Channel-Aware Soft Bandwidth Guarantee Scheduling for Wireless Packet Access

Hung-yu Wei
Columbia University
New York, NY, USA
hywei@ee.columbia.edu

Rauf Izmailov
NEC Laboratories America
Princeton, NJ, USA
rauf@nec-labs.com

***Abstract*— The huge demand and growth of high-speed mobile data applications drive the development of the next generation wireless systems. The emerging 3G cellular networks provide new wireless access technologies for high-speed downlink packet access. The variable nature of wireless channel quality brings up challenges and opportunities for wireless system design. By utilizing channel state information, the next generation wireless packet systems provide high data rate communications with adaptive modulation and coding. To provide Quality of Service (QoS) in such systems is an important engineering issue. In this paper, we propose a novel scheduling algorithm that supports assured QoS. Due to the unpredictability and volatility of wireless medium, wireless QoS design tends to focus on soft QoS guarantee instead of hard one. The proposed scheme can effectively guarantee soft rate reservation and provide high-speed connections with channel-aware radio resource allocation without compromising fairness.**

I. INTRODUCTION

High-speed data applications over wireless networks have been growing rapidly compared to traditional cellular voice services. The third generation (3G) cellular system introduces high-speed data access design in addition to their voice access. Traffic characteristics of data applications, such as Web browsing, suggest an asymmetric and burst pattern. In general, downlink traffic demand is much greater than the uplink traffic. Due to the high throughput demand of downloading data to cellular handsets, system engineers focus on designing high-speed data system for wireless downlink access. CDMA 2000 adopts HDR [5] architecture to provide high data rate services. Similarly, WCDMA introduces HSDPA [6] to offer high-speed downlink data services. These systems utilize instantaneous channel state information and achieve high-speed time division radio resource allocation.

The scheduling algorithms in wireless packet networks should provide channel-aware, high-speed, and fair radio resource allocation. A good wireless scheduler should also provide Quality of Service (QoS), which can be in the form of differentiated QoS, assured QoS, or both. Because of wireless channel quality variation, it is extremely difficult to provide hard (absolute) QoS guarantee. Wireless systems are usually designed to provide soft QoS. We propose a scheduling algorithm to provide assured QoS with soft rate reservation over the next generation wireless data systems.

The proposed CARR (Channel-Aware Round Robin) scheme utilizes channel state information to enhance system throughput. CARR scheduler guarantees to allocate certain amount of time slots to users within each assignment round. The achievable rate is determined by the actual SINR over the allocated time slots. Therefore, it will provide absolute time slot assignment guarantee and soft data rate reservation. It can also provide fair and smooth resource allocation. Variants of CARR can be used in a flexible QoS framework that features both guaranteed QoS and high data rate best effort service. The flexible architecture is suitable for mixed Assured Service/Best Effort service classes.

II. RELATED WORK

We could categorize wireless scheduling algorithms into two types: Generalized Processor Sharing (GPS)-based schedulers and rate-based schedulers. GPS-based scheduling schemes follow the GPS principle [4] and apply it to wireless networks [3]. Rate-based scheduling schemes [2,7] allocate link-layer time frames at the base station of wireless high-speed packet access networks. The rate-based scheduler could utilize channel state information and previous allocation history to optimize the system performance. Round robin scheduling, proportional fair scheduling and C/I scheduling belong to this category. For further information regarding wireless scheduling, we refer readers to a comprehensive review of wireless scheduling algorithms provided in [1].

The proposed soft-QoS guarantee scheduler CARR (Channel-Aware Round Robin) belongs to the class of rate-based schedulers. The main design goal is to provide soft guaranteed Quality of Service at the link-layer frame level. CARR and other rate-based scheduling schemes have certain advantages over GPS-based schemes. GPS-based schemes are more suitable for scheduling tasks on per packet basis. The per-packet time stamping requirement increases the system complexity. Previous GPS-based papers analyzed performance of these schemes using two-state Markov channel model (one error-free state and one error-prone state). These schemes may not be scalable for HSDPA or HDR system when the number of channel states becomes large; for example, there are 11 channel states in HDR. Application of GPS-based schemes to HSDPA RLP frames also encounters scalability problem. Due to the implementation complexity, 3G wireless data systems (e.g. CDMA2000 HDR and WCDMA HSDPA) implement rate schedulers at base stations.

III. Scheduling Algorithm Design

A. Design Concept

Due to random variations of wireless channel quality, it is difficult to provide guarantee on absolute Quality of Service (hard QoS). The research trend on wireless QoS design is either providing soft QoS guarantee or differentiated QoS in wireless systems. Since the time granularity of higher level QoS requirement is much longer than the HSDPA TTI (Transmission Time Interval) scale (2ms), we can provide soft QoS reservation in a more coarse time granularity.

Currently, HSDPA system lacks of mechanism that can provide *guaranteed* Quality of Service. We propose a novel HSDPA scheduling algorithm that provides soft bandwidth reservation and utilizes temporal channel state variation to achieve high data rates. Since the radio channel condition cannot be predicted, the user throughput, which is significantly affected by the radio channel condition, cannot be absolutely guaranteed. However, we can engineer the system so that the number of time slot assignments to mobile terminals can be guaranteed. As a result, the mobile terminals are guaranteed to be assigned some time slots while the actual allocated rates depend on the wireless channel quality during the assigned slots. Mobile terminals are guaranteed to be assigned certain amount of transmission time slots during one assignment *round*, which is in the range of tens or hundreds of time slots.

Round Robin scheduler provides a similar mechanism for soft bandwidth allocation guarantee. Nevertheless, the time slot allocation does not consider the Channel State Information (CSI) of mobile terminals. Failing to utilize CSI to provide adaptive rate allocation leads to suboptimal system performance. On the other hand, C/I scheduling algorithm utilizes CSI to allocate time slots to the best instantaneous quality mobile terminals. Using CSI as the only criterion to assign radio resource results in unbalanced time slot allocation: some users could get excessive allocation while other users could get only limited allocation or no resource at all.

The proposed Channel Aware Round Robin (CARR) scheduling algorithm provides time slot assignment guarantee while allocate time slots according to the instantaneous wireless channel quality. The design goal of CARR is to satisfy the guaranteed time slot assignment constraint in a time assignment *round* while allocating the best possible time slots to mobile users.

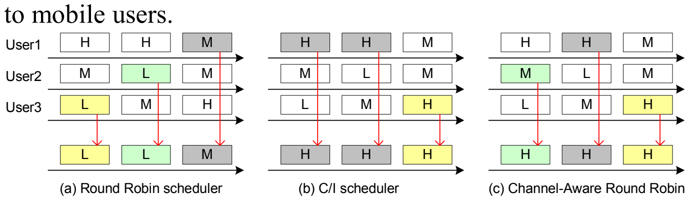

Figure 1: Round Robin, C/I, and CARR scheduler.

Figure 1(a) shows the case with Round Robin scheduling and Figure 1(b) shows an example of C/I scheduling. The supported data rates are denoted as H(high), M(medium), and L(low). Round Robin scheduler allocates one time slot for each user. Regardless of instantaneous channel quality, the first time slot is assigned to user 1. The second time slot is assigned to user 2. The third time slot is assigned to user 3. Even though each user gets one time slot allocation, the quality of the time slots is poor. On the other hand, C/I scheduler allocates the best quality time slots to users; however, the allocation is unbalanced. User 1 gets two good quality time slots while user 3 is not assigned any time slot at all.

CARR scheduler combines good aspects from Round Robin scheduler and C/I scheduler. CARR achieves user fairness in terms of time slots and adaptively allocates radio resource in a channel-aware fashion. The assignment round of CARR is the time granularity of the guaranteed QoS mechanism. We assume there are N mobile terminals in the HSDPA system. During the assignment round of T time slots (assuming T>N), the scheduling algorithm will guarantee that each mobile terminal will be assigned one or more time slots.

At the beginning of the first time slot, the HSDPA scheduler will assign the time slot to the mobile terminal with the best C/I ratio. At the beginning of the second time slot, the HSDPA scheduler will compare the C/I ratios of the (N-1) mobile terminals, excluding the mobile terminal that got the first time slot. The second time slot is assigned to the best C/I mobile terminal among the (N-1) mobile terminals. Likewise, the third time slot will assign to the best C/I terminal among the (N-2) mobile terminals, excluding the mobile terminals that got the previous two time slots. We will continue the similar assignment process until time slot N when every mobile terminal gets exactly one time slot. Afterward, the HSDPA will run the best C/I scheduling algorithm from time slot (N+1) to time slot T. Time (T+1) is the beginning of a new assignment round. The HSDPA scheduler will repeat this assigning process.

Figure 1(c) illustrates an example of CARR scheduling in the same three-user system. The assignment *round* is composed of three time slots in this example. Hence, each user will be assigned exactly one time slot during one assignment round. The first time slot is assigned to user 3 because user 3's channel condition is the best. By comparing the channel condition of user 1 and user 2 at time 2, the second time slot is assigned to user 1. At the last time slot in the round, the time slot is assigned to user 2. Each user is assigned by CARR scheduler 1 good quality time slot during this assignment round.

B. Basic Algorithm: CARR(1,N)

In the basic Channel Aware Round Robin (CARR) algorithm, we assume that there are totally N users {1,2,3,…,N} in the system. The instantaneous data rate of user *k* at time slot *t* is denoted as $r_k(t)$. We use $u(t)=k$ to denote the time slot *t* is assigned to user *k*. One time slot is to be assigned to each user in an assignment round, which is composed of T time slots (T=N in basic CARR scheme). The set A includes users who are eligible to get time slot assignment in this round. At the beginning of each round, we initialize $A=\{1,2,3,\ldots,N\}$. The first time slot is assigned to the user with the best channel quality at $t=1$. The user who gets the first time slot is removed from the set A; hence, this user is excluded from the forthcoming time slot assignments. The second time slot is assigned to the best quality user among the (N-1) users in set A. Then the assigned user is removed from A. Likewise, we compare the channel quality information at the beginning of each time slot, and assign the time slot to the best quality user among the users who have not received any slots. Since one user gets one time slot in every N slots, this basic algorithm is denoted as CARR(1,N).

```
Basic Algorithm: CARR(1,N)
Initialize A = {1,2,3,......, N}
For t = 1 to N
   k = arg max {r_i(t)}
        i, i∈A
   u(t) = k
   Remove k from the set A
End loop
```

Figure 2: CARR(1,N) -allocate 1 time in every N-slot round

C. *Hybrid Soft QoS Guarantee: CARR (1,N+x)*

In the basic CARR algorithm, one user is given one slot in a round. We can increase the overall system throughput by introducing some flexibility on high data rate assignment. We extend the length of an assignment round in CARR scheduler to ($N+x$) and assign these x time slots to the maximum rate users in a non-guaranteed fashion; thus, this modified CARR scheme becomes a hybrid resource allocation scheme that provides both soft QoS guarantee and best effort service. The notation CARR(1,$N+x$) suggests that every single user is assured to get one time slot in ($N+x$)-slot duration. In every allocation round, x time slots will be assigned to users with the best instantaneous channel quality. The hybrid QoS scheme includes N slots of assured QoS allocation and x slots of Best Effort service.

D. *Adjusting Time Granularity: CARR (k,kN)*

The CARR scheduling can provide soft bandwidth reservation at different time granularities. Depending on the jitter requirements of the application QoS, the modified CARR scheme can guarantee user rate allocation in a longer or shorter allocation round. CARR(k,kN) scheduling algorithm guarantees k time slots to every user in kN duration. The parameter k can be adjusted to provide QoS at an appropriate time scale. The more relaxed time constraint makes the resource allocation more flexible. As a result, the average overall throughput is expected to increase.

E. *Generalized CARR Scheme*

The previously mentioned CARR scheduling variants treat all users equally. All users are given the same degree of time slot allocation guarantee. Here, we describe a generalized CARR scheme that guarantees user j for g_j time slots in one round.

```
Algorithm: Generalized CARR scheme
Notations:
  g_i : g_i slots are guaranteed to be assigned to user i
  f_i : counter that records the time slots will be assigned to user i in this assignment round
  Define g_all = Σ_{∀i} g_i     (Assume g_all <T)
  Initialize f_i = g_i   ,∀i
  For t = 1 to g_all
        k = arg max{r_i(t)}
             i, f_i>0
        u(t) = k
        f_k = f_k − 1
  End loop
  For t = (g_all +1) to T
        k = arg max{r_i(t)}
               ∀i
        u(t) = k
  End loop
```

Figure 3: Generalized CARR scheme

F. *Improve Allocation Quality with Rate Threshold*

The overall throughput of CARR scheduler will increase when applying minimum rate threshold to each allocation. CARR with rate threshold will basically follow the basic CARR(1,N) algorithm. However, before assigning time slots to users, the scheduler checks the instantaneous channel quality of the slot going to be allocated. The supported data rate of user j at time t,$r_i(t)$, is compared with the rate threshold r_{th}. The time slot is assigned to candidate j if $r_j(t)$ is greater than r_{th} or if there is no other available user rate greater than r_{th}. The minimum rate threshold can effectively increase the allocation quality and hence the average throughput. However, it results in a *softer* rate guarantee than the basic CARR scheduler because users no longer have absolutely hard guaranteed time slot allocation during each assignment round. Choosing an adequate rate threshold could benefit the system performance and avoid wasting time assignment to users in bad channel condition.

```
Algorithm: CARR with Rate threshold
Notations:
 r_th = constant rate threshold
Initialize A={1,2,3, …, N}
Initialize Cnt = T-N
Initialize t =1
While {t < T}
        If {A is not empty}
                j = arg max {r_i(t)}
                     i, i∈A
                k = arg max {r_i(t)}
                      ∀i
                If {r_j(t) < r_th} AND {r_k(t) >= r_th} AND {Cnt>0}
                        u(t) = k
                        Cnt = Cnt −1
                Else
                        u(t) = j
                        Remove j from the set A
                End If
        Else
                k = arg max {r_i(t)}
                      ∀i
                u(t) = k
        End If
        t = t +1
End while
```

Figure 4: CARR with rate threshold

IV. SYSTEM PERFORMANCE EVALUATION

A. *Performance Evaluation Method*

We conducted wireless packet scheduling simulation on a cell of 1km radius. Ten rounds of simulation were conducted, and each round of simulation consisted of 1000 time slots. The supported user rate is determined from the instantaneous SNR value according to [5]. The radio propagation model is composed of two components: path loss component and shadowing component. The path loss component follows an outdoor to indoor pedestrian signal model [8]. The shadowing component is modeled by lognormal random variable ξ, and $\log_{10}(\xi)$ follows normal distribution with zero mean and standard deviation σ=8 dB.

There are 50 mobile terminals randomly distributed over a cell with uniform density at the beginning of the simulation. The user mobility model follows the Random Waypoint model with speed uniformly distributed between [0,2] m/second, which represents the pedestrian scenario. Our main design objective is to provide a soft bandwidth reservation scheme in high-speed wireless packet system. The intended simulation scenario is that the HSDPA or HDR system provides assured QoS for real-time applications or a hybrid case with both best effort non-real-time and assured real-time applications. We are interested in the scenarios in which traffic will be constant rate application (e.g. Voice over IP) or semi-constant rate application (e.g. buffered streaming video), and traffic load is from moderate to high such that there will always backlog at the base station to be transmitted.

To examine the effectiveness of rate reservation, we look into the cumulative distribution of allocated user rates in assignment rounds. We also examine the degree of unbalanced allocation in terms of both amount of allocated time slots and the achieved user rates. In terms of allocated data rates, we measure the fairness by the standard deviation of data rate allocated to each user during the simulation run. In terms of allocated time slots we can define the time fairness indicator *ft* as normalized average difference between allocated time slots to user j and the average allocated time slots. $ft = \sum_{i=1}^{N} \left[\left| \bar{x} - x_i \right| / N\bar{x} \right]$

B. *Comparison to other schedulers*

We compared the system performance of the proposed CARR scheduling algorithm with other algorithms including C/I, Proportional Fair (PF), and Round Robin (RR) scheduling algorithms in this section. As shown in simulation results, the average user rates in C/I and Proportional Fair scheduler approximate the maximum available data rates. Since there are 50 mobile terminals in one cell, the chance that there exists some maximum rate user will be high. The size of moving average window of Proportional Fair scheduling also affect the average throughput. When the moving average window size increases, the average throughput of Proportional Fair scheduling increases because the allocation criterion weights more on the instantaneous user rate. The simulated Proportional Fair computes the allocated rate moving average from the beginning of the simulation. This high overall throughput is the upper bound of possible achieve overall rate in all Proportional Fair variants.

The proposed Channel Aware Round Robin scheduler has average 41kbps per-user throughput, which is a significant improvement over the poor performance (16kbps) in Round Robin scheduling. CARR also allocates user rate in a balanced way. Unsurprisingly, the time fairness indicator is perfectly zero in CARR and RR. The standard deviation average rate that user *i* get is also small, which means different users in general are allocated fairly in terms of both effective rates and amount of time slots. C/I scheduler achieves high average throughput; however, this is the result of an unbalanced allocation. The median throughput is only 18.43kbps, which implies radio resources are extensively allocated to some users and many other users are starving.

Then, the probability distribution of the allocated rate per user per round is plotted in Figure 5. Both CARR(1,50) and RR can guarantee non-zero rate allocation during one assignment round due to the guarantee time slot allocation. On the other hand, less than 80% of users get non-zero allocation in Proportional Fair scheduling. Even worse, the C/I scheduler allocates the time slots to only 42.26% of users in one round.

The efficiency of bandwidth allocation guarantee is shown in Figure 5. The maximum achievable per user rate is 49.2kbps in this system; this happens when the system allocate all time slots to users with SINR that support maximum data rate. The simulation results show that all of the CARR users can be guaranteed non-zero rate allocation. About 97% of CARR users can get 5kbps or greater in any given assignment round. There are still more than 95% of CARR users can achieve 10kbps. There is about 90% chance that CARR scheduler allocates more than 20kbps to any single user during one assignment round (i.e. 100ms in HSDPA). The results demonstrate the proposed CARR scheduling algorithm can effectively guarantee bandwidth allocation to wireless terminals. On the contrary, there are only 79% of PF users are allocated 20kbps or greater. Only 42.6% of C/I users and 33.6% of RR users can achieve such allocation. PF scheduling provides certain degree of fairness by incorporating the average service rate in its resource allocation criterion. Nevertheless, Proportional Fair cannot provide assured bandwidth reservation.

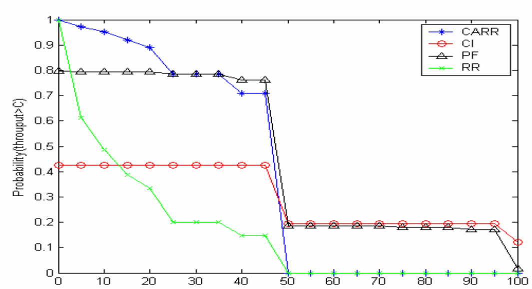

Figure 5: Probability distribution of allocated user rates.

kbps	CARR	CI	PF	RR
mean	41.38	49.15	48.23	16.15
median	42.44	18.43	49.15	12.47
standard dev	7.76	78.91	4.09	11.17
t-fair	0	0.992	0.042	0

Table 1: Statistics of different scheduling algorithms.

C. *Time Granularity in Assured Service: CARR(k,kN)*

Modified CARR(k,kN) allocates each user *k* time slots in every *kN* time slots. The system performance is demonstrated in Figure 6 with different *k* values. As *k* increases the average throughput increases due to the increased flexibility of time slot assignment in longer assignment rounds. Every user is allocated the same amount of time slots; therefore, the time fairness indicator equals zero in all CARR(k,kN) scenario. The longer assignment round results in greater throughput on average and the balanced rate allocation among different users due to the increase in time granularity. According to the application requirement and the tolerance of the transmission delay and jitter, the HSDPA scheduler can choose the appropriate parameter *k* to optimize the system performance.

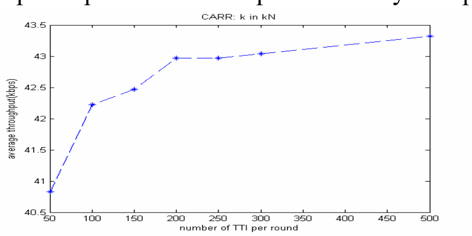

Figure 6: Performance of CARR(k, kN).

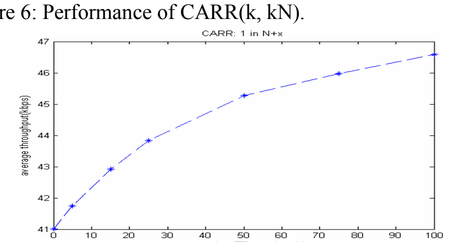

Figure 7: CARR(1,N+x).

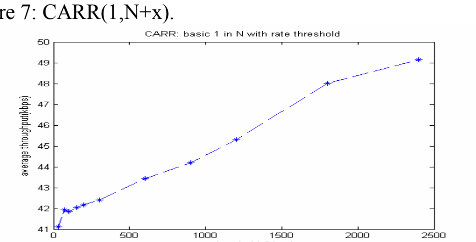

Figure 8: CARR with rate threshold.

D. *Integrated Best Effort and Assured Services*

In this section, we present CARR variants that provide both assured time slot allocation and high speed best effort allocation. In one time slot assignment round, the round is divided into two parts. In the first part, CARR scheduler assigns users with the guaranteed amount of time slots. In the second part, CARR scheduler allocates users with the best signal quality so that the average throughput will be high.

Figure 7 show the performance of an integrated best effort and assured reservation scheduling algorithm. In each assignment round, there are *N* time slots for assured service, and *x* time slots for best effort service with C/I scheduling. CARR(1,N+x) guarantee each user 1 time slot in a *N*+*x* duration. Since *x* models the ratio of C/I best effort service, the average throughput increases with *x*. With large parameter *x*, the CARR(1,N+x) scheduler acts more like a C/I scheduler with high data rate and unfair allocation. The standard deviation of user rate increases as *x* increases. With small parameter *x*, the CARR(1,N+x) scheduler performs similarly to the basic CARR(1,N) scheduler to provide assured service. The average throughput, user rate standard deviation, and time fairness indicator all increase as *x* increases.

E. *Soft QoS with Rate Threshold*

CARR with minimum rate threshold can achieve greater throughput. The average throughput increases as the threshold increases. When the threshold equals 2400kbps, the system throughput is the maximum achievable rate when all allocated time slot can support the maximum rates. However, the rate threshold results in *softer* bandwidth guarantee and more unbalanced rate allocation. When rate threshold increases, the rate standard deviation increases and the time fairness indicator also increases.

F. *Effectiveness of Rate Guarantee*

We demonstrate the effectiveness of rate reservation in different variants of CARR schemes, and compare CARR to the proportional fair scheduling. Only 80% of users under proportional fair scheduling are allocated non-zero rates. On the other hand, CARR variants (except CARR with rate threshold) can 100% guarantee non-zero rate allocation within each assignment round. In CARR with rate threshold, the scheduler still allocates non-zero rate to a high percentage of users (94.6%). Figure 9 (N=50, k=2, x=50) shows that satisfactory user rate guarantee can be achieved in CARR with 900kbps threshold, CARR(1,N), and CARR(k,kN). These schedulers can reserve 20kbps or more (maximum value is about 50kbps) for more than 90% of users in one assignment round. While CARR(1,N+x) scheduler performs like a hybrid rate guarantee scheduler and best effort maximum rate scheduler, there are less than 80% of users can achieve 20kbps or greater rates.

In addition, the duration of an assignment round also affects the effectiveness of rate guarantee. Compared CARR(1,N) to CARR(k,kN), we can see the difference between the CARR curve and the PFair curve in Figure 9. The size of this region represents the degree of rate reservation guarantee in these two schemes. The percentage of users who get 25kbps or greater rates is 79.2% in CARR(1,N) and is 90.2% in CARR(2,2N). It shows that choosing longer assignment round increases the strength of rate guarantee. We should examine the time delay constrains and jitter requirement of applications to tune the CARR assignment round to optimize the system performance.

Besides tuning the *k* parameter in CARR(k,kN) scheme for optimal performance, we also proposed another mechanism to strengthen the rate reservation scheme. The strengthened rate reservation scheme is a modified CARR in which each assignment round is divided into two stages. The first stage is the usual guaranteed time slot assignment. Each user is allocated *k* time slots in this stage. The second stage is the rate compensation stage. Allocated user rates are examined after the first stage allocation. If the allocated user rate is below the *low rate threshold*, poor users will get more compensation at the second stage. Hence, the rate compensation mechanism strengthens the degree of rate guarantee.

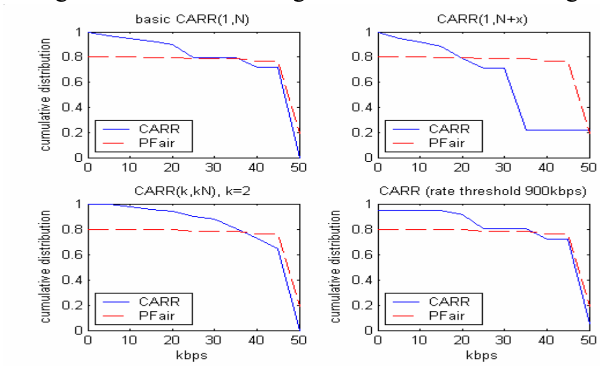

Figure 9: Cumulative distribution of CARR rate in a round.

V. Discussion

A. CARR with Fast Retransmission

Generalized CARR scheme provides flexibility in radio resource allocation. The assignment round can be divided into more than one stage for assured time slot allocation and other types of scheduling algorithms. In HSDPA, hybrid ARQ is used to provide better quality on link layer transmission. Designing a HSDPA scheduler to differentiate the users with and without the need of fast ARQ retransmission can enhance system performance. CARR with fast retransmission has a two-stage assignment round. The first stage is the usual guaranteed time slot allocation. In the second stage, time slots are given to users demanding high priority retransmission. If there are not many users with fast retransmission need, we can allocate time slots to best rate users or apply variable length assignment round.

B. CARR with Handoff

Previously, HSDPA scheduler design mostly considers only the single cell scenario. With multiple cells in a HSDPA system, handoff issue and admission control need to be considered. The simplest scheme to handle handoff users is to allow both existing and arriving mobile terminals to share the *x* best effort time slots. CARR scheduler design can also incorporate time slot reservation for the new arrival mobile terminals. To provide seamless handoff and soft reservation for handoff mobile terminals, each assignment round can reserve several time slots for newly handoff users.

Admission control can also be applied to provide assured QoS. To guarantee higher protocol level service quality, the lower level protocols need to ensure the corresponding mechanisms. More specifically, to provide assured QoS at higher level, there should be assured QoS supports at the link layer. The soft rate reservation feature in CARR is the link layer QoS infrastructure for assured QoS at application level. In addition, the admission control mechanism can ensure the soft rate reservation of current users.

A generic CARR scheduler can be described as CARR (k_{min},$k_{min}N_{max}+x_m$). Parameter k_{min} shows the minimum degree of assured allocation. Parameter N_{max} represents the maximum number of users that can be served in the system. The current system load can be described as CARR(k_t, $k_tN_t+x_t$). The admission control entity compares N_t with N_{max} to decide if the system can admit additional users. For advanced QoS and admission control framework, CARR can also be modified to incorporate different admission control schemes.

VI. Conclusion

The proposed Channel Aware Round Robin (CARR) scheduler provides a method for soft bandwidth reservation in wireless high data rate downlink packet access systems. CARR guarantees users with time slot allocation and also utilizes channel state information to improve the quality of radio resource allocation. The simulation results show that CARR scheduler provides soft QoS effectively. They also demonstrate the ability to provide different degree of soft rate reservation in different time scales and the flexibility to adapt to wireless channel variation and operational environments. Extension of CARR algorithms can also facilitate the fast ARQ retransmission and supports QoS for seamless handoff.

References

[1] H. Fattah and C.Leung, "An Overview of Scheduling Algorithms in Wireless Multimedia Networks", IEEE Wireless Communications Magazines, October 2002

[2] S. Shakkottai & A. Stolyar, ``Scheduling Algorithms for a Mixture of Real-Time and Non-Real-Time Data in HDR", Proc. of the 17th International Teletraffic Congress (ITC-17), Salvador da Bahia, Brazil, September 2001.

[3] A. Furuskar, S. Parkvall, M. Persson, and M. Samuelsson, "Perforamcne of WCDMA High Speed Packet Data", IEEE VTC 2002

[4] A. K. Parekh and R.G. Gallager, "A geralized processor sharing approach to flow contro I integratd services networks: the single node case", IEEE Transactions on Networking, vol 1, no 3, June 1993

[5] P. Bender, P. Black, M. Grob, R. Padovani, N. Sindhushyana, and A. Viterbi, "CDMA/HDR: a bandwidth efficient high speed wireless data service for nomadic users," IEEE Communications Magazine, vol. 38, pp. 70-77, 2000.

[6] S. Parkvall, E. Dahlman, P. Frenger, P. Beming, and M. Persson, "The evolution of WCDMA towards higher speed downlink packet data access," in IEEE VTS 53rd Vehicular Technology Conference (VTC 2001 Spring), 2001.

[7] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, P. Whiting, and R. Vijayakumar, "Providing Quality of Service overa Shared Wireless Link", IEEE Communications Magazine, February 2001

[8] "Evaluation Methodology for IMT-2000 Radio Transmission Technologies", Association of Radio Industries and Businesses, 1998