Statistical QoS Assurances for High Speed Wireless Communication Systems

F. Ozan Akgül and M. Oğuz Sunay

***Abstract*— In this paper we propose the use of statistical QoS guarantees for transmission over the wireless channel. Here, instead of QoS assurances, we propose to guarantee the percentage of time the QoS requirements are satisfied. We present an associated scheduling algorithm for the opportunistic multiple access system. We compare the proposed scheduler with popular schedulers from the literature. We observe that the statistical QoS guarantee is an attractive alternative to the assured QoS service for the wireless platform, since such strict QoS assurances decrease the wireless system performance significantly.**

***Index Terms*– Wireless packet data provisioning, resource allocation, scheduling, QoS, 3G, 1xEV-DO.**

I. INTRODUCTION

With the ever increasing use of the Internet, there is a significant interest in making this technology available anywhere, anytime. To this end, research in wireless systems has lately focused on providing high speed packet data access. Recent advances in the design of wireless packet data systems have made it possible to achieve higher spectral efficiencies and thus higher system throughput. Such enabling technologies for high speed wireless data have also brought up possibilities for the provision of a multitude of services in addition to the traditional voice service. Streaming video, and audio as well as broadcast of multimedia content are a few such examples. As a result, wireless system designs of today need to explicitly take the quality-of-service (QoS) requirements of the services offered.

The term QoS may imply different service provisioning policies in several different contexts. It may be regarded as having a certain maximum delay requirement for packets, a certain minimum throughput level or a certain maximum data loss rate. In this paper we regard QoS as a certain minimum average data rate intended to be supplied to active users over a certain time window.

The current Internet provides only best effort type of service to all subscribers. Enhanced services to the Internet are being studied and a number of proposals are on the table. IETF's Differentiated Services (DiffServ) Working Group [1] propose offering QoS in terms of Assured Forwarding [5] and Expedited Forwarding [7] for the packet data transmission. Expedited Forwarding corresponds to a low loss, low latency, low jitter, assured bandwidth service whereas Assured Forwarding further classifies services into 4 classes and 3 degrees of drop precedence (high, medium, low). Each of these DiffServ mechanisms correspond to a Per Hop Behavior (PHB) Group [1]. The PHB Groups may be specified in terms of their observable traffic characteristics (e.g delay, throughput).

QoS assurances in the form of Expedited Forwarding or Assured Forwarding can become prohibitively costly in wireless systems. This is due to the time-varying and error-prone nature of the wireless channel. If QoS assurances are given to users, the wireless system design needs to ensure that even when all users' channels deteriorate simultaneously, the QoS requirements of these users are still satisfied. Physical layer resources need to be reserved accordingly, resulting in poor spectral efficiency. In fact, one can argue that, for practical purposes, it is very difficult to provide QoS guarantees in wireless systems, unless the QoS requirements are no more stringent than the current voice service.

An intermediate level for the definition of QoS is necessary then for wireless communications, between best effort and expensive and spectrally inefficient guaranteed service. In this paper, building on [2] we investigate a definition that is neither. Instead, we propose the use of statistical QoS guarantees. Specifically, we propose a wireless system where the QoS requirements are guaranteed to subscribers for a given percentage of time (PoT) . This definition allows flexibility to the physical layer resource allocation protocol so that the system profits from the channel fluctuations of the users rather than being penalized.

The definition of the PoT QoS assurance fits perfectly into the opportunistic multiple access scheme described in [9]. The opportunistic multiple access scheme allocates (schedules) all physical layer resources to only one user at a given predefined time slot. If the user observing the best channel conditions is scheduled for service at a given time, the scheme is shown to be optimal in terms of system throughput in frequency flat fading channels [9]. In opportunistic multiple access, adaptive coding and modulation need to be employed for each scheduled user so that the transmission is done at the highest possible data rate that is allowed by the current channel conditions [3]. The recently standardized 3G system, IS-856, is a packet data only system that utilizes opportunistic multiple access with adaptive coding and modulation [15].

At the heart of the opportunistic multiple system there is a scheduler that selects which user to service at a given time instance and its proper design is key in ensuring satisfactory system performance [14]. The scheduler allocates the system resources to different users in a time-multiplexed fashion. The choice of the scheduling algorithm affects the system throughput as well as the average delay experienced by users in between successive accesses to the system. The throughput-optimal scheduling rule is one where the user with the best channel conditions is scheduled for service for each time slot. In such a scenario, the larger the number of users in the system, the more likely it is to find a user experiencing a really good channel resulting in a better system throughput. This is referred to as multi-user diversity in the literature. The throughput optimal scheduling algorithm would be impractical as users closer to the base station would almost always observe better channel conditions than those further away and thus would grab the system resources continuously, starving the others for service. Then, ideally scheduling algorithms that provide fairness across subscribers while utilizing multi-user

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Manuscript received 28 September, 2006.

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TABLE I
AVAILABLE DATA RATES IN IS-856

Data Rate (kbps)	Slots	Packet Size (bits)	Code Rate	Modulation
38.4	16	1024	1/5	QPSK
76.8	8	1024	1/5	QPSK
153.6	4	1024	1/5	QPSK
307.2	2	1024	1/5	QPSK
614.4	1	1024	1/3	QPSK
307.2	4	2048	1/3	QPSK
614.4	2	2048	1/3	QPSK
1228.8	1	2048	1/3	QPSK
921.6	2	3072	1/3	8-PSK
1843.2	1	3072	1/3	8-PSK
1228.8	2	4096	1/3	16-QAM
2457.6	1	4096	1/3	16-QAM

diversity as much as possible are desirable. The study of scheduling algorithms is an active research topic.

This paper aims to show that an opportunistic multiple access scheme, such as IS-856, can provide PoT QoS assurances to its customers using an appropriately defined scheduling algorithm. Here, we present one example of such a scheduler, and show that it outperforms the traditional schedulers from the literature in providing statistical QoS assurances. The IS-856 system is described for a bandwidth of 1.25 MHz and provides peak data rates of over 2 Mbps. When the QoS requirements are stringent and a moderate number of subscribers are active in the system, this bandwidth may not be sufficient to properly operate the system. A multi-carrier extension of the IS-856 system is also studied in this paper that operates on a bandwidth of 5 MHz.

The rest of the paper is organized as follows: in Section II, we provide a brief overview of the IS-856 system and its multi-carrier extension. A brief overview of the traditional scheduling algorithms from the literature is given in this section as well. Building on these schedulers, we develop a statistical-QoS scheduler in Section III and provide a detailed, comparative performance analysis in Section IV. Finally, we conclude the paper with conclusions in Section V.

II. OVERVIEW OF THE IS-856 SYSTEM

The wireless system under consideration in this paper is the recently standardized North American 3G system for packet data, IS-856 [15]. IS-856 offers spectrally efficient high data rate access by jointly utilizing the findings of [9] and [3] which state that the maximum spectral efficiency is achieved when one is able to adjust the transmission modulation, coding and power according to the changes of the channel characteristics and that it is best to provide all of the resources of the system to serve to only one user at a given time if the communication channel experiences frequency flat fading. Indeed, over a single-carrier of 1.25 MHz bandwidth (referred to as 1x), the IS-856 system divides the time into slots of length 1.67 ms and allocates all of its resources to a single user at a given time slot. A scheduler located at the base station decides which user to service at a given time slot. To aid the scheduling operation, all active users send channel quality feedback to the serving base station every 1.67 ms. Once a user is scheduled, based on the observed channel quality between the base station and this user, the modulation and coding levels are adjusted to provide transmission at the maximum possible data rate while ensuring a given level of packet error rate (=1% in IS-856).

Adaptive coding and modulation allows for a total of 12 signaling schemes in IS-856 with 9 distinct data rates. Each signaling scheme has a corresponding physical layer packet size. In IS-856, the physical layer packet is defined as the block in which the information data is encoded. 4 physical layer packet sizes are defined in IS-856 revision 0. The notion of the physical layer packet is there to ensure that there is always a sufficient amount of data bits for the error control coding algorithm regardless of the transmission rate. Clearly, this results in physical layer packets sometimes spanning multiple slots depending on the data rate. The available data rates that can be served to the users in the IS-856 system are given in Table 1 along with the associated modulation and coding levels and the number of time slots necessary to transmit the physical layer packets.

When more than one slot is allocated for the transfer of information data, the transmit slots use a 4-slot interlacing to perform a simple hybrid ARQ operation. Here, the transmit slots of a physical layer packet are separated by three intervening slots, and slots of other physical layer packets are transmitted in the slots between these transmit slots. If a positive acknowledgement is received on the reverse link ACK Channel before all of the allocated slots have been transmitted, the remaining slots of the physical layer packet need not be transmitted and the next allocated slot may be used for the first slot of the next physical layer packet transmission. In this case, the net effective transmission rate of the physical layer packet is increased.

In IS-856, the MS, using the time-multiplexed pilot channels to produce estimates of the SNR levels from each BS, selects the best possible server. Based on the SNR level from the serving BS, the MS can then determine the highest data rate that it can support at the required packet error rate. The data rate used to transmit the information packet is determined by channel conditions. When conditions are unfavourable, a lower data rate with more slots is used. As stated earlier, each BS transmits to only one MS at any given time in IS-856. If there are more than one MS requesting service at any given time, the BS must select which mobile to transmit to using a scheduling algorithm. To aid the BS with this process, each MS sends a message indicating the maximum data rate it can support on the downlink every 1:667 ms:

A multi-carrier option for IS-856 is easily feasible where an integer multiple of neighboring carriers are used simultaneously by a base station. The simplest implementation of such a system would be to use exactly the same air interface as the 1x IS-856 for each of the carriers. In this case, for a system with n carriers, the scheduler can schedule up to n users in parallel and allocate all of the per-carrier resources to the scheduled users at a given time. It may be possible for a user to get scheduled for some or even all of the n carriers at the same time. Thus the peak data rate for the multi-carrier IS-856 is effectively $n \times 2.4576$ Mbps. The 3x IS-856 resource allocation is illustrated in Figure 1. In multi-carrier opportunistic multiple access, the scheduler may need to decide which user to schedule for each of the carriers by incorporating information from all of the carriers. Indeed, the active users need to send channel quality feedback for all of the carriers to the serving base station. Since scheduling of a given user for service in one of the carriers affect its QoS performance, the scheduler cannot perform resource allocation independently for each carrier.

Numerous schedulers have been studied in the literature for systems employing opportunistic multiple access, including the 1x IS-856, with the aim of offering various notions of

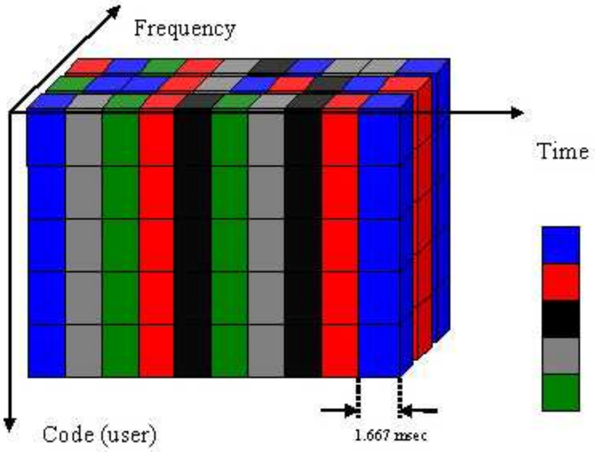

Fig. 1. Resource Allocation in Multi-Carrier Opportunistic Multiple Access

fairness among users without deviating too much from the throughput optimal operating point. Next, we provide a brief overview of some of the scheduling algorithms from the literature.

A. Round Robin Rule

One well-known scheduling scheme is the Round Robin (RR) rule. In RR scheduling, the users are selected in cyclic order without any regard to their channel conditions unless they are in outage. If no user ever experiences outage, this scheduling has the highest level of fairness in terms of resource use time amongst users. However, the system performance suffers from low average throughput since multi-user diversity is not exploited.

B. Maximum Rate Rule

The maximum rate (MaxR) rule aims to maximize the overall system throughput without any delay or fairness constraints. This algorithm is theoretically the optimal algorithm for the total system capacity [9]. However it cannot be directly implemented in practice since it may cause user starvation. The rule schedules user s such that,

$$s = \text{arg max}_i \left(R_i(t)\right) \tag{1}$$

where $R_i(t)$ is the data rate user i can support at time t. If all active users in the system have independent, identically distributed carrier-to-interference (C/I) distributions, the maximum rate rule not only provides the maximum network throughput, but also provides equal time share amongst the users in the long run. However, in a cellular system, it is obvious that the C/I distributions of the users will not be identical. The users further away form the base stations will have distributions with means lower than those of users that are closer to the base stations. For this reason, the maximum C/I scheduler is likely to cause unfairness across users and at worst, user starvation and thus is not suitable for practical use.

C. The Proportional Fair Rule

The proportional fair (PF) rule as described by [8] serves a user whose current channel condition relative to its own mean (averaged over a certain window) is the best. The rule schedules user s such that,

$$s = \text{arg max}_i \left(\frac{R_i(t)}{\overline{R_i(t)}}\right) \tag{2}$$

where $\overline{R_i(t)}$ is the average rate actually provided to user i over a window of size W_s. W_s is chosen as 1000 slots in this paper.

The PF rule aims for fairness through the observation that the user with a geographically closer location to the base station will most likely have a higher average throughput than a user at the cell boundary. Since, the PF rule only ranks the users according to their instantaneous channel qualities relative to their own average channel conditions, the users that have higher average throughputs are not necessarily at an advantage.

D. The Exponential Rule

The authors in [12] describe an exponential scheduling algorithm that takes into account the delays of the head of line (HOL) packets in the user queues as well as the current channel conditions of the users to find a compromise between fairness of the user observed latency and the overall system throughput. The rule schedules user s such that,

$$s = \text{arg max}_i \left(\frac{R_i(t)}{\overline{R_i(t)}}\right) \exp\left(\frac{L_i(t) - \overline{L}}{1 + \sqrt{\overline{L}}}\right) \tag{3}$$

where $L_i(t)$ is the latency of the HOL packet for user i at time t and $\overline{L}$ is defined as the observed latency averaged across all users.

In (3), a large latency observed by one of the users relative to the overall average latency results in a very large exponent, overriding the channel conditions and leading to the large latency user getting priority. On the other hand, for small latency differences, the exponential term is close to 1 and the policy is only ruled by the experienced user channel conditions relative to their own means.

E. Minimum Performance Rule

The authors in [11] describe a scheduling algorithm in which users are guaranteed a certain minimum throughput. The minimum throughput can be chosen differently for each user. The algorithm selects user s such that,

$$s = \text{arg max}_i \alpha_i(t) U_i(t) \tag{4}$$

where $\alpha_i(t)$ is a parameter with a minimum value of 1 (also the initial value for each user) that is updated every slot and $U_i(t)$ is the performance value of user i in time slot t. The performance value we are going to assume in this paper will be the throughput of a user normalized to the lowest throughput available in the system. For IS-856, the lowest throughput is 38.4 kbps so a user with a scheduled transmission rate of 614.4 kbps would, as the performance value, have 16.

The update of the parameter $\alpha_i(t)$ is made using a stochastic approximation [10] and includes the minimum performance guarantee. The update is as follows:

$$\alpha_i(t) = \max\left(\alpha_i(t-1) - a[\overline{R_i(t)} - C_i], 1\right) \tag{5}$$

where $\overline{R_i(t)}$ is the average user data rate and C_i is the minimum guaranteed performance value for user i specified in this paper as the desired QoS value in terms of the average data rate.

TABLE II

SYSTEM PARAMETERS AND FORWARD LINK BUDGET.

Carrier Frequency	2 GHz
Radiation Pattern	Omnidirectional
Path Loss Model (dB)	$30\log_{10} f_c + 49 + 40\log_{10} d$ $d(km), f_c(MHz)$
Log-normal Shadowing	4.3 dB variance
Short term fading	Rayleigh with Jakes spectrum
Total Forward Traffic Channel Tx Power	52.8 dBm

TABLE III

ADDITIONAL SYSTEM PARAMETERS FOR 3X.

Carrier Frequencies	1.99875 GHz, 2 GHz, 2.00125 GHz
Correlation Between Carriers	$1/(1+[\Delta f/B_c])$ Δf= Carrier Frequency Separation B_c= Coherence Bandwidth

III. QOS AWARE SCHEDULING ALGORITHM FOR IS-856

As stated before, the goal of this paper is to develop a scheduling algorithm for wireless opportunistic multiple access systems such that QoS guarantees may be offered to users statistically. Furthermore, the appropriate scheduler should be fair to all its users in terms of these QoS assurances. The above described scheduling algorithms in their originally proposed forms do not have satisfactory QoS performances in terms of the percentage of time performance (PoTP).

A fair scheduling algorithm that aims for statistical QoS assurances should incorporate the QoS parameters directly into the decision process. We propose to use a modified version the exponential rule for this purpose. Our motivation for using the exponential rule is that instead of equalizing weighted delays of the queues, it is easily possible to equalize the average data rates of all the users with respect to the QoS requirements, provided that the QoS requirements (desired average data rates in this paper) for all of the users are the same. However, the proposed scheduling algorithms can also be extended for use in a wireless system that provides a multitude of services, each requiring different QoS values. The proposed Statistical QoS Aware Exponential scheduling algorithm can be described as follows:

1) For each of the carriers select user i that provides the largest argument

$$s_i = R_i(t)\exp\left(\frac{QoS - \overline{R_i(t)}}{1+\sqrt{QoS}}\right) \tag{6}$$

where QoS is the minimum average data rate requested by the service under consideration.

2) Check the current supported data rate of the selected user, $R_i(t)$.

3) If the current requested data rate for the selected user is equal to or greater than a certain threshold, $R_i(t) \geq T(t)$ service this user. The threshold values are a function of the number of active users in the system and is determined and stored a priori at the base station. Threshold values providing the best statistical QoS measures may be found via numerical optimization tools. Simulations may be run for all possible threshold values and the set providing the best performance may be chosen.

4) Otherwise select user j with the next highest argument, s_j, and proceed with step 2 until all the users are exhausted in the user array.

5) If none of the users satisfy the threshold requirement, select the user with the highest argument regardless of its requested data rate.

In (6), if the average data rate of a user falls below the QoS requirement by more than order $\sqrt{QoS}$ the exponential term dominates, overriding the $R_i(t)$ term, thus favoring this user over users with better channel conditions. When the average data rate is close to the desired QoS, the exponential term is close to 1 and the algorithm behaves like the MaxR scheduler.

Without the steps 3-4, the proposed algorithm favors a user whose QoS level is below and furthest away from the desired QoS level over other users with better QoS levels. If, however, the scheduled user with the lowest QoS level also happens to have a low transmission data rate, $R_i(t)$, the scheduling operation will not provide a significant increase in the average data rate. In fact, the data rate may be so low that the QoS, even after the user is scheduled, may not get close to the minimum desired threshold. In this case, the system resources of time and transmission power will be spent with no apparent benefit to the scheduled user. Furthermore, users that may actually benefit from utilizing these resources will not have access to them. The threshold operation is there to weed out such users from getting scheduled. This way, users in critical conditions with transmission data rates that are actually beneficial to them get priority over users in critical conditions that have no way of immediate recovery. The threshold levels are clearly functions of number of users as well as the specific QoS requirement. As the number of users increase, thresholds also increase. Similarly, an increase in the desired QoS level also results in an increase in the threshold level. Figure 2 presents the optimized threshold values for the 1x and 3x IS-856 system. The thresholds are computed using a simple optimization of the PoTP QoS via simulations. The details of the simulation set-up for this purpose is given in the next section.

IV. PERFORMANCE OF THE STATISTICAL QOS AWARE SCHEDULER

To assess the relative performance of the proposed statistical QoS aware scheduler and the scheduling rules from the literature described in the previous section, we have performed detailed simulations of the IS-856 system for both single carrier and multi-carrier options.

We consider a 2-tier 19-cell environment. Here, the first tier has 6 and the second tier has 12 cells centered around the cell of interest. Each cell is considered to have a radius of 1 km in the layout. We assume that users are dropped uniformly over the center cell. For each user, the signal to interference plus noise (SINR) is calculated using the ITU pedestrian A channel model for each of the carriers [6]. The channel model includes path loss, Rayleigh fading and shadow fading effects. In modeling the pedestrian A channel we have assumed that the receiver can capture only 97% of what was transmitted. The link budget and the system parameters are summarized in Table II.

The multi-carrier system has the same propagation model of Table II for each carrier. However, if the sub-carriers are adjacent, inter-carrier correlation needs to be taken into account as well. The additional system parameters for the 3x multi-carrier system are given in Table III.

The sampling rate for the simulations is 600 Hz which also corresponds to the channel quality feedback rate from all the users in IS-856. The simulations have been performed for 18000 slots corresponding to 30 seconds of real time.

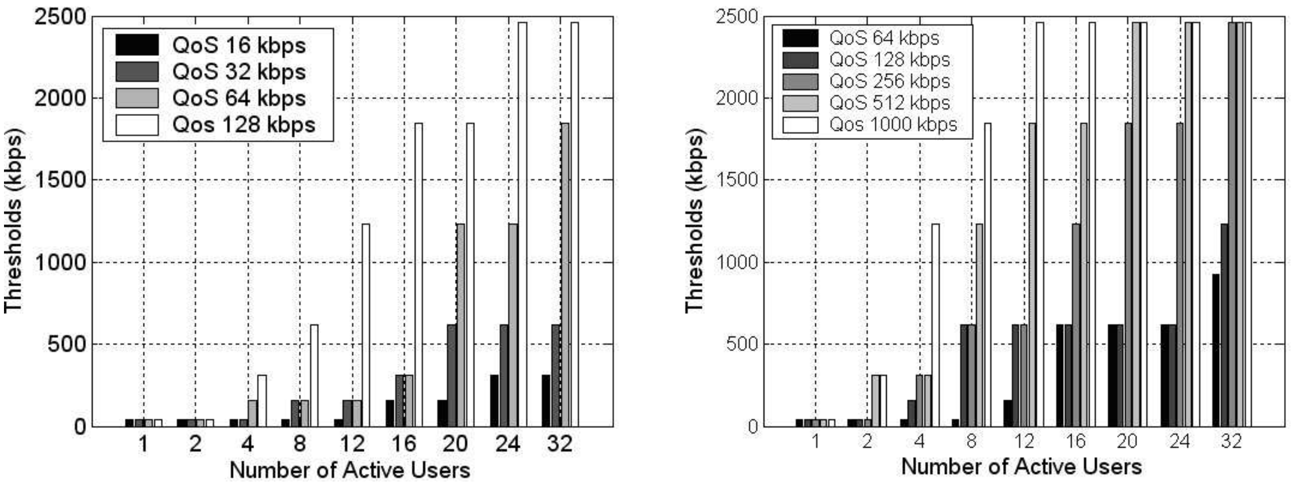

Fig. 2. Optimized threshold values for the 1x and 3x IS-856 System

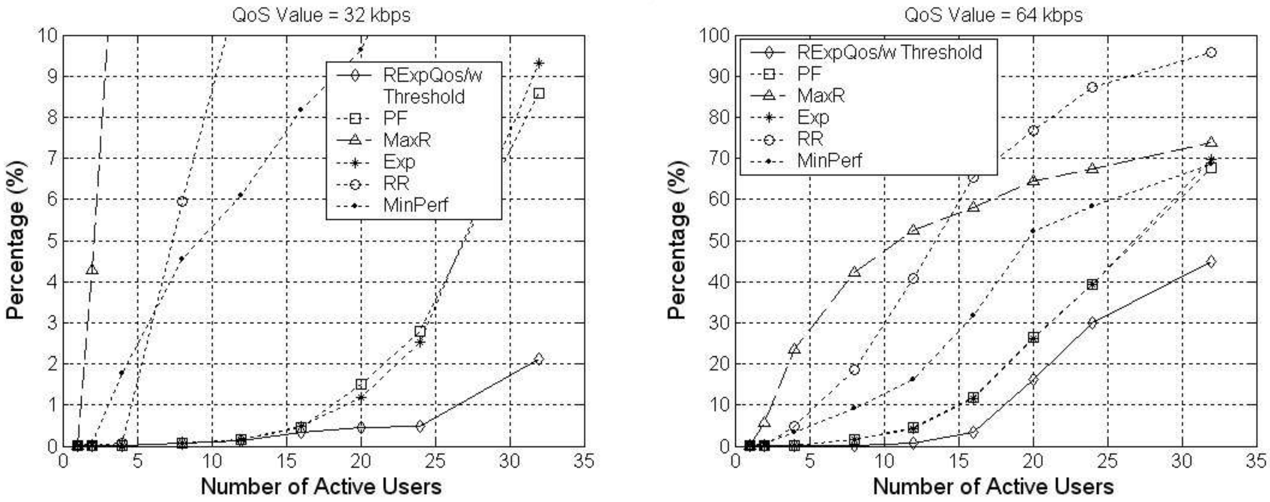

Fig. 3. PoT QoS is not satisfied for QoS = 32 kbps and 64 kbps for 1X

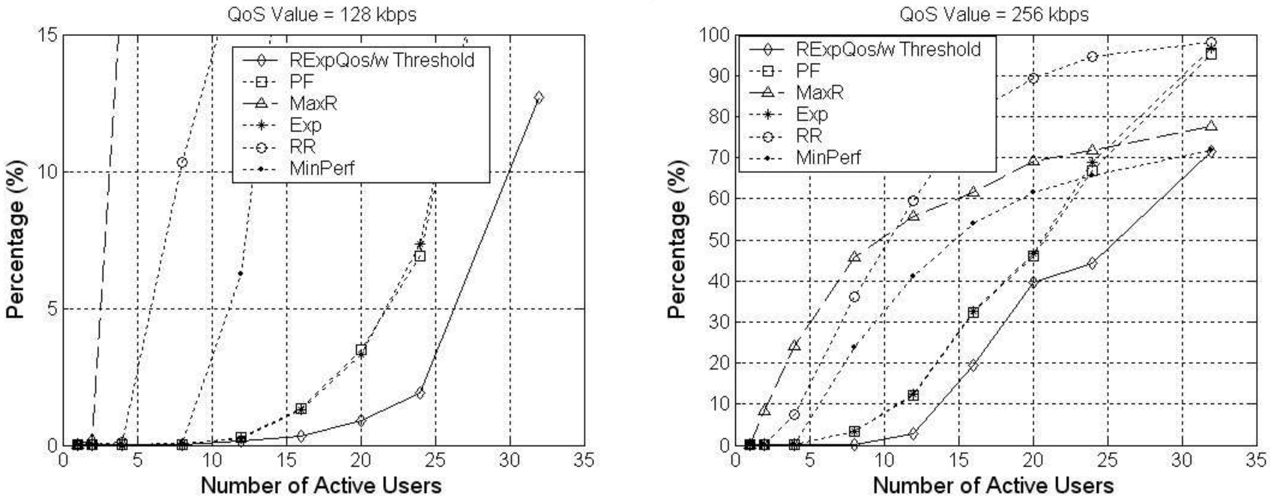

Fig. 4. PoT QoS is not satisfied for QoS = 128 kbps and 256 kbps for 3X

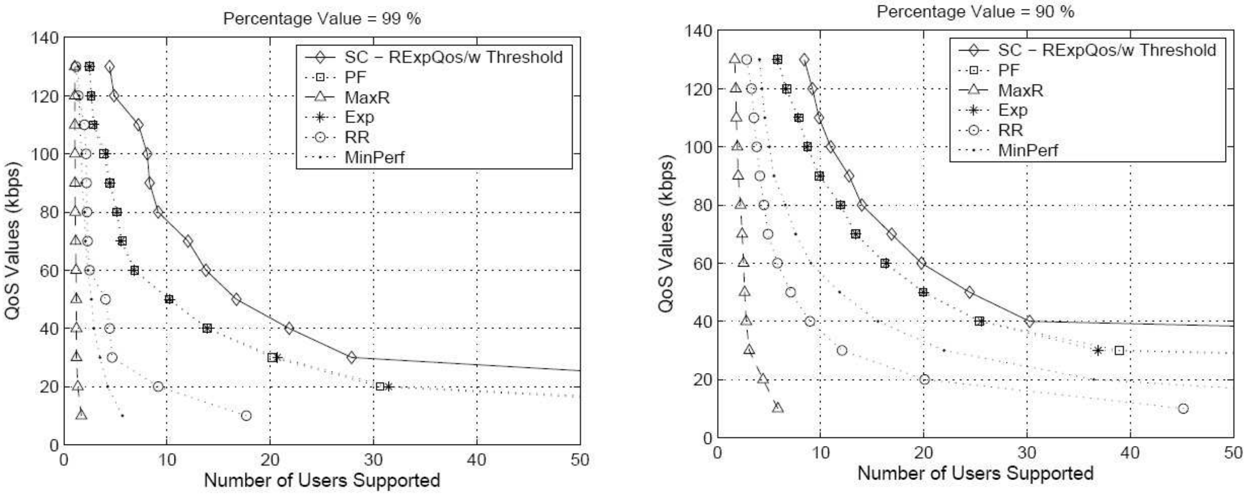

Fig. 5. Supported QoS Levels versus Number of Users at the 99% Operating Level

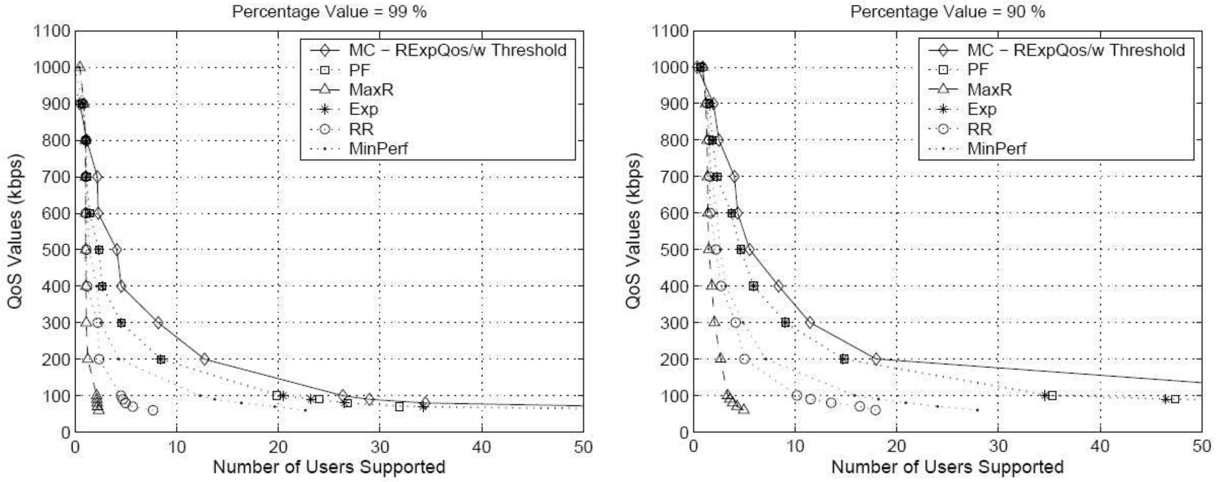

Fig. 6. Supported QoS Levels versus Number of Users at the 90% Operating Level

For each time slot, the SINR value of each user is used to generate the channel quality feedback of the users and these values are used in the scheduling simulations to obtain PoT results.

Simulations have been performed to obtain the PoTP values for different scheduling algorithms based using the above described set-up. Figures 3 and 4 show the percentage of time the desired QoS is not satisfied as a function of the number of users for the proposed scheduling algorithm as well as the traditional algorithms from the literature for the single carrier and multi-carrier IS-856 system, respectively. Desired data rates of 32 kbps and 64 kbps are considered for the single carrier and 128 kbps and 256 kbps for the 3x multi-carrier system. From the graphs we can see that the proposed scheduling algorithm performs significantly better than the other scheduling algorithms for all of the QoS requirements. In fact, when the desired QoS level is relatively low, the difference between the proposed algorithm and the rest can be as high as 5-fold. For larger QoS levels and high number of users, the difference between the performances is reduced. This is because, the system operates near its full capacity in this case and even the best scheduler can not handle all of the active users at the same time.

Figures 5 and 6 illustrate results for the supported QoS levels at 99% and 90% operating levels as a function of number of users. In this illustration, it is once again clear that the proposed scheduler outperforms the others significantly. Once again, as the system capacity is neared, the gains somehow decrease, but gains are observed at all operating levels.

V. CONCLUSIONS

In this paper we have introduced the notion of statistical QoS assurances as a feasible alternative to assured QoS in wireless time-varying and error-prone channels. We have proposed a new scheduling algorithm for the IS-856 system that takes the statistical QoS requirements directly into account. Both single carrier and multi-carrier wireless systems are considered. The multi-carrier system naturally provides higher data rates and thus is capable of reasonable quality streaming video transmission over the wireless channel.

The proposed scheduling algorithm is shown to perform significantly better than previously developed scheduling algorithms from the literature. In fact, for the single carrier system, an average data rate of 60 kbps may be guaranteed 99% of the time for only 1 user using the maximum rate scheduler, 2 users using the round robin and minimum performance schedulers, 7 users using the exponential and proportional fair schedulers. The proposed scheduler on the other hand, provides this guarantee for 13 users, over 50% more users than the best performing scheduler from the literature. Similarly, for the 3x multi-carrier system, a data rate of 200 kbps may be guaranteed 99% of the time for only 1 user using the maximum rate scheduler, 2 users using the round robin, 4 users using the minimum performance scheduler, 8 users using the exponential and proportional fair schedulers. The proposed scheduler in this case provides the service for a total of 13 users, once again an over 50% increase over the best performing scheduler from the literature.

We conclude that the proposed statistical QoS assurance idea and the associated scheduling algorithm works very well for the wireless channel and is a perfect fit for the opportunistic multiple access scheme.

REFERENCES

[1] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, and W. Weiss, “RFC 2475: An Architecture for Differentiated Services”, *IETF*, December 1998.

[2] D. Clark and J. Wroclawski, “An Approach to Service Allocation in the Internet”, *Internet Draft*, MIT LCS, July 1997.

[3] A. J. Goldsmith and P. P. Varaiya, “Capacity of Fading Channels with Channel Side Information,” *IEEE Transactions on Information Theory*, vol. 43, no. 6, June 1997, pp. 1986-1992.

[4] M. Gudmundson, “Correlation Model for Shadow Fading in Mobile Radio Systems”, *Electronics Letters*, vol. 27, November 1991, pp. 2145-2146.

[5] J. Heinanen, F. Baker, W. Weiss, and W. Wroclawski, “Assured Forwarding PHB Group”, *RFC 2597*, June 1999.

[6] International Telecommunication Union, “Guidelines for Evaluation of Radio Transmission Technologies for IMT-2000”, *Recommendation, ITU-R, M.1225*, 1997.

[7] V. Jacobson, K. Nichols, and K. Poduri, “An Expedited Forwarding PHB Group”, *RFC 2598*, June 1999.

[8] A. Jalali, R. Padovani, and R. Pankaj, “Data Throughput of CDMA-HDR: A High Efficiency-High Data Rate Personal Communications System”, in *Proc. IEEE VTC ’00*, Tokyo, Japan, May 2000.

[9] R. Knopp and P. Humblet, “Information Capacity and Power Control in Single Cell Multi-User Communications”, in *Proc. IEEE ICC ’95*, Seattle, USA, June 1995.

[10] X. Liu, E.K.P. Chong, and N. Shroff, ”Opportunistic Transmission Scheduling with Resource-Sharing Constraints in Wireless Networks”, *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 10, October 2001, pp. 2053-2064.

[11] X. Liu, E.K.P. Chong, and N. Shroff, “Transmission Scheduling for Efficient Wireless Resource Utilization with Minimum-Performance Guarantees”, in Proc. *IEEE INFOCOM 2001*, Anchorage, Alaska, USA, April 2001.

[12] S. Shakkottai and A. Stolyar, “Scheduling Algorithms for a Mixture of Real-Time and Non-Real-Time Data in HDR”, *Bell Laboratories Technical Report*, 2000.

[13] G.L. Stuber, *Principles of Mobile Communications, 2nd Ed.*, Kluwer Academic Publishers, 2001.

[14] M.O. Sunay and A. Ekşim, ”Fair Scheduling for Spectrally Efficient Multi-service Wireless Data Provisioning”, *Wiley International Journal of Communication Systems*, vol. 17, no. 6, August 2004, pp. 615-642.

[15] TIA/EIA/IS-856 “cdma2000 High Rate Packet Data Air Interface Specification”, *3GPP2*, C.S0024, v4.0, October 2002

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