Subband Level Adaptation for Bit-interleaved Coded OFDM (BIC-OFDM)

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***Abstract*— Subcarrier level adaptive modulation and coding (AMC) for BIC-OFDM has been shown to give significant performance gains over conventional BIC-OFDM systems such as IEEE 802.11a standard. But subcarrier level adaptation involves a large signaling overhead. Subband level adaptation can give performance close to subcarrier level adaptation systems with reduced signaling overhead. We analyze two techniques to do subband level AMC over BIC-OFDM. In the first technique, the rate and power for a subband is chosen based on the channel information of the subcarrier in the subband with the minimum channel gain. Since this technique is found to be far too conservative for large subband sizes, we analyze another approach to subband adaptation in the second part. Here, the subband allocation is performed based on an equivalent subband channel. Simulation results show that the second technique is better than the first technique in terms of data rates achievable for the same number of subbands. Simulation results also show that, with these subband level adaptation techniques, we can achieve performance levels close to that of subcarrier level adaptation with a significant reduction in signaling overhead.**

I. Introduction

Adaptive modulation and coding (AMC) is considered a powerful technique to achieve high throughput in time-varying fading channels. The basic premise of AMC is to improve spectral efficiency by varying the transmit power level, constellation size and coding rate depending on the channel state. In [1], an adaptive variable-rate variable-power transmission scheme using MQAM is shown to achieve a 17dB power gain over non-adaptive modulation on a flat Rayleigh fading channel. An adaptive coding strategy over time-varying channels is described in [2] to achieve significant throughput gains over conventional nonadaptive methods.

For the frequency selective channels, Orthogonal Frequency Division Multiplexing (OFDM) [3] has been seen as a possible solution to combat ISI effectively and achieve high data rates. The OFDM technique divides the channels into many narrowband subchannels such that each subchannel is a flat fading channel. Adaptive modulation has been used in OFDM in [4] to achieve significant performance gains. Recently, [5] proposed a method to jointly adapt the coding rate, modulation schemes and power for Bit Interleaved Coded-OFDM (BIC-OFDM) packet transmission. Both these techniques adapt at a subcarrier level and hence the information on rate and power allocated on each subcarrier needs to be exchanged between the transmitter and receiver. This necessitates a large signaling overhead in practical systems. The receiver needs to feedback the complete subcarrier level channel information to the transmitter. The transmitter uses this information to decide upon the bit allocation and power allocation vectors. Finally, the transmitter sends this allocation information through a control signaling channel.

Subband level modulation adaptation can be used to achieve performances close to the subcarrier level adaptation systems, with reduced amount of signaling overhead. A subband is a set of adjacent subcarriers. In [7], a subband level rate and power variation has been proposed in a turbo coded OFDM system. We analyze two subband level allocation approaches for adaptive BIC-OFDM. We modify the optimization problem in [5] to include adaptation at a subband level. We study the effects of the variation of subband size on the throughput and Packet Error Rate (PER). The simulations results show that, we can achieve performance close to that in [5] and better than the current IEEE 802.11a standard, even with significantly reduced amounts of signaling.

The remainder of the paper is organized as follows. In the next section, we describe the adaptive BIC-OFDM structure. Transmitter, receiver and channel models are explained here. In section III, we review the optimization problem in [5] for the adaptation at subcarrier level. Then we define the modified optimization problems for the two approaches to subband level adaptation. In section IV, we present the simulation parameters and results and in the last section we conclude.

II. System Model of adaptive BIC-OFDM

We assume a quasi-static fading channel in which the channel remains static for L OFDM symbols. We represent the N frequency domain channel gains as $H_1, \ldots, H_N$. As shown in Fig. 1, under the quasi-static fading assumption these channel gains remain unchanged during one packet transmission although each packet may experience different frequency selective pattern. For all L OFDM symbols, the nth

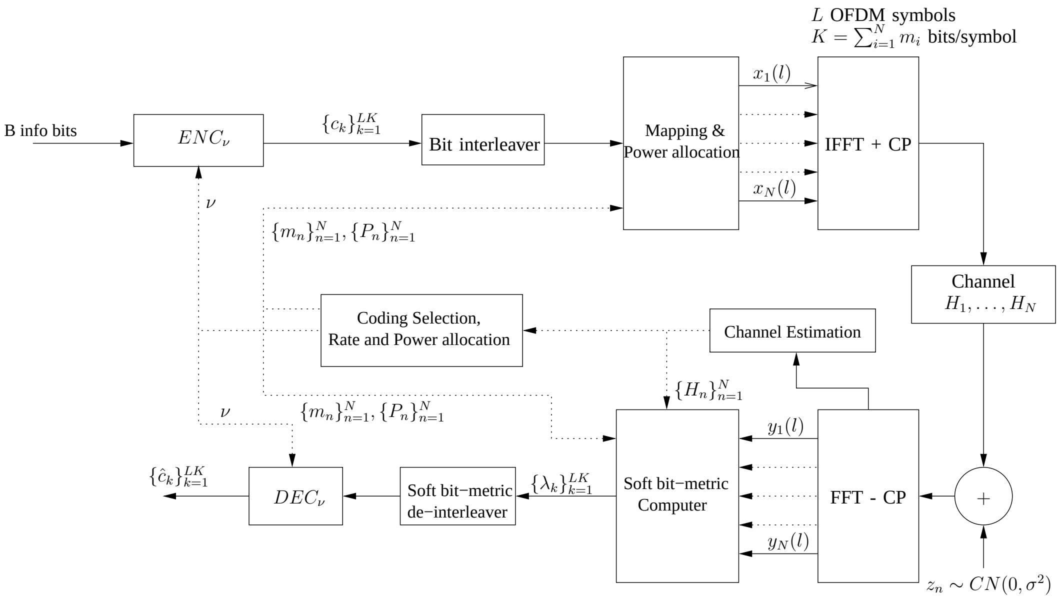

Fig. 1. Adaptive BIC-OFDM System Model

sub-carrier delivers one of $M_n = 2^{m_n}$ symbols in a QAM signal set χ_n with the average transmit power P_n. Hence, $K = \sum_{n=1}^{N} m_n$ bits are present in each OFDM symbol and LK coded bits are sent in each transmitted packet. For each packet transmission, the input bit stream is encoded using one of V different *binary* linear codes, $\{C_i\}_{i=1}^{V}$. Associated with each code C_i is the information rate of a code $0 < r(C_i) \leq 1$ and the minimum Hamming distance $d_H(C_i)$. The sequence of encoded bits c_k's $(k = 1, \ldots, LK)$ from the output of the binary channel encoder is interleaved by a random block bit-interleaver π, which determines the OFDM symbol, subcarrier and bit positions for each encoded bit. The mapping rule μ_n relates the bits allocated for the nth subcarrier to a complex symbol $x_n \in \chi_n$. We use a Gray-mapping rule.

With IDFT at the transmitter and DFT at the receiver and appropriate cyclic prefix processing, the channel output at the nth frequency tone of the lth OFDM symbol can be written as

$$y_n(l) = H_n x_n(l) + z_n(l),$$

where $z_n(l)$ is i.i.d complex Gaussian with variance σ^2 per complex dimension. At the receiver, the simplified bit-metrics $\lambda^i(y_n(l), m_n, b)$ for the bits are computed from the channel output as follows,

$$\lambda^i(y_n(l), m_n, b) \equiv - \min_{x \in \chi_b^{(i,n)}} \frac{|y_n(l) - H_n x|^2}{\sigma^2}$$

where $\chi_b^{(i,n)}$ is a set of complex QAM signals in χ_n whose ith bit is b $(i = 1, \ldots, m_n, b = 0, 1)$. These soft-bit metrics are de-interleaved and the maximum-likelihood decoder finds a sequence of codewords such that

$$\underline{\hat{c}} = \arg\max_{c \in C_\nu} \sum_{k=1}^{LK} \lambda^i(y_n(l), m_n, c_k)$$

where C_ν is the codebook selected at the trasmitter.

III. Coding Selection and Rate and Power Allocation for Adaptive BIC-OFDM

A. Subcarrier level Rate and Power Allocation

In [5], the instantaneous channel knowledge of all the subcarriers is used to adapt the coding rate for every packet, the rate and power being variable over subcarriers. After rigorous pair-wise error probability analysis (PEP) of the BIC-OFDM system, the allocation problem is defined as follows,

$$\max_{i \in \{1,\ldots,V\}, \{m_1 \ldots m_n\}, \{P_1 \ldots P_N\}} R = \frac{r(C_i)}{N} \sum_{n=1}^{N} m_n \quad (1)$$

$$\text{subject to} \qquad \sum_{n=1}^{N} P_n \leq P_T$$

$$m_n \leq \min \left\{ \log_2 \left(1 + \frac{d_H(C_i) |H_n|^2 P_n}{\Gamma \sigma^2} \right), m_{\max} \right\} \quad (2)$$

where R is the data rate, Γ is a parameter which should be designed so that system performance satisfies the PER requirement. P_T is the maximum total transmit power, $m_{\max}$ is the maximum allowable bit loading per subcarrier. We use only square QAM bit-loading schemes, since these constellations always have Gray-map labeling. So m_n's are constrained to be even integers. This optimization problem can be solved as follows. First fix C_i. Now this becomes a standard discrete-rate capacity maximization problem with SNR gap of $\frac{\Gamma}{d_H(C_i)}$ and infinite cost penalty above $m_{\max}$. We can find the numerical solution using the iterative algorithm suggested in [6]. Let R_i, $\{m_{1,i},\ldots,m_{N,i}\}$, and $\{P_{1,i},\ldots,P_{N,i}\}$ be the resulting data rate, subcarrier rate and power allocation scheme respectively. Finally, the rate-maximizing coding scheme can be chosen as $\nu = \arg\max_i R_i$. The corresponding optimal sub-carrier rate and power allocation strategies are $\{m_{1,\nu},\ldots,m_{N,\nu}\}$ and $\{P_{1,\nu},\ldots,P_{N,\nu}\}$, respectively.

B. Subband level Rate and Power Allocation

Although subcarrier level adaptation achieves high spectral efficiency, the information on rate and power allocation on each subcarrier needs to be exchanged between the transmitter and the receiver. This demands a large signaling overhead in practical OFDM systems. To reduce this overhead, we can adapt at a subband level. All the subcarriers in a subband are allocated equal number of bits and same amount of power. We analyze two approaches for subband level allocation.

1. In the first approach, the rate and the power for a subband is decided so as to satisfy (2) for the subcarrier with the minimum channel gain in the subband. Let $H_{g,i}$ represent the channel gain of the ith subcarrier in the gth subband ($g \in \{1,\ldots,G\}, i \in \{1,\ldots,N/G\}$). If $S_g = \{|H_{g,1}|^2,\ldots,|H_{g,N/G}|^2\}$ is the set of absolute channel gains of the subcarriers of the gth subband and G the number of subbands, then

$$m_g \le \min\left\{\log_2\left(1+\frac{d_H(C_i)\min(S_g)P_gG}{\Gamma\sigma^2N}\right), m_{\max}\right\}$$

where m_g is the rate for all the subcarriers of the subband. $\min(S_g)$ represents the minimum of the values in the set S_g and $\frac{P_gG}{N}$ is the power allocated to each subcarrier in the subband. We can see that, satisfying (2) for the subcarrier with minimum channel gain ensures satisfaction of (2) for each of the subcarriers in the subband. We can redefine the optimization problem for this allocation as,

$$\max_{i\in\{1,\ldots,V\},\{m_1,\ldots,m_G\},\{P_1,\ldots,P_G\}} R = \frac{r(C_i)}{N}\sum_{g=1}^{G} m_g$$

$$\text{subject to} \qquad \sum_{g=1}^{G} P_g \le P_T$$

$$m_g \le \min\left\{\log_2\left(1+\frac{d_H(C_i)\min(S_g)P_gG}{\Gamma\sigma^2N}\right), m_{\max}\right\}$$

Again we can find the rate maximizing coding scheme ν, the subband rate allocation $\{m_{1,\nu},\ldots,m_{G,\nu}\}$ and the subband power allocation $\{P_{1,\nu},\ldots,P_{G,\nu}\}$ by executing the algorithm in [6] multiple number of times. Since allocation using this approach satisfies (2) for each of the subcarriers, we can safely assume that, an error performance close to the target PER will be maintained.

For subband sizes comparable to the coherence bandwidth, this allocation should perform similar to the system with complete channel information, since the subcarriers within the coherence bandwidth are highly correlated. However for adaptation schemes with larger subband sizes, there would be power wastage on good subcarriers. Simulation results shown in the next section support this argument.

2. Here we analyze a second approach to subband adaptation. We define a term $\Upsilon(m_n) = \frac{(2^{m_n}-1)\Gamma\sigma^2}{d_H(C_i)}$, which is intuitively the SNR requirement for the rate m_n. For a subband rate m_g, the power allocation which ensures (2) for all subcarriers within the gth subband is,

$$P_{g,i} = \Upsilon(m_g)/|H_{g,i}|^2 \qquad (g \in \{1,\ldots,G\}, i \in \{1,\ldots,N/G\}) \tag{3}$$

But this allocation needs signaling at subcarrier level. Since we restrict ourselves to subband level signaling, we allocate power uniformly within the subband. Thus in this approach, we allocate the subband rate m_g, and subband power P_g such that,

$$P_g \ge \sum_{i=1}^{N/G}\frac{\Upsilon(m_g)}{|H_{g,i}|^2}$$

And subsequently, the total subband power P_g, is allocated uniformly within the subband. We define the equivalent subband channel as $H_{eq}(g)$ where

$$\frac{1}{|H_{eq}(g)|^2} = \sum_{i=1}^{N/G}\frac{1}{|H_{g,i}|^2}$$

which derives its name from the fact that, using $H_{eq}(g)$ as a single representative channel for the whole gth subband would need as much subband power as when power allocation for the subcarriers within the subband is done according to (3).

Thus we define the allocation problem for this approach as,

$$\max_{i\in\{1,\ldots,V\},\{m_1,\ldots,m_G\},\{P_1,\ldots,P_G\}} R = \frac{r(C_i)}{N}\sum_{g=1}^{G} m_g$$

$$\text{subject to} \qquad \sum_{g=1}^{G} P_g \le P_T$$

$$m_g \le \min\left\{\log_2\left(1+\frac{d_H(C_i)|H_{eq}(g)|^2P_g}{\Gamma\sigma^2}\right), m_{\max}\right\}$$

After solving for the rate maximizing coding scheme ν, the rate allocation $\{m_{1,\nu},\ldots,m_{G,\nu}\}$ and the power allocation $\{P_{1,\nu},\ldots,P_{G,\nu}\}$, all the subcarriers in a subband are allocated equal power.

Although this approach doesn't strictly satisfy (2) for each of the subcarriers, we can bank on the code diversity gain of the overlying coding scheme and the correlation of channel gains of the subcarriers, to carry the bits through at the required PER. Moreover the power margin $P_{marg} = (P_T - \sum_{g=1}^{G} P_g)$ is allocated equally to all the subcarriers to provide some redundant power. Later in the simulation results we can see that the error performance of the system using this allocation approach, is indeed maintained close to the target PER. A similar approach can be seen in [7], where the authors propose subband adaptation methods for a turbo coded OFDM system.

IV. SIMULATION

In the simulations, we use a quasi-static non-line-of-sight (NLOS) exponentially decaying multi-path Rayleigh fading channel model with 50ns RMS delay spreads. The sampled discrete-time channel impulse response $h(t)$ is modeled as a finite impulse response, inter-symbol-interference (FIR-ISI) channel,

$$h(t) = \sum_{i=1}^{\nu} h_i \delta(t - iT_s)$$

where $h_i \sim CN(0, \sigma_0 e^{-iT_s/T_{rms}})$ is a complex Gaussian with $\sigma_0 = 1 - e^{-T_s/T_{rms}}$. In our simulations, $\nu = 16$ and $T_s = 50$ns. The OFDM system bandwidth is 20MHz with 64 subcarriers of which 48 are data carriers [8]. The cyclic prefix length is 16. Channel coding schemes are 64-state rate-$1/2, 2/3$ and $3/4$ punctured convolutional codes. We use QPSK, 16-QAM and 64-QAM with Gray-mapping rule for bit-loadings. The error performance parameter $\Gamma = 8.8$dB for a PER corresponding to 1%.

We define $SNR = \frac{E(\sum_n P_{n,\nu})}{N\sigma^2}$. Fig. 2 shows the data rate vs SNR curves for the two subband adaptation approaches discussed in this paper. As we can observe, for both the approaches the performance goes down as the number of subbands is reduced. For $N_g = 12$, the figure shows that both the approaches shows performance close to that of the system with subcarrier level adaptation. This can be attributed to the significant amount of correlation between channel gains of the adjacent subcarriers within a subband. For the same number of subbands (or same amount of signaling required), we can observe that the second approach to subband level adaptation performs better than the first approach. For example, in the Fig. (2) the performance curve of subband adaptation system using the second approach with $N_g = 4$, shows a power gain $\sim$ 2dB over the subband adaptation system based on the first approach. This is because, the first approach selects the worst subcarrier in a subband to determine the rate and power for the whole subband, which leads to very conservative performance especially when number of subbands is small. The performance of the IEEE 802.11a standard is also shown for comparison. The performance of the IEEE 802.11a standard is as reported in [5] and does not consider adaptive modulation at the subcarrier level. We can see that subband adaptation

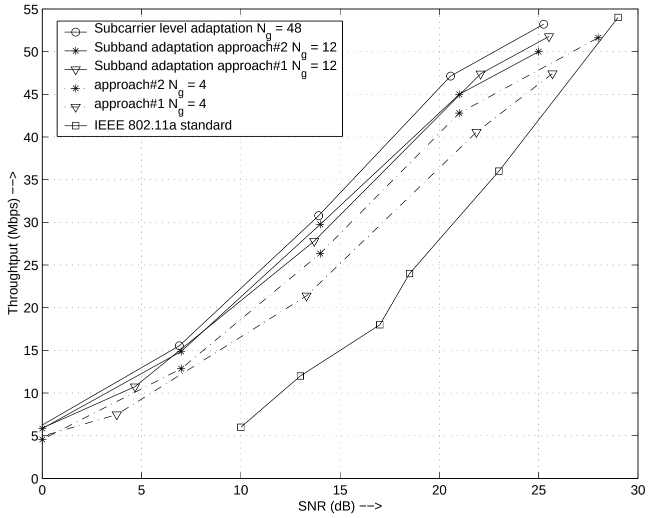

Fig. 2. Comparison of data rates of systems with various subband sizes

TABLE 1

PER (IN %) PERFORMANCE FOR THE TWO APPROACHES

SNR (dB)	0	7	14	21	28
N_g = 12 approach2	0.11	0.12	0.07	0.24	0.81
N_g = 12 approach1	0.10	0.08	0.06	0.15	0.60
N_g = 4 approach2	0.13	0.16	0.20	0.14	0.09
N_g = 4 approach1	0.09	0.08	0.18	0.09	0.09

schemes perform better than IEEE 802.11a standard even for $N_g = 4$.

Table. 1 shows the error performance of the above discussed systems. We can see all the systems perform quite close to the target PER of 1%, justifying our adaptation techniques. Also the system using the subband adaptation based on the first approach has a lower PER than that using the second approach for the same number of subbands. This could be explained on the fact that, in the first approach, the rate for a subband is chosen based on the rate that could be supported over the worst subcarrier in the subband, and hence is very conservative.

V. CONCLUSION

We analysed two approaches to subband level AMC over BIC-OFDM. Optimisation problems were formulated for the two approaches and performances analysed using the simulation results. We find that using subband level adaptation techniques, we can achieve performance close to that of the subcarrier level adaptation with reduced signaling. For the same number of subbands, the system using the equivalent subband channel approach to subband adaptation is found to perform better than that using the worst case channel.

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