QoS Provisioning in Wireless Data Networks under Non-Continuously Backlogged Users

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Abstract—**This paper addresses the problem of efficient resource allocation in CDMA wireless networks, supporting non-real-time services with various long-term QoS requirements, by exploiting the advantages of opportunistic scheduling. Most of the existing work covers the analysis of the system under the assumption of infinite backlogs. In this paper, we remove this assumption and analyze the behavior of the system with respect to its overall achievable performance and its ability to gratify users' individual QoS requirements under different fundamental opportunistic scheduling policies, for the more realistic case of non-continuously backlogged users. Motivated by the corresponding results that indicate the unsatisfactory performance of these schedulers when considering finite backlogs, and in order to overcome these inefficiencies, a new non-work-conserving opportunistic scheduling framework is proposed which is seamlessly integrated within the operation of the various schedulers. The corresponding results demonstrate that the proposed approach results in the fulfillment of users' QoS prerequisites while still maintaining the opportunistic nature of the schedulers and thus achieving high system throughput.**

Keywords- CDMA wireless networks, opportunistic scheduling, finite backloggs.

I. INTRODUCTION

Towards optimizing system's throughput performance over fast-fading wireless environments in code division multiple access (CDMA) networks, channel-aware opportunistic scheduling policies have been adopted that positively exploit multi-user diversity affect [1]-[10]. However, most of the related existing work on opportunistic scheduling algorithms covers the analysis of the system for static user population and assuming infinite backlogs. The potential instability effects and the corresponding sub-optimal system's throughput performance under dynamic user configuration, when greedy opportunistic policies are applied to maximize system's overall throughput performance, is addressed in [11]. However, in that study only a certain class of policies, based on Proportional Fair algorithm [4], has been considered. Moreover in [12], it is further shown that opportunistic TDMA based scheduling schemes do not always lead to optimality, in terms of overall power consumption, when finite users' backlogs are considered.

In this paper we remove the assumption of continuously backlogged users, since in real environments users may often experience empty queues, due to their potentially good channel conditions, the bursty nature of their traffic, as well as the possibly low or moderate system load. Therefore, we initially study the performance of fundamental opportunistic scheduling approaches under non-continuously backlogged users' scenarios. The under consideration algorithms achieve system's performance maximization, while either asserting weighted users' long-term access time fairness [7] or long-term utilitarian fairness [8], when considering infinite backlogs. The corresponding results indicate their insufficiency in supporting users' Quality of Service (QoS) prerequisites under non-continuously backlogged users' scenarios. Furthermore, the underlying reasons and common design options that lead them in achieving sub-optimal solutions and break the fairness in realistic environments are also revealed and discussed.

Motivated by the above observations we introduce a generic Non-Work-Conserving Opportunistic Scheduling (NWCOS) framework, which can be seamlessly integrated with various existing scheduling policies, and asserts users' QoS requirements satisfaction, while still scheduling them in an opportunistic way even in the case where the assumption of infinite backlogs is removed. This is accomplished by decoupling the operation of the online tuning mechanism that controls users' QoS from the operation of users' selection procedure that controls their actual transmission in an opportunistic scheduling policy.

The rest of the paper is organized as follows. In section II, the system model and some background information with respect to the operation of basic opportunistic schedulers are presented. Section III, discusses the basic reasons that lead these scheduling schemes to unsatisfactory behavior under non-continuously backlogged users while in section IV, the operation of the proposed non-work-conserving opportunistic scheduling framework is described. Finally, in section V, the efficacy of the proposed approach in asserting user's QoS requirements while still achieving high system performance is demonstrated via modeling and simulation.

II. SYSTEM MODEL & BACKGROUND INFORMATION

We consider a single cell time-slotted CDMA wireless system accessed by a static population of N non-continuously backlogged active users. A time slot is a fixed interval of time and could consist of one or several packets. Users' channel conditions, which are affected by shadow fading and fast fading, are considered to be fixed within the duration of a time

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This work was partially supported by EC EFIPSANS project (INFSO – ICT – 215549)

WIOPT 2008, 1st – 3rd Apr 2008, Berlin, Germany.

DOI 10.4108/ICST.WIOPT2008.3184

slot. In each time slot t the base station, which is assumed to have perfect knowledge of users' instantaneous channel conditions, transmits with maximum power P_{max} to only one user i from the set S of N active users, in accordance to a specific scheduling policy Q (i.e. $i_Q^*(t) = i \ \ \forall t$ where $i \in S$). Moreover, let us denote as $R_Q(t) = (R_{Q,1}(t), ..., R_{Q,N}(t))$ the users' transmission rate vector under policy Q at time slot t. Furthermore, due to their diverse service demands as well as their varying channel conditions, active users are distinguished with respect to their queues' amount of data in two time-varying complementary sets, a set of instantaneously backlogged users and a set of users without data to transmit denoted as $S_{BQ}(t)$ and $S_{EQ}(t)$, respectively.

Each mobile user is associated with a proper utility function $U_i(t)$ which represents his degree of satisfaction with respect to the level of performance that he would experience if he is served at time slot t. Following the approach of [7], a user's i utility is a general function of his instantaneous channel conditions, in terms of instantaneous signal to noise ratio (SNR) $\rho_i(t)$, and is assumed to be non-negative and bounded. Intuitively, a user's utility is also a function of his instant transmission rate $R_{Q,i}(t)$.

In the rest of this section, we outline the operation of two fundamental representative opportunistic scheduling policies.

A. *Temporal Fairness Schedulinng Scheme (TF)*

Temporal fairness scheduler aims at the maximization of the total expected system performance while asserting a minimum amount of time slots that an active user i will have access at the system's resources with respect to pre-assigned weights $\varphi_i \, \forall i \in S$. The corresponding optimization problem can be defined as follows:

$$\max E\left[\sum_{i \in S} U_i(t) I_{i_{TF}(t)=i}\right] \tag{1}$$

$$s.t. \ \ \Pr(i_{TF}(t) = i) \geq \phi_i \quad \forall i \in S \tag{2}$$

where $I_{i_{TF}(t)=i}$ denotes the indicator function with value 1 if user i is selected to receive service a time slot t and 0 otherwise. Satisfying inequality $\sum_{i \in S} \phi_i \leq 1$ asserts feasibility. The optimal solution to the above optimization problem can be expressed as [7]:

$$i_{TF}^*(t) = \arg\max_{i \in S_{BQ}(t)} \left\{ U_i(t) + w_i^{TF}(t) \right\} \tag{3}$$

$$w_i^{TF}(t+1) = w_i^{TF}(t) - a(t)\left(I_{i_{TF}(t)=i} - \phi_i\right) \quad \forall i \in S_{BQ}(t) \tag{4}$$

where we can set $a(t)=1/t$. According to (3), a user's priority of being selected at time slot t is not only affected by the temporal value of his utility function but also by his time-varying weight $w_i^{TF}(t)$. Users' weights reflect their achieved service performance into the scheduling policy, and hence converge at such optimal values through a stochastic approximation procedure that forces the scheduler to achieve users' long-term access time goals. Let us underline that only users having data to transmit participate at the comparison performed in each time slot and thus update their weights, since the policy is optimal under infinite backlogs. Moreover, when users are continuously backlogged then $S_{BQ}(t) \equiv S$.

B. *Utilitaria Fairness Scheduling Scheme(UF)*

The goal of utilitarian fairness scheduling scheme is to maximize the overall expected system performance while asserting that each user i receives at least a certain share of the entire resources, in terms of average system's performance, according to his pre-assigned weight g_i. Therefore, the optimal scheduling problem can be stated as:

$$\max E\left[\sum_{i \in S} U_i(t) I_{i_{UF}(t)=i}\right] \tag{5}$$

$$s.t. \ \ E\left[U_i(t) I_{i_{UF}(t)=i}\right] \geq g_i E\left[\sum_{j \in S} U_j(t) I_{i_{UF}(t)=j}\right] \quad \forall i \in S \tag{6}$$

where inequality $\sum_{i \in S} g_i \leq 1$ declares feasibility. Moreover, the optimal scheduling policy can be written as [8], [10]:

$$i_{UF}^*(t) = \arg\max_{i \in S_{BQ}(t)} \left\{ (k + w_i^{UF}(t)) U_i(t) \right\} \tag{7}$$

$$\begin{aligned} & w_i^{UF}(t+1) = w_i^{UF}(t) - a(t) \cdot \\ & (w_i^{UF}(t) - \min_{j \in S_{BQ}(t)} (w_j^{UF}(t))) \left[\frac{E\left[U_i(t) I_{i_{UF}(t)=i}\right]}{E\left[\sum_{j \in S} U_j(t) I_{i_{UF}(t)=j}\right]} - \frac{g_i}{\sum_{j \in S} g_j} \right], i \in S_{BQ}(t) \end{aligned} \tag{8}$$

where $k = 1 - \sum_{i \in S_{BQ}} g_i w_i^{UF}(t)$, $\min(w_i^{UF}(t)) = 0$ and $w_i^{UF}(t) = 0$ if $E\left[U_i(t) I_{i_{UF}(t)=i}\right] \geq g_i E\left[\sum_{j \in S} U_j(t) I_{i_{UF}(t)=j}\right]$. Furthermore, in order to approximate $E\left[\sum_{j \in S} U_j(t) I_{i_{UF}(t)=j}\right]$ a smooth factor can be used which is updated as $\bar{U}(t+1) = \beta \cdot \bar{U}(t) + (1-\beta) \sum_{j \in S_{UF}} U_j(t) I_{i_{UF}(t)=j}$ where $0<\beta<1$. Letting $U_i(t)=R_{UF,i}(t)$, long-term throughput fairness can be achieved.

III. Opportunistic Scheduling under Non-Continiously Backlogged Users Scenario

As the system evolves, the stochastic nature of users' channel conditions that result in time-varying service performance necessitates the existence of an on-line updating mechanism to reflect their service experience into the scheduling policy. Therefore, the examined opportunistic scheduling schemes share a common design principle even if their QoS goals differ. Specifically, both temporal fairness and utilitarian fairness approaches use a stochastic approximation mechanism to introduce users' channel conditions as well as their up to date performance, into the scheduling policy (i.e. as in (4),(8)). Through the stochastic approximation users' weights are periodically fine-tuned, pursuing a set of optimal fixed values that balance their average utility performance and hence keep the fairness, while maximizing overall system's performance.

The proper convergence of users' weights, forced by parameter *a(t)*, requires to be correctly updated at every time slot. In a system with continuously backlogged users (i.e. $S_{BQ}(t) = S \ \ \forall t$) the efficacy of all user's weights convergence relies on their participation at every slot's comparison which also permits their immediate weights update, accordingly. Under moderate or light system's or individual user's load, or due to the potentially bursty nature of the traffic, users' probabilities of experiencing empty queues increases along with their overall probabilities of belonging to the set $S_{EQ}(t)$. Moreover, if we let a user $i \in S$ which has no amount of data to transmit at time slot *t* to be excluded from the comparison process, then his weight is not properly tuned.

The previous scheduling option leads to fault users' weights update, and as a result to the failure of the stochastic approximation procedure and the break of the fairness. Unexpectedly, the better a user's channel conditions are, the higher is his probability of experiencing an empty queue and therefore being un-favored. Finally, let us underline the fact that, as the system evolves the current information used towards updating users' weights, affects less their final values due to factor *a(t).* Therefore, it is vital that all users' weights are properly tuned, and thus echo their average channel conditions in initial time slots, whether are served or not, and independently of their instantaneous backlog state.

IV. A Non-Work-Conserving Opportunistic Scheduling Framework

In order to overcome the identified drawbacks emerging in the view of non-continuously backlogged users' scenario, we initially propose a basic non-work-conserving framework - in the following we refer to as B-NWCOS - which can be integrated in a seamless way with the under consideration opportunistic scheduling schemes. B-NWCOS lets all active users to participate in the weighted utilities comparison procedure at every time slot whether having data to transmit or not. Furthermore, if a user *i* is relatively better than others at time slot *t* under policy *Q* but he lucks of data to transmit (i.e. $i_Q^*(t) = i, \ \ i \in S_{EQ}$), then the base station would remain idle within the duration of that time slot. However, user's *i* weight $w_i^Q(t)$, as well as all active users' weights are updated, as if user *i* was normally accessing the system's resources at the considered slot. Such design option allows users' weights to be properly tuned and the stochastic approximation mechanism to meet its goal, in terms of reflecting users' average channel conditions and their expected service performance at the values of the weights, thus leading the scheduling policy to accomplish its QoS demands.

The following algorithm illustrates the operation of the proposed B-NWCOS framework under a general policy *Q*, where $Q \in \{TP, UF\}$. For presentation purposes, we denote as TF_i^Q the information used to update users' weights at each time slot *t*, which is further expressed as a function of the indicator $I_{i_Q(t)=i}$.

Algorithm B-NWCOS

```
IN time slot t, let $i_Q^*(t) = i$ where $i \in S$.
    IF $i \in S_{BQ}(t)$ then
        $I_{i_Q(t)=i} = 1$, $I_{i_Q(t)=j} = 0 \quad \forall j \neq i \in S$ and
        $R_Q(t) = (0, ..., R_{Q,i}(t), ..., 0)$
    ELSE IF $i \in S_{EQ}(t)$ then
        $I_{i_Q(t)=i} = \hat{I}_{i_Q(t)=i} = 1$, $I_{i_Q(t)=j} = 0 \quad \forall j \neq i, j \in S$ and
        $R_Q(t) = \vec{0}$. The system remains idle.
$w_i^Q(t+1) = w_i^Q(t) - TF_i^Q(I_{i_Q(t)=i}) \qquad \forall i \in S \ \ if \ \ Q \in \{TP, UF\}$
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Indicator $\hat{I}_{i_Q(t)=i}$ is 1 when user *i* is "relatively better" than others in time slot *t* but he lucks of data to transmit.

In order to satisfy non-continuously backlogged users' QoS performance demands, B-NWCOS keeps the base station idle when the maximum priority user has no backlogs, and thus system's scarce radio resources are not fully utilized. To overcome the problem of wasting the available resources, we modify B-NWCOS framework in a way that maximizes system's utilization. Under the enhanced framework, referred to as E-NWCOS, when the "relatively best" user (as selected by policy *Q*) has no data to transmit the scheduler permits the allocation of system's resources to the one with the higher priority among those belonging to the set of active users with data to transmit (i.e. set $S_{BQ}(t)$). Additionally, both users' weights are updated in order to properly reflect the corresponding service performance deviations. The proposed modification is still a non-work-conserving scheme from the perspective of the instantaneously highest priority user, but is work-conserving to the whole system, when $S_{BQ} \neq \varnothing \ \ \forall t$. The operation of E-NWCOS under a general policy *Q* is illustrated bellow.

Algorithm E-NWCOS

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IN time slot t, let $i_Q^*(t) = i$ where $i \in S$,
                let $i_Q^*(t) = k$ where $k \in S_{BQ}(t)$.
    IF $i \in S_{BQ}(t)$ then
        $i = k$ therefore, $I_{i_Q(t)=i} = 1$, $I_{i_Q(t)=j} = 0 \quad \forall j \neq i \in S$ and
        $R_Q(t) = (0, ..., R_{Q,i}(t), ..., 0)$
    ELSE IF $i \in S_{EQ}(t)$ & $S_{BQ} \neq \varnothing$ then
        $I_{i_Q(t)=i} = \hat{I}_{i_Q(t)=i} = 1$, $I_{i_Q(t)=k} = 1$,
        $I_{i_Q(t)=j} = 0 \quad \forall j \neq i, j \neq k, j \in S$,
        $R_Q(t) = (0, ..., R_{Q,k}(t), ..., 0)$.
    ELSE
        The system remains idle.
$w_i^Q(t+1) = w_i^Q(t) - TF_i^Q(I_{i_Q(t)=i}) \qquad \forall i \in S \ \ if \ \ Q \in \{TP, UF\}$
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V. Numerical Results

In this section, the operation of the proposed B-NWCOS and E-NWCOS frameworks over temporal fairness and utilitarian fairness schemes is evaluated via modeling and simulation, under both continuously backlogged and non-continuously backlogged users' scenarios. In order to better illustrate the performance efficacy of the proposed schemes, we assume linear relationship between users' utilities and their corresponding transmission rates (i.e. $U_i(t)=R_{Q,i}(t) \ \ \forall i \in S$). Hence, all schedulers aim at system's throughput maximization.

Throughout our study we consider a single cell time-slotted CDMA system. The duration of a slot is assumed to be *1.67 msec* and the simulation lasts for *200.000* slots. The total number of active users in the system is *N=20*, and we consider two types of users with respect to their average channel conditions, namely "good" users, users *1* to *10,* and "bad" users, users *11* to *20*, with average SNR ρ_G *= 4 (6dB)* and ρ_B *= 2 (3dB)*, respectively. To consider the impact of users' channel condition variations on the system's performance, we model their channels through an 8-state Markov Rayleigh fading channel model [13]. Moreover, the instantaneous transmission rate of a user is determined from the instantaneous SNR (dB) value according to Table 1 as used in the CDMA 1xEV-DO system [7].

TABLE I. DATA RATE (Kbps) AS FUNTCION OF SINR (dB)

SNR ≥	-12.5	-9.5	-8.5	-6.5	-5.7	-4.0
Rate (Kbs)	38.4	76.8	102.6	153.6	204.8	307.2
SNR ≥	-1.0	1.3	3.0	7.2	9.5	
Rate (Kbs)	614.4	921.6	1228.8	1843.2	2457.6	

Active users are assumed to submit file transfer requests according to a Poisson process with rate $\lambda_i \, \forall i \in S$ and average file size F_i (F_i*=480Kbps* $\forall i \in S$). In order to represent both infinite and finite backlogs throughout our experiments we consider two different user rates of submitting file transfer requests, as follows: λ_i *= 2 files/sec* or λ_i *= 0.2 files/sec* $\forall i \in S$, respectively. Therefore, for every scheduling policy $Q \in \{TP, UF\}$ the system performance is demonstrated under four scheduling scenarios. The first depicts scheduler's *Q* performance under continuously backlogged users case (λ_i *= 2 files/sec*, referred as CB_Q), the second under non-continuously backlogged users case (λ_i *= 0.2 files/sec*, NCB_Q), while the third and the fourth scenarios concern its corresponding performance under finite backlogs over the two versions of our proposed framework, namely B-NWCOS_Q and E-NWCOS_Q, respectively.

A. Asserting Temporal Fairness (TF) QoS Criteria

For demonstration purposes, the provisioning of long-term access-time fairness among all active users was considered under TF scheme (that is $\Pr(i_{TF}(t)=i)=1/N \ \ \forall i \in S$). Fig.1 illustrates all users' percentage of time at which they had access at system's resources within the duration of the simulation. Each radius in the figure represents an active user (i.e. user *i=1, 2,..., 20*), while the value of its radius length determines user's *i* corresponding access time percentage. Under infinite backlogs (CB_TF, grey line), all users' access time percentages are almost the same (i.e. approximately 5%) under TF algorithm, which confirms its ability of achieving users' desirable long-term QoS goals. On the other hand, under non-continuously backlogged users' scenario (NCB_TF, black lines), where active users' percentage of experiencing empty queue is 9.5% of the total simulation time on average, TF fails to provide fairness among them. The results indicate that the

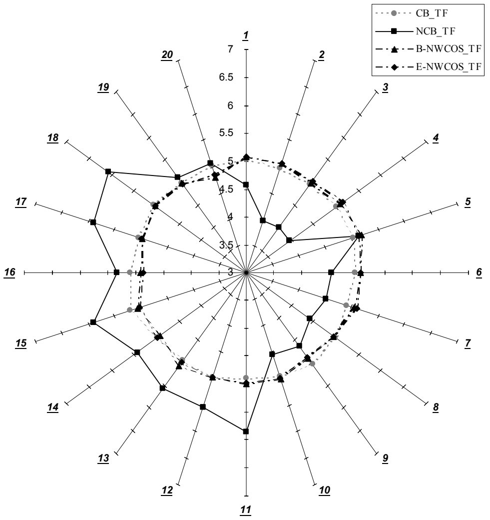

Figure 1. Users' access-time percentage under TF policy

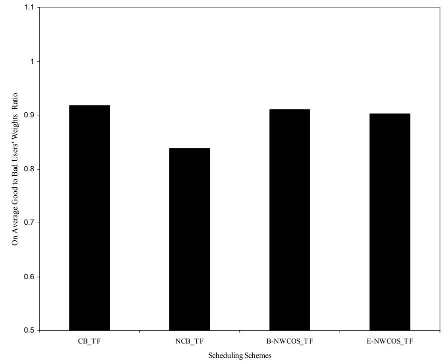

Figure 2. *Good to bad user's weights' ratio under TF policy*

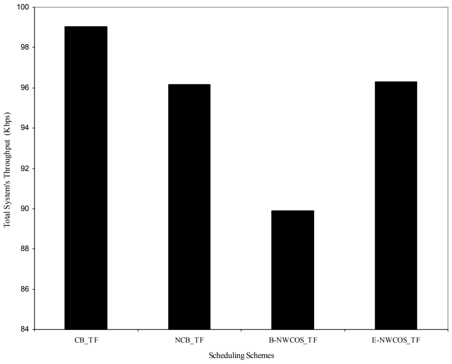

Figure 3. *Total average system's throughput under TF policy*

inner reason for such an unsatisfactory behavior is users' weights fault values. Therefore, Fig.2 demonstrates the average weights ratio of good to bad user's after converging to their final values, under all scheduling scenarios. The optimal weights' ratio that efficiently reflects into the scheduling policy good and bad users' channel conditions, can be determined by the one achieved under CB_TF scenario. Moreover, we can observe that the corresponding average users' weights ratio is much smaller than the optimal achieved under NCB_TF; therefore good users' are highly un-favored in terms of time slots allocation compared to bad users as is illustrated in Fig.1 (black line).

Under the proposed B-NWCOS and E-NWCOS frameworks access time fairness among active users is accomplished under finite backlogs, as the cycle-shape lines in Fig.1 confirm. Moreover, the correct function of the stochastic approximation procedure that leads to proper users' weights convergence, is verified by the resultant good to bad users' weights ratios values which are very close to the one achieved under TF in CB_TF scenario, as presented in Fig.2 (two last columns). Finally, the efficient utilization of system's radio resources under E-NWCOS is shown in Fig.3 (last column compared to others) where system's total average throughput is demonstrated. Let us underline, that even when the system's load is low (i.e. users' incoming files ratio is *0.2 files/sec*) which leads to empty queues effects, it is still sufficient to maintain the system fully occupied.

Moreover, under E-NWCOS_TF framework system's slot utilization approximates 100%, in contradiction to the 91% slot utilization achieved under B-NWCOS_TF and therefore, system's corresponding throughput performance approximates the one achieved under infinite backlogs case, while still asserting fairness.

B. Asserting Utilitarian Fairness (UF) QoS Criteria

In the following, we study the system's performance under utilitarian fairness scheme when long-term throughput fairness QoS requirements among all active users are set (i.e. $\sum_{i\in S} g_i = 1$ and $g_i = 1/N \quad \forall i \in S$). Fig.4 shows all users' achievable average transmission rates considering infinite backlogs (CB_UF, gray line) and finite backlogs (NCB_UF black lines) under the basic UF scheduling scheme as well as over B-NWCOS_UF and E-NWCOS_UF frameworks. Moreover, Fig.5 depicts the average weights ratio of good to bad users after convergence.

When UF algorithm operates under non-continuously backlogged users' scenario fails to provide long-term performance fairness by over-provisioning bad users while restricting the allocation of system's resources to good users, as it is indicated by the corresponding deviations on their achieved average throughput (Fig. 4, black line) and confirmed by the value of their weights ratio (Fig.5, NCB_UF column). On the other hand, over B-NWCOS framework UF accomplishes its QoS goal (Fig.4, triangle marks), while under E-NWCOS framework achieves to further improve both the overall system and individual user performance by approximately 8% (Fig.4, rhombus marks).

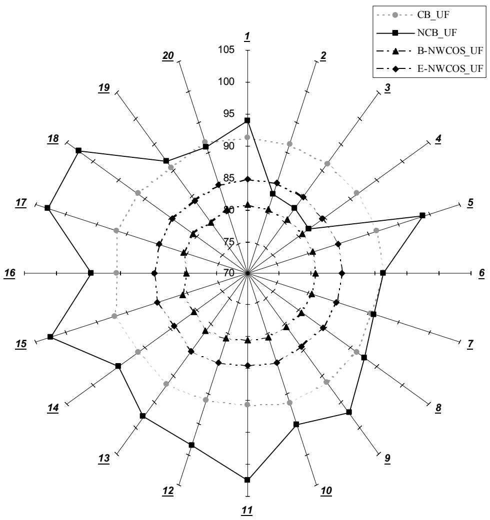

Figure 4. *Users' average throughput under UF policy*

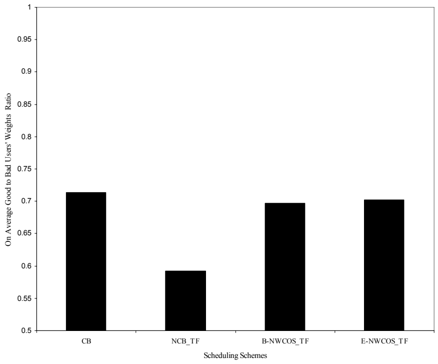

Figure 5. *Good to bad user's weights' ratio under UF policy*

It should be emphasized that E-NWCOS framework achieves to utilize the idle system's time slots occurred under B-NWCOS, (i.e. slot utilization under B-NWCOS_UF is 85%), while still satisfying the users' QoS prerequisites since their corresponding weights' that control the fairness still converge at their proper values.

Finally, it should be noted that the effectiveness and efficiency of the proposed framework has also been studied under Proportional Fair [4] and Minimum Performance guaranty [8] scheduling schemes, and similar observations have been made. However the corresponding analysis and results are omitted here due to the space limitations.

VI. CONCLUDING REMARKS

In this paper, we address the problem of efficient resource allocation in CDMA wireless networks. The common assumption of infinite backlogged users is removed in this work and an extensive analysis of system's behavior, in terms of overall performance as well as the ability to gratify users' individual QoS requirements is performed. Our study and corresponding results obtained under two fundamental opportunistic scheduling policies indicate insufficient system's performance when considering finite backlogs and thus, the inner reasons for this behavior are identified and discussed. Therefore, a non-work-conserving opportunistic scheduling framework, seamlessly integrated and in line with all considered scheduler's operation is devised, that leads to users' QoS prerequisites fulfillment while maintaining their opportunistic scheduling character even under non-continuously backlogged users' scenario. Moreover, through simulation and experimentation, the advantages of the proposed framework are revealed while the revised policies' efficiency in supporting users' QoS requirements under both infinite and finite backlogs are illustrated.

Throughout our analysis we consider finite users' backlogs while still assuming static users' population. The system performance evaluation under time varying users' population along with the appropriate users' fairness criteria re-definition required in such case is a problem of a great importance towards designing scheduling policies that proficiently operate under realistic scenarios.

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