A Joint Channel-Aware and Queue-Aware Scheduling in OFDM Networks

[*]Mohammad Fathi, [**]Mehri Mehrjoo, [*]Hassan Taheri
[*]Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran
[**]Department of Electrical and Computer Engineering, University of Waterloo, Ontario, Canada, N2L 3G1
Email: {mfathi, htaheri}@aut.ac.ir, mmehrjoo@uwaterloo.ca

***Abstract*— In this paper we investigate joint channel-aware and queue-aware scheduling to downlink subcarrier allocation in the context of Orthogonal Frequency Division (OFDM) networks. The objectives are to provide users with high throughputs and queues with high degree of stability that decreases the service discontinuity of non-real-time applications. The term stability for a queue is defined as the ratio of average departure rate to the average arrival rate. To achieve this, Multi Carrier Opportunistic Stability Queue (MC-OSQ) scheduling scheme is proposed and multi carrier implementation of well-known MLWDF scheduling scheme is extended. Comparing throughput and degree of stability performance of these schemes with queue-ware scheduling scheme demonstrates that joint channel-aware and queue-aware scheduling schemes perform absolutely well. Furthermore, simulation results reveal that MC-OSQ scheme, by taking the stability degree of queues into account performs the same as multi carrier implementation of MLWDF.**

I. INTRODUCTION

Radio Resource Scheduling (RRS) is a crucial scheme to provide users with quality of service (QoS) requirements in cellular communication networks. RRS allocates the network resources (namely power and bandwidth) among the users efficiently in order to compensate users' service degradation due to channel impairments.

Random variation nature of wireless channel in the time and frequency domains causes multi path propagation and fading. These phenomena vary the received SNR rapidly that must be treated appropriately in order to establish efficient connections. OFDM (Orthogonal Frequency Division Multiplexing) is the most recently physical layer technique proposed to encounter impairment effects of fading channels in broadband wireless communication. This technique divides the entire bandwidth by the set of subcarriers and allocates them to users based on the scheduling scheme. Exploiting the fact that a subcarrier in fading for some users may not be in fading for others, causes the network performance to be improved by a concept called multi-user diversity gain [1], i.e., transmitting to a user with high received SNR.

Opportunistic scheduling based on multi user diversity allocates each subcarrier to the user that has the highest channel gain on that subcarrier. Despite of total capacity maximization, opportunistic scheduling causes that users with poor channel quality fail to access the channel most of time and hence degrades the service satisfaction. Stable Queue scheduling (SQ) is an alternative to increase service satisfaction in non-real-time applications. The term stability for a queue is defined as the ratio of average departure rate to the average arrival rate [3]. In the SQ scheme, users with low stability value have higher priority to be allocated subcarriers. However, not considering channel gains in subcarrier allocation causes the capacity in the network to be degraded significantly. Accordingly, an applicable scheduling scheme for wireless medium used by non-real-time applications must be both Channel Aware and Queue Aware (CAQA).

Following are such scheduling schemes that have been proposed for single carrier channels under the assumption that channel state information (CSI) and queue state information (QSI) are available at the scheduler. In [2], a joint subcarrier and power allocation CAQA scheduling scheme for multi user OFDM has been proposed and it has been shown that CAQA performs better than Channel Aware Only (CAQ) scheduling, where scheduling decisions are based on channel information alone. Modified Largest Weighted Delay First (MLWDF) [3] is a well-known scheduling scheme proposed for real-time applications. In each interval, MLWDF serves the queue m with the highest $\gamma_m r_m W_m$ value, where γ_m is a positive arbitrary constant for priority control, r_m is the channel capacity for flow m and W_m is the head-of-line packet delay in the queue m. In the case of non-real-time applications W_m can be replaced by queue length Q_m. In [4], Opportunistic Stable Queue (OSQ) scheduling was proposed and compared with MLWDF for non-real-time applications. In this scheme scheduler determines the order of transmissions based on both channel quality and stability status of each queue.

In this paper we extend the Multi Carrier Opportunistic Stable Queue (MC-OSQ) scheduling scheme proposed in [4] for single-carrier communications, to the context of OFDM systems with non-real-time application. Throughout simulations, the throughput and stability of MC-OSQ is evaluated and compared with proposed multi carrier MLWDF and Multi Carrier Stable Queue (SQ) scheduling scheme, where all subcarriers are allocated to a user with the lowest degree of stability.

Due to high computational complexity, scheduling problem is decoupled into two sub problems including subcarrier allocation and power allocation to obtain sub optimal solution.

The rest of the paper is organized as follows. The system model including the architecture, bit loading and problem formulation is described in section 2. In section 3 the proposed scheduling scheme is expressed and the performance evaluation of it including throughput and stability is presented in section 4. The paper is concluded in section 5.

II.SYSTEM MODEL

A. System Architecture

We consider the downlink scheduling in a communication system with point to multi point infrastructure, where the base station (BS) allocates OFDM subcarriers and power to the users based on CSI and QSI. The scheduling decision is made periodically at the beginning of an interval consisted of N OFDM symbols, noted as time slot in this paper. It is assumed that channel conditions remain unchanged during a time slot.

Fig.1 illustrates the system architecture along with CSI and QSI signaling. A separate buffer for each user is considered in BS.

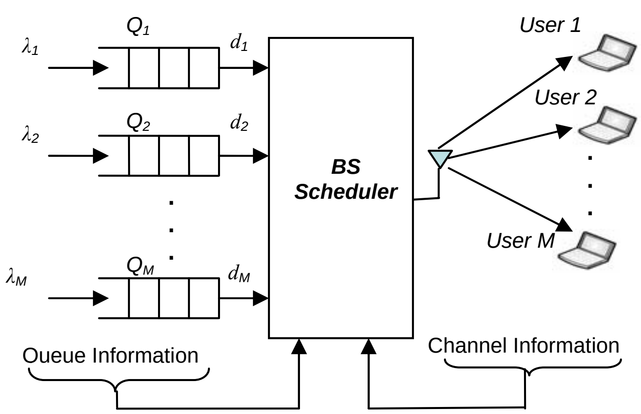

Fig. 1: System Architecture

B. Bit Allocation

The channel gain on subcarrier k during a time slot is defined as $\rho_k=|H_k|^2/N$, where N represents the noise power and H_k depends on path loss, shadowing and fading. Therefore, received signal to noise ratio (SNR) is obtained by $\gamma_k=\rho_k \,.\, p_k$, where p_k is the allocated power to subcarrier k. According to [10], bit adaptation corresponding to this subcarrier can be expressed as $c_k = log_2 (1+\beta\gamma_k)$ bps/Hz, where β is a function of link bit error rate (BER) defined as $\beta=-1.5 / (ln (5.BER))$. An adapti ve modulation (AM) takes channel SNR into account to adopt the type and order of modulation of each subcarrier [11]. We consider M-QAM modulation with $M=2^c$, c = 1, …, C, where C determines the highest modulation allowed. The set of possible received SNR is partitioned into $C+1$ disjoint regions by boundary points $b_0<b_1<...b_C<b_{C+1}$, where $b0=0$, $b_{C+1}=\infty$ and $b_c=(2^c-1)\ (ln(5.BER))\ /(-1.5)$. The discrete rate adaptation in bps/Hz during is obtained as follows:

$$c_k = \begin{cases} \lfloor \log_2(1+\beta\gamma_k) \rfloor & \gamma_k < b_C \\ C & \gamma_k \geq b_C \end{cases} \qquad (1)$$

For a subcarrier with Δf bandwidth the achievable rate is $r_k = c_k. \Delta f$.

C. Problem Formulation

Scheduling for OFDM systems can be modeled as an optimization problem in which the objective function and constraints are determined by the scheduling goals and users' requirements. The parameters used in the formulation are given in Table 1. The main objectives of the opportunistic stability queue scheduling scheme is maximizing long term system throughput along with stabilizing queues in the system.

The long term system throughput maximization is considered as the objective function (U) in the optimization problem, i.e., $U=\sum_{m=1}^{M}\eta_m$, where $\eta_m=\lim_{t\to\infty}\frac{1}{t}\sum_{n=1}^{t}\min(R_m(n),Q_m(n))$ is the long term average throughput for user m [2]. Also $R_m(n)=\sum_{k\in\Phi_m} r_k(n)$ is the total achieved rate of user m with queue length $Q_m(n)$ at time slot n. We restrict the objective function U with a set of constraints (2) that maintain the same degree of stability for the users. The degree of stability S_m of queue m at time instant n is defined as the ratio of the average departure rate $D_m(n)$ to the average arrival rate $A_m(n)$ to queue m:

$$S_m=D_m(n) / A_m(n),\ S_1=S_2=...=S_M \qquad (2)$$

TABLE I: PARAMETERS USED IN THE FORMULATION

Notation	Description
M	number of the users
K	number of OFDM subcarriers
m	user index
k	subcarrier index
Φ_m	subcarrier set allocated to user m
R_m	data rate of user m
S_m	degree of stability of user m
P_{BS}	BS total power
p_k	power allocated to subcarrier k

Each subcarrier should be allocated exclusively to one user to avoid intra cell interference ($\Phi_m \cap \Phi_{m'}=\varnothing\ \forall\ m\neq m'$). It is assumed that all of the subcarriers should be allocated,

($\bigcup_{m=1}^{M} \Phi_m = K$), and total transmission power must be limited to P_{BS}, ($\sum_{k=1}^{K} p_k \le P_{BS}$). These conditions can be considered as the constraints in the optimization problem (*P1*). Problem (*P1*) is a mixed integer nonlinear programming problem with integer variable set $\{\Phi_m\}_{m=1}^{M}$ and continuous variable $\{p_k\}_{k=1}^{K}$. The optimal solution of (*P1*) will obtain the subcarrier set allocated to the users and the portion of the BS power allocated to each subcarrier such that the maximum aggregate rate along with the constraints could be achieved.

$$(P1): \quad \max_{\{\Phi_m\}_{m=1}^{M}, \{p_k\}_{k=1}^{K}} \; U = \sum_{m=1}^{M} R_m \tag{3.1}$$

$$subject\ to: \quad \Phi_m \cap \Phi_{m'} = \varnothing \;\; \forall\, m \ne m' \tag{3.2}$$

$$\bigcup_{m=1}^{M} \Phi_m = K \tag{3.3}$$

$$\sum_{k=1}^{K} p_k \le P_{BS} \tag{3.4}$$

$$S_1 = S_2 = \ldots = S_M \tag{3.5}$$

Jointly subcarrier and power allocation in OFDM networks is almost formulated as a Mixed Integer Nonlinear Programming (MINLP) problem. In [5], a subcarrier allocation scheme was proposed to minimize the transmit power and satisfy a minimum rate constraint for each user. Problem is formulated as an integer programming and suboptimal solution is found by continuous relaxation. In [6], the subcarrier assignment problem with fix modulation level is solved using Hungarian method [7]. Hungarian is a solution for assignment problems with high computational complexity of $O(N^4)$, where N is the number of subcarriers. A dynamic subcarrier allocation based on users' traffic and channel state information has been derived in [8] by modeling each user's buffer as an M/D/1 queue with finite space. The power constraint is not involved in the proposed optimization. In [9], a utility-based theoretical framework for radio resource allocation in OFDMA wireless networks including DSA, APA, and joint DSA & APA was provided and evaluated in physical layer in term of bit rate.

III. SCHEDULING ALGORITHMS

Due to high complexity of finding optimal solution for P1, the problem can not be solved in real-time. As most of the practical applications need a real-time scheduling scheme, we propose a two-stage allocation algorithm that can be performed in real-time. First, a dynamic subcarrier allocation is performed by considering uniform power distribution. In this stage, a heuristic algorithm is proposed to allocate subcarriers based on the joint channel and queue information feedback from the users. The algorithm is presented in section *III .A*. Second, having the knowledge of allocated subcarriers to the users, the BS power is allocated to each subcarrier with power allocation algorithm expressed in section *III. B*.

A. Subcarrier Allocation

By taking advantages of CSI and QSI, not only the capacity in the system is maximized but also the users' service satisfaction is maintained high due to stable queues for non-real-time applications. Although these applications are bursty in nature, the elastic property of non-real-time traffic allows the scheduler to take advantage of time diversity in the scheduling of arrival traffic instead of serving as soon as it arrives. By using time diversity, scheduler can postpone to serve poor channels until they would be recovered. As a result, besides arrival and departure rates in the current time slot, the scheduler needs an estimation of them in the past time slots. To achieve this, an exponentially weighted moving average (EWMA) technique from [4] is adapted to estimate the average rates. This technique as a low pass filter provides robust scheduling scheme against fast variations in the arrival traffic. As a result, at the start of any time slot $n+1$ average departure rate $D_m(n+1)$ and average arrival rate $A_m(n+1)$ are updated as follows:

$$A_m(n+1) = (1 - 1/T_c) A_m(n) + (1/T_c)\, a_m(n) \tag{4}$$

$$D_m(n+1) = (1 - 1/T_c) D_m(n) + (1/T_c) \min(Q_m(n) + a_m(n),\, d_m(n)) \tag{5}$$

$D_m(n+1)$ and $A_m(n+1)$ are exponential window moving averages (EWMA), where the weights of the current and previous rates are determined by Tc, $(Tc>1)$, for both arrival and departure. Tc is the number of time slots that rates are averaged over it. Also $a_m(n)$ and $d_m(n)$ are instantaneous arrival and departures, respectively during time slot n as shown in the figure below. $Q_m(n)$ is the queue length and is updated as follows.

$$Q_m(n+1) = (1 - \frac{1}{T_c}) Q_m(n) + (\frac{1}{T_c}) \min(q_m(n), B) \tag{6}$$

Where $q_m(n) = (Q_m(n) + a_m(n) - d_m(n))^+$ and $x^+ = \max(x, 0)$.

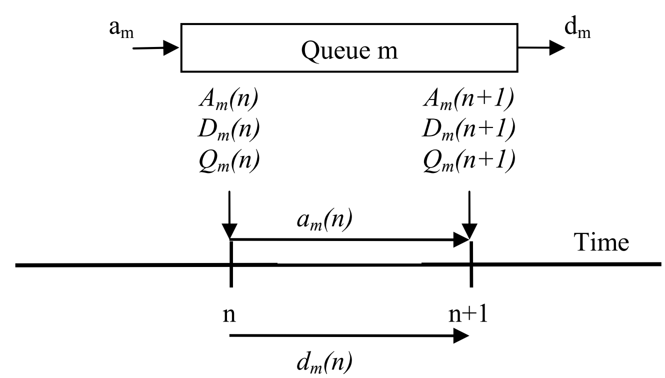

Fig. 2: Timing representation of arrival and departure rates

In the proposed multi carrier scheduling scheme, subcarrier allocation decisions are made through a priority matrix $P(n) = [p_{m,k}(n)]$ at each time slot n, where $p_{m,k}(n)$ is the priority value of user m on subcarrier k. Based on this matrix, each subcarrier is allocated to the user for whom it has the highest priority value. Corresponding priority values for MC-OSQ and multi carrier implementation of MLWDF are defined as $p_{m,k}(n) = r_{m,k(n)}10^{-S_m(n)}$ and $p_{m,k}(n) = Q_m(n).\frac{r_{m,k}(n)}{D_m(n)}$ respectively, where $r_{m,k}(n)$ is the user *m* packet rate at time slot *n* on subcarrier *k* with uniform power distribution. Also $S_m(n)$ is the degree of stability for queue *m*. Contrary to MC-OSQ and MLWDF, in MC-SQ scheduling scheme all subcarriers are allocated to the user with the minimum degree of stability at each time slot.

B. Power Allocation

Next in the second stage having the knowledge of subcarriers allocated to each user, problem (P1) is converted to Non-Linear Programming (NLP) optimization, which can be solved optimally as the water-filling problem using Lagrangian method. But in the case of practical communication system with discrete bit loading this method has not optimality. In contrast to OFDM where channel is sampled in subcarriers, water-filling is based on continuous rate adaptation and continuous frequency channel. As a result, we adapt a greedy bit loading algorithm as an alternative approach proposed in the literature [8] in which bits are loaded on subcarriers progressively. According to rate and power relation, the power requirement to map *b* bits on subcarrier *k* during a symbol time is $\Delta p_k = \frac{2^b - 1}{\beta \alpha_k}$, where α_k is the channel gain for the user owning this subcarrier. Power allocation algorithm based on this relationship is as follows. In each iteration the required power for just one bit increasing in the loaded bits is allocated to the user with minimum Δp_k. This performs until the total power exceeds the BS power, P_{BS}.

Power allocation:

$b_k = 0 \ \forall k, pt = 0$

while(1)

$$\Delta p_k = \frac{2^{b_k+1} - 2^{b_k}}{\beta \alpha_k} \ \forall k; \ k^* = \arg\min_k \Delta p_k;$$

$if\,(pt + \Delta p_{k^*}) > P\_BS \quad break;$

$b_{k^*} = b_{k^*} + 1; \ \ pt = pt + \Delta p_{k^*};$

end

IV.PERFORMANCE EVALUATION

This section provides the simulation results of the performance of throughput and stability for the MC-OSQ, multi-carrier implementation of MLWDF and MC-SQ schemes. Packet arrival processes is Poisson and system duplexing mode is FDD. Packet service rate for subcarriers are determined at the start of each time slot with assumption that channel conditions is static during it. Table 2 includes parameters used in the simulation.

TABLE 2: SIMULATION PARAMETERS

Description	Notation	value
total bandwidth		3.2MHz
number of OFDM subcarriers	K	256
number of users	M	8
base station power	P_{BS}	2Watt
noise power per subcarrier		-110dB
bit error rate		10^{-3}
packet length		66*8 bit
buffer Size for each user		25 bytes
time slot length		10 ms
path loss exponent		3
shadowing standard deviation		10dB
fading channel	Raleigh distribution with mean 0dB	
maximum modulation level	C	6
time constant	T_c	10

Simulations are provided in two scenarios: a) Homogenous users with different channels, b) Heterogeneous users with similar channels. In scenario (a) users have the same arrival rates with different distances from the BS, while the users are located in the same distance from the BS and have different arrival rates in scenario (b). The average throughput and degree of stability for a network with 16 users are shown in Fig. 3 and 4 respectively, where users are sorted in ascending order according to their distance from BS in case (a) and arrival rate in case (b). In case (a) with different located users, performance is decreased when the distance from BS is increased due to path loss. The effective parameters in the priority value of M-LWDF scheme are queue length and departure rate while it is just departure rate in the case of MC-OSQ. So M-LWDF outperforms the MC-OSQ in both throughput and stability terms as shown in Fig. 3a and Fig. 4a respectively.

In the case (b) with heterogeneous users, the higher arrival rates cause the stability parameter to affect the priority value strongly in MC-OSQ scheme. This results in choosing corresponding users to be served more and more as is shown in Fig. 3b. By this way the degree of stability remains the same for all users approximately in Fig. 4b. Contrary to MC-OSQ, throughput parameter is saturated in M-LWDF and this decreases the degree of stability for high arrival rate users.

MC-SQ scheme has the lowest performance in these figures as it attempts to provide the users with the same degree of stability with out considering the CSI.

Besides to mentioned scenarios, evaluating throughput and stability parameters under variable conditions including location, rate and the number of users in the system is crucial to be examined. Fig.5 demonstrates these parameters versus variable number of users. In each instance heterogeneous users are located randomly in the system. As shown, while achieved throughput and stability per user are decreased with increase the number of users, MC-OSQ and M-LWDF has the performance in both terms. Also MC-SQ has the lowest performance.

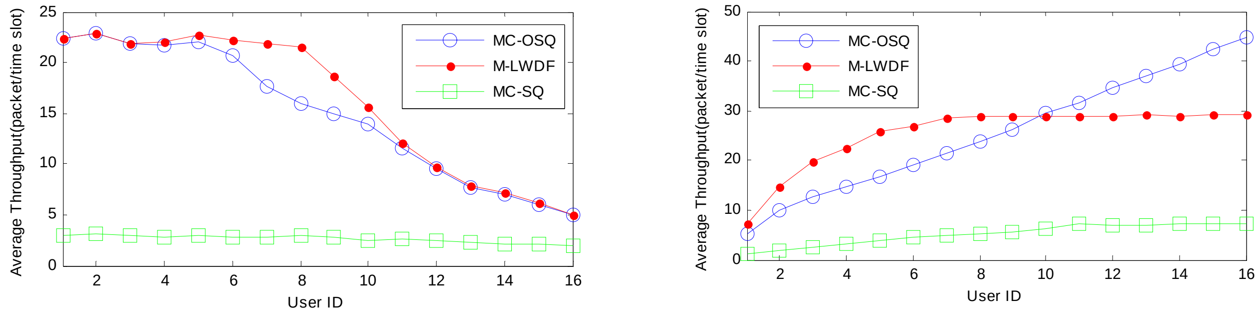

Fig. 3: Average throughput for users (a) Homogenous users with different channels (b) Heterogonous users with similar channels

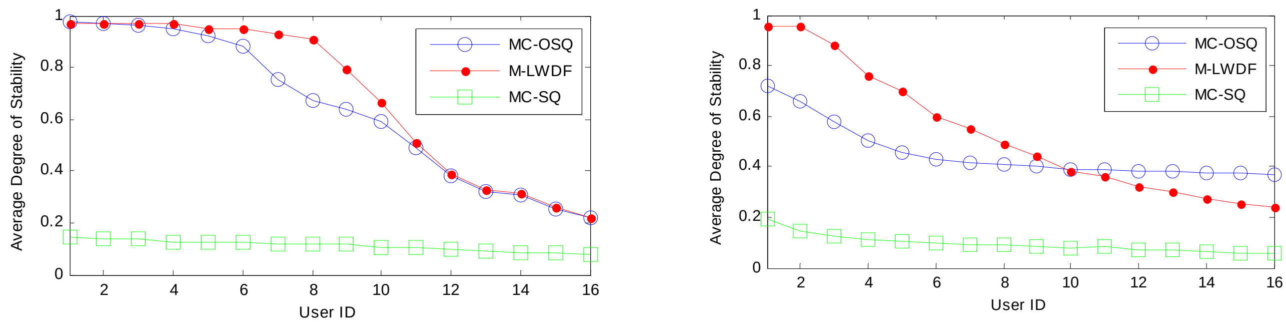

Fig. 4: Stability (a) Homogenous users with different channels (b) Heterogonous users with similar channels

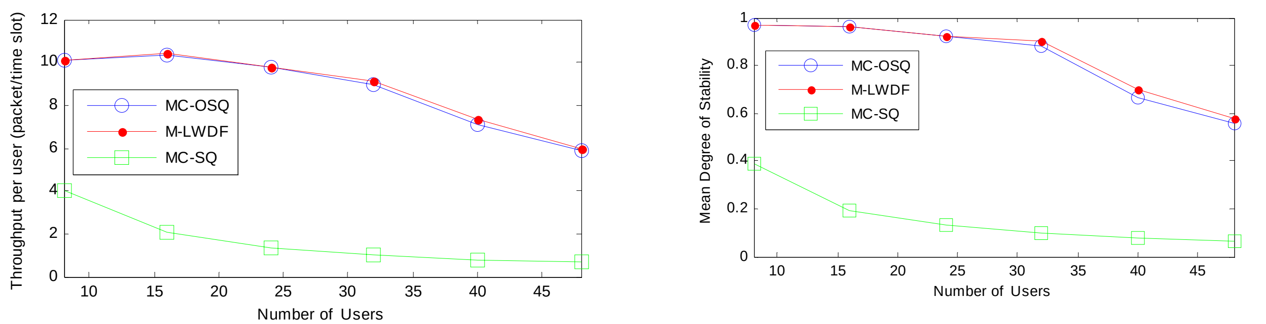

Fig. 5: (a) Average throughput per user (b) Stability

The fairness performance in the degree of stability is another parameter that affects the system performance. In Fig. 6 the Jain fairness index [12] of MC-OSQ and MLWDF schemes is provided in the form of $F = \frac{(\sum_{i=1}^{M} s_i)^2}{M\sum_{i=1}^{M} s_i^2}$, where s_i is the fairness of user i and M is the number of users. When the number of users in the network increases, resources are not sufficient to serve them efficiently and this causes the fairness to be decreased. As shown in Fig. 5, the fairness of M-LWDF falls more rapidly than the fairness of MC-OSQ when the number of users increases. So MC-OSQ satisfies the constraint (3.5) in the (P1) problem more efficiently than MLWDF scheme.

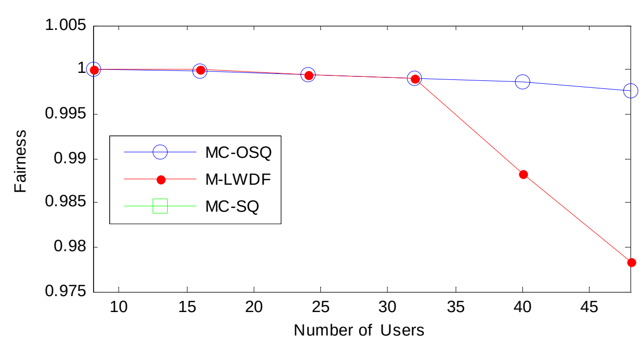

Fig. 5: Fairness in the degree of stability

V.CONCLUSION

Due to high computational complexity of scheduling problem in the context of OFDM networks, a two way approach including subcarrier allocation and power allocation have been adopted in a heuristic manner to gain suboptimal solutions. Multi Carrier Opportunistic Stability Queue (MC-OSQ) scheduling scheme is proposed to allocate subcarriers for non-real-time applications. To evaluate the performance of proposed scheme several scenarios was deployed under the assumption that channel state and queue state information are available for the scheduler.

Performance evaluation of proposed MC-OSQ scheme and multi carrier implementation of MLWDF scheme demonstrate that joint channel-aware and queue-aware scheduling performs absolutely well in terms of throughout and stability compared with just queue-aware scheduling. Furthermore, simulation results reveal that MC-OSQ scheme by taking the stability degree of queues into account performs the same as multi carrier implementation of MLWDF. By this way more stable queues are established in the base station.

REFERENCES

[1] P. Viswanath, D.N.C. Tse and Laroia, "Opportunistic beam forming using dumb antennas," *IEEE Transaction on Information Theory*, vol. 48, pp. 1277–1294, June 2002.

[2] C. Mohanram, and S. Bhashyam, "Joint subcarrier and power allocation in channel-aware queue-aware scheduling for multiuser OFDM," *IEEE Transaction on Wireless Communication*, vol. 6, no. 9, pp. 3208-3213, Sep. 2007.

[3] M. Andrews, M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, P. Whiting, and R. Vijayakumar, "Providing quality of service over a shared wireless link," *IEEE Communication. Magazine*, pp. 150–154, Feb. 2001.

[4] M. Mehrjoo, X. Shen, and K. Naik, "A Joint Channel and Queue-Aware Scheduling for IEEE 802.16 Wireless Metropolitan Area Networks," *WCNC Conference*, 2007.

[5] C. Y. Wong, R. S. Cheng, K. B. Lataief, and R. D. Murch, "Multiuser OFDM with adaptive subcarrier, bit, and power allocation," *IEEE J. Sel. Areas Communication.*, vol. 17, no. 10, pp. 1747–1758, Oct. 1999.

[6] S. Pietrzyk, and G. J. M. Janssen, "Multiuser subcarrier allocation for QoS provision in the OFDMA systems," in *Proceeding of IEEE Veh. Technol. Conf.*, vol. 2, Sep. 2002, pp. 1077–1081.

[7] H.W. Kuhn, "The Hungarian method for the assignment problem," *Naval Research Logistic Quarterly*, Vol. 2, pp. 83-97, 1955.

[8] G. Li and H. Liu, "Dynamic resource allocation with finite buffer constraint in broadband OFDMA networks," *IEEE Wireless Comm. and Networking*, v. 2, pp. 1037-1042, March 2003.

[9] G. Song and Y. Li, "Cross-layer optimization for OFDM wireless networks-Part I: Theoretical framework", *IEEE Transactions on Wireless Communications*, vol. 4, no. 2, 2005.

[10] X. Qiu, and K. Chawla, "On the performance of adaptive modulation in cellular systems," *IEEE Transaction on Communication*, vol. 47, pp. 884–895, June 1999.

[11] A. J. *Goldsmith* and S. G. Chua, "Variable-rate variable-power MQAM for fading channel," *IEEE Transaction on Communication*., vol. 45, no. 10, pp. 1218–1230, Oct. 1997.

[12] R. Jain, The art of computer systems performance analysis: techniques for experimental design, measurement, simulation and modeling. *New York: Wiley*, 1991.