An Efficient Cross-Layer Scheduling with Partial Channel State Information

Indumathi Ganesan
Mepco Schlenk Engineering College Sivakasi, TamilNadu, India
E-mail: indupriyanga@gmail.com

Murugesan Karuppasamy
Bharathiyar Institute of Engineering for Women
Chinna Salem, Villupuram Dist., TamilNadu, India

Keywords: cross-layer scheduling, heterogeneous applications, orthogonal frequency division multiple access (OFDMA), adaptive modulation and coding (AMC)

Received: April 28, 2010

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 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 In practice, users have heterogeneous delay requirements and CSIT usually becomes outdated in time varying channel, which in turn leads to systematic packet errors and hence results in significant degradation on the throughput.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 paper, 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 above proposed work, 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.

Povzetek: Opisana je metoda razporejanja za OFDMA sisteme s poudarkom na odpravljanju zamud.

1 Introduction

There are quite a large number of existing works on cross-layer scheduling design for OFDMA such as [1]-[4] and the optimal sub carrier allocation and the transmitter power adaptation in an OFDMA system having users with fixed data rate requirements have been studied in [1] & [2] respectively. The authors in [4] & [5] provided a general theoretical frame work as well as practical algorithm implementation schemes addressing the cross-layer optimization problem of OFDMA systems.

These cross-layer designs achieve throughput gain by exploiting spatial diversity as well as multiuser diversity. But these designs were only based on a decoupled approach where source statistics and queue dynamics were ignored from the physical layer information theoretical models. To provide diverse QoS requirements in terms of delay performance, some cross-layer designs were proposed in [6, 7, 8 & 9] to incorporate both source statistics and queue dynamics. In [6], a simple on-off physical layer model was assumed in [6] and multiple access channel model with homogeneous users was studied in [7] & [8] through combined information theory and queuing theory. In [9], a heuristic scheduler design maximizes the system throughput while providing fairness between users in an OFDMA system was proposed. All of these cross-layer designs were targeted for system with homogeneous uses only. Also they rely on two important assumptions: users are delay sensitive and Channel State Information (CSI) 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 requirements.

Recently more publications are addressing the issue of imperfect CSI at the transmitter on scheduler design. Generally there are two types of imperfect CSI at the transmitter namely "limited CSI" and "outdated CSI" at the transmitter. Limited CSI refers to the incomplete knowledge of CSI at the transmitter whereas outdated CSI refers to the partial knowledge of CSI at the transmitter. Under outdated CSI, systematic errors occur whenever the scheduled data rate exceeds the instantaneous mutual information rate. Therefore it is very important to control the packet error probability of a lo level for reasonable system throughput and delay performance. To our best of knowledge there are only a few works considered the outdated CSI at the transmitter [10, 11, 12] considering single user OFDM systems. In [10, 11], the authors had addressed the issue of outdated CSI at the transmitter and those designs were applicable to delay-insensitive applications. In [12], the authors proposed a delay sensitive sub carrier allocation strategy which obtains a substantial throughput gain.

In this paper, our objective is to design a cross-layer scheduler for OFDMA systems consisting of users with mixed traffics and heterogeneous delay requirements. To achieve this objective, priority levels are assigned at the MAC layer using the partial knowledge of the CSI obtained from the physical layer and also by using the Queue State Information (QSI) at the MAC layer. Then based on the priority levels sub carrier allocation is made. To improve spectral efficiency, adaptive Modulation and Coding (AMC) mode of transmission is considered at the physical layer. By including the link adaptation procedure along with the methodology proposed in [12] in our work, we are able to achieve the enhanced spectral efficiency.

The rest of the paper is organized as follows. Channel model which includes downlink channel model and CSI at the transmitter estimation model is explained in Section 2. Multiuser Physical layer model for OFDMA systems with AMC is discussed in Section 3. In Section 4, Scheduler design at the MAC layer model is described. The simulation results are presented in Section 5. Finally concluding remarks are given in section 6.Text of the introduction.

2 Channel model

The cross-layer system model considered for multiuser wireless systems is shown in Fig. 1. Before the scheduling operation is performed, the cross-layer resource scheduler first collects the QoS (delay) requirements of all users. In the beginning of each scheduling interval, the scheduler obtains the partial CSI and QSI by observing the number of backlogged packets in all these user's buffers. The resource scheduler then makes a scheduling decision based on this information and passes the resource allocation scheme to the OFDMA transmitter. The updates of scheduling decision process are made once for every time slot.

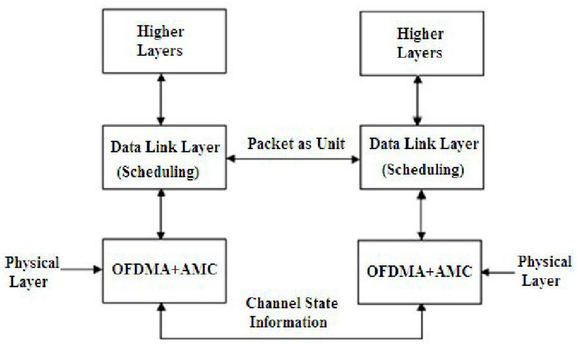

Figure 1: Cross-Layer System Model.

2.1 Downlink channel model

An OFDMA system containing K users with frequency selective channel model consisting of $L = \lfloor BW / \Delta f_c \rfloor$ i.e., [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 $j^{\text{-th}}$ user at the time slot *m*, $h_j(m)$, can be modeled through a L-tap delay line channel model, i.e. $h_j(m) = \sum_{l=0}^{L-1} h_{j,l}(m)\delta(m - l/w)$, 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). The channel is assumed to be quasi-static within each time slot *m*, but slowly time varying across time slots according to Jakes' model where the scheduling slot duration t_s will be very much less than the doppler spread f_d of the channel. The scheduling duration is considered within 2 ms. It is reasonable assumption for users with pedestrian mobility where the coherence time of the channel is around 20 ms or more.

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

$$Y_{ij} = H_{ij} U_{ij} + Z_{ij} \qquad (1)$$

where (i denotes subcarrier index and j denotes user index) Y_{ij} is the received symbol, U_{ij} is the data symbol from the transmitter / BS to user j on sub carrier i , Z_{ij} is the noise distributed with $CN(0, \sigma^2{}_z)$, $H_{ij} = \sum_{l=0}^{L} h_{j,l} e^{-j2\pi li/N_F}$ is the complex channel gain of the i^{th} sub carrier for the j^{th} user. Z_{ij} is a zero mean complex Gaussian noise with unit variance i.e. i.i.d. for different users but correlated within user j. The transmitter power allocated to user j through the subcarrier i is given by $P_{ij} = E]U_{ij}]^2$. We define subcarrier allocation strategy as $S_{N_F xK} = \lfloor S_{ij} \rfloor$, where s_{ij}=1 when user j is selected for subcarrier i, otherwise s_{ij}=0. The average total transmitter power is constrained by $P_{tot,}$ i.e. $\overline{P} \leq P_{Tot}$, where $\overline{P} = E\left[(1/N_F)\sum_{j=1}^{K}\sum_{i=1}^{N_F} S_{ij} P_{ij}\right]$ and P_{Tot} is the available average power in the transmitter.

2.2 CSIT estimation

Assuming that proposed system is using Time Division Duplex (TDD) with channel reciprocity, the downlink CSI at the transmitter could be obtained by channel estimation based on uplink preambles given by the transmitter. However, due to duplexing delay between uplink and downlink, the estimated downlink CSI at the transmitter will be outdated. Thus the estimated downlink CSI at the transmitter in frequency domain

$\{\hat{H}_{ij}\}$for all users over all subcarriers at the transmitter accounting the outdatedness can be modeled as:

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

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

3 Multi-user physical layer model for OFDMA systems with AMC

We consider the information theoretical capacity [7] as the abstraction of the multi-user physical layer 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". In channel outage case, the effect is systematic and cannot be eliminated, because the instantaneous mutual information between transmitter and user j in i^{th} subcarrier $c_{ij} = \log_2\left(1 + p_{ij}\left|H_{ij}\right|^2 / \sigma^2{}_z\right)$ is contributed by two factors, namely the "channel noise" and the "channel outage." In channel outage case, the effect is systematic and cannot be eliminated, because the instantaneous mutual information between transmitter and user j in i^{th} subcarrier $c_{ij} = \log_2\left(1 + p_{ij}\left|H_{ij}\right|^2 / \sigma^2{}_z\right)$ is a function of actual CSI H_{ij}, which is unknown to the transmitter. So 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 j^{th} user (which measures the instantaneous data bits/s/Hz successfully delivered to user j) as

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

where $I\left[r_{ij} \le c_{ij}\right] = \begin{cases} 1, & if\ r_{ij} \le c_{ij} \\ 0, & if\ r_{ij} > c_{ij} \end{cases}$ is an indicator function, and r_{ij} is the scheduled data rate of the j^{th} user on the i^{th} subcarrier.

3.1 Design of AMC at the physical layer

The Adaptive Modulation and Coding (AMC) is the technique to maximize the data rate and to utilize the bandwidth efficiently under a prescribed Packet Error Rate (PER) performance at the Physical layer. This AMC scheme matches the transmission parameters to the time-varying wireless channel conditions adaptively [13] and has been used by many standard wireless network specifications, such as IEEE 802.11/15/16 [14].

Let N denote the total number of transmission modes available at the wireless link between transmitter and receiver (say N=6 for IEEE 802.16). As in [15], fixed power transmission is assumed and partition the entire Signal-to-Noise Ratio (SNR) range in N+ 1 non-overlapping consecutive interval, with boundary points denoted as $\{\gamma_n\}_{n=0}^{N+1}$. The transmission mode n is chosen when,

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

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_0 =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

$$PER(\gamma) = \begin{cases} 1, & if\ 0 < \gamma \le \gamma_{pn} \\ a_n \exp(-g_n \gamma) & if\ \gamma \ge \gamma_{pn} \end{cases} \quad (5)$$

where n is the mode index and γ is the received SNR.

Exact closed-form expressions for PER and BER are not available for transmission modes with convolutionally coded modulations. Hence, the exact PER and BER is obtained through Monte Carlo simulations [15]. From that the mode parameters a_n, g_n, and γ_{pn} in (5) are obtained by fitting (5) to the exact PER via Monte Carlo simulations. Using the approximate yet simple expression (5) facilitates the mode selection. The mode fitting parameters for each transmission modes are provided 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_{target}. With the boundaries $\{\gamma_n\}_{n=0}^{N+1}$ specified by (6), one can verify that the AMC in (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 (5),

$$\gamma_0 = 0,$$
$$\gamma = \frac{1}{g_n}\ln\left(\frac{a_n}{P_{target}}\right), \ n=1,2, \ldots, N, \quad (6)$$

and $\gamma_{N+1} = +\infty$

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 at the transmitter then updates the transmission mode. 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. 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. Therefore, the average spectral efficiency (bit rate per bandwidth) achieved at the physical layer without considering possible packet retransmission is

$$\overline{S}_{e,Physical} = \sum_{n=1}^{N} R_n P_r(n), \quad n=0,1,2\ldots \quad (7)$$

where $P_r(n)$ is the probability of choosing the transmission mode n.

4 Scheduler design at the MAC layer model

The system dynamics are characterized by system state $\chi = (\hat{H}_{N_F \times K},\ \gamma,\ Q_K)$, which composed of channel state the $H_{N_F x K} = [|h_{ij}|^2]$ 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 j^{th} 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 $P_{N_F \times K} \lfloor \hat{H}, Q \rfloor$ for the selected users (ie.,) the users having the scheduling rate less than the mutual information rate.

5 Simulation results

In the simulation an OFDMA system with total system bandwidth of 5 MHz with carrier frequency of 2 GHz consisting of 192 data subcarriers and 5 pilot subcarriers and 5 users, is considered(users are specified by arrival rate and delay requirements). Each user is having different information field size. Results are obtained with the frame duration of 2.5 milliseconds. The channel model is constructed to simulate the multipath fading channel. The multipath fading is modelled as a tapped delay-line with 8 taps with non uniform delays. The gain associated with each tap is characterized by a distribution Rayleigh with a K-factor=0 and the maximum Doppler frequency of 25 Hz. For each tap, a method of filtered noise is employed to generate coefficient with the specified distribution and spectral power density. For our simulation, Matlab and the simulink models are considered.

The main function of the AMC design is to adopt the transmission modes according to the channel conditions. The transmission mode selection is based on the obtained SNR values by fitting them into the estimated SNR boundaries or thresholds. The corresponding mode is selected for the next transmission. As per IEEE 802.16 fixed Wimax standard, six transmission modes along with new modulation of BPSK are considered. From the Fig 2, we depict that in a low SNR regime (below 4 dB) the throughput achieved is lower when the user requirement is more stringent. This is because more urgent users with heavy traffic loading will have higher chances of seizing subcarriers, causing losses in degree of freedom in exploiting throughput maximization by other users with better CSI at the transmitter. In a high SNR regime, (above 4 dB), the throughput performance is the same regardless of the value of the imposed delay requirement of that user thi is because in a high SNR regime, the service provision are the same for all users and thus the optimal subcarrier allocation reduces to the conventional scheduling. Also when we see the effect of transmission modes in AMC, M_n-ary QAM modulations are providing high throughput.

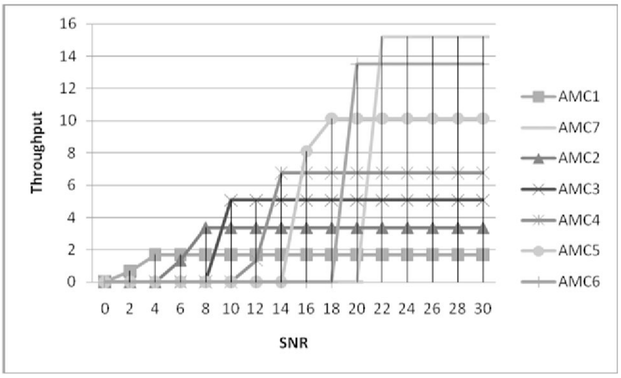

Figure 2: Performance in terms of Throughput for various modes

From Figs. 3 & 4, it is understand that the Bit Error Rate (BER) and Frame Error Rate (FER) measures obtained from the simulations are verifying the throughput achieved shown by Fig.2.

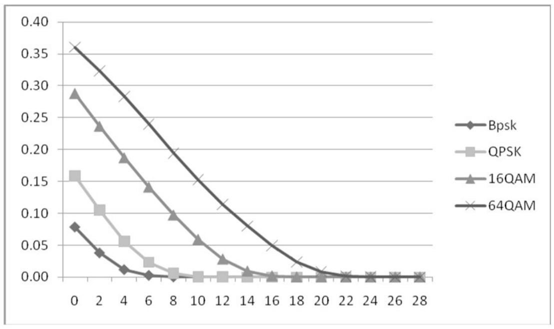

Figure 3: Performance in terms of Bit Error Rate for various modes

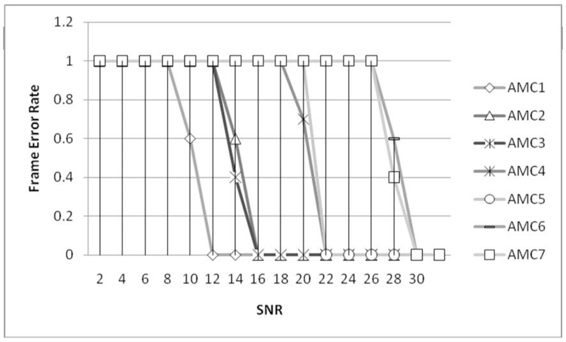

Figure 4: Performance in terms of Frame Error Rate for various modes

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
$\gamma_{pn}(dB)$	3.7164	5.9474	9.6598	12.3610	16.6996	17.9629

Table 1: Transmission modes Specified in IEEE 802.16 standard

From the above all figures, the truth of achieving high throughput or low BER /FER at high SNR regime or when the active channel condition is proved.

When we consider only AMC at the physical layer without the inclusion of queue state information from the MAC layer for scheduling (conventional method), the spectral efficiency gain achieved seems to be slightly lower than cross-layer design with combination of AMC and queue state information. This shows the significance of cross-layer approach of scheduling. The corresponding average packet error rate is tabulated and given in Table 2.

Parameters	**Conventional Scheduling**	**Proposed Cross-layer scheduling using CSI at the transmitter**
Spectral efficiency (b/s)/Hz	3.6219	**3.8769**
Average packet error rate	$8.56\text{x}10^{-2}$	$\mathbf{4.57x10^{-2}}$

Table 2: Analytical Results

6 Conclusion

In this paper, we presented a delay sensitive cross-layer scheduler for OFDMA systems with heterogeneous delay requirements and outdated CSI at the transmitter. The cross-layer design problem is formulated by taking into account ot the outdated CSI at the transmitter, source statistics with implementation of AMC and queue dynamics of the OFDMA systems. The optimal delay sensitive subcarrier allocation is obtained and the proposed scheduler gives a very good balance of maximizing the throughput and providing QoS (delay) differentiation of the mixed heterogeneous users. Further the work may be extended by including retransmission procedures to reduce the error rate which in turn to increase the throughput.

References

[1] C.Y. Wong, R.S. Cheng, K.B. Letaief, and R.D. Murch, "Multiuser OFDM with adaptive subcarrier, bit amd power allocation, " *IEEE J. Select. Areas Commun.*, vol.17, no.10, pp.1747-1758, Oct.1999.

[2] M.Ergen, S.Coleri, and P.Varaiya, "QoS awre adaptive resource allocation techniques for fair scheduling in OFDMA based broadband wireless access systems, " *IEEE Trans. Broadcasting*, vol.49, no.4, pp 362-370, Dec.2003.

[3] J.Jang and K.B.Lee, "Transmit power adaptation for multiuser OFDM sytems," *IEEE J.Select. Areas Commun.*, vol.21, no.2, pp.71-178, Feb.2003.

[4] G.Song and Y.(G.) Li, "Cross-layer optimization for OFDM wireless network – Part-I: Theoretical framework, " *IEEE Trans. Wireless Commun.*, vol.4, no.2, pp 614-624, Mar.2005.

[5] G.Song and Y.(G.) Li, "Cross-layer optimization for OFDM wireless network – Part-I: Algorithm development," *IEEE Trans. Wireless Commun.*, vol.4, no.2, pp 65-634, Mar.2005.

[6] S.Kittipiyakul and T.Javidi, "Resource allocation in OFDMA: How load balncing maximizes throughput when water-filling fails," UW *Tech. Report*, UWEETR-2004-0007, 2004.

[7] E.M.Yeh and A.S.Cohen, "Information theory, queueing, and resource allocation in multi-user fading communications, " in *Proc. Information Sciences Syst. Conf*, Mar.2004, pp.1396-1401.

[8] E.M.Yeh, "Multiaccess and Fading in Communication Networks, " *Ph.D. Thesis*, Department of Electircal Engineering and Computer Scienec, MIT, 2001.

[9] P.Parag, S.Bhashyam, and R.Aravind, " A sub carrier allocation algorithm for OFDM using buffer and channel state information, " in *Proc. IEEE VTC-Fall*, Sep. 2005, pp.622-625.

[10] Y.W.Yao and G.B.Giannakis, "Rate-maximizing power allocation in OFDM based on Partial channel knowledge," *IEEE Trans. Wireless Commun.*, vol.4, no.3, pp.1073-1083, May 2005.

[11] A.Leke and J.M.Cioffi, "Multicarrier systems with imperfect channel knowledge, " in *Proc. IEEE International Symposium PIMRC*, Set.1998, vol.2, pp.549-553.

[12] D.S.W. Hui and V.K.N.Lau, "Design and analysis of Delay-sensitive Cross-layer OFDMA systems with Outdated CSIT," *IEEE Trans. On Wireless Commn.*, vol.8, no.7, pp. 3484-3491, July 2009.

[13] Xin Wang, Georgis B.Giannakis, and Antonio G.Marques, "A Unified Approach to QoS-

Guarenteed Scheduling for Channel-Adaptive Wireless Networks," *Proceedings of IEEE,* vol.95, no. 12, pp 2410-2413, Dec 2007.

[14] IEEE Standard 802.16 Working Group, *IEEE standard for local and metropolitan area networks part 16: air interface for fixed Broadband Wireless Access Systems*, 2002.

[15] Qingwen Liu, Shengli Zhou and Georgios B. Giannakis, "Cross-Layer Combining of Adaptive Modulation and Coding with Truncated ARQ over Wireless Links," *IEEE Transactions on Wireless Communications*.vol.3, no.5, pp1746-48, Sep.2004.