Optimization of Adaptive Modulation and Coding Techniques for OFDM Systems

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***Abstract*—Bit rates in flat-fading OFDM wireless systems can be improved through the use of Adaptive Modulation and Coding (AMC). In this paper, we propose two practical, efficient link adaptation algorithms that use fixed link tables defined by SNR ranges for supported spectral efficiencies. The purpose is to design non-iterative algorithms with acceptable performance and reduced computational complexity relative to the alternative iterative solutions. Our simulations indicate that the proposed algorithms come within 3 dB of the spectral efficiency of the optimal Water-Filling AMC method and 2 dB of the BL-AMC model, but with significantly reduced computational complexity.**

***Index Terms*— link adaptation, OFDM, switching algorithms, adaptive modulation and coding.**

I. Introduction

The burgeoning demand for telecommunications services, voice, data and multimedia services has motivated interest in cognitive radios and intelligent communication systems. These systems are capable of providing spectrally efficient and flexible data rate access and are able to adjust and adapt to transmission parameters based on the link quality. In this paper, we investigate one of the adaptation techniques, known as adaptive modulation and coding (AMC), that enables a system to track channel variations, and adapt its modulation and coding schemes to yield higher throughput. Higher throughput is achieved by transmitting at high information rates when the channel conditions are favorable and lower information rates when channel conditions are degraded. For the purpose of this paper, we considered the physical (PHY) layer specifications of AMC in the IEEE 802.16 standard specifications [1].

We use the OFDM technique which divides a wideband transmission channel into several narrowband channels known as subcarriers that can then be viewed as single flat fading sub-channels. This approach allows for various forms of link adaptation to be performed on either a subcarrier basis or under a single carrier assumption. The objective is to improve system performance in terms of Bit Error Rate (BER) and/or spectral efficiency at specific channel Signal-to-Noise Ratios (SNRs).

Three important AMC models are presented in [2], [3], [4]. The authors of [2] propose a model for single carrier systems: a variable-rate, variable-power M-QAM modulation scheme with a Bit Error Rate (BER) constraint. The model uses the SNR to define operating regions for each supported modulation; however, it does not use bit-interleaving nor account for the frequency selectivity of the channel in OFDM systems. The work in [3] addresses these issues through adaptive allocation and bit loading on a subcarrier basis, using a technique known as Water-Filling AMC (WF-AMC). This model however requires significant traffic overhead for the feedback channel to report information for all subcarriers. Block AMC (BL-AMC) [4] builds on the model in [3] by reducing the required feedback information through adaptation, based only on one OFDM symbol rather than across all subcarriers. It uses the average channel statistics in lieu of individual subcarrier information. The paper proposes a BER estimation scheme and another AMC selection method, characterized by low computational complexity.

We present two simple, non-iterative, efficient algorithms that use fixed link tables defined by SNR ranges for supported spectral efficiencies (as in [2]). We show through simulations that the proposed algorithm significantly reduces the computational complexity (at a cost of performance loss) compared to the models in [3], [4]. The first algorithm is a rate maximization technique that selects the highest data rate AMC option from the set of available options which satisfy a target BER constraint. The second algorithm is a margin adaptive technique that optimizes data rate subject to minimum constraints of BER and data rate. This algorithm also attempts to minimize the frequency of switching between the AMC schemes as the channel changes, and therefore reduces feedback overhead. The main contribution of our models is therefore the provision of practical alternatives to established algorithms which may prove difficult to implement in certain circumstances due to their high computational complexity.

The rest of the paper is organized as follows: Section II describes the system model, followed by a description of the adaptive modulation and coding schemes in Section III. The switching algorithms are then discussed in detail in Section IV, and the simulation results in Section V.

II. System Model

A. Channel Model

The communication system under study can be modeled as a linear equation given by

$$y_k = \sqrt{e_k} H_k x_k + n_k \qquad (1)$$
$$1 \le k \le N$$

where y_k is the received symbol, e_k is the power, H_k is the

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channel matrix, x_k is the transmitted symbol, n_k is the Additive, White Gaussian Noise (AWGN) of the k^{th} sub-carrier, and N is the total number of subcarriers. The noise for the transmission, n_k, is eliminated using Zero-Forcing (ZF) – a linear equalization algorithm which inverts the frequency response of the channel. Here,

$$s_k = \sqrt{e_k}\, x_k ,$$

$$y_k = H_k s_k + n_k ,$$

$$\hat{s}_k \approx \frac{y_k}{H_k} \text{, and}$$

$$SNR = \frac{1}{N}\sum_{k=1}^{N} SNR_k = \frac{|H_k|^2}{\sigma^2} , \qquad (2)$$

where σ^2 is the noise variance of the system. The SNR is used by the adaptation algorithms, as will be discussed in Section III.

B. Adaptive OFDM Transmission

In comparing our simulation results to those of the models in [3] and [4], we consider a Single-Input, Single-Output (SISO) OFDM channel. The OFDM scheme uses 64 subcarriers, 48 for information data transmission and 16 for preamble and pilot symbols. All packet transmissions consist of a 24 byte header which includes a Cyclic Redundancy Check (CRC) modulated with BPSK and coded at rate 1/2. The payload contains 1KB of data followed by a 4 byte CRC.

III. Adaptive Modulation and Coding schemes

A. Switching thresholds in AWGN channels

The AMC options are based on the seven different combinations of modulation schemes and coding rates specified in [1], as shown in Table I below.

TABLE I
MODULATION TYPES AND CODING RATES
Target BER = 10^{-3}

AMC Mode	Modulation Scheme	Coding Rate	Bit Rate (Mbps)	SNR Regions(dB)
AMC1	2-QAM	1/2	6	SNR < 2.2
AMC2	4-QAM	1/2	12	2.2 ≤ SNR < 6.8
AMC3	4-QAM	3/4	18	6.8 ≤ SNR < 8.6
AMC4	16-QAM	1/2	24	8.6 ≤ SNR < 13.6
AMC5	16-QAM	3/4	36	13.6 ≤ SNR < 15.3
AMC6	64-QAM	2/3	48	15.3 ≤ SNR < 21.3
AMC7	64-QAM	3/4	54	21.3< SNR

The theoretic expression for the probability of symbol error in AWGN channels is given by:

$$P_{symbol} \approx 2\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3c}{M-1}\frac{E_b}{N_0}\frac{1}{r}}\right) , \qquad (3)$$

where M defines the modulation alphabet, r is the coding rate, E_b/N_0 is the SNR per bit, and $c = log_2(M)$. $Q(x)$ is related to the complementary Gaussian error function by

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} \exp\left(\frac{-x^2}{2}\right)dx = \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right) . \qquad (4)$$

Each of the schemes is assigned to operate within a particular SNR region R_j, where j = 1,2,…,7 is the index of the AMC mode as shown in Figure 1. When the channel SNR γ falls within the region $\xi_j \le \gamma < \xi_{j+1}$, the receiver transmits the index of the AMC mode back to the transmitter to initiate the switch. When the SNR falls into the outage region, we continue to transmit at the AMC which corresponds to region R_1, even though the target BER will not be satisfied. For most applications, this is preferable to not transmitting at all.

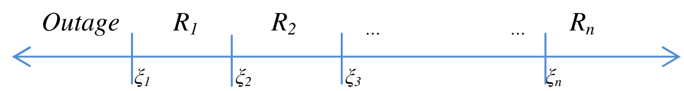

Fig. 1. Switching thresholds.

B. Switching thresholds in fading channels

In an AWGN channel, the probability of symbol error depends on the received SNR. In fading environments, the received signal power varies randomly over distance and time due to shadowing and multipath fading. Thus, in fading channels, the SNR per symbol, $\gamma_s = c\, E_b/N_0$, is random with a distribution $p_\gamma(\gamma)$. By extension, $p_{symbol}(\gamma)$ is also random. The performance metric therefore depends on the rate of change of the fading.

One of the criteria that can be used to characterize $p_{symbol}(\gamma)$ [2] is the outage probability, denoted here by p_{out}. It is the probability that γ_s falls below a given value corresponding to the maximum allowable p_{symbol}.

C. Outage Probability as a performance metric

Let γ_0 denote the threshold value for a specified target BER, then the outage probability relative to γ_0 is defined as

$$P_{out} = p(\gamma_s \le \gamma_0) = \int_0^{\gamma_0} p_{\gamma_s}(\gamma)d\gamma \qquad (5)$$

where γ_0 is the minimum SNR required for acceptable performance. In Rayleigh fading, the outage probability is

$$P_{out} = p(\gamma_s \le \gamma_0) = \int_0^{\gamma_0} \frac{1}{\bar{\gamma}_s} e^{-\gamma_s/\bar{\gamma}_s} d\gamma = 1 - e^{-\gamma_0/\bar{\gamma}_s} . \qquad (6)$$

Consequently, if the outage probability is given, the average SNR is

$$\bar{\gamma}_s = \frac{\gamma_0}{-\ln(1 - P_{out})} . \qquad (7)$$

The value of $10\log_{10}(\gamma_s)$ (in dB) must therefore exceed the target $10\log_{10}(\gamma_0)$ by margin, $F_d = -10\log_{10}[-\ln(1-p_{out})]$. This margin maintains acceptable performance more than 100*(1-p_{out}) percent of the time [2].

IV. Proposed Switching algorithms

The proposed algorithms attempt to solve a complex optimization problem using simple but efficient use of link tables. The problem is mathematically modeled as follows.

Each AMC level, denoted by χ (χ=1,2,…, χ_{max}), consists of a convolutional encoder ς_χ with coding rates $R_c(\varsigma_\chi)$ and constellation size M_χ, where

$$\log_2 M_\chi = m(\chi) \in \{1, \dots, m_{\max}\} . \tag{8}$$

Spectral efficiency is then given obtained by solving the following optimization problem:

$$\underset{\chi}{\text{maximize}} \quad \Psi = R_c(\varsigma_\chi)\log_2 M_\chi \tag{9}$$
$$\text{subject to} \quad \overline{P_b}(\chi) \le P_e ,$$

where P_e is the target BER and the estimated BER is

$$\overline{P_b}(\chi) = \frac{1}{N}\sum_{k=1}^{N}\frac{1}{\log(M)} Q\left(\sqrt{\frac{|H_k|^2|\hat{s}_k - s_k|}{4\sigma^2}}\right) . \tag{10}$$

A. Maximum Option algorithm

This algorithm attempts to maximize spectral efficiency by selecting the highest data rate AMC option from the set of available AMC options that satisfy the target BER constraint. In contrast to the search algorithms in [3] and [4], it attempts to solve (9) by using predetermined link tables to obtain the AMC scheme that maximizes throughput. We restrict the set of modulation schemes and coding rates by adopting the seven different combinations of modulation types and coding rates specified in [1].

Each scheme is assigned to operate within a particular SNR region based on the BER constraint as illustrated in Table I. For each packet reception, the receiver determines the channel SNR and selects the maximum AMC. The receiver then reports the index χ for the selected AMC to the transmitter.

Our model significantly reduces feedback overhead since only one index representing the selected AMC scheme is fed back rather than one for each subcarrier as proposed in [3]. The feedback information in our model is independent of the total number of subcarriers (N) and requires only $\lceil \log_2(\chi_{max}) \rceil$ bits compared to $N \lceil \log_2(m_{max}) \rceil + N_q + \lceil \log_2(\chi_{max}) \rceil$ as in [3], where N_q is the number of bits to represent the quantized power level. This simplification would of course come at performance cost.

B. Fade Optimum algorithm

We introduce a margin adaptive algorithm that optimizes spectral efficiency subject to constraints on BER and data rate. In the design of this algorithm, we also considered that the feedback information is often relayed through the fading channel and is therefore prone to errors. We thus consider a non-zero probability of feedback packet loss which may result in a mismatch of switching decisions (the transmitter may not be able to determine the correct AMC scheme that the receiver sent). To decrease the occurrence of a mismatch, a switch in AMC level should only be initiated when the BER constraint cannot be achieved. Switching is minimized when the AMC scheme used in the previous packet transmission is still a candidate for a subsequent transmission. The optimization problem becomes a slightly modified version of (9) given by

$$\underset{\chi}{\text{maximize}} \quad \Psi = R_c(\varsigma_\chi)\log_2 M_\chi \tag{14}$$
$$\text{subject to} \quad \overline{P_b}(\chi) \le P_e$$
$$\log_2(1+SNR) \ge \Psi_0$$

where $\Psi_0 = R/B$ is the target spectral efficiency given by the target data rate R and the bandwidth B.

The pseudo-code for both proposed algorithms is included below.

ALGORITHM 1 MAX OPTION / FADE OPTIMUM

1: Compute channel SNR
2: Initialize target_BER, target_DataRate and AMC_IDs
3: Obtain SNR bounds and AMC performance regions
for *each AMC j* **do**

$$bound(j) = \frac{2(M-1)*r}{3}\left(Q^{-1}\left(\frac{(\log_2(M)*t\arg et\_BER)}{4(1-\frac{1}{\sqrt{M}})}\right)\right)^2$$

end
If *target_DataRate==54* **then**
Min_Required_SNR = bounds(7)
else If *target_DataRate==48)* **then**
Min_Required_SNR = bounds(6)
else If *target_DataRate==36)* **then**
Min_Required_SNR = bounds(5)
else If *target_DataRate==24)* **then**
Min_Required_SNR = bounds(4)
else If *target_DataRate==18)* **then**
Min_Required_SNR = bounds(3)
else If *target_DataRate==12)* **then**
Min_Required_SNR = bounds(2)
else
Min_Required_SNR = bounds(1)
end
4: Find the SNR Range
If *channel_SNR > Min_Required_SNR* **then**
SNR_Range = [[Min_Required_SNR:0.5:channel_SNR] channel_SNR]
else
SNR_Range = channel_SNR;
end
5: Pre-populating the 2D lookup table
for *each AMC,* **do**
for *all values in the SNR_Range,* **do**
Populate the columns of the 2D lookup tables with AMC candidates that satisfy both constraints
end
end
6: Max Option: Select the highest AMC_ID using link Table 1 so that BER < target BER.
Fade Optimum: Select the AMC_ID with the maximum occurrence across the lookup table which satisfies BER < target BER. This is the scheme that minimizes switching.
return *AMC_ID*

C. Computational Complexity

The computational complexity, T(N), for the WF-AMC is given by

$$T(N) = O(\varsigma_{\max}(2N + 2N_{EF} * N + N_{ET} * N)) \tag{11}$$

where N is the total number of subcarriers while N_{EF} and N_{BT} denote the number of iterative searches to obtain the solutions for the “Efficientizing” and “E-tightening” subroutines in the Levin-Campello algorithm, respectively. The two parameters can grow up to N in the worst case, depending on the initial bit-loading [16].

For the BL-AMC model in [4],

$$T(N) = O(\chi_{max} N) \tag{12}$$

which depends on the number of subcarriers due to the computation of the instantaneous Bhattacharyya factor in the bit error probability estimation.

The complexity of our models is given by

$$T(N) = O(\chi_{\max} + N) \tag{13}$$

which is the sum of a constant complexity independent of the number of subcarriers due to the use of pre-determined lookup link tables and N due to the computation of the average SNR.

V. SIMULATIONS

A. Parameters and Assumptions

The simulation channel was modeled as TGn channel environment with the delay profile of Model A [17]. The Model A profile is a typical office environment with 50 ns RMS delay spread as developed in [17] by Medbo et al. The main assumption in this simulation is that the receiver has perfect channel knowledge and the closed-loop feedback channel is error-free with no delay. The channel training sequence is adapted from [1] with a sampling frequency of 20MHz, carrier frequency of 2.4GHz, target BER of 10^{-3}, and target Data Rate of 18Mbps. For each simulation run, 10^4 packets were transmitted.

B. Results

Figure 3 shows simulation results of the average throughput per channel SNR for WF-AMC, BL-AMC, and our two proposed models (Max Option and Fade Optimum). There is a 2 dB gap in performance between WF-AMC and BL-AMC for system throughput. The Max Option algorithm comes within 3dB of WF-AMC and 1dB of BL-AMC. The Fade Optimum algorithm performs similar to the Max Option at low SNRs where it is necessary to switch AMC schemes to maintain the desired BER. Once the SNR increases sufficiently, the Fade Optimum algorithm no longer switches since it is already achieving the target BER.

In Figure 4, the BER performance of the adaptive models is shown. The Fade Optimum algorithm consistently meets the target BER constraint. The other models cannot satisfy the constraint at SNRs less than 14dB since the minimum AMC scheme with a spectral efficiency of 1bps/Hz exceeds the actual supported rate for the outage SNR range. Also, the BER curves indicate saw-toothed trends due to the fact that the AMC levels were selected from a restricted set and were assigned to operate within specific SNR regions.

Figure 5 shows a comparison of the complexity of the algorithms as determined by the number of operations performed. WF-AMC is the most complex and performs worst relative to both BL-AMC and the proposed algorithms. The proposed algorithms show a significant reduction in computational complexity over both WF-AMC and BL-AMC.

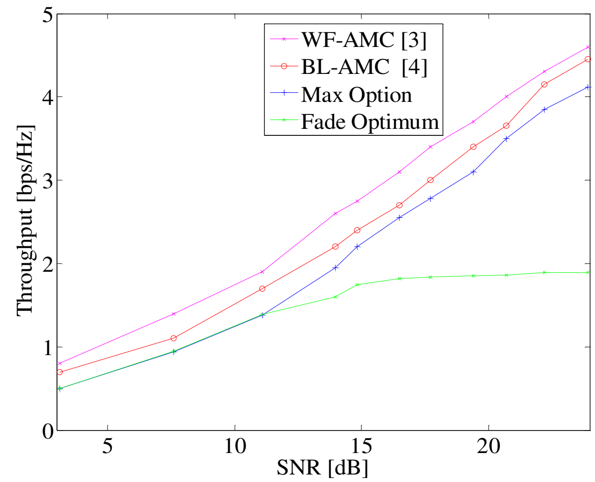

Fig.3. Average throughput versus SNR for the adaptive models.

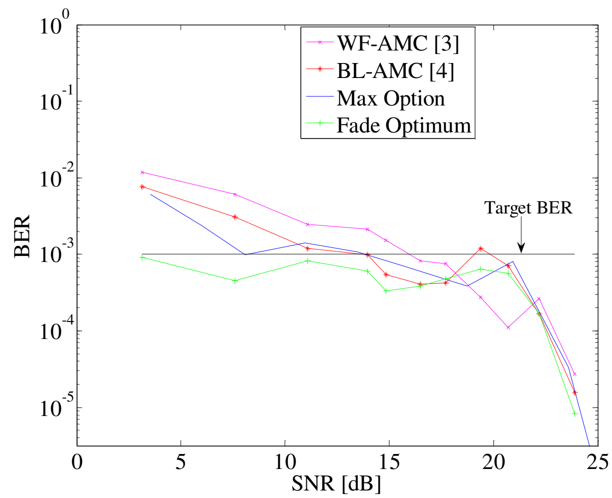

Fig. 4. Average BER versus SNR for the adaptive models.

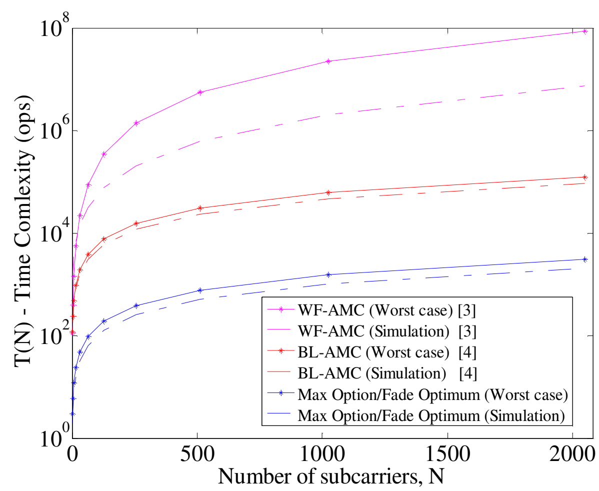

Fig. 5.Time complexity versus number of subcarriers for the adaptive models.

VI. CONCLUSION

We proposed two low complexity link adaptation algorithms with reduced feedback overhead. Through simulations, we have shown that the spectral efficiency of the proposed algorithm comes within 3 dB of the optimal WF-AMC method and 2 dB of the BL-AMC model but with significantly less system complexity than both. In future work, we will investigate practical feedback mechanisms and analyze the effects of feedback delay on the AMC selection methods. We will also consider the net effect on goodput which is the application layer metric for system performance as it takes into account the total overhead on the wireless packet transmission.

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