Opportunistic Subcarrier Management for Delay Sensitive Traffic in OFDMA-based Wireless Multimedia Networks

Ahmed K. F. Khattab and Khaled M. F. Elsayed, *Senior Member, IEEE*

Abstract— **Radio resource allocation in OFDMA can exploit multiuser diversity to increase system capacity by implementing opportunistic scheduling and resource management techniques. This paper presents a new opportunistic subcarrier management scheme for OFDMA-based wireless multimedia networks. The scheme targets the class of delay-sensitive packets that belong to interactive applications. The subcarrier management is done in two steps: the OFDMA subcarrier allocation and subsequently the subcarrier assignment. Both the sub-carrier allocation and assignment algorithms exploit multi-user diversity and are designed to provide fairness with respect to the realizable per user performance. We compare the performance of the proposed algorithm with static OFDM-FDMA assignment with actual MPEG-4 traffic traces under different system loading and requested deadline values. The results show the superiority of the proposed scheme and its excellent performance with respect to throughput, packet dropping, and delay distributions.**

Index Terms— **Multiuser diversity, OFDMA, opportunistic scheduling, subcarrier allocation and assignment**

I. INTRODUCTION

Orthogonal Frequency Division Multiple Access (OFDMA) is a promising multiple access scheme that has attracted recent interest. OFDMA is based on Orthogonal Frequency Division Multiplexing (OFDM) and inherits OFDM immunity to inter-symbol interference and frequency selective fading. OFDM is a special case of multicarrier transmission, where a single high-speed data stream is transmitted over a number of lower rate subcarriers. In a single carrier system a single fade can cause the entire link to fail, but in multicarrier systems, only a small percentage of the subcarriers will be affected. So, multiuser OFDM is identified as a promising interface option for broadband wireless networks.

The scheduling problem in OFDMA-based wireless networks is more challenging than scheduling in other systems. Here, the scheduler is responsible for deciding how the available subcarriers will be distributed among different users. Recently, dynamic resource management of OFDMA-based networks has attracted enormous research interest [1-11]. Fixed assignment of subcarriers to terminals will waste system resources in the form of either power or bit rate [2],[3]. In this paper, we consider the subcarrier management problem in the downlink of OFDMA wireless multimedia networks. The problem is divided into two sub-problems: the subcarrier allocation problem and subcarrier assignment problem. Based on the principles of multi-user diversity [12], we propose an opportunistic subcarrier allocation algorithm that uses the channel state information and the delay information of different users to calculate the number of subcarriers to be assigned to each active user in the system, while attempting to guarantee the QoS required by these users. We also propose an opportunistic algorithm for the subcarrier assignment problem. The proposed algorithm monitors the deadline violations in all queues, then progresses to ensure fairness among different users in their service rates. This is achieved by distributing the violation occurrences among all users evenly.

The work presented here is mostly related to [10],[11], however it offers several advantages. The work in [10] considers only the subcarrier assignment problem without addressing the allocation problem. The work in [11] is focused on minimizing total power subject to constraints on bit error rates and throughput per user. No explicit provisioning for delays or fairness is considered in the formulation. Our work distinguishes itself by taking the delays (which also carries queue size information) into the formulation and by setting the objective to achieving the maximum throughput in the downlink (where transmit power is not severely limited). Fairness and multiuser diversity are explicitly targeted in the subcarrier assignment and allocation steps.

The rest of the paper is organized as follows: Section II defines the OFDMA network model. Then we present and evaluate the performance of our proposed subcarrier management scheme in sections III, IV, respectively. Section V summarizes the main findings of the paper.

II. OFDMA NETWORK MODEL

We consider a cell-structured OFDMA system model that consists of a base station communicating simultaneously with N mobile user terminals using S OFDM subcarriers. The presented study is applicable both to the uplink and the downlink, but we concentrate here on the downlink only. An OFDMA transmitter employs a subcarrier allocation and assignment function instead of the serial to parallel conversion used in OFDM systems as a first step. Different modulation schemes could be used to transmit data efficiently over the subcarriers with different gains. The rest of OFDMA system is the same as an OFDM system.

The base station is responsible for informing each user terminal which subcarriers are assigned to it via a set of subcarriers reserved for control channel(s). Therefore, the data sent to this user is retrieved by demodulation of the user's assigned subcarriers.

Wireless channels operating at high frequencies, like those used in OFDMA-based networks, are characterized by their

---

The authors are with the Department of Electronics and Communications Engineering, Cairo University, Giza, Egypt 12613, (e-mails: khaled@ieee.org and ahmedkhattab@eng.cu.edu.eg)

time-varying, frequency-selective fading nature. Channel gains vary from subcarrier to subcarrier for a single wireless terminal due to multipath propagation. Besides, channel gains of each subcarrier vary over time for the same user terminal, due to the movement of the terminal and other objects within the surrounding area. It may occur that certain subcarriers that are in deep fade for some users are not necessarily bad for others since the user channel fading characteristics are not the same for different users. This gives the general motivation to develop resource allocation framework that exploits multiuser diversity to assign an active user its best subcarriers.

III. THE PROPOSED SCHEDULING SCHEMES

In this paper, we introduce a new opportunistic approach to subcarrier management in OFDMA-based wireless multimedia networks. The idea behind this approach is that the subcarrier allocation and assignment is not only dependent on the instantaneous channel conditions of different users, but also on the QoS requirements and fairness among users. The QoS requirement of real-time traffic users are generally defined in terms of a delay bound. The system parameters are as follows:

N_t: The number of active users (with at least one valid packet queued) at time *t*.

S: The total number of data subcarriers available to the system.

$n_i(t)$: The number of subcarriers to be assigned to the i^{th} user at the slot starting at time *t*.

r_i: The average traffic rate of i^{th} user.

$\mu_{ij}(t)$: The channel capacity (maximum possible transmission rate) of the subcarrier number *j* if allocated to the i^{th} user.

$\bar{\mu}_i(t)$: The average "potential" subcarrier capacity of the i^{th} user (if it was allocated all the subcarriers).

$$\bar{\mu}_i(t) = \frac{1}{S}\sum_{j=1}^{S}\mu_{ij}(t) \qquad (1)$$

$d_i(t)$: The time to expire of the i^{th} user head of line (HoL) packet, which is the difference between the deadline, T_i, and the delay experienced by its HoL packet up till time *t*, $W_i(t)$, i.e

$$d_i(t) = T_i - W_i(t) \qquad (2)$$

Let's define the indicator function $\delta_{ij}(t)$ as

$$\delta_{ij}(t) = \begin{cases} 1 & \text{if subcarrier } j \text{ is assigned to user } i \\ 0 & \text{otherwise} \end{cases} \qquad (3)$$

We assume that the channel information is known at both the transmitter and the receiver. The channel is assumed to be reciprocal.

Our objective of the resource allocation problem can be defined as maximizing the total system throughput subject to a constraint on the packet delays. The total instantaneous system throughput $R_T(t)$ is

$$R_T(t) = \sum_{i=1}^{N}\sum_{j=1}^{S}\delta_{ij}(t)\mu_{ij}(t) \qquad (4)$$

The subcarrier management problem is formulated as follows:

$$\max_{\delta_{ij}(t)} R_T(t) \qquad for\ \delta_{ij}(t) \in \{0,1\} \qquad (5)$$

subject to

$$\sum_{i=1}^{N}\sum_{j=1}^{S}\delta_{ij}(t) = S \qquad (6)$$

and

$$W_i(t) < T_i \qquad i = 1,2,...,N \qquad (7)$$

A mathematically optimal solution of the above problem in its most generic form cannot be obtained (for further details check [13]). We propose a heuristic suboptimal solution of the above problem in two steps:

1) Subcarrier Allocation: This scheme decides **how many** subcarriers to be assigned to each user (i.e. determines $n_i(t)$).

2) Subcarrier Assignment: This scheme determines **which** subcarriers to be assigned to each terminal (i.e. the vectors $\delta_{ij}(t)$ are calculated).

A. Subcarrier Allocation Algorithm

The subcarrier allocation is based on three factors: 1) the instantaneous subcarrier channel gains of active users, 2) the users' average rates, and 3) the delay of the HoL packets of these users. We not only exploit the statistical variations of the users' channels, but also use the statistical variations of users' queues in order to increase the efficiency of channel throughput utilization.

The first step of the proposed opportunistic subcarrier allocation algorithm is to initially allocate to every active user in the system a number of subcarriers $n_i^{'}(t)$ given by:

$$n_i^{'}(t) = \left\lceil \frac{r_i}{\frac{1}{|N_t|}\sum_{j\in N_t} r_j} \frac{\bar{\mu}_i(t)}{\frac{1}{|N_t|}\sum_{j\in N_t}\bar{\mu}_j(t)} \right\rceil \qquad (8)$$

In essence, this allocation exploits multiuser diversity by allocating more subcarrier to the users with better channels. At the end of this step, if all the available data subcarriers are allocated to the set of users currently seeking service from the system, the allocation algorithm terminates. However, if some subcarriers remain unused after this step, the unused subcarriers are allocated to some of the active users. Let us denote the number of the remaining unused subcarriers by S', where

$$S' = S - \sum_{N_t} n_i^{'}(t) \qquad (9)$$

The next two steps of the algorithm are responsible for distributing these remaining subcarriers efficiently among the active users in order to prevent as many packets from expiry and to compensate users who suffered from recent packet drops. This is done by using $NV_i(t)/d_i(t)$ as the distributing ratio, where $NV_i(t)$ is the number of deadline due violations of the i^{th} user packets up to time *t*. At this point, the number of subcarriers to be assigned to the i^{th} active user is:

$$n_i(t) = n_i^{'}(t) + \left\lceil S' \frac{\frac{\max\{1, NV_i(t)\}}{d_i(t)}}{\sum_{j\in N_t}\frac{\max\{1, NV_j(t)\}}{d_j(t)}} \right\rceil \qquad (10)$$

If the total number of allocated subcarriers equals the available number, the algorithm terminates, and then moves to the subcarrier assignment algorithm.

The last step in our subcarrier allocation procedure is only used when the subcarrier allocation done in the first two steps exceeds the total number of data subcarriers available to the system. Its function is to decrease the number of subcarriers allocated to some users, so that the total allocated subcarriers equals S. Our criteria in choosing these users, whose number of allocated subcarriers are to be decreased, is the time to expire of their HoL packets and their violation occurrences similar to what was done in the previous step of the algorithm. First, the algorithm sorts the set of active users in a descending order according to their time to expire. Then, it iterates over users in that order. In every iteration, the algorithm decreases the number of subcarriers allocated to the user in turn by one. Then checks whether the total subcarrier allocated equal to S or not. If it was not yet equal, the algorithm continues one more iteration. The algorithm is shown in Figure 1.

B. *Subcarrier Assignment Algorithm*

The objective of the subcarrier assignment algorithm is to find the subcarrier assignment that maximizes the total rate. This can be achieved if multiuser diversity is used to assign every active user its best $n_i(t)$ subcarriers. Such an assignment problem is equivalent to the maximum weighted perfect matching problem in bipartite graphs [6]. An optimal solution can be generated by the Hungarian algorithm [14], which has the complexity of $O(S^3)$, where S is the number of subcarriers.

With the objective of enhancing the fairness characteristics of the scheduling algorithm while maximizing the total rate, we propose a new low complexity opportunistic subcarrier assignment algorithm. The algorithm assigns initially a unity priority to all users. Whenever a packet is dropped from a certain user's queue, that queue priority is incremented by one. In every scheduling interval, the subcarrier assignment algorithm sorts the active users in the system in a descending order according to their priorities. The user with the highest priority starts to pick its best-responding subcarriers from the set of all subcarriers. After assigning those subcarriers to that user, the algorithm removes them from the set of available subcarriers. Then the algorithm assigns the next higher priority user the best set of remaining subcarriers, and so on. This mechanism should enhance the fairness performance of the scheduler. If more than one user share the same priority level, ties are broken by giving priority to the user with the best channel quality (averaged over all subcarriers) to pick up its allocated subcarriers first. The algorithm is shown in Figure 2.

IV. PERFORMANCE EVALUATION

A. *Simulation Setup*

In order to evaluate the performance of the proposed subcarrier allocation and assignment algorithms, we consider the IEEE 802.20 Mobile Broadband Wireless Access (MBWA) system model [15]. Among the different channel bandwidths suggested in [15], we use a channel of 5 MHz bandwidth. We assume that the number of data subcarriers S is equal to 128 subcarriers. Adaptive modulation is used to transmit data on each subcarrier such that the highest possible rate can be transmitted in every scheduling interval. The scheduler chooses the suitable type out of five modulation types available (BPSK, QPSK, 16-QAM, 64-QAM and 256-QAM). The parameters of the simulation are summarized by table 1.

TABLE I SUMMARY OF SIMULATION PARAMETERS.

Carrier frequency	1.9 GHz
Channel bandwidth	5 MHz
Number of data subcarriers (S)	128
User mobility speeds	3 – 120 Km/hr
Doppler frequency	211 Hz
Channel coherence time	4.7 msec
Doppler spectrum	Jakes' (6 rays)
Scheduling interval	1.667 msec
Traffic model	Real trace file of MPEG-4 encoder Frame rate: 30 frames/sec
Traffic average rate / peak rate	256 Kbps / 2.3 Mbps
Packet size	50 bytes

Traffic is generated from a trace file of a 30 frames/sec MPEG-4 encoder with an average rate of 256 Kbps and a peak rate of 2.3 Mbps [17]. Each frame is decomposed into 50 bytes packets to be transmitted. A packet is assigned a deadline before which it should be served. We consider three values of this deadline, specifically, 20, 50, and 100 milliseconds.

B. *Results and Discussions*

In this section we present numerical results of the introduced opportunistic subcarrier allocation and assignment algorithms. For comparison reasons the results of the static OFDM-FDMA subcarrier assignment is used as a bench mark for illustrating the performance gains achieved by our opportunistic subcarrier allocation and assignment. As discussed earlier, OFDM-FDMA has been identified as the best static subcarrier assignment. The simulation period of each of the following experiments is three minutes.

1) *Throughput and Capacity*

Defining the system capacity as the number of users beyond which the average throughput per user falls to 99% of the average arrival rate; we find that when the opportunistic allocation/assignment is used, the system can support 120, 165, and 165 users for a 20, 50, and 100 milliseconds delay bound, respectively. When OFDM-FDMA assignment is used, the maximum allowable number of users is 42 users only, however, we found that the system can only support 15 (10) users for the 50 (20) milliseconds delay bounds without degrading their service rates significantly. Figure 3 shows the average user throughput versus the number of admitted users for a 20 milliseconds delay bound.

2) Fairness

In order to qualify the fairness characteristics of the proposed opportunistic subcarrier allocation and assignment algorithms, we study the maximum and the minimum achieved throughput for the above experiment. We define the throughput fairness index as the ratio of the difference between the maximum and the minimum achieved throughput (λ_{max} and λ_{min}, respectively) to the average throughput per user (λ_{avg}), i.e

$$\mathit{Throughput\ Fairness\ Index} = \frac{|\lambda_{\max} - \lambda_{\min}|}{\lambda_{avg}} \tag{11}$$

The throughput fairness indices of both the opportunistic algorithm and the static algorithm for different delay bounds are plotted in Figure 4. The almost-perfect fairness (fairness index approaches 0) of the opportunistic algorithm when the system is operating with a number of users less than its capacity can be easily noticed. The static subcarrier assignment lacks such characteristics.

3) Delay Performance

We also study the delay performance of the proposed subcarrier allocation and assignment algorithms. This can be achieved through investigating the distribution of the delays that users' packets incur at the base station. A good scheduling algorithm should keep all delays below the delay bound with high probability, which is achieved roughly when the delays are kept close for all users. Due to the large number of users the system can support, we focus only on the delay distribution of the users with the best and worst channel quality.

The delay distributions of the best and the worst channel users for a 20 milliseconds delay bound for 42 and 120 users is shown in Figures 5 and 6, respectively. Two observations could be easily made: The first observation is that the delay performance of the opportunistic algorithm (the delay distributions and the maximum delays of the best and the worst channel users) are similar (this remarkably was consistent for other values of the delay bound not shown here due to space limitation). The other observation is that the opportunistic algorithm keeps the delay of all users far below the deadline and also close to each other. The static OFDMA-FDMA does not exhibit such excellent performance.

Though rather a computationally inexpensive algorithm, the proposed opportunistic scheduling algorithm can be used to provide statistical delay guarantees for time-sensitive traffic required by a wide range of applications in OFDMA-based wireless networks. Moreover, multiuser diversity is used in the algorithm to offer orders of magnitude increase in the system capacity.

V. CONCLUSIONS

This paper addresses the problem of scheduling real-time users over OFDM-based wireless multimedia networks. We introduced new opportunistic subcarrier allocation and assignment mechanisms for parallel transmission of data streams to different terminals in OFDMA-based broadband wireless systems. The subcarrier allocation algorithm instantaneously determines the number of subcarriers each terminal should receive by the assignment algorithm for the next downlink scheduling interval. Gains in throughput and realized delay are achieved by exploiting multi-user diversity techniques, the subcarrier allocation algorithm takes into account the current channel state for each user in the system, as well as other stream specific delay information (the time to expire of the HoL packet) and the number of recent deadline violations. The allocated number of subcarriers is assigned to terminals dynamically in a manner that ensures fairness in the deadline violation occurrences among different users.

The proposed algorithm exhibits a unique fairness behavior in the services (packet delays, throughput and loss ratios) delivered to different users. The proposed policies have low computational complexity and are suitable for application in future broadband wireless systems such as the IEEE 802.16a and the 802.20 MBWA systems.

REFERENCES

[1] S. Pietrzyk and G. J. M. Janssen, "Multiuser subcarrier allocation for QoS provision in the OFDMA systems," in Proc. VTC 2002, vol. 2, 2002, pp. 1077–1081.

[2] C. Wong, R. Cheng, K. Letaief, and R. Murch, "Multiuser OFDM with adaptive subcarrier, bit and power allocation," IEEE Journal on Selected Areas of Communications, vol. 17, no. 10, pp. 1747–1758, October 1999.

[3] W. Rhee and J. Cioffi, "Increase in capacity of multiuser OFDM system using dynamic subchannel allocation," in Proc. Vehicular Technology Conference (VTC), 2000, pp. 1085 – 1089.

[4] H. Yin and H. Liu, "An efficient multiuser loading algorithm for ofdm-based broadband wireless systems," in Proc. IEEE Globecom, 2000.

[5] M. Ergen, S. Coleri, and P. Varraiya, "QoS aware adaptive resource allocation techniques for fair scheduling in OFDMA based broadband wireless access systems," IEEE Transactions on Broadcasting, vol. 49, no. 4, December 2003.

[6] J. Gross, H. Karl, F. Fitzek, and A. Wolisz, "Comparison of heuristic and optimal subcarrier assignment algorithms," in Proc. of Intl. Conf. on Wireless Networks (ICWN), June 2003.

[7] G. Zhang, "Subcarrier and bit allocation for real-time services in multiuser OFDM systems," in Proc. of Intl. Conf. on Communications (ICC), June 2004.

[8] D-H. Kim, B-H. Ryu, and C-G. Kang, "Packet scheduling algorithm considering a minimum bit rate for non-realtime traffic in an OFDMA/FDD-based mobile internet access system," ETRI Journal, Volume 26, Number 1, February 2004.

[9] P. Svedman, S. Wilson, and B. Ottersten, "A QoS-aware proportional fair scheduler for opportunistic OFDM," Proc. IEEE VTC, Fall, Sep. 2004.

[10] J. Gross, J. Klaue, H. Karl, and A. Wolisz, "Subcarrier allocation for variable bit rate video streams in wireless OFDM systems," in Proc. of Vehicular Technology Conference (VTC), 2003.

[11] Y. Zhang, and K. Letaief, "Adaptive resource allocation and scheduling for multiuser packet-based OFDM networks," in Proc. of Intl. Conf. on Communications (ICC), June 2004.

[12] R. Knopp and P. A. Humblet, "Information capacity and power control in single-cell multiuser communications," in Proc. IEEE International Conference on Communications (ICC'95), Seattle, USA, June 1995.

[13] A. Khattab. "Channel-aware scheduling of delay-bounded multimedia traffic in wireless networks beyond 3G," M.Sc. Thesis, Cairo University, Egypt, 2004. Available at http://khattab-ahmed.tripod.com/thesis/Channel-Aware-Scheduling.pdf

[14] H. Kuhn, "The Hungarian method for the assignment problem," Naval Research Logistics Quarterly, no. 2, pp. 83–97, 1955.

[15] M. Klerer, "Introduction to IEEE 802.20: technical and procedural orientation," IEEE802.20 PD-04, March 2003.

[16] IEEE C802.20-04/30 "Channel models for IEEE 802.20 MBWA system simulation - Rev 04," March 2004

[17] Arizona State University Trace Website, Video Library: "Jurassic Park One". Available at http://trace.eas.asu.edu/

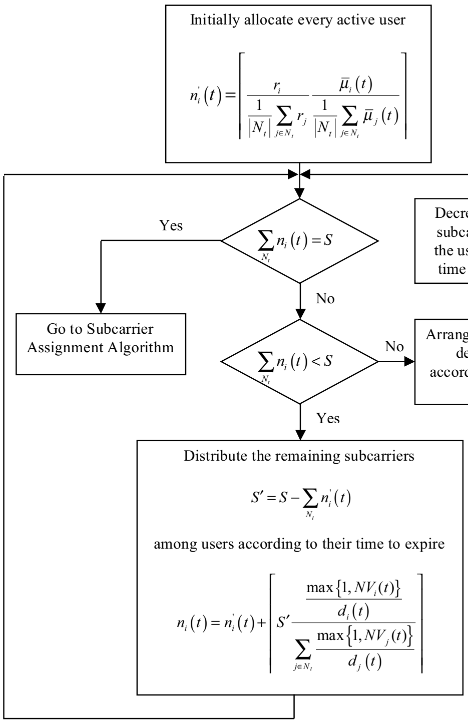

Figure 1: Subcarrier Allocation Algorithm

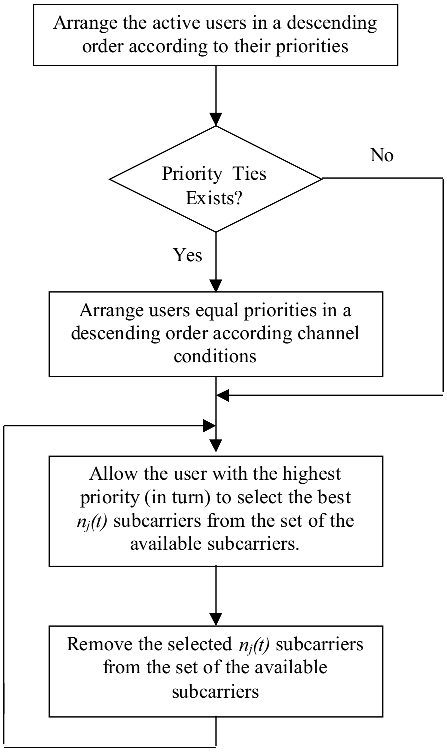

Figure 2: Subcarrier Assignment Algorithm

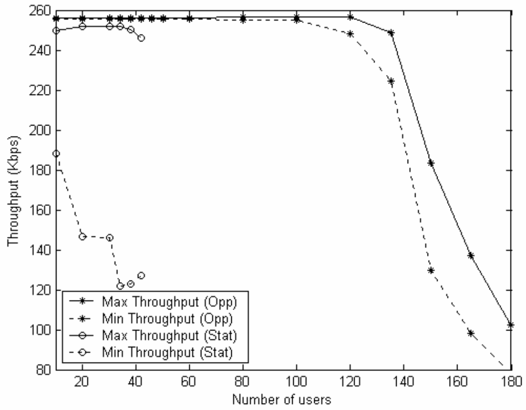

Figure 3: The maximum and the minimum achieved throughput for a 20 msec delay bound.

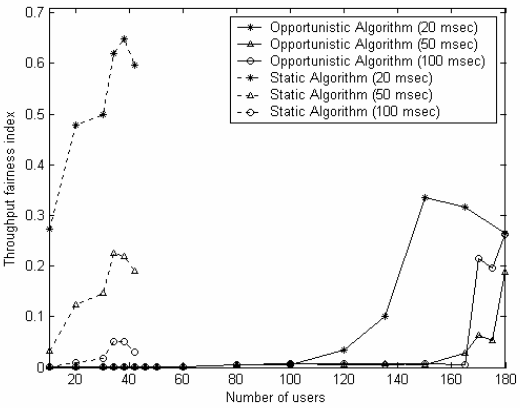

Figure 4: Throughput fairness indices of both the opportunistic algorithm and the static algorithm for different delay bounds

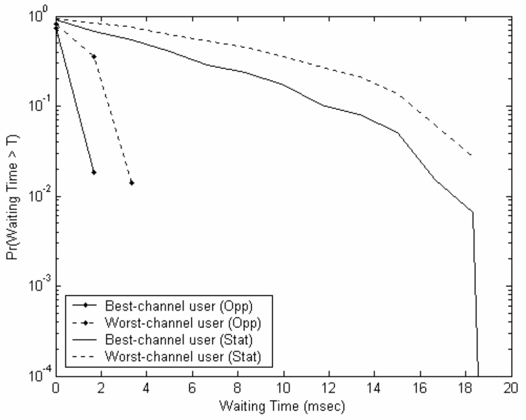

Figure 5: Delay tails of the best and worst channel users for a 20 msec delay bound and 42 users (5.3% and 48.5% of the best and the worst users packets were lost).

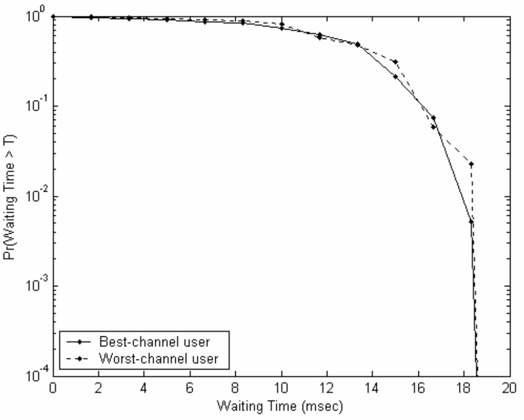

Figure 6: Delay tails of the best and worst channel users for a 20 msec delay bound and 120 users (1.5% and 2.3% of the best and the worst users packets were lost).