Scheduling Algorithms for Downlink Rate Allocation in Heterogeneous CDMA Networks

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Abstract

The downlink rate scheduling problem is considered for CDMA networks with multiple users carrying packets of different types of traffic (voice/audio only, bursty data only or mixed traffic), each of which has its own distinct Quality of Service requirements. Several rate scheduling algorithms are developed, the common factor of which is that part of the decision on which users to serve is based on a function of the deadline of their head-of-line packets. An approach of Andrews, et al., in which the basic Earliest-Deadline-First algorithm is simulated for similar systems, is extended to allow service of more than one user per timeslot if power resources permit it. Finally performance of the proposed schemes is compared through simulations.

Keywords

Rate allocation, CDMA Networks, Heterogeneous Traffic, Quality-of-Service requirements, Deadline

I. INTRODUCTION

An inevitable issue in the design of wireless networks is that of energy conservation, making power control and power allocation two important factors that must be addressed in such design. Since power and rate are essentially equivalent notions (as one can be derived from the other), power considerations can be addressed by examining the problem of rate allocation. This paper is concerned with the allocation of rate among the users of a CDMA network with heterogeneous traffic.

Recent work in this area is found in [1], in which the authors consider CDMA systems with delay-tolerant bursty data users. They examine the problem of scheduling the rate of CDMA data users on the downlink such that certain Quality-of-Service (QoS) requirements are met. They evaluate the performance of several different scheduling schemes with the main conclusion being that it is optimal for the base station to transmit to only one user at a time by operating either at zero or at full power. As a result, their best rate scheduling scheme is the "Earliest-Deadline-First" (EDF) algorithm (or its weighted version WEDF). According to EDF, at each timeslot the user carrying in its head-of-line the packet with the earliest deadline is served, thereby assigning all the power resources to this single user. Hence only one bursty-data user can be served per timeslot.

Emerging wireless networks, such as third-generation cellular networks, anticipate an inevitable combination of data and voice/audio services in the same wireless system. In this paper we consider downlink rate allocation for such systems. We do so by expanding the model of [1] in [2], to include three different cases: users carrying data packets only, voice/audio (CBR) only, or mixed traffic. We consider an algorithm that we call "Powered Earliest-Deadline-First" (PEDF) which, like EDF, finds at the beginning of a timeslot the user with the closest deadline for the head packet and assigns all the power to it. However, if after serving that packet (user) there is still some power remaining, the algorithm serves the user with the *next* earliest deadline. The algorithm then continues serving the complete head packets of the chosen users according to the available power resources. If a point is reached where there is not enough power left to serve a chosen user, the algorithm serves part of the corresponding packet and moves to the next timeslot. Hence, this approach differs from the one of [1] both in terms of the more complex traffic input and in terms of its decision to serve more than one user per timeslot, power permitted.

We further consider three additional new algorithms for rate scheduling of heterogeneous traffic. In the first one (see also [3]), the head packet of each user is assigned a pseudoprobability, which is a function of its deadline. The pseudoprobabilities are then normalized by the packet lengths and the packet having the maximum normalized quantity is served first. If there is power remaining in the system after the packet is served, the procedure is repeated with the *next* maximum normalized pseudoprobability packet and so on. Even though this scheme is similar in philosophy to PEDF, the serving criterion is different, thus allowing dramatic improvement in performance as we will see in the sequel.

The second and third new algorithms are versions of PEDF and the above pseudoprobability approach, with the additional feature of fairness queueing. ”Fairness queueing” is considered in [4] in the context of an ATM switch. This technique is implemented by dividing the system bandwidth equally among all users. If a user cannot satisfy its needs with the given bandwidth allocation, it is characterized as bottlenecked. Otherwise it is marked as satisfied. It may be the case that some satisfied users will not need all of their allocated bandwidth. In this situation excess bandwidth from the satisfied users can be used to ease up the bottlenecked ones. Again this excess is divided equally among all bottlenecked users. This approach guarantees max-min fairness. Since the notions of available bandwidth and available power are equivalent, we can combine the PEDF and normalized pseudoprobability schemes with the idea of fairness queueing. We do so here and show through simulations that these combinations can lead to better performance when compared to the PEDF and pseudoprobability algorithms.

This paper is organized as follows. In Section II, we introduce the main model while in Section III we present sketches of the new algorithms. The mathematical analysis is presented in Section IV. In Section V, we provide simulation examples to demonstrate the performance of the algorithms proposed in this paper. Section VI contains our conclusions.

II. Main Model

As in [1], we concentrate on a single-cell model in which the total available transmission power is constant in time and normalized to unity. There are K active users in the system, and the downlink is modeled as a multiple server queue. Traffic is generated for every user for a specific time period. The packets generated can be either CBR packets only, or bursty data traffic packets only, or mixed traffic ones. The bursty data case is generated by an On-Off fluid source.

Let us concentrate on a specific timeslot and denote by W_i the waiting time for the head packet of user i and by T_i the delay threshold, which is a predefined constant and will be different for each kind of traffic. At every timeslot the queues of all users are examined to decide which clients to serve. It is assumed that every user has to meet a delay QoS requirement regardless of traffic type; i.e., we must have

$$Pr\{W_i \leq T_i\} \geq \delta_i \tag{1}$$

where δ_i is the minimum probability with which the constraint must be met.

The Earliest Deadline First (EDF) algorithm, which is the main rate scheduling scheme considered in [1], assigns all the power to the user for which the deadline of the packet at the head of the queue is earliest, i.e., for which the difference $T_i - W_i$ is smallest. Therefore only one user is served in one time slot.

Powered Earliest Deadline First (PEDF), proposed in [2], looks at the beginning of a timeslot for the user with the earliest deadline for the head packet and assigns all the power to it. Then, if after serving that user's packet there is still power left, the head packet of the user with the *next* earliest deadline is served. This process continues with the full head packets of chosen users according to the power resources. If a point is reached where there is not enough power left to serve an entire packet, part of the next packet is served and attention switches to the next timeslot. Therefore, this approach serves more than one user when enough power to do so is available. A disadvantage of choosing multiple users in this way, is that multiuser interference arises among them. But, this disadvantage is often outweighed by the tendency to make use of more of the available power. Thus PEDF can outperform EDF, as will be verified below through simulations.

III. SKETCHES OF THE ALGORITHMS

A. HOLPRO

In this section we develop a modification of PEDF, which we call "Head Of Line PseudopRObability" (or HOLPRO), which serves more than one user at a time according to the same notion used in PEDF. HOLPRO however uses a different serving criterion than PEDF. In particular, in HOLPRO each user is assigned a pseudoprobability p_i and the user with the maximum normalized pseudoprobability is chosen as long as power resources remain.

More specifically, in each timeslot each user's head packet is assigned a pseudoprobability p_i, given by

$$p_i = \frac{\frac{1}{(T_i - W_i)^3}}{\sum\limits_{k \in H} \frac{1}{(T_k - W_k)^3}} \tag{2}$$

where W_i and T_i are the waiting time and delay threshold as before, and where H contains the indices of all the users that coexist in the given timeslot. Although $\sum\limits_i p_i = 1$, the p_i's are not necessarily non-negative, and hence the term "pseudoprobability". The pseudoprobabilities p_i are normalized by the size of the head packet, which is denoted by

l_i, and the user with the maximum normalized probability is served first. Note that when packets of different users are served, multiuser interference may result. However, different packets of the same user do not interfere with one another. The algorithm is summarized as follows.

Algorithm *1:* HOLPRO

```
1. Given $T_i$, $W_i$ and $l_i$ for each user, compute $p_i$.
2. For every time slot in the time window
  (a) Start with full transmission power ($P = 1$).
  (b) While power $P > 0$
    i. Find the user with $\max_i \frac{p_i}{l_i}$
    ii. Compute the power $P'$ this user needs to transmit its packet in this time slot.
    iii. Compute the marginal power $P''$ required by all previous packets that were to be transmitted during this slot, to account for the interference due to this new packet $i$
    iv. If the power allocated to the newly chosen packet is not enough to serve it completely (i.e., $P' > P - P''$), serve as much of it as possible in this time slot, set $P = 0$, and move to the next time slot.
    v. Otherwise ($P' \leq P - P''$)
      • serve the entire packet
      • find the power left in the system ($P = P - P' - P''$)
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B. PEDFF

We also consider allocation according to a combination of the PEDF algorithm with the fairness queueing technique of [4]. In particular, as long as enough power resources remain, the closest deadline user is served if we can serve its complete head packet and then the remaining power is divided among the other active users. Again more than one user per timeslot is served, but the system is now ”fairer” since all the users other than the one with the earliest deadline packet receive their equal power share. The algorithm in this case, which we call ”Powered Earliest Deadline First Fair” (PEDFF) is thus:

Algorithm *2:* PEDFF

```
1. For every time slot in the time window
  (a) Start with full transmission power ($P = 1$).
  (b) While power $P > 0$
    i. Given $W_i$, $T_i$ for each user, find the one with the earliest deadline $T_i - W_i$
    ii. Compute the power $P'$ needed to transmit its packet in this time slot.
    iii. Compute the marginal power $P''$ required by all previous packets that were to be transmitted during this slot, to account for the interference due to this new packet i
    iv. If the power allocated to the newly chosen packet is not enough to serve it completely (i.e., $P' > P - P''$), serve as much of it as possible in this time slot, set $P = 0$ and move to the next time slot.
    v. Otherwise ($P' \leq P - P''$)
      • serve the entire packet
      • find the power left in the system ($P = P - P' - P''$)
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- *find how many users have packets in the queue now and divide the remaining power equally among them*
- *for each one of these users, serve as much as possible of its head packet according to the power allocated, keeping in mind that the interferences may need to be updated if there are packets served in the same time interval from the same user*
- *update the power left in the system*

C. HOLPF

As we already mentioned, it will become clear through simulations later on that HOLPRO outperforms PEDF. Also PEDFF is fairer than PEDF and turns out to have better performance. This suggests a combination of the fairness queueing notion of PEDFF with the idea of the HOLPRO algorithm. This produces the following scheduling scheme, which we call "Head Of Line Pseudoprobability Fair" (HOLPF):

Algorithm *3:* HOLPF

```
1. Given $T_i$, $W_i$ and $l_i$ for each user, compute $p_i$.
2. For every time slot in the time window
    (a) Start with full transmission power ($P = 1$).
    (b) While power $P > 0$
        i. Find the user with $\max_i \frac{p_i}{l_i}$
        ii. Compute the power $P'$ this user needs to transmit its packet in this time slot.
        iii. Compute the marginal power $P''$ required by all previous packets that were to be transmitted during this slot, to account for the interference due to this new packet $i$
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iv. If the power allocated to this user is not enough to serve its packet completely ($P' > P - P''$), serve as much as possible in this time slot, set $P = 0$, and move to the next time slot.

v. Otherwise ($P' \leq P - P''$)

- *serve the entire packet*
- *find the power left in the system ($P = P - P' - P''$)*
- *find how many users have packets in the queue now and divide the remaining power equally among them*
- *for each one of these users, serve as much as possible of its head packet according to the power allocated to it, keeping in mind that the interferences may need to be updated if there are packets served in the same time interval from the same user*
- *update the power left in the system*

IV. Mathematical Analysis

In analyzing and simulating the performance of the above rate-allocation schemes, we will consider the performance in the central cell of 18 surrounding cells placed in two rings. Using the models of [5], [6], we have the following relation (see also [2]) for the power $\Gamma_{j,i}$ that mobile i receives from the base of the j-th cell:

$$\Gamma_{j,i} = P_T \left(\frac{d_{j,i}}{d_0} \right)^{-4} 10^{0.1\sigma_s Y_j} \tag{3}$$

where P_T is the total power that each cell transmits on the downlink, $d_{j,i}$ is the distance between base station j and mobile i, d_0 is a reference distance, σ_s is the deviation of log-normal shadow fading and Y_j is a zero-mean unit variance gaussian random variable. If the power $\Gamma_{j,i}$ coming from the central cell's base is the maximum, then the user is placed in that cell.

Assuming that the total cell site power is divided between the users/subscribers and the pilot, let β denote the fraction of the power devoted to the traffic channels (i.e., $1-\beta$ is devoted to the pilot) and let P_i denote the fraction of this devoted to user i. Define the following parameters:

E_b/N_o: required bit energy to noise ratio

G : spreading gain

η: noise power

α: probability that user is ON

ρ: an "orthogonality loss" factor, where $\rho = 0$ corresponds to perfect orthogonality and $\rho = 1$ corresponds to random codes

Then, according to [2] and [6], the E_b/N_o's and rates for user i are given by

$$(E_b/N_o)_i = \frac{\alpha\beta\Gamma_{0,i}P_iG}{\rho\Gamma_{0,i}\left(1-\beta+\alpha\beta\sum\limits_{\forall j\neq i}P_j\right)+(1-\beta+\alpha\beta)(\sum\limits_{n\neq 0}\Gamma_{n,i}+\eta)} \tag{4}$$

$$\text{and} \qquad R_i = \min\{1, \bar{R}_i\} \tag{5}$$

$$\text{where} \qquad \bar{R}_i = \frac{1}{G} = \frac{\alpha\beta\;\Gamma_{0,i}P_i}{(E_b/N_o)_i\left(\rho\Gamma_{0,i}(1-\beta+\alpha\beta I_i)+(1-\beta+\alpha\beta)(\sum\limits_{n\neq 0}\Gamma_{n,i}+\eta)\right)} \tag{6}$$

where for simplicity the interference $\sum\limits_{\forall j\neq i} P_j$ is denoted by I_i. Here the rates are assumed to be normalized by the system bandwidth, which means that we must multiply the above rates by the system bandwidth B to get rates in bps.

We see from (6) that the rate needed for a user's packet is a function of the power needed for that packet and of the interference. Some care must be taken in computing interference when more than one packet from the same user is served in the same timeslot. When a given user is having its first packet served in a given timeslot, its rate is a function of the needed power and the interference power. That interfering power is roughly calculated to be equal to $1 - P_{needed}$. If in the same timeslot, the given user subsequently has a further packet served, then this packet's power was included in the interfering power for the first packet, which is inaccurate since packets belonging to the same user do not interfere with each other.

Hence we can solve the equation for the required power by distinguishing the following two cases.

A. Case 1: the packet to serve belongs to a user not served in the same timeslot

In this case, it is easy to conclude (as in [2], [3] and [7]) that $I_i = 1 - P_i$ and therefore

$$P_i = \frac{R_i (E_b N_o)_i (1 - \beta + \alpha\beta)(\rho \Gamma_{0,i} + \Sigma_i)}{\alpha\beta \Gamma_{0,i} (B + \rho R_i (E_b/N_o)_i)} \tag{7}$$

where, in order to simplify notation, we have denoted $\sum \Gamma_{n,i}$ by Σ_i.

B. Case 2: the packet to serve belongs to a user already served in the same timeslot

We can now suppress the index i from the rates, powers, interferences, $\Gamma_{0,i}$ and Σ_i, for ease of notation, since we are always referring to the same user. Let us use instead the index of a packet for the fixed user as the index of powers, rates and interferences. Suppose thus that n packets from this user were previously served in this timeslot, with required rates $R_1, \cdots, R_n$. The packet in question is then the $(n+1)$-st and $I_{n+1} = 1 - P_{n+1} - P_1 - \cdots - P_n$ where the P_i's are the quantities we are trying to compute, i.e, the updated powers of the packets. Then, denoting $(E_b/N_o)_i$ by E, we can write

$$\alpha\beta\Gamma(B+\rho E R_{n+1})P_{n+1}+\alpha\beta\Gamma\rho E(P_1+\cdots+P_n)=ER_{n+1}(1-\beta+\alpha\beta)(\rho\Gamma+\Sigma) \quad (8)$$

By generating similar equations for the other packets we arrive at the following system of equations for the desired powers:

$$\begin{bmatrix} \alpha\beta\Gamma(B+\rho E R_1) & \alpha\beta\Gamma\rho E R_1 & \cdots & \alpha\beta\Gamma\rho E R_1 \\ \alpha\beta\Gamma\rho E R_2 & \alpha\beta\Gamma(B+\rho E R_2) & \cdots & \alpha\beta\Gamma\rho E R_2 \\ \vdots & \vdots & & \vdots \\ \alpha\beta\Gamma\rho E R_{n+1} & \alpha\beta\Gamma\rho E R_{n+1} & \cdots & \alpha\beta\Gamma(B+\rho E R_{n+1}) \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_{n+1} \end{bmatrix} = C \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_{n+1} \end{bmatrix} \quad (9)$$

where $C=E(1-\beta+\alpha\beta)(\rho\Gamma+\Sigma)$. The solution of this system is the vector of desired powers that are used to calculate the marginal power P'' in the algorithms.

V. Simulations

To simulate the algorithms described above, we consider a configuration of 19 cells ordered in two rings around a central cell, in which all the users of interest are placed. We assume that E_b/N_o is 5.0 dB, β is 0.8, α is 3/8, the shadow fading has standard deviation 8, and the bandwidth of the system is 5 MHz (the value proposed for cdma2000). Constant Bit Rate (CBR) packets are assumed to contain 100 bits and 10 msec interarrival time, while bursty packets are assumed to have exponential size and interarrival times with means 10 Kbits and 100 msec analogously. Note that the ON-OFF durations were chosen to be exponential with means 93 msec and 907 msec, the same values as in [1] and [2], for the purpose of comparison.

The simulations were run for many different values of CBR and bursty delays. The graphs considered here depict system behavior over a period of 5 sec, where the delay for the CBR packets is 2 msec and that for the bursty packets is 0.1 sec. These values for the delays were carefully chosen in [2]. It is known that bursty data can tolerate higher delays than CBR traffic, which should be served in a couple of milliseconds at most. The above choice arises from a combination of the fact that the traffic entering the system approximated that exiting for the cases of CBR-only and data-only traffic, and from the fact that the resulting probabilities should not be trivial (i.e. equal to one all the time) but rather should exhibit a smooth decrease.

Our plots show the successful probabilities of meeting the QoS constraints $Pr(W_i \leq T_i)$ as well as the Kbps entering and exiting the system versus the number of users in the system, for all different types of traffic.

In Figures 1 and 2, we reproduce a comparison of EDF and PEDF from [2] for the purpose of comparison. In the case where the waiting times of the users exceed their delay constraints, the algorithm in [2] serves the packets anyway; but of course those packets served do not contribute to the calculation of the success probabilities, since the constraints are clearly violated. This is the main reason why we also include plots of the Kbits entering and exiting the system. As we can clearly observe from these figures, PEDF performs almost as well as EDF in the cases of data-only packets, while it outperforms it in all other cases.

Figures 3 and 4 depict results of a simulation of the HOLPRO algorithm [1], while Figures 5 and 6 compare PEDF to HOLPRO. Clearly these results indicate that HOLPRO

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[1] The success probabilities should decrease as the number of the users in the system increases. Thus, in the case of CBR-only graph, we believe that two of the simulation points for more than 80 users are slightly displaced due to computational error caused by the high complexity of the algorithm at that point.

outperforms PEDF. From the EDF-PEDF-HOLPRO comparisons we can see that if, for example, we want more than 90% of users to satisfy QoS, then for the given data EDF supports only 1 user with CBR-only traffic, 24 with bursty-only traffic and 1 user with mixed traffic, while PEDF gives around 64 users for CBR, 24 for bursty and 16 for the mixed case. On the other hand, HOLPRO can support 72 users for CBR, 40 for bursty, and approximately 32 for mixed traffic.

Figures 7(a) and (b) show PEDFF's performance for a system with CBR-only or bursty-only traffic, while Fig. 8 depicts PEDFF's performance for the mixed-traffic case. The analogous results for HOLPF are shown in Figs. 9 and 10. In Figs. 11 and 12 PEDFF is compared to PEDF, while in Figs. 13 and 14 HOLPRO is compared to HOLPF. The comparison between PEDFF and HOLPF is found in Figs. 15 and 16.

From these results, we can see that HOLPRO and PEDF outperform HOLPF and PEDFF in the case of CBR-only traffic. We infer that, in this case, the serving criteria influence the performance significantly. It seems that it is more efficient for the remaining users to be served one by one according to the earliest deadline or maximum normalized pseudoprobability criteria rather than by using small equal portions of the remaining power, especially since the number of coexisting CBR users is large and therefore equally-divided power portions are small. The same phenomenon appears also to be behind the CBR-in-mixed-traffic graph for HOLPF for more than 56 users in the system. It is important to notice, though, that HOLPF and PEDFF outperform their peers in all other cases. Thus, for the cases considered here, we can see that if we want more than 90% of users to satisfy QoS, PEDF supports only 64 users with CBR-only traffic, 24 with bursty-only traffic and 16 users with mixed traffic, while HOLPRO gives around 72 users for

CBR, 40 for bursty and 32 for the mixed case. On the other hand, PEDFF can support 52 users for CBR, 32 for bursty and approximately 32 for mixed traffic, while HOLPF can hold 52 for CBR, 44 for bursty, 44 for the mixed case. Also we can clearly see that again HOLPF outperforms PEDFF.

These comparisons for 90% success probability are summarized in Table 1.

VI. CONCLUSIONS

In this paper, we have developed three new rate allocation algorithms for the downlink of CDMA multiuser systems with heterogeneous traffic. We have simulated these new schemes and compared them to each other and to existing algorithms, with the conclusion that there are many cases in which they can significantly improve the system performance. In particular, HOLPRO outperforms PEDF under all types of traffic. PEDFF improves PEDF's performance significantly for the cases of bursty-traffic and mixed-traffic. HOLPF outperforms HOLPRO for up to 80 users in a bursty-only traffic system. In the case of mixed traffic, the HOLPF bursty portion of traffic outperforms its HOLPRO peer for as high as 100 users, while the HOLPF CBR portion outperforms its HOLPRO peer for as many as 56 users. Finally PEDFF and HOLPF give similar results for CBR-only traffic, while HOLPF outperforms PEDFF for all other cases.

REFERENCES

[1] Matthew Andrews, Krishnan Kumaran, Kavita Ramanan, Alexander Stolyar, Phil Whiting, "Data Rate Scheduling Algorithms and Capacity Estimates for the CDMA Forward Link", *Bell Labs Technical Journal,* September 13, 1999.

[2] Aikaterini C. Varsou, Howard C. Huang, Laurence Mailaender, "Rate Scheduling for CDMA Downlink Mixed Traffic Networks", *submitted to WCNC 2000.*

[3] Aikaterini C. Varsou, H. Vincent Poor, "HOLPRO: A New Rate Scheduling Algorithm for CDMA Downlink Networks", *submitted to VTC 2000.*

[4] Lampros Kalampoukas, Anujan Varma, "Design of a Rate-Allocation Algorithm in an ATM Switch for Support of Available-Bit-Rate (ABR) Service", *Design SuperCon 1997.*

[5] K. Gilhousen, I. Jacobs, R. Padovani, A. Viterbi, L. Weaver, C. Wheatley III, "On the Capacity of a Cellular CDMA System", *IEEE Transactions on Vehicular Technology*, Vol.40, No.2, 1991.

[6] Laurence Mailaender, "CDMA Downlink Capacity with High-Speed Packet Data", *Bell Labs Engineer's Notes*, May 1999.

[7] Aikaterini C. Varsou, H. Vincent Poor, "A Pseudoprobability Assignment and Fairness Queueing Combination Algorithm for Rate Allocation in CDMA Downlink Networks", *to be submitted to GLOBECOM 2000.*

[8] Dimitrios Stiliadis, Anujan Varma "A General Methodology for Designing Efficient Traffic Scheduling and Shaping Algorithms", *Proceedings of IEEE INFOCOM 1997.*

[9] CDMA/HDR: A Constructive (Backward Compatible) Approach for Migration to Wider Band Wireless Services, *3rd Generation Wider Band CDMA Technology Conference,* Atlanta, GA, Feb 1998.

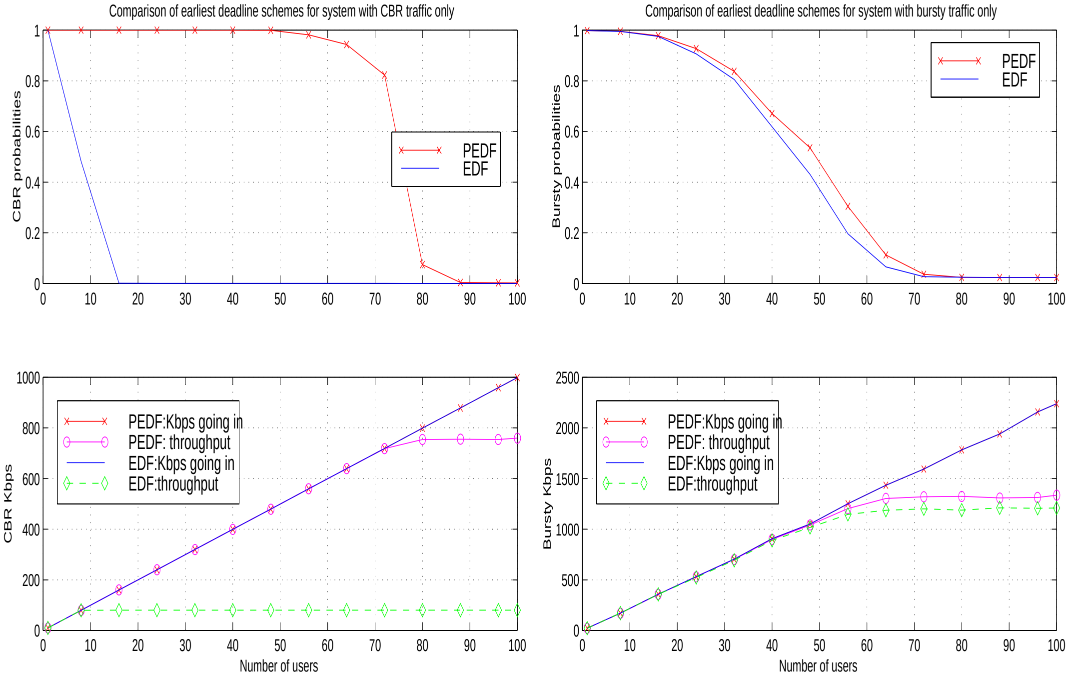

Fig. 1. PEDF vs. EDF - (a) CBR, (b) Bursty

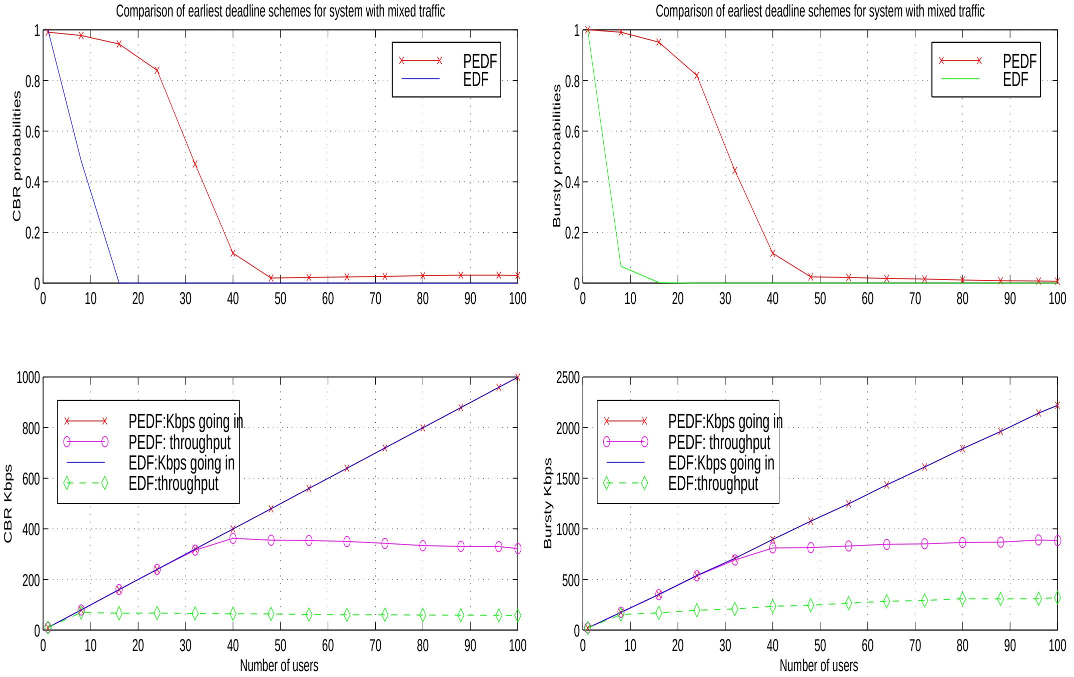

Fig. 2. PEDF vs. EDF in mixed traffic - (a) CBR, (b) Bursty

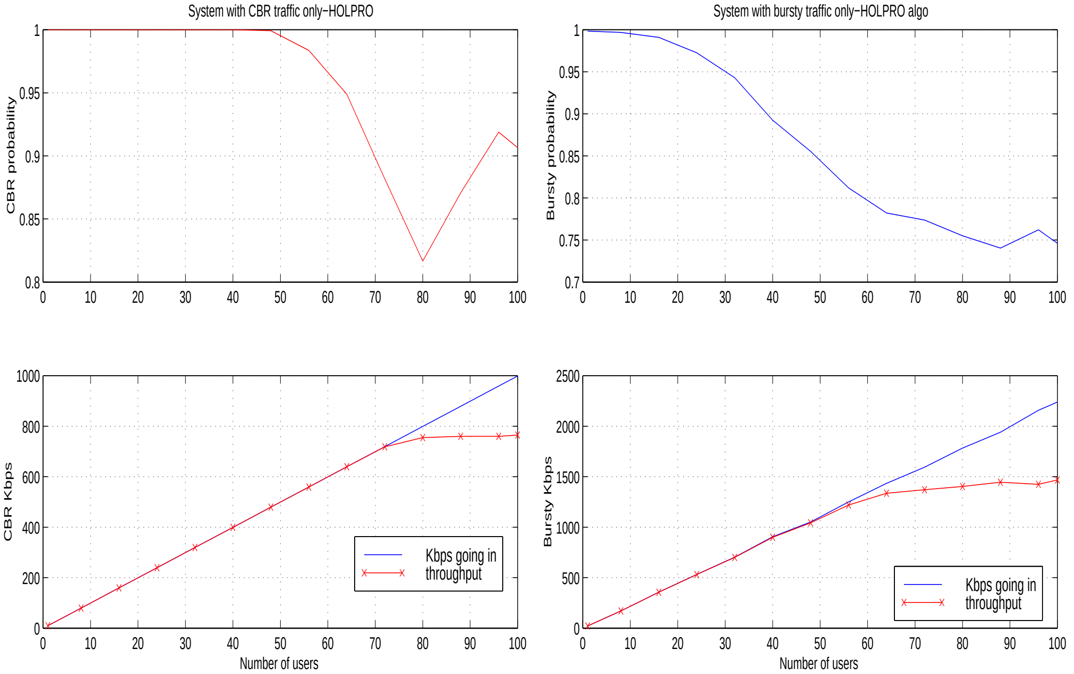

Fig. 3. HOLPRO - (a) CBR, (b) Bursty

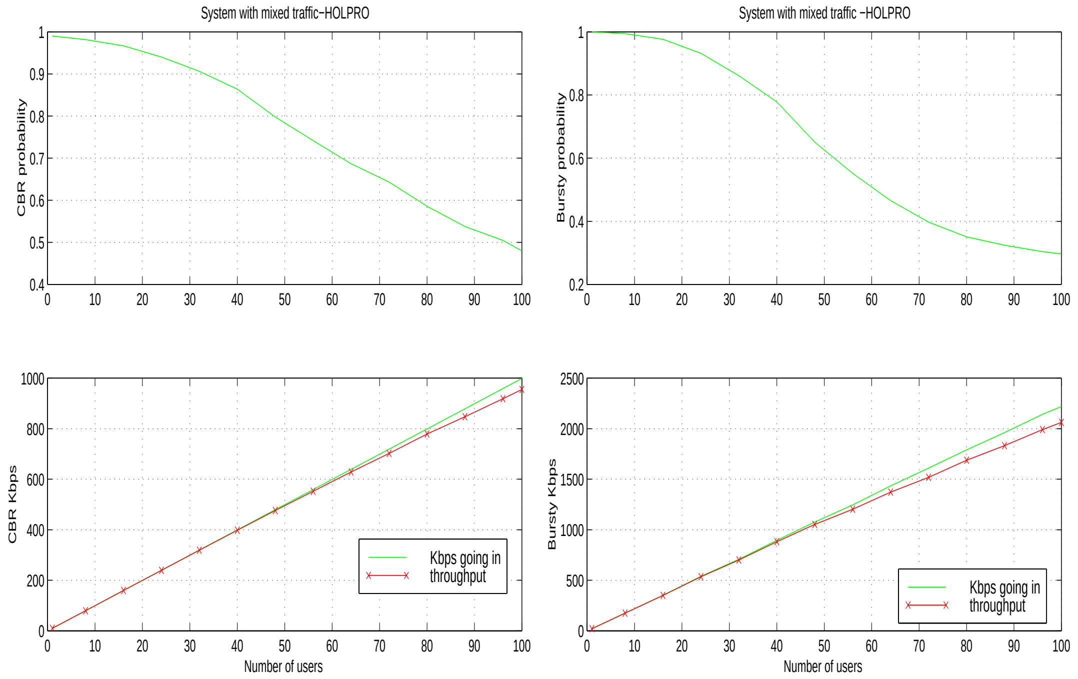

Fig. 4. HOLPRO in mixed traffic - (a) CBR, (b) Bursty

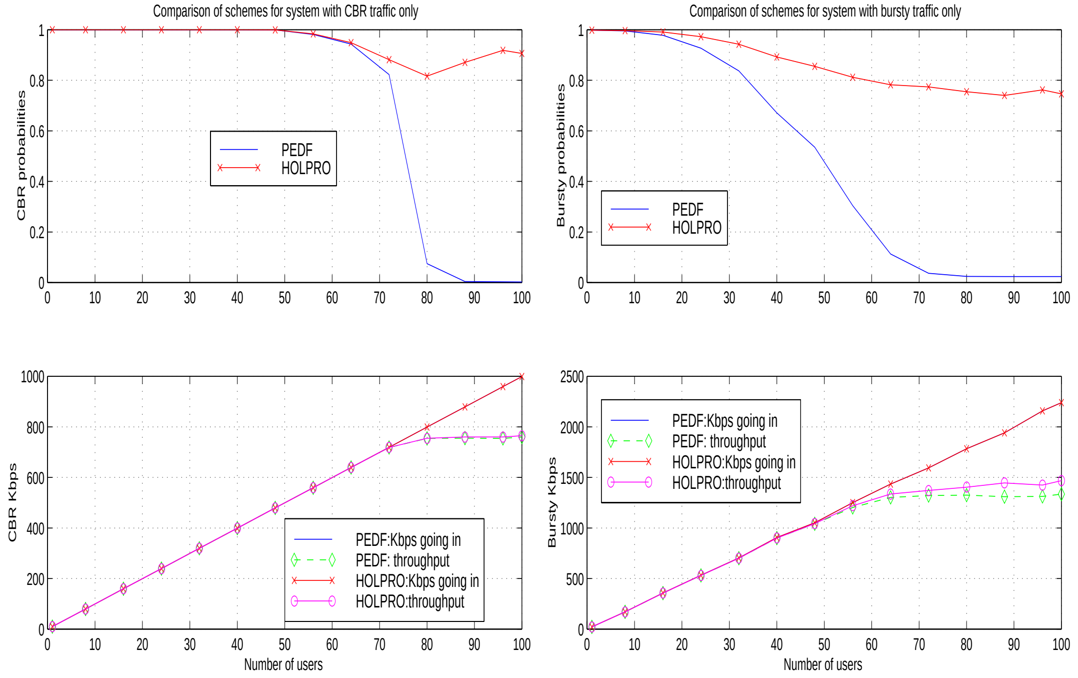

Fig. 5. HOLPRO vs. PEDF - (a) CBR, (b) Bursty

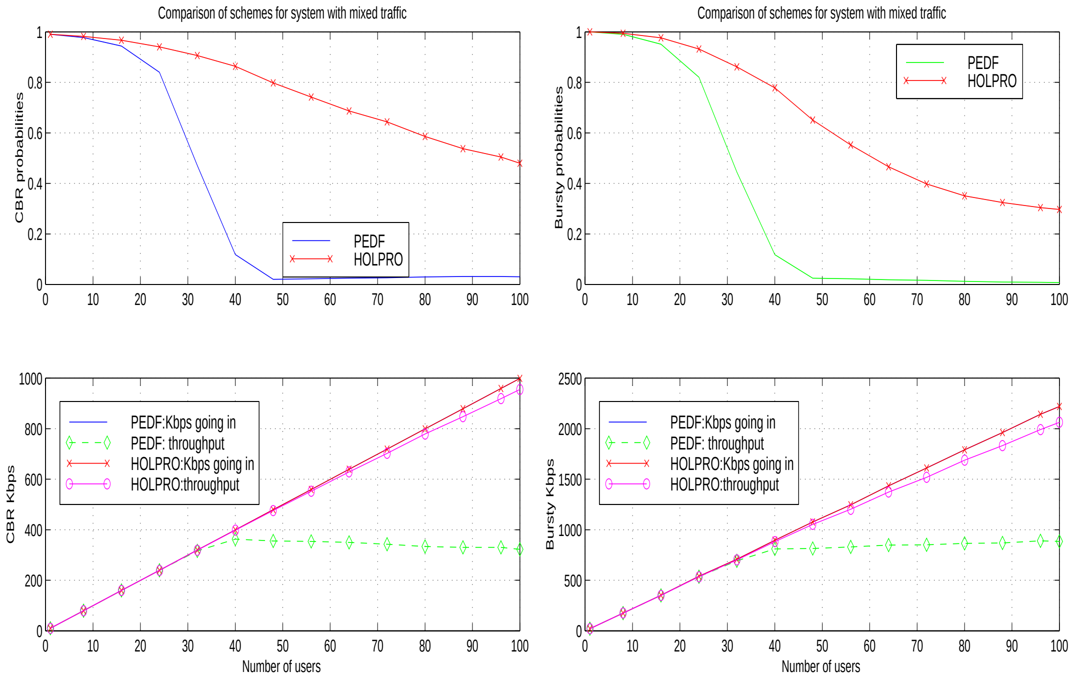

Fig. 6. HOLPRO vs. PEDF in mixed traffic - (a) CBR, (b) Bursty

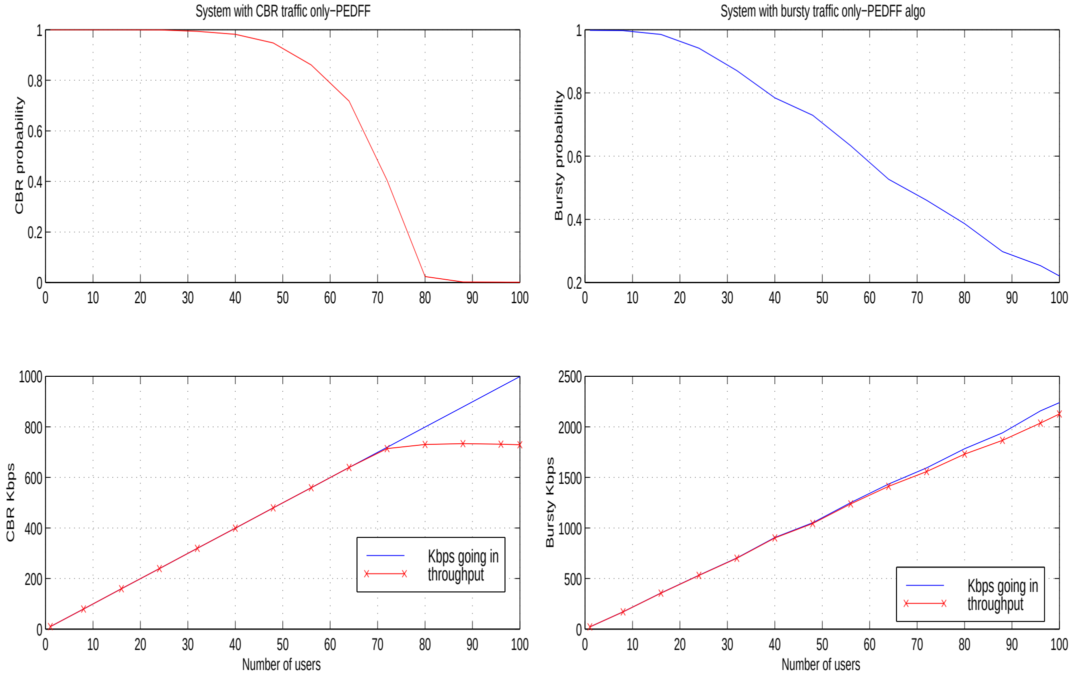

Fig. 7. PEDFF - (a) CBR, (b) Bursty

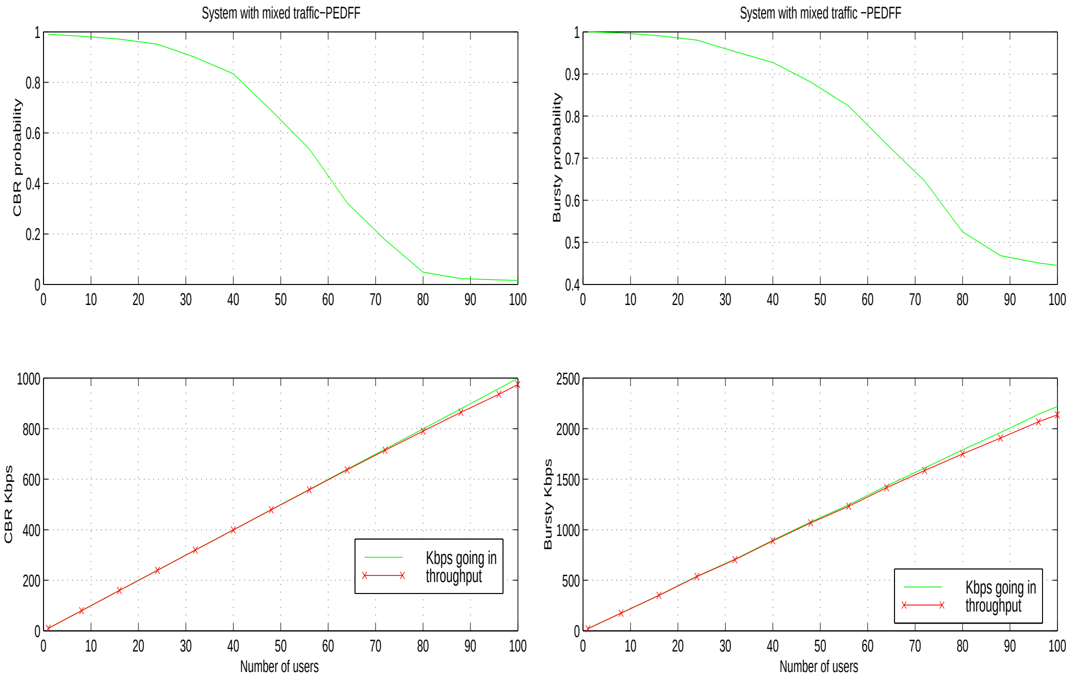

Fig. 8. PEDFF in mixed traffic - (a) CBR, (b) Bursty

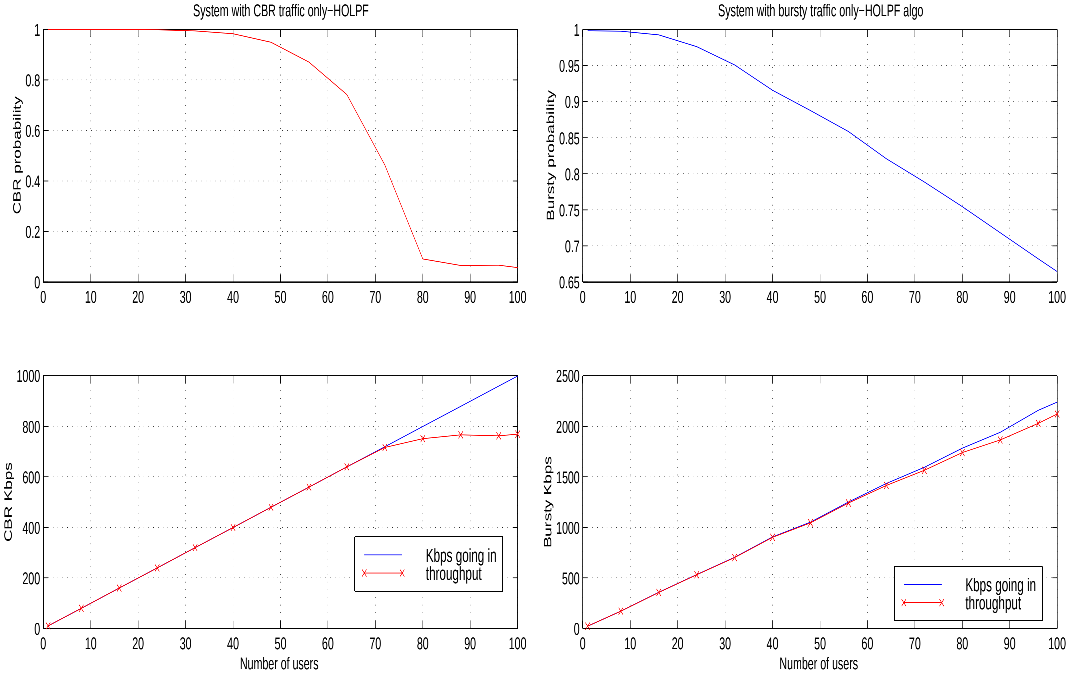

Fig. 9. HOLPF - (a) CBR, (b) Bursty

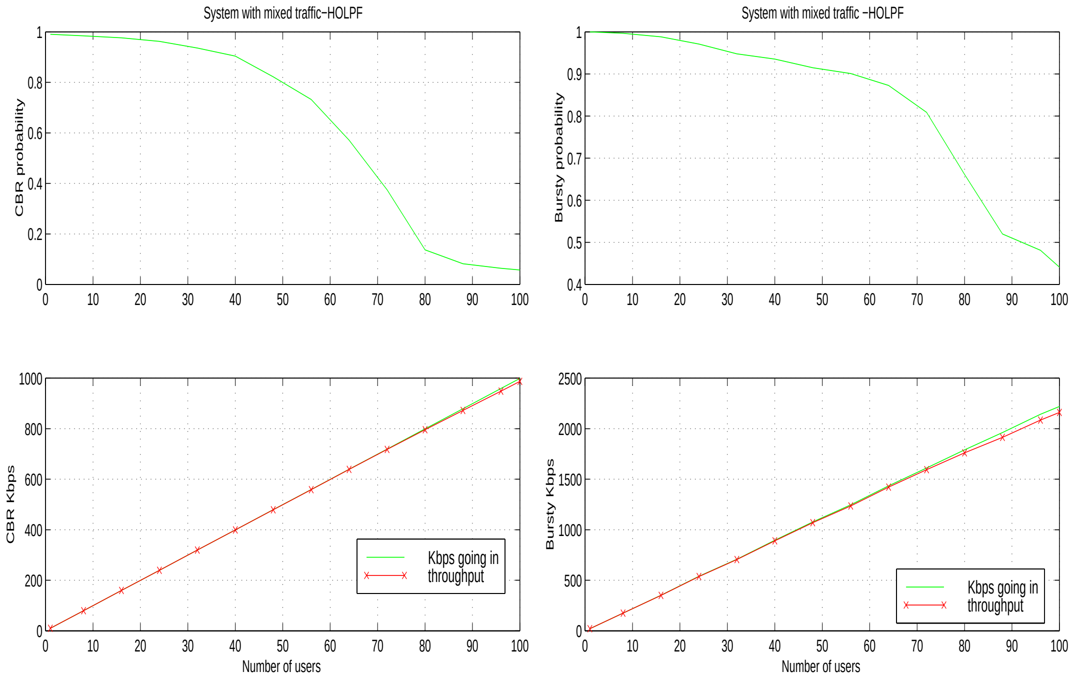

Fig. 10. HOLPF in mixed traffic - (a) CBR, (b) Bursty

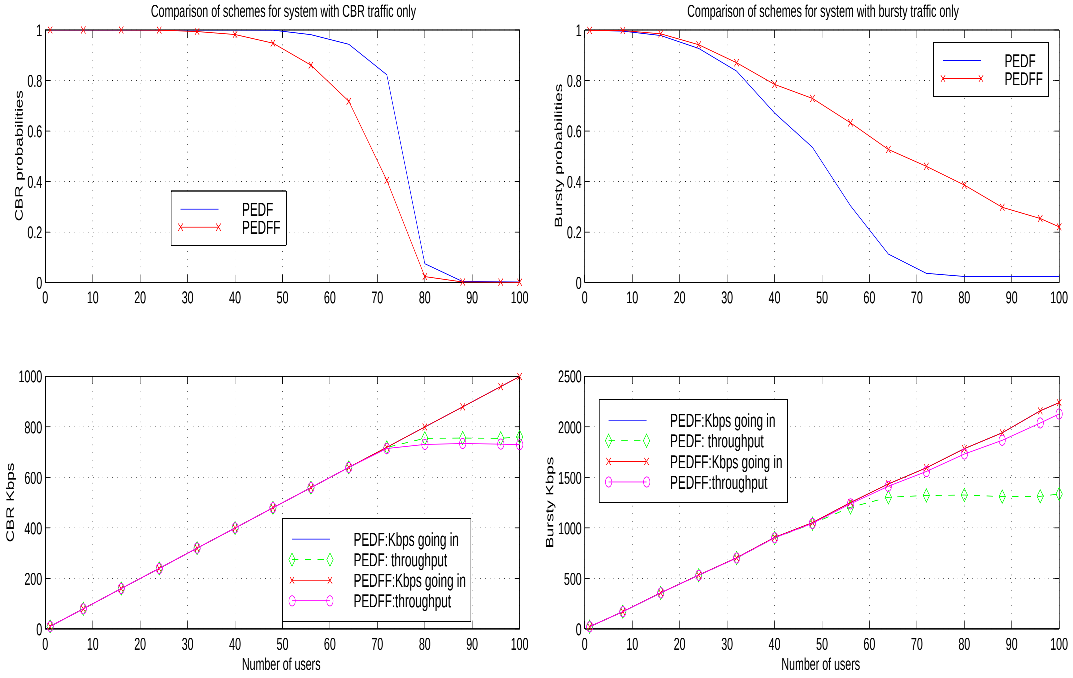

Fig. 11. PEDF vs. PEDFF - (a) CBR, (b) Bursty

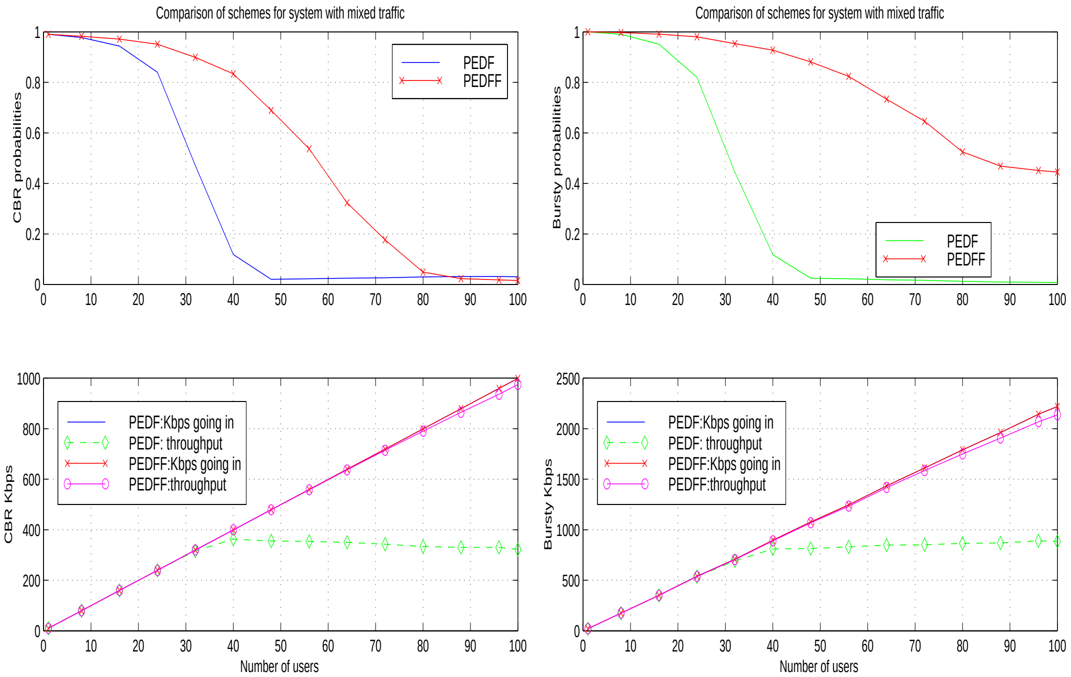

Fig. 12. PEDF vs. PEDFF in mixed traffic - (a) CBR, (b) Bursty

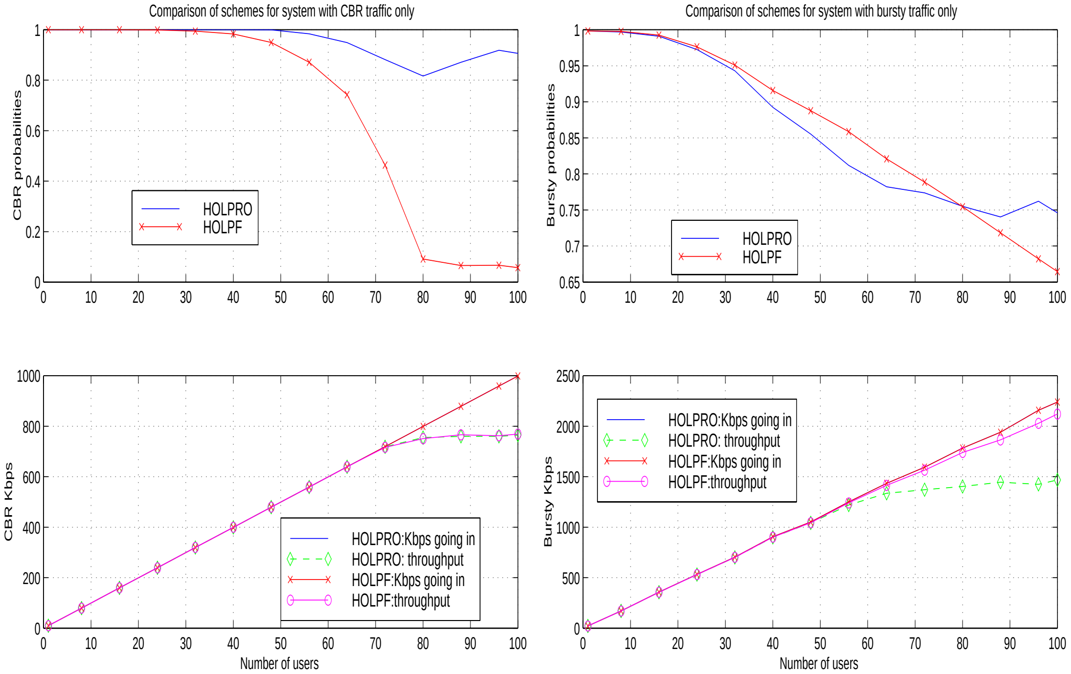

Fig. 13. HOLPRO vs. HOLPF - (a) CBR, (b) Bursty

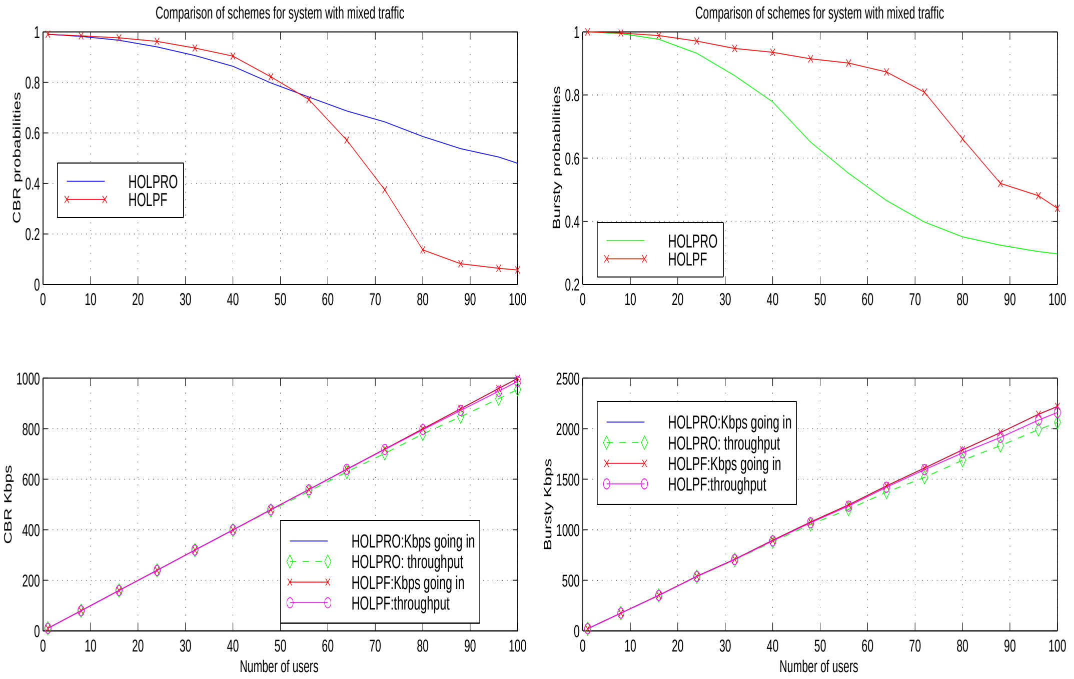

Fig. 14. HOLPRO vs. HOLPF in mixed traffic - (a) CBR, (b) Bursty

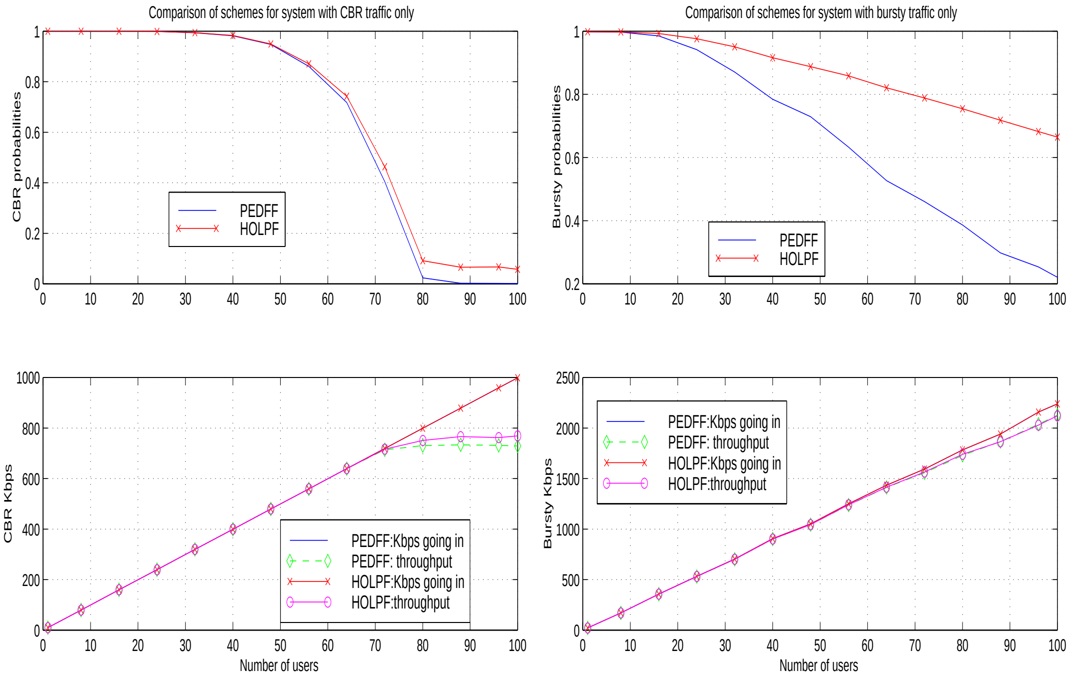

Fig. 15. PEDFF vs. HOLPF- (a) CBR, (b) Bursty

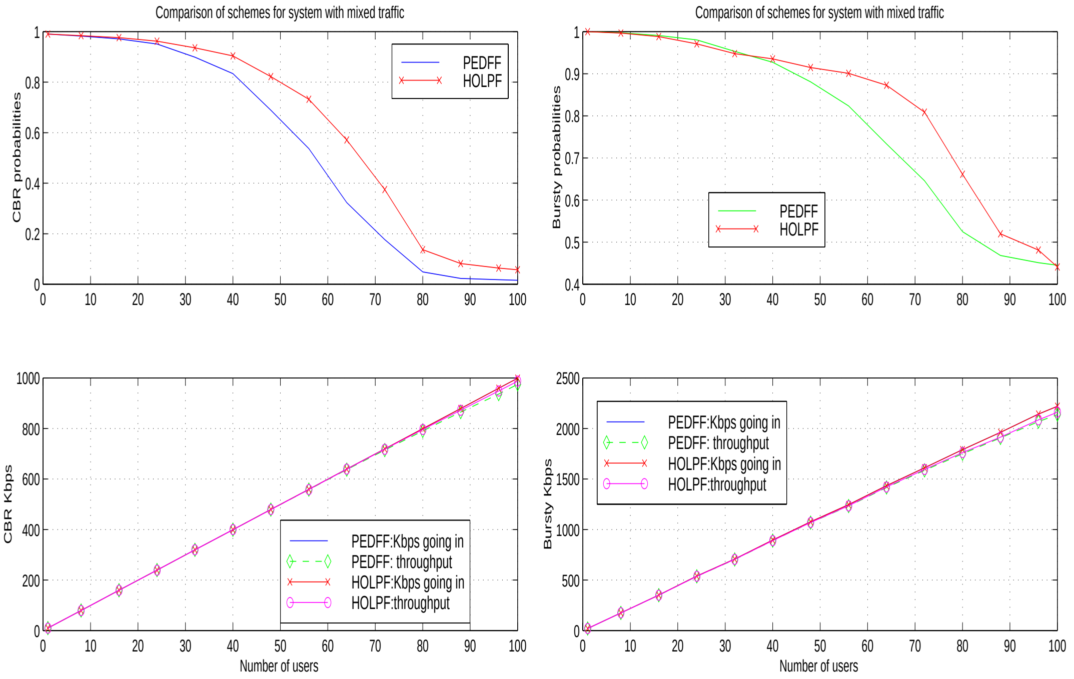

Fig. 16. PEDFF vs. HOLPF in mixed traffic - (a) CBR, (b) Bursty

Scheme	*CBR only*	*Bursty only*	*Mixed*
EDF	1	24	1
PEDF	64	24	16
HOLPRO	72	40	32
PEDFF	52	32	32
HOLPF	52	44	44

Table 1. Numerical comparison of the number of users supportable within 90% probability of QoS for the different allocation schemes.