An Opportunistic DRR (O-DRR) Uplink Scheduling Scheme for IEEE 802.16-based Broadband Wireless Networks

Hemant Kumar Rath, Abhijeet Bhorkar, Vishal Sharma

Department of Electrical Engineering
Indian Institute of Technology Bombay, Mumbai
Email: {hemantr, bhorkar, vsharma}@ee.iitb.ac.in

***Abstract*— We present a novel scheme for uplink scheduling in WiMax networks that attempts to balance worst-case fairness in bandwidth allocation with the delay requirements of traffic, while taking the varying nature of the wireless channel into account. We assume a polling-based mode of operation at the base station (BS), and provide a method of obtaining an optimal polling interval k at which the BS should poll the subscriber stations (SSs) to ensure that the delay requirements of traffic are met, while the relative unfairness in bandwidth allocation remains bounded. We devise an** *opportunistic* **deficit round robin (O-DRR) scheme that schedules sessions by taking into account the variations in the wireless channel, and demonstrate that there exists a range of values k of the polling interval over which our proposed scheduler is fair (as measured by Jain's fairness index), thus giving a service provider a choice of balancing fairness with delay, and pricing its services accordingly.**

I. INTRODUCTION

Among various broadband access systems, fixed broadband wireless access (FBWA) systems are expected to be the most flexible systems in the future. Although a fiber optic links and digital subscriber line link (DSL) are existing broadband wired technologies in the last mile, broadband wireless access (BWA) [1] based services, have the advantages of fast deployment, dynamic sharing of radio resources, and low cost. Due to the upcoming different air interface technologies, BWA systems promise high data rates in the last mile. BWA systems are expected to support QoS for real time applications, such as video conferencing, video streaming and voice-over-IP . IEEE 802.16 [1], [2], [3] is a BWA standard, sponsored by the IEEE LAN/MAN society, operating in the 2-11 GHz range and provides non line of sight (NLOS) access. The IEEE 802.16 (or the so-called WiMax) standard defines the physical (PHY) and medium-access control (MAC) layers for fixed (and, eventually, mobile) broadband wireless access networks.

The WiMax standard, in its simplest form, uses time-division duplex (TDD), and provides access to each subscriber station (SS)/user using demand assignment multiple-access time-division multiple access (DAMA-TDMA). DAMA is a capacity assignment technique that adapts to the demands of multiple users by dynamically assigning time slots to users depending on their bandwidth and QoS requirements.

In WiMax, time is divided into frames, each of which, in turn, is composed of a fixed number of slots [4], [5], [6]. Each frame consists of an *uplink subframe* and a *downlink subframe* (cf. Fig. 1). Requests by SSs are made during control slots in the uplink subframe, while grants from the BS are communicated to SSs during control slots in the downlink subframe. The grants thus communicated are used to schedule data either in the uplink subframe corresponding to the ongoing frame or the next one. While the WiMax standard specifies the grant mechanisms, it leaves open the scheduling mechanism to be used allowing for different providers, vendors to innovate in this area. To fill the gap, we suggest a polling-based opportunistic deficit round robin (O-DRR) scheduling scheme for the uplink flows in WiMax. This is a unique scheme and attempts to balance worst-case fairness in bandwidth allocation with the delay requirements of traffic, while taking the varying nature of the wireless channel into account.

The rest of the paper is organized as follows. In Section II, we discuss the various QoS classes defined in WiMax standard and the need of a scheduling mechanism for WiMax. We give an operational overview of our O-DRR scheme in Section III. Further, in Section IV, we explain the optimization technique to find the polling interval for uplink scheduling. A closed-form expression is obtained to find the polling interval for different classes of traffic. In Section V we explain the bandwidth assignment technique to SSs/users using our O-DRR scheme, which exploit the channel condition between BS and SSs during the scheduling process. Finally, in Section VI, we discuss our simulation model and experiments.

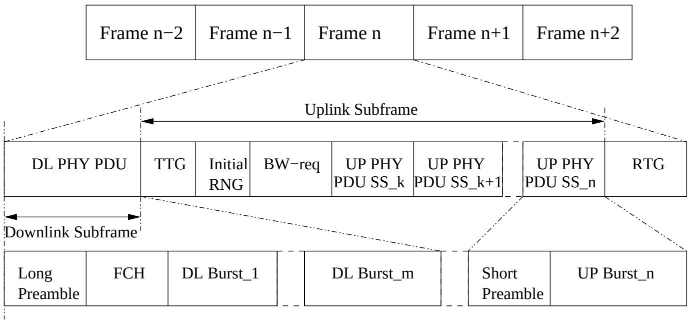

Fig. 1. Frame Structure in IEEE 802.16

II. IEEE 802.16 QOS CLASSES AND SCHEDULING

The IEEE 802.16 standard [2] can support multiple communication services (data, voice and video) with different QoS requirements. The MAC layer defines QoS signaling mechanisms and functions that can control BS and SS data transmissions.

On the downlink, the transmission is relatively simple, because the BS is the only one that transmits during a

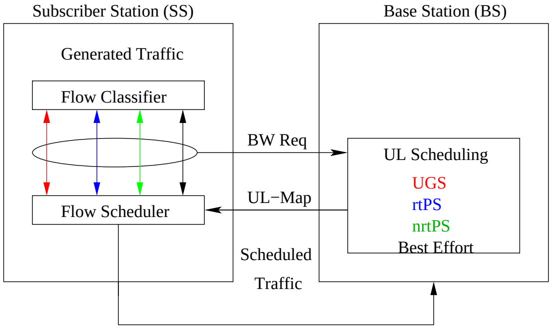

Fig. 2. QoS Architecture of IEEE 802.16

downlink sub-frame. Data packets are broadcast to all SSs and an SS only listens in on the packets destined for it. On the uplink, the BS determines the number of time slots for which each SS will be allowed to transmit in an uplink sub-frame. This information is broadcast by the BS through the uplink map message (UL-MAP) at the beginning of each frame. The UL-MAP contains an information element (IE) per SS, which includes the transmission opportunities for each SS, i.e., the time slots in which a SS can transmit during the uplink sub-frame. The BS uplink-scheduling module determines the IEs by using the bandwidth request message sent from the SSs to the BS.

In the IEEE 802.16 standard, bandwidth-requests are normally transmitted in two modes: a *contention mode* and a *contention-free mode* (polling). In the contention mode, the SSs send bandwidth-requests during a contention period, and contention is resolved by the BS using an exponential back-off strategy. In the contention-free mode, the BS polls each SS, and an SS in reply sends its BW-request. There are four types of basic services described in the standard. Namely, Unsolicited Grant Service (UGS); Real-Time Polling Service (rtPS); Non-Real-Time Polling Service (nrtPS); Best Effort (BE) service [2]. Variable bandwidth assignment is possible in rtPS, nrtPS and BE services, whereas UGS service needs fixed and dedicated bandwidth assignment. Figure 2 shows the QoS architecture of IEEE 802.16 based services.

A. Scheduling in IEEE 802.16-based Network

IEEE 802.16 standard defines the QoS signaling mechanisms, whereas it is silent on the scheduling policy for the services and users. Scheduling in both uplink and downlink are left open in the standard. However, the standard defines grant per SS basis(GPSS) [2] and grant per connection basis (GPC) schemes for scheduling. Scheduling in the downlink direction is simpler than in the uplink direction. This is because, the BS has the knowledge of all queues assigned to SSs in the downlink, whereas it does not have in the uplink. BS can use a scheduler similar to that used in traditional wire-line network in downlink scheduling, whereas in the uplink, it can't. This is because the BS does not have the complete information of all SSs and the links are wireless in nature with random channel characteristics. Also, IEEE 802.16 is a frame based system, not like usual packet based or TDMA system. The usual scheduling algorithms of wire-line networks like WFQ [7], SCFQ [8], W^2FQ [9] and wireless network like TBFQ [10] can't be used here. This is because WiMax is not a work conserving scheme and definition of time, virtual time, service time for the incoming packets of connected SSs are not possible at the BS. Hence there is a need of a new uplink scheduling algorithm for IEEE 802.16 based networks. Our aim in this paper is to find a new scheduling mechanism in the uplink for IEEE 802.16 based network. In the following sections we discuss our proposed scheduling algorithm for IEEE 802.16 based networks. This is a unique scheme and is completely different from usual wire-line and wireless scheduling algorithms.

III. OPERATIONAL OVERVIEW

Our scheme works by obtaining a list of *schedulable users*, based on the traffic requirements of the users and the signal-to-interference-plus-noise ratio (SINR) of the wireless channel. In our scheme, polling is performed by the BS, only once every k frames, which we term a *scheduling epoch*. That is, once every k frames the BS determines the set of SSs that are *eligible* to transmit, and their bandwidth requirements. We label these SSs the *eligible set*. An SS is eligible if, at the polling instant, it has a non-empty queue and the SINR of its wireless link to the BS is above a minimum threshold (say, $SINR_{th}$). We observe here that the SINR of a wireless link between a SS and a BS is obtainable in the IEEE 802.16-standard, during each frame, from measurements that are automatically made at the physical layer.

Once determined, the membership of the eligible set is frozen for the entire scheduling epoch. We also define a *schedulable* SS to be one that is eligible during a given frame of a scheduling epoch and that was eligible at the start of that epoch. During a scheduling epoch, therefore, the BS only schedules traffic from the schedulable set. (That is, the BS does not discover the status of the queue and wireless link of the remaining SSs in the network until its next polling opportunity.)

For each subsequent frame in the scheduling epoch (that is, for every frame for the next k frames), the BS schedules, using Opportunistic Deficit Round Robin (to be described shortly), the transmissions of the *schedulable* SS's. Note that the membership of the schedulable set *changes dynamically* from frame to frame during a scheduling epoch, depending on the state of the wireless channel between the SS and the BS. At the end of k frames, the BS recomputes the states of all of the SSs (by polling), and begins the above process over again.

The best choice of the polling interval k is determined by considering the maximum delay that a set of SSs can tolerate and the worst-case relative fairness in their bandwidth allocations. That is, our goal is to ensure that we choose a k such that every session is polled within a time kT_f (where T_f is the duration of a frame) that is less than its delay tolerance T_D, while still being fair to the different sessions.

IV. DETERMINING THE OPTIMAL POLLING INTERVAL k

As explained earlier, the BS needs to poll the SSs to discover the bandwidth and QoS requirements of the SSs. Intuitively, there is a trade off here. If the BS polls very frequently, it would have the most current information and may successfully satisfy the QoS requirements of the SS's, but the polling overhead, and, therefore, the efficiency, would be low. By contrast, if the BS polls the SS's very infrequently, it may have a very low overhead but would likely run the

Scheduling epoch Frame = 1

SS	SINR	DRR Flag	Lag/Lead
1	20	0	+Q
2	35	1	−Q
3	30	1	−Q
4	25	0	+Q

Scheduling epoch Frame = 2

SS	SINR	DRR Flag	Lag/Lead
1	32	1	+2Q
2	35	1	0
3	30	1	0
4	33	1	+2Q

Fig. 3. Operation of O-Deficit Round Robin Scheduling

risk of being quite unfair to the traffic at the SSs and of not meeting their QoS requirements (e.g. delay constraints). So, it is crucial to find appropriate value for k, such that both efficiency and fairness are balanced. Our proposal is to minimize a combination of the worst-case relative fairness in bandwidth plus the normalized delay, such that the provider can choose the relative weightage of fairness and delay.

We denote the duration in slots of the downlink subframe by T_{dl} and the duration in slots of the uplink subframe by T_{ul}. So that the frame duration $T_f = T_{ul} + T_{dl}$ slots.

In our scheme, the BS maintains a list L of the addresses of all SSs. If we denote by ϕ_i the ideal share of bandwidth to be obtained by SS_i, the slots in the uplink subframe T_{ul} can be divided proportionately among the SSs in the ratio of their ϕ_i's. The BS polls the SSs to discover their bandwidth requirements and updates an active list L_{active} of SSs, with the polling repeated at the start of every scheduling epoch.

Although the BS polls the SS's only once at the start of each scheduling epoch the, scheduling itself is performed in each frame, based on the opportunity condition $SINR_i \geq SINR_{th}$, where $SINR_i$ is the SINR of the channel between the BS and SS_i. Hence, polling is done over kT_f slots, whereas the scheduling is done over T_f slots. Therefore, if a packet/data at an SS misses one round of polling, it will require at least $(k+1)T_f$ time slots to be transmitted.

Let i and j be a pair of SSs that are maximally backlogged during an interval (t_1, t_2). The *fairness measure* $FM(t_1, t_2)$ over all pairs of flows/SSs i and j that are backlogged in interval (t_1, t_2) is defined as:

$$FM(t_1,t_2) = \left(\frac{sent_i(t_1,t_2)}{\phi_i} - \frac{sent_j(t_1,t_2)}{\phi_j} \right), \qquad (1)$$

where $sent_i(t_1,t_2)$ and $sent_j(t_1,t_2)$ represent the amount of traffic sent by the backlogged flows i and j, respectively, and ϕ_i and ϕ_j represent the bandwidth share of flows i and j, respectively.

If the share of all SSs is equal (when all are backlogged), $\phi_i = \phi_j = 1$, and $\sum_i \phi_i = N$, where N is the total number of SSs in the system. As discussed in [11], if Q_i is the quantum of slots for SS_i in each round of a DRR scheme, then we define:

$$\phi_i = \frac{Q_i}{Q}, \text{ where } \quad Q = \min_i \{Q_i\} = \frac{T_f}{N}. \qquad (2)$$

The worst-case occurs when only one SS (say SS_i) is backlogged at the instant of polling by the BS, but each of the $N-1$ remaining SS's becomes backlogged *immediately* thereafter. Hence, $Q_i = T_f$ and $\phi_i = N$. In this case, the worst-case fairness measure $FM_w(t_1,t_2)$ can be expressed as:

$$FM_w(t_1,t_2) = \left(\frac{R(t_2 - t_1)}{N} \right). \qquad (3)$$

The worst case time interval for our system occurs when $(t_2 - t_1) = kT_f$. Note that each frame actually consists of both uplink as well as downlink slots, while it is only the uplink slots that are used for SS to BS transmission. Assuming that the uplink and downlink subframes occupy an equal number of slots, and that there is no wastage of slots (i.e., the administrative slots are negligible, so that all the slots in the uplink can be assigned to the traffic), the usable slots in $(t_2 - t_1)$ are $\alpha k T_f$, where α is a system parameter that lies between 0 and 1. We assume $\alpha = \frac{1}{2}$, henceforth. So, the worst case fairness measure $FM(t_1,t_2)$ is:

$$FM_w(t_1,t_2) = FM_w(kT_f) = \left(\frac{\alpha R k T_f}{N} \right), \qquad (4)$$

where R is the maximum data rate that is achievable at this moment (as per the IEEE 802.16 standard it is 120Mbps for 64-QAM modulation scheme). Our aim is to find a k such that the BS can poll the SSs to achieve the smallest worst-case fairness measure FM_w and minimum delay. For this, we define a normalized delay (ND) as: $ND = \frac{T_D}{kT_f}$, where T_D is the delay bound of traffic at a SS (the maximum delay that a flow for a particular application can tolerate, e.g., 10msec, 50msec, 200msec and 500msec for UGS, rtPS, nrtPS and BE services, respectively). We would like the optimal k in our solution to be such that the worst case fairness measure and normalized delay are minimum. This can be achieved by the following optimization framework.

$$\min_k f(k) = c_1 |FM_w(k)| + c_2 ND(k), \qquad (5)$$

where c_1 is the cost for unit of FM per bit and c_2 is the cost per normalized delay. The worst case value of k can be found at the equilibrium point, where, $c_1|FM_w'(k)| = -c_2 ND'(k)$, which simplifies to,

$$k = \sqrt{\left(\frac{c_2}{c_1} \frac{NT_D}{R\alpha T_f^2} \right)} = \sqrt{\left(c \frac{NT_D}{R\alpha T_f^2} \right)}, \qquad (6)$$

where c is the ratio of the cost per unit delay to the cost per unit FM. The value of c depends upon the type of traffic, as the value of T_D is different for different traffic types.

Having obtained the optimum value of k, we perform uplink bandwidth assignments using our modified DRR algorithm.

V. BANDWIDTH ASSIGNMENT USING OPPORTUNISTIC DRR (O-DRR)

We suggest a deficit round robin (DRR) based scheduling technique that runs at the BS to allocate bandwidth to the contending uplink flows. Our scheme assumes that: (i) The channel between the SS and the BS is a Rayleigh fading channel, (ii) the coherence time of the channel is greater than the frame length (the IEEE 802.16 standard for point-to-multipoint network supports the frame lengths of is 0.5msec, 1msec, and 2msec), i.e., the channel does not change during a frame duration and that the (iii) SINR of each channel is known to the BS (which, as pointed out earlier, is obtainable from measurements at the physical layer).

We utilize DRR's idea of maintaining a quantum size Q_i and a deficit counter for SS_i, which we term the lead/lag counter L_i. The BS also maintains an indicator variable $DRRFlag_i$ for each SS. $DRRFlag_i = 1$, if SS_i is assigned bandwidth in this frame, else $DRRFlag_i = 0$. If, at a polling interval n during a scheduling epoch, $SINR_i$ is less than $SINR_{th}$, SS_i is not scheduled, and its quantum Q_i is distributed among the remaining SSs in proportion to their weights, while SS_i's lead/lag counter is *incremented* by Q_i, the amount of service it missed. Likewise, the lead/lag counter of an SS_j that received more than its minimum share Q_i of the uplink slots is decremented by the amount of slots that SS_j received over and above its quantum Q_j. The idea being to enforce fairness between different SS's in the long term.

Figure 3 illustrates our O-DRR scheme. We assume that the minimum SINR requirement for each SS is 30dB, the share for each user i is Q and all users have data to send. We also assume the lag/lead counter is 0 for each user at the beginning of the k^{th} scheduling epoch. At the k^{th} epoch, SS's 1 and 4 do not satisfy the SINR requirements, so their DRR flag is set to zero while the DRR flags of SSs 1 and 3 are set to 1. Since, SSs 1 and 4 are lagging, their lag/lead counter is set to +Q after the first scheduling frame. Similarly, the lag/lead counters of SSs 2 and 3 are set to -Q after the first scheduling frame, since SSs 2 and 3 are assigned their normal share Q and also receive the unused share Q of SSs 1 and 4. In the next frame, the SINR of each link exceeds the threshold. Hence, the DRR flag for each SS is 1. SSs 1 and 4 now receive bandwidth $2Q$ where as SSs 2 and 3 receive bandwidth 0. This is because SSs 2 and 3 have already used $2Q$ slots each in the previous polling interval, so their share in the current polling interval is reduced by the extra share previously received. This dynamic bandwidth assignment process continues and the BS schedules the SSs at a polling frequency obtained from Eq. 6. Our scheduling algorithm for the uplink flows, based on DRR is explained in Algorithm 1.

VI. SIMULATION MODEL AND EXPERIMENT

We simulated an IEEE 802.16 environment with one BS and different sets of SSs ($N = 50, 100$). The optimization-based method to determine the polling interval, described in Section IV was used to find the range of values of k and the worst case k. Using simulations with different sets of N, T_D, T_f and R, we obtained a set of cs and ks, summarized in Table I. A WiMax service provider can thus select a c that is most suitable for the business, provided the delay and fairness constraints of the users are met. We then simulated the O-DRR algorithm described in Algorithm 1. For different N, k, we observed the the lag/lead counter of each SS, the instantaneous queue status of each SS, the delay characteristics of the scheduler, the queue size of each SS over a long time interval (1000 frames). The queue sizes were found to be bounded over the period. The lag/lead counter and the slot allocation varied with SINR and k. Assuming 100 slots per T_{ul}, we show how the slots assignment for 100 users varied with different k in Figs. 4, 5, 6. Each point in each of the curves was obtained by averaging the SS slot assignments over several simulation runs. We observe that as k increases, the difference in the number of slot assignment to different SSs also increases (as expected). We see from Figure 5 that Jain's Fairness Index [12], however, remains above 90% for a fairly large range of k, suggesting that it is possible for the provider to trade of fairness for delay by choosing an appropriate value of k at which the fairness and the bandwidth requirements of different users are satisfied.

Algorithm 1 : O-DRR Algorithm for UL Scheduling (at BS)

```
1:  Set initial $k = k_{initial}$, the polling interval,
2:  Set the $polling\ timer = kT_f$
3:  if $polling\ timer$ has not expired then
4:      $BS$ polls and updates the $SINR$, Queue state for each $SS$
5:      $BS$ updates the active list ($L_{active}$) of $SS$. ($i \in L_{active}$,
        if $(I(SINR_i > SINR_{th_i})) \wedge Queue\ state_i)! = 0$)
6:      for $\forall i \in L_{active}$ of $BS$, check $SINR_i$ do
7:          if $SINR_i \leq SINR_{th_i}$ then
8:              Withdraw the BW assigned to $SS_i$ and mark $SS_i$
                as "lagging" other $SS$s as "leading"
9:              Re-assign the withdrawn BW to "leading" $SS$s
                proportionate to their weights $\phi_i$.
10:         end if
11:     end for
12: else
13:     Update $k$ (either with off-line values of $k$ or by using
        the Eqn. 6)
14: end if
15: Continue with step 2
```

REFERENCES

[1] "Understanding Wi-Fi and WiMAX as Metro-Access Solutions," *Intel Corporation, White Paper*, August 2004. Available at: http://whitepapers.silicon.com. Accessed on:10/10/2005.

[2] LAN/MAN Standards Committee, *IEEE Standards for Local and Metropolitan Area Network: Part 16: Air Interface for Fixed Broadband Wireless Access Systems*. IEEE Computer Society and IEEE Microwave Theory and Techniques Society, May 2004.

[3] LAN/MAN Standards Committee, *IEEE Standards for Local and Metropolitan Area Network: Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems (Amendments for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands)*. IEEE Computer Society and IEEE Microwave Theory and Techniques Society, September 2004.

[4] C. Eklund, R. B. Marks, K. L. Stanwood, and S. Wang, "IEEE standard 802.16: a technical overview of the WirelessMAN air interface for broadband wireless access," *IEEE Communications Magazine*, vol. 40, pp. 98–107, June 2002.

[5] A. Ghosh, D. R. Wolter, J. G. Andrews, and R. Chen, "Broadband wireless access with WiMax/802.16: current performance benchmarks

N/T_D	N=10	50	100	k	Comments
$50msec$	$c = 1200 - 243 * 10^3$	$c = 1200 - 9.72 * 10^3$	$c = 1200 - 24.3 * 10^3$	1-45	rtPS Traffic
$200msec$	$c = 300 - 972 * 10^3$	$c = 300 - 194.4 * 10^3$	$c = 300 - 97.2 * 10^3$	1-180	nrtPS Traffic
$500msec$	$c = 120 - 2430 * 10^3$	$c = 120 - 486 * 10^3$	$c = 120 - 243 * 10^3$	1-450	BE Traffic

TABLE I

PARAMETERS OF OPTIMIZATION BASED POLLING IN IEEE 802.16 $(R = 120Mbps, T_f = 1msec, \alpha = 0.5)$

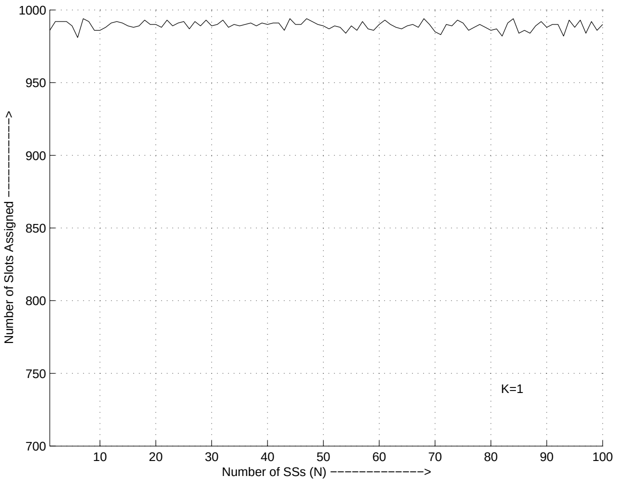

Fig. 4. Slots Assigned with k=1

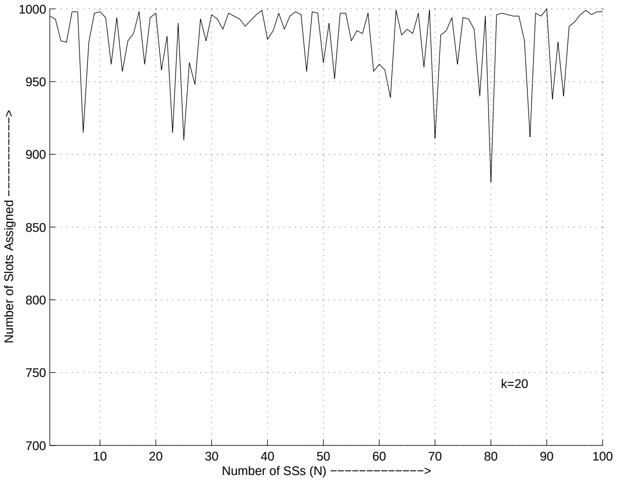

Fig. 5. Slots Assigned with k=20

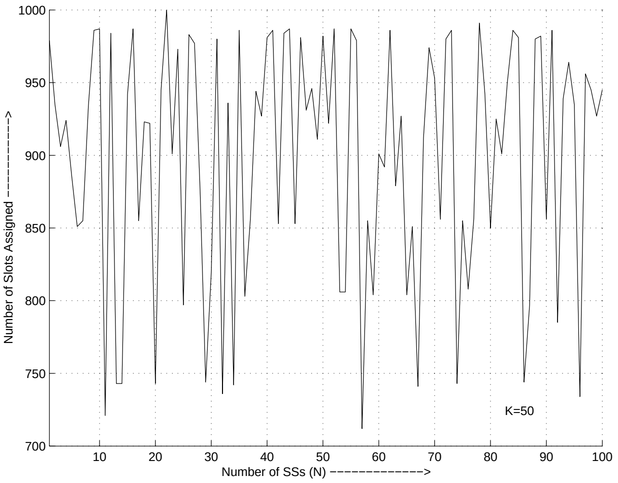

Fig. 6. Slots Assigned with k=50

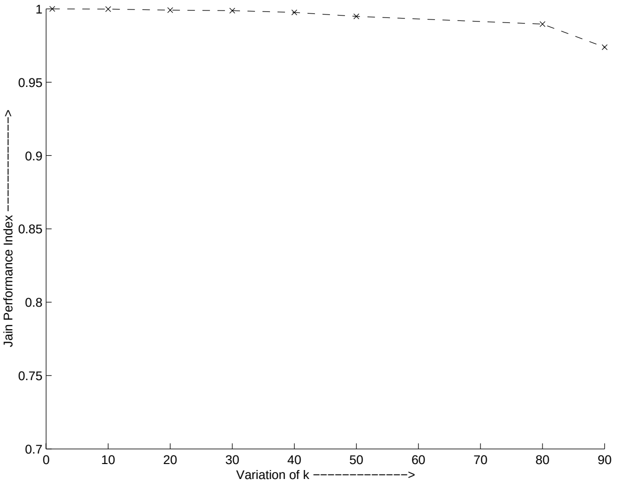

Fig. 7. Fairness in BW using Jain's Fairness Index

and future potential," *IEEE Communications Magazine*, vol. 43, pp. 129 – 136, February 2005.

[6] S. Redana, M. Lott, and A. Capone, "Performance Evaluation of Point-to-Multi-Point (PMP) and Mesh Air-Interface in IEEE Standard 802.16a," in *IEEE VTC2004 Fall*, September 2004.

[7] A. Demers, S. Keshav, and S. Shenker, "Analysis and Simulation of a Fair Queuing Algorithm," in *ACM SIGCOMM Symposium on Communications Architectures and Protocols*, September 1999.

[8] S. Golestani, "A self-clocked fair queuing scheme for broadband applications," in *Proc. IEEE INFOCOM*, pp. 636–646, 1994.

[9] J. C. R. Bennett and H. Zhang, "WF2Q: Worst-case Fair Weighted Fair Queueing," in *Proc. IEEE INFOCOM*, pp. 120–128, 1996.

[10] W. K. Wong, H. Tang, and V. C. M. Leung, "Token bank fair queuing: a new scheduling algorithm for wireless multimedia services," *International Journal of Communication Systems*, vol. 08, pp. 591–614, September 2004.

[11] M. Shreedhar and G. Varghese, "Efficient fair queueing using deficit round robin," *IEEE/ACM Transactions on Networking*, vol. 4, pp. 375–385, June 1996.

[12] R. Jain, D.-M. Chiu, and W. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems," *Technical Report TR-301, DEC Research Report*, September 1984.