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Cross-Layer Scheduler for Wimax Networks with Outdated Channel State Information to Support Guaranteed QoS

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Abstract: The proposed Cross-Layer scheduling can boost the spectral efficiency of multi-user OFDMA wireless systems with heterogeneous delay requirements. The existing designs usually have two important assumptions that are the users are delay insensitive and Channel State Information at the Transmitter (CSIT) is perfect. In practice, users have heterogeneous delay requirements and CSIT usually becomes outdated in time varying channel which in turn leads to systematic packet errors and hence, results in significant degradation on the throughput. The Adaptive Modulation and Coding (AMC) is a promising tool for increasing the spectral efficiency of time varying channel while maintaining the target Bit Error Rate (BER) and the Packet Error Rate (PER). In this study, a novel design problem is formulated which combines AMC and CSI at the physical layer and scheduling using queuing theory at the Medium Access Control (MAC) layer, in order to maximize the throughput and spectral efficiency under the heterogeneous delay constraints. For the proposed research, transmissions on Rayleigh fading channel including Additive White Gaussian Noise (AWGN) are employed. Simulation results show that the proposed scheduler provides robust system performance enhancement over conventional cross-layer scheduler with perfect CSIT.

Key words: Cross-layer scheduling, Heterogeneous applications, Orthogonal Frequency Division Multiple Access (OFDMA), Adaptive Modulation and Coding (AMC), Automatic Repeat Request (ARQ)

INTRODUCTION

In multimedia wire line-wireless communication networks, the demand for high data rates and quality of service is growing at a rapid pace. The bottleneck in such networks is the wireless link, not only because wireless resources are bandwidth and power which are more scarce and expensive relative to their wireline counterparts but also because the overall system performance degrades markedly due to multipath fading, Doppler and time-dispersive effects introduced by the wireless propagation. In order to enhance the spectral efficiency while adhering to a target error performance over wireless channels, Adaptive Modulation and Coding (AMC) has been widely used to match transmission parameters to time-varying channel conditions (Alouini and Goldsmith, 2000; Chung and Goldsmith, 2001; Goldsmith and Chua, 1997; Hole *et al*., 2000; Pursley and Shea, 2000).

Due to its attractive rate and error performance characteristics, AMC has been adopted at the physical layer of several standards, e.g., 3GPP, 3GPP2, HIPERLAN/2, IEEE802.11a, IEEE802.15.3 and IEEE 802.16 (3GPP TS 25.848, 2001; IEEE Std 802.16-2004, 2004; Revision, 1999; Doufexi *et al*., 2002; Karaoguz, 2001).

The OFDMA has been proposed as a multiple access scheme for providing high speed data transmission in many applications such as WLAN and WiMAX because of its robust performance over the frequency selective channel; 802.16, wireless Metropolitan Area Network (MAN) provides network access to building through exterior antennas communicating with central radio base stations. It offers an alternative to cabled access networks such as fiber optic links, coaxial systems using cable modems and Digital Subscriber Link (DSL) and was designed to evolve as a set of air interfaces based on a common MAC protocol but with physical layer specifications dependent on spectrum of use and the associated regulations. OFDMA have been devoted to cross-layer scheduling due to its promising gain through exploitation of multi-user diversity by carefully assigning multiple users to transmit simultaneously on different subcarriers for each OFDM symbol with optimal power and rate allocations as by Wong *et al*. (1999). However, the cross-layer designs rely on two important assumptions-users are delay-insensitive and Channel State Information (CSIT) at the transmitter is perfect. These assumptions are usually impractical since next generation networks are expected to contain real time users of heterogeneous classes with different delay

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requirements. Moreover, due to the delay and resource limitation in feedback of channel states, CSIT obtained at the Base Station (BS) will be outdated and imperfect. There are two types of imperfect CSIT, namely the limited CSIT and the outdated CSIT.

In contrast, outdated CSIT refers to the delay from the CSI estimation time to CSIT utilization time. Under outdated CSIT, systematic packet error occurs whenever the scheduled data rate exceeds the instantaneous mutual information rate (namely channel outage) despite the use of strong channel coding.

MATERIALS AND METHODS

System model: The cross-layer system model considered for multiuser wireless systems is shown in Fig. 1, where outdated CSIT and Queue State Information (QSI) are the inputs to the scheduler at the data link layer. Before the formulation of cross-layer design into an optimization problem, the detailed description of OFDMA channel model, the corresponding CSIT error model, multiuser physical layer utilizing AMC, source and the scheduling strategy at the data link layer are as:

Downlink channel model and CSIT estimation from outdated CSIT: An OFDMA system containing K users with frequency selective channel model consisting of L = [BW/Δf$_c$] = [Signal Bandwidth/Coherent Bandwidth] resolvable paths is considered. For simplicity, uniform power delay profile is adopted, i.e., each path has normalized power given by 1/L. Thus the channel impulse response between the transmitter and the jth user at the time slot m, h_j (m) can be modeled through a L-tap delay line channel model, i.e. ,

$$h_i(m) = \sum_{l=0}^{L-1} h_{j,l}(m)\delta(m - l/W)$$

where h_j, l are modeled as independent identically distributed (i.i.d.) circularly symmetric complex Gaussian random variables with distribution CN (0, 1/L) and assumed to be quasi-static within each time slot m but slowly time varying across time slots according to Jakes' model where t_s being the scheduling slot duration and f_d is Doppler spread of the channel (with t_s<< coherent time, i.e., << $1/f_d$). With N_F point IFFT and FFT in the OFDMA system equivalent discrete channel model in the frequency domain (after the length-L cyclic prefix removal) is:

$$Y_{ij} = H_{ij}U_{ij} + Z_{ij} \tag{1}$$

Where:

i = Subcarrier index
j = User index
Y_{ij} = The received symbol
U_{ij} = The data symbol from the transmitter
Z_{ij} = The noise distributed

$$CN(0, \sigma_z^2),\ H_{ij} = \sum_{l=0}^{L-1} h_{j,l} e^{-j2\Pi l_i / N_F}$$

is the channel gain distributed with CN (0,1/L) which is the i.i.d. for different users. The transmitter power allocated to user j through the subcarrier i is given by:

$$P_{ij} = E\left|U_{ij}\right|^2$$

Subcarrier allocation strategy is such that $S_{NFxK} = [s_{ij}]$, where S_{ij} = 1 when user j is selected for subcarrier i, otherwise S_{ij} = 0. The average total transmitter power is constrained by:

$$\overline{P} \le P_{TOT}$$

Where, P_{TOT} is average power at the transmitter. Assume the system is using TDD with channel reciprocity, the downlink CSIT could be obtained by

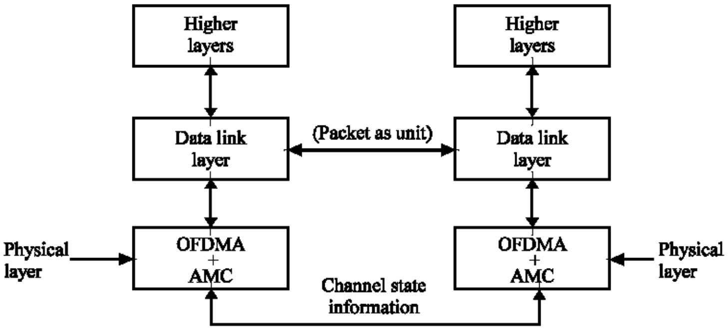

Fig. 1: Cross-layer system model

channel estimation based on uplink preambles by the transmitter. However, due to duplexing delay between uplink and downlink, the estimated downlink CSIT will be outdated. Thus, the estimated downlink CSIT in frequency domain $\{\hat{H}_{ij}\}$ for all users over subcarriers at the transmitter accounting the CSIT out datedness is modeled as:

$$\hat{H}_{ij} = H_{ij} + \Delta H_{ij} \qquad (2)$$

where $\{\hat{H}_{ij}\}$ is the CSIT error with zero mean noise distribution.

Multi-user physical model for OFDMA systems with AMC modeling: Consider the information theory as by Cover and Thomas (1991), as the abstraction of the multi-user physical layer in order to decouple from specific implementation of coding and modulation schemes. In general, packet error is contributed by two factors, namely the channel noise and the channel outage. Given the information theory, the instantaneous mutual information rate is given between the transmitter and user j in ith subcarrier;

$$c_{ij} = \log_2\left(1 + p_{ij}\left|H_{ij}\right|^2 / \sigma_z^2\right)$$

which is a function of actual CSI H_{ij}, and unknown to the transmitter. Packets will be corrupted whenever scheduled data rate exceeds instantaneous mutual information. To take account of the packet error due to channel outage, the instantaneous goodput of the jth user (which measures the instantaneous data bits/s/Hz successfully delivered to user (j) as:

$$g_j = \sum_{i=1}^{N_F} r_{ij} I[r_{ij} \le c_{ij}] \qquad (3)$$

Where:

$$I[r_{ij} \le c_{ij}] = \begin{Bmatrix} 1, \text{ if } r_{ij} \le c_{ij} \\ 0, \text{ if } r_{ij} > c_{ij} \end{Bmatrix}$$

is an indicator function and r_{ij} is the scheduled data rate of the jth user on the ith subcarrier.

Design of AMC at the physical layer: The maximization of data rate and efficient bandwidth utilization for a prescribed PER performance at the PHY layer can be accomplished with AMC schemes which match transmission parameters to the time-varying wireless channel conditions adaptively as by Wang *et al.* (2007) and have been used by many standard wireless network specifications, such as IEEE 802.11/15/16 as by Revision (1999). Each connection with rtps, Nrtps and BE services relies on AMC at the PHY layer. The objective of AMC is to maximize the data rate by adjusting the transmission modes to channel variations while guaranteeing prescribed PER P_o and the design procedure is similar to that proposed by Alouini and Goldsmith (2000).

Let N denote the total number of transmission modes available at the wireless link between BS and SS (say N = 6 for IEEE 802.16). As by Andrews *et al.* (2001), constant power transmission is assumed and partition the entire Signal-to-Noise Ratio (SNR) range in N+1 non-overlapping consecutive intervals with boundary points denoted as:

$$\{\gamma_n\}_{n=0}^{N+1}$$

In this case mode n is chosen when;

$$\gamma \in (\gamma_n, \gamma_{n+1}), \quad \text{for } n = 1, 2, \ldots, N \qquad (4)$$

To avoid deep-channel fades, no data are sent when $\gamma_0 \le \gamma \le \gamma_1$ which corresponds to the mode n = 0, with rate R_o = 0 bit/symbol. The design objective of AMC is to determine the boundary points:

$$\{\gamma_n\}_{n=0}^{N+1}$$

To simplify the AMC design, the PER expression for AWGN channels is approximated to give:

$$\text{PER}_n(\gamma) \approx \begin{Bmatrix} 1, & \text{if } 0 < \gamma < \gamma_{pn} \\ a_n \exp(-g_n \gamma), & \text{if } \gamma \ge \gamma_{pn} \end{Bmatrix} \qquad (5)$$

Where n is the mode index and γ is the received SNR. Parameters a_n, g_n and γ_{pn} in Eq. 5 are mode-dependent and are obtained by fitting 5 to the exact PER via simulations presented by Liu *et al.* (2004).

The mode fitting parameters for each transmission modes are shown in Table 1.

The region boundary (switching threshold) γ_n is set for the transmission mode n which is the minimum SNR required to guarantee P_o. With the boundaries $\{\gamma_n\}_{n=0}^{N+1}$ specified by Eq. 6, one can verify that the AMC in Eq. 4 guarantees that the PER is less than or equal to P_o. To obtain the region boundaries the general PER expression is inverted as in Eq. 5:

$$\gamma_0 = 0,$$

$$\gamma_n = \frac{1}{g_n} \ln\left(\frac{a_n}{P_{\text{target}}}\right), \quad n = 1, 2, \ldots, N$$

and

$$\gamma_{N+1} = +\infty \qquad (6)$$

Table I: Transmission modes specified in IEEE Std.802.16-2004, 2004

Mode	1	2	3	4	5	6
Modulation	QPSK	QPSK	16QAM	16QAM	64QAM	64QAM
RS code	(32,24,4)	(40,36,2)	(64,48,8)	(80,72,4)	(108,96,6)	(102,108,6)
CC code rate	2/3	5/6	2/3	5/6	3/4	5/6
Coding rate	1/2	3/4	½	3/4	2/3	5/6
R_n(bits/symbol)	1	1.5	2	3	4	4.5
a_n	232.9242	140.7922	264.0330	208.5741	216.8218	220.7515
g_n	22.7925	8.2425	6.5750	2.7885	1.0675	0.8125
γ_{pn}(dB)	3.7164	5.9474	9.6598	12.3610	16.6996	17.9629

Scheduler design at the MAC layer: The system dynamics are characterized by system state $\chi = (\hat{H}_{N_F \times K}, \gamma, Q_K)$ which composes of estimated CSIT $\hat{H}_{N_F \times K}$ and SNR value from physical Layer and Queue State Information (QSI) Q_K from MAC layer user's buffer, where $Q_K = [q_j]$ is a K x 1 vector with the jth component denotes the number of packets remains in user j's buffer. The MAC layer is responsible for scheduling at every fading block on the current system state χ. Based on CSIT and QSI obtained, the scheduler determines the subcarrier allocation from the policy $P_{N_F \times K}\left[\hat{H}, Q\right]$ for the selected users. Also based on CSI acquired at the receiver, the AMC selector determines the modulation coding pair (mode) which is sent back to the transmitter through the feedback channel. The AMC controller then updates the transmission mode at the transmitter. Coherent demodulation and maximum-likelihood (ML) decoding are used at the receiver. The decoded bits are mapped to packets which are pushed upwards to the data link layer. At the data link layer, the selective repeat ARQ protocol is implemented. If an error is detected in a packet, a retransmission request is sent by the ARQ generator and is communicated to the ARQ controller at the transmitter via a feedback channel; otherwise, no retransmission request is sent. When mode n is used, each transmitted symbol will carry $R_n = R_c \log_2 (M_n)$ information bits for the mode adhering to a M_n-QAM constellation and a rate R_c FEC code. For uncoded transmission modes, set $R_c = 1$. Therefore, the average spectral efficiency (bit rate per bandwidth) achieved at the physical layer without considering possible packet retransmission is (similar to Eq. 2, where only physical layer AMC design is considered):

$$\overline{S}_{e,\text{physical}} = \sum_{n=1}^{N} R_n P_r(n) \tag{7}$$

Here, the priority scheduling is performed by having the delay requirements by the user. Using the CSI, the subcarrier allocation is performed for those packets having the scheduling rate is less than the mutual information rate and those not satisfying remains in the buffer and also that the modulation scheme is selected based on the IEEE 802.16 standard specifications shown in Table I.

Table 2: A summary of system parameters

Parameters	Value
Central frequency	2 GHz
Channel bandwidth	5 MHz
Number of sub channels	192 + 5
Frame duration	2.5ms
User distribution	Uniform
Channel model	Multipath fading (tapped delay line with 8 taps with non uniform delays)
Number of users	5
Max. Doppler frequency	25 Hz

RESULTS AND DISCUSSION

In the simulation an OFDMA system the following system parameters are considered as in Table 2. The main function of the AMC design is to adopt the transmission modes according to the channel conditions where the SNR value is calculated and it is compared with the estimated boundary values. Then the mode selection is done by verifying the SNR value that lies between any two thresholds and the corresponding mode is chosen. As per IEEE standard six modes are considered. Along with that one new mode with BPSK modulation is included in the design to enhance the spectral efficiency. From the modes that has been selected the average spectral efficiency is calculated.

From Fig. 2, it is observed that for mode 7, the maximum achievable throughput is 15.21 Mbps and for mode 1 it is 1.69 Mbps. Hence, the throughput will be more for good channel condition and gets reduced when the channel condition gets degraded. When it compared with (Wang and Dittman, 2008) results, it is observed that the throughput measure is incremented by about 3 times more. From Fig 3 and 4, it is clear that for good channel conditions with high SNR decreases the Bit Error rate/ Frame error rate and vice versa. Wang and Dittman (2008) proposed a priority based resource allocation to support real time and non-real time data traffic and achieved maximum throughput and compared their results with some other scheduling strategies. Here the same result is adopted for comparison with the proposed cross-layer scheduling strategy. Table 3 shows the comparison and from it it is understand that the proposed cross-layer

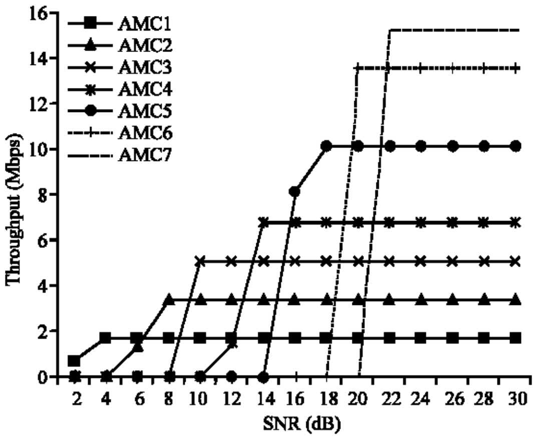

Fig. 2: SNR vs. throughout

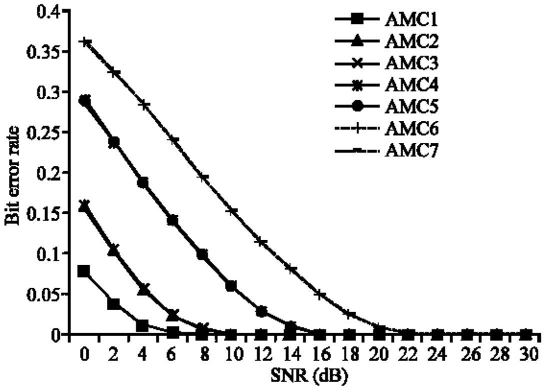

Fig. 3: SNR vs. Bit error rate

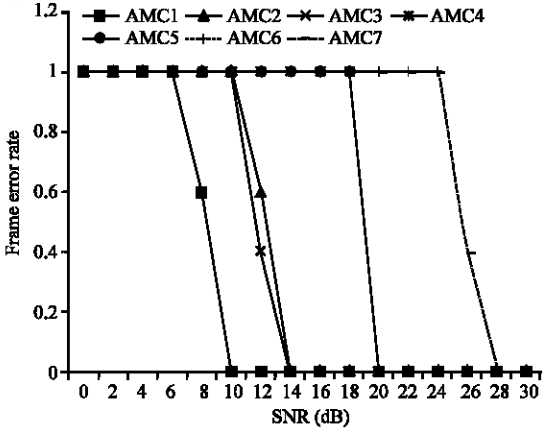

Fig. 4: SNR vs. Frame error rate

Table 3: Analytical results comparison from literature survey (Wang and Dittman, 2008)

Methodology	PF	MAX-SNR	Sub-optimal	Optimal	EXP	Proposed cross-layer scheduling
Max. throughput achieved (Mbps)	4.2	5.4	4.8	4.9	3.5	15.21
Average delay (ms)	20-350	20-450	20-440	20-400	50-350	40-90

Table 4: Analytical results comparison from literature survey (Zhou *et al*., 2009)

Parameters	Conventional model	Result achieved using GA for priority assignment (Wang and Dittman, 2008)	Proposed cross-layer scheduling
Spectral efficiency (b $\sec^{-1}$)/Hz	3.6219	2.4	3.8769

scheduling strategy is achieving high throughput by reducing the error rate and also the average delay taken by the packet is minimum for the considered real time and non-teal time data traffics (Table 1) (Wang and Dittman, 2008). The other performance measure spectral efficiency achieved for the proposed cross-layer scheduling strategy is enhanced from 3.6219-3.8769 (b $\sec^{-1}$), when compared with conventional (WFQ) method and from 2.4-3.8769 (b $\sec^{-1}$)/Hz when compared with the result by Zhou *et al*. (2009). The comparative analytical results are shown in Table 4.

CONCLUSION

In this study, a cross-layer design with a combination of OFDMA scheduler with adaptive coding and modulation scheme at the physical layer and a priority scheduling with subcarrier allocation at the MAC layer is designed by employing the IEEE 802.16 standard settings. Since, the CSI obtained from the physical layer is utilized by the MAC layer to enhance the throughput and efficient bandwidth utilization in terms of spectral efficiency and minimum delay, the proposed scheduling strategy proves itself to be a Cross-layer design. Also it is proved to be better than the conventional model and results obtained from the literature survey.

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