETERS

A. ITU Channel Models							
	Tap i	1	2	3	4	5	6
Pedestrian Channel A	τ_i(ns)	0	110	190	410	-	-
	σ_i^2(dB)	0	-9.7	-19.2	-22.8	-	-
Pedestrian Channel B	τ_i(ns)	0	200	800	1200	2300	3700
	σ_i^2(dB)	0	-0.9	-4.9	-8.0	-7.8	-23.9
Vehicular Channel A	τ_i(ns)	0	310	710	1090	1730	2510
	σ_i^2(dB)	0	-1.0	-9.0	-10.0	-15.0	-20.0

B.OFDM System Configurations	
Carrier frequency (GHz)	2
Radio frame length (msec)	10
HSDPA slot length (TTI)(msec)	2
OFDM symbols per TTI	27
FFT size (points)	512
OFDM sampling rate (Msamples/sec)	7.68
Guard Time Interval (samples/μsec)	57/7.42
Subcarrier separation (KHz)	15
OFDM symbol duration (μsec)	74.09
Channel model and fading rate	CH1: Veh.A, 120km/hr
	CH2: Ped.A, 3km/hr
	CH3: Ped.B, 3km/hr
Channel estimation	Ideal
Channel Coding	OFF
Transmission Power (dBm)	43

in (23), the power allocation and MC selection are given by the two coupled equations

$$\begin{cases} P_k = \frac{P_T(\mathcal{M}(m_k)-1)}{1.6N\overline{\gamma}_k^{(o)}} \ln \frac{0.32\log_2 \mathcal{M}(m_k)}{\mu_2 R[\mathcal{M}(m_k)-1]} \\ (0.2 - \frac{0.32\log_2 \mathcal{M}(m_k)}{\mathcal{M}(m_k)-1}) \exp(\frac{-1.6P_k N\overline{\gamma}_k^{(o)}}{P_T(\mathcal{M}(m_k)-1)}) = -R\mu_1 \end{cases} \quad (24)$$

μ_1, μ_2 are found by solving the transmit power and target bit rate constraints. The power allocations and MC selections are a set of non-linear equations coupled through μ_1 and μ_2. Numerical methods are required to get the final results.

V. SIMULATIONS

The channel models used are the ITU Channel A and B models for vehicular and pedestrian environments described in [12]. The parameters, relative delay τ_i and the relative path power σ_i^2 of path i for $i = 1, ..., 6$, are described in subtable A of Table I. The pedestrian terminal has 3 km/hr velocity while the vehicular terminal has 120 km/hr velocity. The Jakes doppler spectrum is used. The noise power of each subcarrier is 3dBm. Perfect channel estimation is assumed. The simulation is within the framework of 3GPP systems, and the potential benefits of our scheme are evaluated by using the OFDM HS-DSCH transmission as a downlink radio interface for high speed data services in UTRAN. The OFDM system configurations are similar with those in [13] for applications in HS-DSCH transmissions, and are shown in subtable B of Table I. Three channels, CH1, CH2 and CH3, are used for thorough simulations. The DNSGS based adaptive OFDM system architecture is shown in Fig.1.

A. Subcarrier Grouping

The available MCs are: 4QAM, 8QAM, 16QAM. The target BER is $P_{BER} = 10^{-3}$. According to (8), the basic SNRs are: $9.97, 13.65, 16.96$(dB). Each group contains at least 15 subcarriers except the last group. Fig.2, 3 and 4 show some snapshots of the estimated frequency domain channel power gain and the grouping results of DNSGS for CH1, CH2,

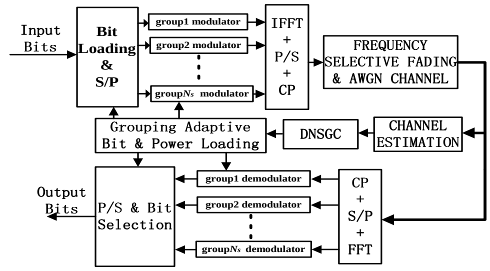

Fig. 1. DNSGS based Adaptive OFDM System Architecture

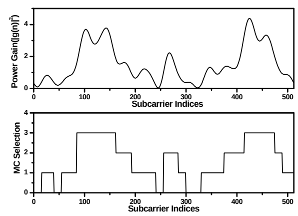

Fig. 2. Snapshots of Estimated Channel Power Gain and Subcarrier Grouping(CH1)

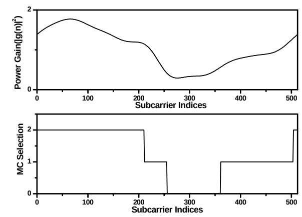

Fig. 3. Snapshots of Estimated Channel Power Gain and Subcarrier Grouping(CH2)

CH3 respectively. As shown in these figures, the proposed DNSGS effectively groups together subcarriers with similar power gain characteristics, and excludes those deeply faded. Besides, DNSGS also successfully absorbs sinking or spurting subcarriers to reduce the number of groups as many as possible (especially in Fig.4), which effectively cuts down feedback information. In Fig.2, 3 and 4, only 12, 4, 15 groups are generated, which means a really small amount of signalling overhead as compared with 512 independent signallings.

B. DNSGS based OFDM Capacity Analysis

The parameters are the same with those in subsection A. Since DNSGS excludes deep faded subcarriers, some channel capacity is lost. Fig.5 gives a channel state snapshot during an OFDM symbol transmit time in CH1 and the corresponding grouping results. Three power allocations are presented. The first curve ”IdealAlloc” is the power allocation to achieve channel capacity when the transmitter has full CSI. The second one ”GIdeal” is the allocation when the transmitter knows the CSI of each subcarrier in each group, and the third one ”DNSGS” is the allocation when the transmitter knows the ESNR of each group only. The allocation for OFDM based

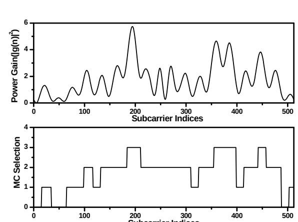

Fig. 4. Snapshots of Estimated Channel Power Gain and Subcarrier Grouping(CH3)

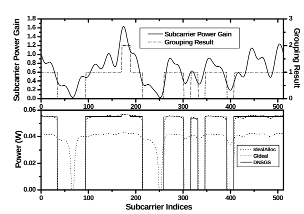

Fig. 5. Snapshots of Power allocation comparison among ideal, group ideal and group ESNR based transmissons in CH1

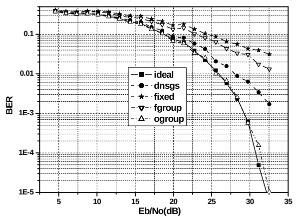

Fig. 6. BER Performance for Various OFDM Schemes in CH1

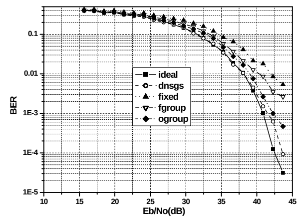

Fig. 7. BER Performance for Various OFDM Schemes in CH2

on DNSGS saves a lot of power from deep faded subcarriers. Based on DNSGS, only 354/512=69% of 512 subcarriers are used, but the capacity reaches 1617bits/1837bits=88% of the capacity of ”IdealAlloc”, and the signalling overhead is only 8*3/512=4.7% of ”IdealAlloc”. For the allocation of DNSGS, though the transmitter has no knowledge of each subcarrier in a group but the ESNR as a representative state, the power allocation has only nuances with ”GIdeal”. The channel capacity of DNSGS is 1617.6 bits while ”GIdeal” 1617.7 bits. Hence, the ESNR works very effectively as a representative for all subcarriers in the group.

C. BER Performance of DNSGS based OFDM Systems

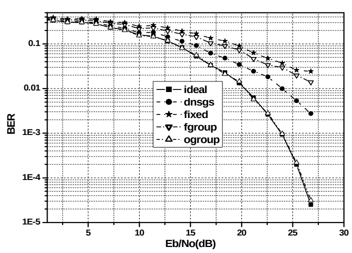

Fig. 8. BER Performance for Various OFDM Schemes in CH3

The available MCs are 2QAM, 4QAM and 8QAM. The BER performance under different Eb/No, i.e. average allocated bit energy to subcarrier noise power ratio, of fixed-modulation and adaptive modulations OFDM systems are shown in Fig.6, Fig.7, and Fig.8 for simulations in CH1, CH2 and CH3 channels. The fixed-modulation performance is marked by ”fixed”. Four adaptive systems based on different feedback schemes are implemented. The adaptive bit loading algorithms in [14] is used. The first adaptive system is based on perfect channel knowledge at the transmitter, and the curve is marked by ”ideal”. The second one, with legend ”fgroup”, is based on equal size continuous subcarrier grouping. The third, with legend ”ogroup”, is based on sorted subcarrier grouping. The last one marked by ”dnsgs” is based on the proposed DNSGS. The total number of bits per OFDM symbol for all five systems were always held constant to ensure fairness. At any given BER, ”fixed” will be outperformed by ”fgroup”, which in turn will be outperformed by ”dnsgs” greatly. Fig.7 shows that in CH2, which is comparatively flat (Fig.3), ”dnsgs” even outperformed ”ogroup”. This shows that although ”ogroup” has sorted the subcarriers before grouping for better grouping effect, the fixed size of each group limits its capability to fully exploit the channel characteristics. In CH2, although the signalling overhead is significantly cut down by DNSGS, ”dnsgs” still exploits the channel characteristics fully, and performs nearly the same with ”ideal” for most Eb/No values. When the channel has fierce frequency fading like CH1 and CH3, ”ogroup” performs better than ”dnsgs”. However, while ”dnsgs” only needs to exchange group information, ”ogroup” still need to exchange the reordered information of all subcarriers, and this huge signalling overhead makes ”ogroup” impracticable.

VI. Conclusion

This paper focused on practical feedback and adaptive signalling designs of OFDM systems. Based on the investigations of the characteristics of frequency selective channels, the DNSGS is proposed to cut down the feedback and adaptive signalling overhead, and to simplify the implementation of OFDM adaptive techniques. Then the capacity of DNSGS based OFDM systems is also given. The simulation results powerfully show that DNSGS is flexible enough for different kinds of communication environments, and can effectively cut down the feedback and signalling overhead with rather limited performance penalty. Besides, DNSGS outperforms the existing grouping schemes greatly.

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