Channel-Quality Dependent Earliest Deadline Due Fair Scheduling Schemes for Wireless Multimedia Networks

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ABSTRACT
Providing delay guarantees to time-sensitive traffic in wireless multimedia networks is a challenging issue. This is due to the time-varying link capacities and the variety of real-time applications expected to be handled by such networks. We propose and evaluate the performance of two channel-aware scheduling schemes that are capable of providing such delay guarantees in wireless networks. In the first proposed scheme, the Channel-Dependent Earliest-Due-Date (CD-EDD) discipline, the expiration time of the head of line packets of users' queues is taken into consideration in conjunction with the current channel states of users in the scheduling decision. This policy attempts to guarantee the targeted delay bounds in addition to exploiting multiuser diversity to make best utilization of the variable capacity of the channel. In the second scheme we attempt to ensure that the number of packets dropped due to deadline violation is fairly disturbed among users. This provides fairness in the quality of service (QoS) delivered to different users. A unique feature of our work is explicit provisioning of statistical QoS as well as ensuring fairness in data rates, delay bound, and delay bound violation. We provide extensive simulation results to show the different performance aspects of the proposed schemes.

Categories and Subject Descriptors
C.2.1 [**Computer Communication Networks**]: Network Architecture and Design – *Wireless Communication;*
C.4. [**Performance of Systems**]: Modeling Techniques

General Terms
QoS Provisioning, Performance evaluation and modeling.

Keywords
Fairness, Multiuser diversity, Scheduling, Wireless networks.

1. INTRODUCTION
Scheduling in wireless networks have become the focus of recent research. This is due to the expectations that the next generation networks will combine the advantages of the Internet with the mobility characteristics of the wireless systems. Many scheduling algorithms, capable of providing certain guaranteed QoS, have been developed for wireline networks. However, these existing service disciplines, such as Weighted Fair Queuing (WFQ), virtual clock, and Earliest-Due-Date First (EDD) [1], are not directly applicable in wireless networks because they do not consider the characteristics of wireless channel. These characteristics include high error rate, bursty errors, location-dependent and time-varying wireless link capacity, scarce bandwidth, user mobility, and power limitation of the mobile hosts. All of the above characteristics leads to the fact that developing efficient and effective scheduling algorithms for wireless networks is very challenging.

An effective way to increase the capacity of a time-varying channel is the use of diversity. The idea of diversity is to create multiple independent signal paths between the transmitter and the receiver so that higher channel capacity can be obtained. Diversity can be achieved over time, space, and frequency. These traditional diversity methods are essentially applicable to a single-user link. Recently, however, Knopp and Humblet [2] introduced another kind of diversity, which is inherent in a wireless network with multiple users sharing a time-varying channel. This diversity, termed multiuser diversity, comes from the fact that different users usually have independent channel gains for the same shared medium (e.g. downlink). With multiuser diversity, the strategy of maximizing the total Shannon (ergodic) capacity turns out to be a greedy scheduling rule where the scheduler allows at any time slot only the user with the best channel to transmit [3]. Results in [4] have shown that such scheduling technique can increase the total (ergodic) capacity dramatically, in the absence of delay constraints, as compared to the traditionally used scheduling techniques.

One problem with such greedy scheduling is the unfairness in resource sharing between users in the network. This is due the fact that the user with the best channel conditions will always receive the biggest share of network resources; while the user suffering from bad channel conditions will not be able to be served. The research reported in [5-10] was concerned with the problem of achieving throughput and/or temporal fairness among users. These works report on scheduling algorithms that attempt to guarantee that the difference in the services obtained by users with different channel conditions are as close as possible either on short-term basis and/or on long-term basis. However, these schemes provide no delay guarantees and thus are not suitable for delay-sensitive applications, such as voice and video. In this paper we propose a scheduling scheme based on Earliest-Due-

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Date First (EDD) that exploits multi-user diversity and can provide statistical guarantees on delays, achieves high throughput, and exhibits good fairness performance with respect to throughput and deadline violations.

The rest of this paper is organized as follows: is section 2 we describe the model of the system under consideration. Then in section 3, a survey of scheduling delay-sensitive traffic in wireless network in the literature is presented. In section 4, we propose two new scheduling policies and discus their operation. While in section 5, an extensive set of simulation is carried out to explore the characteristics of these disciplines. Section 6 summarizes the main findings of this paper.

2. SYSTEM MODEL

We first describe the cellular wireless network model used, and more specifically the downlink of such a network. A base station transmits data to N mobile terminal users, each of which requires certain QoS guarantees. In cell-structured wireless networks, the service area is divided into cells, and each is served via a base station. A single cell is considered in which a centralized scheduler at the base station controls the downlink scheduling, whereas uplink scheduling uses an additional mechanism such as polling to collect transmission requests from mobile terminals [5], [6]. We assume that the downlink and uplink transmission don't interfere with each other.

We consider a time slotted system, where time is the resource to be shared among users. A time-slotted cellular system can have more than one channel (frequency band), but at any given time, only one user can occupy a given channel within a cell. Here, we focus on the scheduling problem for a single channel over which a number of users could be time-division multiplexed. Time division multiple access (TDMA) systems divides the time into time slots of length Ts, during which data transmission of a single user, the scheduled user, is carried out using all resources available to the base station at that time instant. For downlink scheduling, packets destined to different users are put in separate queues, one corresponding to a user's data flow.

The time varying channel conditions of wireless links are related to three basic phenomena: fast fading on the order of milliseconds, shadow fading on the order of tens to hundreds of milliseconds, and finally, long time-scale variations due to user mobility. The channel fading processes of the users are assumed to be stationary, ergodic and independent of each other, and we also assume that the channel gains are constants over one time slot's duration. Since our algorithm will exploit the users' channel conditions in making the scheduling decision, we consider wireless systems with mechanisms to make predicted channel conditions available to the base station as is commonly the case with technologies such as HDR [11], UMTS-HS-DPA [12], (E)GPRS [13], etc. The particular mechanism employed by a system depends on the communication standard. In general, the faster and more precisely the channel quality can be predicted, the better the scheduler can incorporate this information into its decision as to which user to schedule next [5]. Thus, we will assume that base station has the current (or delayed) channel state information of each user.

An important and challenging problem in the design of high speed communications networks is that of providing Quality of Service (QoS) guarantees, usually specified in terms of rate guarantees, loss probabilities or delays of packets in the network. The control of delays is often of crucial importance, especially for real-time applications such as audio and video streaming. Real-time traffic classes are modeled as a stream of packets, with each packet having an expiry time beyond which the packet is of no use to the end user. The objective of the scheduler is to transmit each packet before its expiry, and if this is not possible, to minimize the number of lost packets due to deadline expiry. Expiry occurs when a packet have been waiting in the base station queue for a time greater than its deadline without being served. Such a packet is dropped by the system.

Such QoS requirements can be specified in terms of deadline T_i (deterministic QoS requirements) or accompanied with allowed violation probability δ_i (statistical QoS) for each user traffic flow. In this paper, we will use the following model in defining QoS requirement of user i

$$\mathrm{P}\left(W_i > T_i\right) \le d_i \tag{1}$$

for i = 1, 2, …. , N, where W_i to be the delay encountered by user i packets. Under this constraint, the problem is to minimize the violation occurrences.

3. PREVIOUS WORK

In this section, we present a survey of existing scheduling disciplines applicable in wireless networks with delay-sensitive users' traffic. In [14], the authors proposed to apply the wireline EDD discipline scheduling in wireless networks. The scheme is called Feasible Earliest Due Date (FEDD) scheduling. They assumed a simple channel state model in which the channel can be either "good" or "bad". Thus, FEDD scheduling chooses to schedule the packet which has the earliest time to expiry from the set of queues whose channels are marked good only.

The authors in [16] proposed a modification to the Largest Weighted Delay First (LWDF) scheduling discipline that takes the time varying characteristics of wireless channels into account. The LWDF [15] discipline is a parameterized version of the first-input first-output (FIFO) that works as follows: at the beginning of the time slot starting at time t, serve at the maximal possible rate the queue of user j, where

$$j = \arg\max_i \{a_i W_i(t)\} \tag{2}$$

where $W_i(t)$ is the waiting time of head of line (HoL) packet of the i^{th} user at the time slot starting at time t, and $a_i > 0$, i = 1,2, …., N, are a fixed set of constants. If the delay QoS requirements for all users are as expressed by (1), it was proved in [15] that the choice of weights a_i that makes LWDF discipline nearly throughput optimal (note however that this choice of weights is valid only for large values of the delay bound T_i and very small values of δ_i) is:

$$a_i = -\log \frac{d_i}{T_i} \tag{3}$$

The proposed modification of [16] was to use multiuser diversity in order to increase the efficiency of channel utilization (and hence the system throughput) and also compensate delayed users. The proposed Modified Largest Weighted Delay First (M-LWDF) discipline schedules the j^{th} user, where

$$j = \arg\max_i \{ g_i \mu_i(t) W_i(t) \} \tag{4}$$

where $\mu_i(t)$ is the state of the channel of user i at time t, i.e. the actual rate supported by the channel. This rate is assumed to be constant over one slot. It had been proven in [16] that setting $g_i = a_i / \overline{\mu}_i$,where a_i is given by (3) and $\overline{\mu}_i$ is the mean rate supported over the i^{th} channel, makes the M-LWDF discipline throughput optimal. In practice, the mean rate can be measured over a certain, but relatively long, time window [4] by averaging the rate actually given to that user in that window. The M-LWDF scheduling rule could be rewritten as schedule the j^{th} user, where

$$j = \arg\max_i \{ a_i \frac{\mu_i(t)}{\overline{\mu}_i} W_i(t) \} \tag{5}$$

The exponential rule scheduling discipline have been also proposed in [16] (further investigated and implemented in [17] for CDMA/HDR system and modified in [18].) This scheme schedules the j^{th} user at the time slot starting at time t for transmission, where

$$j = \arg\max_i \{ a_i \frac{\mu_i(t)}{\overline{\mu}_i} e^{\frac{a_i W_i(t) - \overline{aW}}{1+\sqrt{\overline{aW}}}} \} \tag{6}$$

and

$$\overline{aW} = \frac{1}{N} \sum_{i=1}^{N} a_i W_i(t) \tag{7}$$

This policy attempts to equalize the weighted delays $a_i W_i(t)$ of all the queues when their differences are large. If one of the queues would have larger (weighted) delay than the others by more than order $\sqrt{\overline{aW}}$, then the exponent term becomes very large and overrides the channel considerations (as long as its channel can support a non-zero rate), hence giving priority to that queue. On the other hand, for small weighted delay differences (i.e. less than order $\sqrt{\overline{aW}}$), the exponential term is close to unity, and the policy behaves as the proportionally fair rule. Hence, the exponential rule policy gracefully adapts from a proportionally fair one to one which balances delays [16], [17]. Simulation results in [17] showed that the exponential rule scheduling exhibits better delay tails compared to any other scheduling policy in the sense that the delays of all users are about the same and are all reasonably small. This occurs, however, for large values of T_i and very small values of δ_i, which is not desired practically. Moreover, the exponential rule scheduling was found to be highly dependent on parameter settings. Therefore, It was advised that identifying good scheduling rules which are less dependent on the "proper" parameter setting would be desirable [16].

4. THE PROPOSED SCHEDULING SCHEMES

The goal of our work is to design scheduling schemes for delay sensitive traffic that exhibits “good performance” in wireless networks. From the above study of such a problem, we mean by the word "good performance" that such a discipline should attempt to achieve the following objectives: 1) Maximizing the overall system throughput by utilizing multiuser diversity, 2) Providing a mechanism to compensate queues whose packets are experiencing long delays in the system in order to prevent their packets from being lost, 3) Achieving fairness in resource sharing, and 4) Exhibiting weak dependency on the parameters setting.

4.1 Channel Dependent Earliest Deadline Due (CD-EDD) Scheduling Discipline

In classical wireline earliest due date scheduling, each packet is assigned a deadline, and the scheduler serves packets in order of their deadlines. The queue with the smallest deadline is served first by the maximum available rate. If the scheduler is overcommitted, then some packets miss their deadlines. This policy was shown to be optimal in the wireline case (for independent identically distributed Bernoulli arrival and channel processes). EDD cannot be efficiently employed in wireless networks since it does not consider the time varying characteristics of wireless links. It was not reported in the literature the existence of a scheduling discipline that combines the EDD scheduling concept with a mechanism to adapt with the characteristics of wireless networks (with the exception of the attempt in [14] which does not actually adapt with the time varying nature of wireless channel, since it assumed the simplified channel model of good or bad).

We propose a new scheduling discipline, which we call the Channel Dependent Earliest Due Date first (CD-EDD) policy. This is basically a channel-state dependent EDD policy where the scheduler chooses to schedule the queue whose HoL packet has the earliest time to expire and the best channel conditions, and consequently the highest transmission rate, among all queues. The proposed CD-EDD scheduling policy is as follows:

At the time slot starting at time t, schedule with the maximum possible rate the queue of the j^{th} user, where

$$j = \arg\max_i \{ a_i \frac{\mu_i(t)}{\overline{\mu}_i} \frac{W_i(t)}{d_i(t)} \} \tag{8}$$

where

a_i is the weighting parameter reflecting the statistical QoS requirements of the i^{th} user.

$\mu_i(t)$ is the actual rate that could be used for transmission by the i^{th} user at time t, which reflects the current channel state of the user's channel.

$\overline{\mu}_i$ is the mean rate supported or previously offered to the i^{th} user.

$W_i(t)$ is the delay experienced by the HoL packet since its entrance to the i^{th} user queue in the base station.

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

$$d_i(t) = T_i - W_i(t) \tag{9}$$

The behavior of the CD-EDD policy can be explained as follows: when a certain queue has its HoL packet waiting in the system for a relatively long period (but have not expired yet), its time to expire will decrease significantly. in such a situation, the term $W_i(t)/d_i(t)$ will grow significantly due to the contribution of $1/d_i(t)$ until it overcomes other terms in (8). This has an effect akin to reducing the number of dropped packets due to deadline violation. On the other hand, if the delay characteristics of all users are about the same, i.e. their time to expire and waiting times are close, the term $W_i(t)/d_i(t)$ will be common to all users, and the policy then reduces to a proportionally fair one that exploit multiuser diversity to efficiently utilize the channel bandwidth of multiuser systems in a fair manner. It is worth mentioning that weights a_i doesn't contribute significantly in the decision. A rule of thumb for choosing a_i which works in practice is the one given in (3) since this choice is suggested by large deviations of optimality results.

In other words, the CD-EDD is a scheduling discipline that can be used to provide QoS guarantees, defined in terms of delay bounds, for real-time traffic in wireless networks. This is achieved by increasing the priority of delayed users to get access to the medium over time. An important feature of the CD-EDD policy is its weak dependency on the value of QoS required, and thus can be used for a wide variety of QoS requirements.

4.2 A Set of Violation Fair Rules

Another new idea than can be applied in conjunction with any scheduling discipline in order to enhance the fairness characteristics of these policies is proposed here, which is based on the number of deadline violations occurring to packets of different queues. This requires that each queue in the base station to be accompanied with a counter that counts the number of packets lost in this queue's flow. This may be implemented practically be means of sliding windows basis. Let us define

$NV_i(t)$ to be the number of deadline due date violations encountered in the flow of the i^{th} user up to time t.

$\overline{NV(t)}$ to be the average of the number of violations in all N queues, i.e.

$$\overline{NV(t)} = \frac{1}{N}\sum_{i=1}^{N} NV_i(t) \tag{10}$$

The scheduler may use the number of deadline violations to find a way to compensate users suffering from unfairness in the number of dropped packets. For example the scheduler could give more credit or increase the priority level so that such a user could access the system resources. This could be achieved be a scheduling discipline that uses a term like $NV_i(t)/\overline{NV(t)}$ in making the scheduling decision. We call such a scheduling discipline a violations-fair (VF) discipline.

Initially, we applied this idea directly to the proportionally fair [4] scheduling discipline, yielding the violations-fair proportionally fair policy. So, in each time slot the scheduler chooses the j^{th} user, where

$$j = \arg\max_i \{\frac{m_i(t)}{\overline{m_i}} \frac{NV_i(t)}{\overline{NV(t)}}\} \tag{11}$$

This reduces the number of packets lost for users with bad channel conditions, therefore, enhancing the fairness characteristics of the proportionally fair policy. On the other hand, it still lacks a mechanism for provisioning of QoS guarantees for delay sensitive traffic.

We further apply the proposed modification to both the M-LWDF and the exponential rule policies. In the violations-fair modified largest weighted delay first (VF-M-LWDF) discipline, the scheduling decision is such that at the time slot starting at time t, schedule with the maximum possible rate the queue of the j^{th} user, where

$$j = \arg\max_i \{a_i \frac{m_i(t)}{\overline{m_i}} \frac{NV_i(t)}{\overline{NV(t)}} W_i(t)\} \tag{12}$$

In the violations-fair exponential (VF-EXP) discipline, the scheduling decision is such that at the time slot starting at time t, schedule with the maximum possible rate the queue of the j^{th} user, where

$$j = \arg\max_i \{a_i \frac{m_i(t)}{\overline{m_i}} \frac{NV_i(t)}{\overline{NV(t)}} e^{\frac{a_i W_i(t) - \overline{aW}}{1+\sqrt{\overline{aW}}}}\} \tag{13}$$

The proposed modification enhance their performance since the addition of the violations-fair term will ensure fairness in both the delay times and throughput. This could be explained since both the M-LWDF and the exponential disciplines minimize the packet delay, and when the number of dropped packets is fairly distributed among the users, the long term service rate will be equal for all users. Another very important gain of the violations-fair version of these discipline, is that their performance is not much dependent on the parameter setting as was the case in the original rules (this will be seen in the simulation results).

Finally, if the proposed violations-fair technique is applied on the proposed CD-EDD, we can get a scheduling discipline applicable in wireless network that explicitly provide QoS to delay sensitive traffic, with excellent fairness characteristic with respect to data rate, delay bound, and delay bound violation. The violations-fair –channel-dependent earliest deadline due date (VF-CD-EDD) scheduler chooses, at the time slot starting at time t, the j^{th} user for transmission, where

$$j = \arg\max_i \{a_i \frac{m_i(t)}{\overline{m_i}} \frac{W_i(t)}{d_i(t)} \frac{\overline{NV_i(t)}}{\overline{NV(t)}}\} \quad (14)$$

In the next section, we provide an extensive set of simulation that explore the performance of the proposed CD-EDD discipline compared with the M-LWDF and the exponential rule disciplines as a reference. We also show the advantages achieved by their violations- fair versions, namely the VF-CD-EDD, the VF-M-LWDF, and the VF-exponential scheduling disciplines.

5. PERFORMANCE EVALUATION

5.1 Simulation Setup

First, we describe the simulation setup used. We chose the High Data Rate (HDR) CDMA system model. HDR technology has recently been proposed as a TDM-based overlay to CDMA with the goal of providing packet data services to mobile users. A very attractive feature of HDR is enabling the use of efficient scheduling algorithms since it provides a mechanism for link status monitoring. The cell serves ***N*** mobile users each receiving a data flow. The base station contains ***N*** queues, one corresponding to a different data flow and an associated scheduler. The scheduler makes a decision every 1.667 millisecond based on the current information available at the start of the time slot. Arrival process of the real-time traffic is modeled as a Bernoulli processes with a mean rate of 28.8 Kbps for each of the ***N*** user's queues. This rate corresponds to the typical rate required for streaming audio over the Internet. The HDR packet size is 128 bytes. We assume for simplicity that all users require the same service quality, i.e. they all have the same deadline (T_i) and the same violation probability (δ_i) of 95%.

Even thought all users share a common channel, the channel capacity of that channel seen by different users is different. This is due to the wireless link characteristics described above. The instantaneous capacity of a wireless channel is given by

$$C(t) = B \log_2 (1 + |h(t)|^2 \; SNR) \quad (15)$$

where ***C(t)*** is the channel capacity or the data rate (in bits per second) that can be transmitted on a channel of bandwidth ***B*** (Hertz). The bandwidth of HDR/CDMA channel is 1.25 MHz. The term $|h(t)|$ is the normalized gain (or fading level) of the wireless channel at time *t*, and ***SNR*** is the required signal to noise ratio at the receiver antenna (13 dB for HDR/CDMA system). For simulation purposes, we use the typical HDR and cell parameters given in [11]. The average fade level distribution of a typical mobile in HDR cell can be easily found. The fading process of each user's channel can be represented by a Rayleigh process. So, in order to simulate *N* channels, we pick *N* fading levels according to the above distribution, and generate *N* Rayleigh processes with means equal to these fading levels after being normalized. It is worth mentioning that HDR doesn't not support arbitrary transmission rates, i.e. the scheduled user cannot transmit with the rate computed above but with the maximum possible rate from a set of discrete rates. An HDR user can transmit data at a rate of $9.6 * 2^i$ Kbps, i = 0, 1,…, with a maximum rate of 2 Mbps. Thus the state of channel $m_i(t)$ at the start of the time slot at time *t* will be the actual rate that the channel can support, rather than the channel capacity at that time instant. We have assumed that the channel conditions do not change significantly within a time slot duration. Finally, all simulations will be carried out for a duration of 10 minutes.

5.2 Performance Metrics

For real-time traffic, a good measure of performance is the delays packets incur at the base station. A good scheduling algorithm should keep all delays below the delay bound T_i with high probability. The delay distribution curves can be used to illustrate the delay behavior of the scheduling disciplines under consideration. Some parameters of the delay distribution, such as the worst-case delay, the mean delay, or the 95-percentile delay, could be used to evaluate the QoS received by a user. We will consider the 95-percetile delay as our measure of the delay guarantees offered by a scheduling discipline.

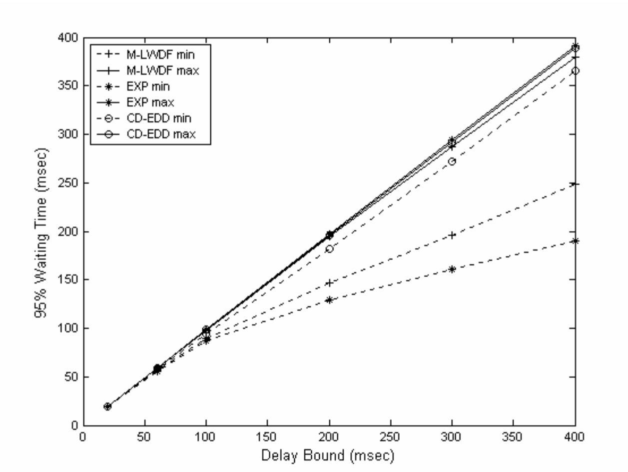
Our measure of the throughput performance of the scheduling disciplines at hand will be the total throughput achieved by the system. The fairness of bandwidth sharing among users is also a good indication of the efficiency of any scheduling discipline.

The fraction of packets dropped, due to deadline violation, for a user can be used to evaluate the loss performance of a scheduling discipline. For real-time traffic, this fraction is required to be as small as possible. From fairness point of view, it is better to equalize the fraction of packets lost in different queues.

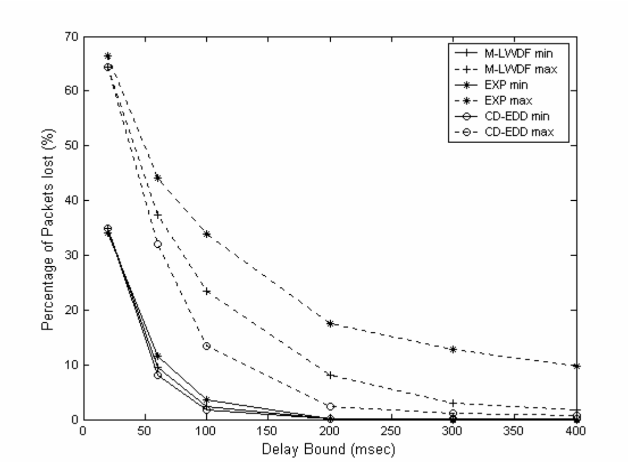
5.3 Results and Discussions

First, we estimate the number of users, with traffic like the one described above, that can be supported by a single HDR cell under each of the previously mentioned scheduling policies. In this experiment, we simulate *N* users, uniformly distributed throughout the cell, and monitor the average service rate received by a single user for different values of *N*. As *N* increases, and as long as the channel capacity can support such a number of users, it is expected that the service rate received by each user will be close to its arrival rate. Any further increase of the number of user, while keeping the channel capacity unchanged, will make the scheduler unable to serve such users in the appropriate time so more packets will be dropped and thus the average throughput share of each user will decrease. So, we will take the number of users beyond which the average service rate received by any user in the system start to decrease as the system capacity. Simulation results showed that the considered scheduling disciplines allow the system to support from 12 to 16 users depending on the value of the deadline.

In our second experiment, we investigate the delay performance of various scheduling disciplines. We begin with a comparison of the proposed CD-EDD scheduling disciplines versus to both the M-LWDF and the exponential rule scheduling disciplines reported as the most suitable policies for scheduling delay sensitive traffic in the literature. In order to be able to evaluate the performance of the scheduling techniques, the system should be loaded with its maximum capacity. Based on the results of the first experiment, we assume that the cell is serving 14 mobile terminals, i.e. *N* =14. The delay distribution tails for both user 1 (with the best channel conditions) and user 14 (with the worst channel conditions) for the M-LWDF, exponential rule, and the

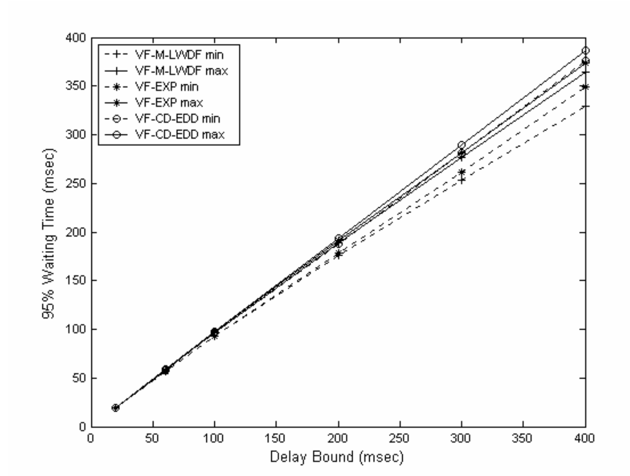


(a) The maximum and minimum 95% delays.

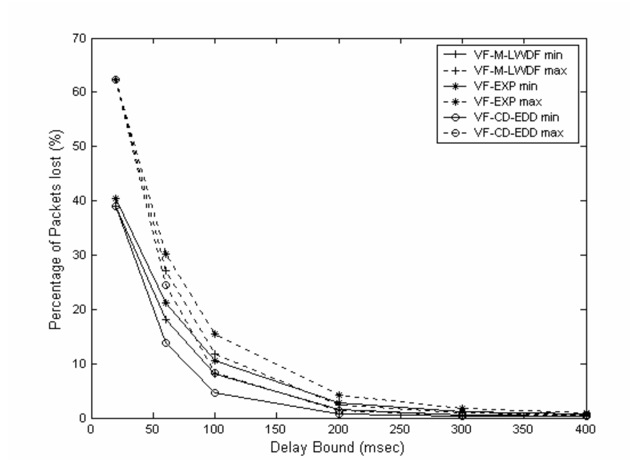


(b) The maximum and minimum percentage of packets lost.

Figure 1. Fairness Behavior of the original disciplines.



(a) The maximum and minimum 95% delays.



(b) The maximum and minimum percentage of packets lost.

Figure 2. Fairness Behavior of the violation fair disciplines.

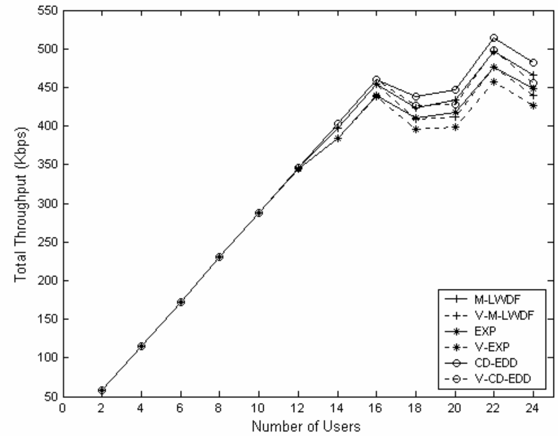
proposed CD-EDD scheduling disciplines for delay bounds of 60, 100, 200, and 400 milliseconds have been studied. These bounds are encountered practically in multimedia streams. However, due to space constraints, we are not able to show these curves. We refer the reader to [20] for further details. We observe that for moderate delay bounds, e.g. 60 and 100 milliseconds, the performance of the exponential rule scheduling slightly outperforms both the M-LWDF and CD-EDD disciplines. In this case, all delays are kept at small value and about the same for all users. For higher bounds, e.g. 200, and 400 milliseconds, we find that the delay performance of the CD-EDD scheduler does not change significantly. On the other hand, the performance of both the M-LWDF and the exponential rule schedulers degrades severely as the gab between the tails of the best user and the worst user becomes wider. This severe degrading in performance is caused by the dependency of both rules on the quality of service required, which affects the value of the weights $\{a_i\}$ that controls the performance of these rules. (Keep in mind that the goal of the M-LWDF is to minimize the weighted delays while the exponential rule scheduling tries to keep all the delays around the average of these weighted delays ($\overline{aW}$), and they both do not target a certain delay bound to serve as much packet as possible before this bound is violated.) On the other hand, the CD-EDD policy does not suffer from such a dependency on the QoS, and consequently the weight values, since the philosophy of this rule is mainly to serve more packets before their deadlines expire. This may cause the packets of the best channel users to experience relatively higher delays than in the case of other rules, but still lower than the worst user. This occurs on the expense of preventing more packets from being dropped due to deadline violation.

This can be further demonstrated when we plot the maximum and the minimum (corresponding to the best and worst users) 95-percentile delay and percentage of packets dropped due to deadline violations versus the delay bounds as shown in Figure 1-a and 1-b, respectively. It is clear that it is not desirable to keep one or some users' delays below a value much smaller than the required bound while leaving one or some users suffering from dropping a large percentage of their packets as the case with both the M-LWDF and exponential rule schedulers. While in CD-EDD discipline, the maximum and the minimum 95 percentile delay are about the same and so close to the delay bound, besides the packet loss ratios are very small and very close to each other. **So, the base stations can guarantee strong delay bounds for all delay sensitive users in a fair manner by using the CD-EDD scheduling discipline, regardless of the value of these bounds.**

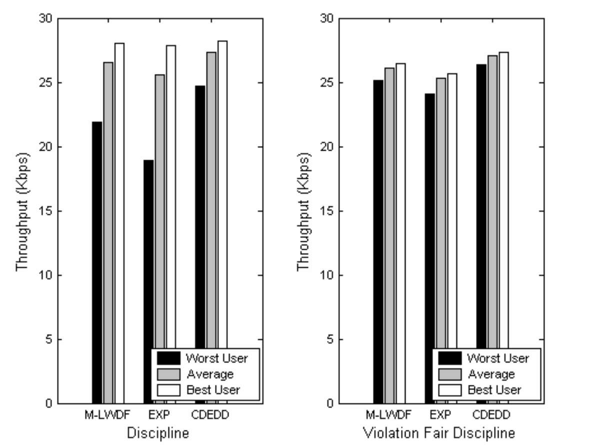
When the same experiments were carried out for the violations-fair versions of the above disciplines, it was found that the performance of all the violations-fair policies is not much dependent on the QoS required (including the disciplines which are originally suffering from that dependency). The delay distribution tails of the best user and the worst user for different delay bounds have been studied [20]. It is observed that the tails became much more closer for the VF-CD-EDD, but with a little bit higher delays than those of either the VF-M-LWDF or the VF-EXP policies. As shown in Figures 2-a and 2-b, where the maximum and the minimum 95-percentile delay and percentage of packets dropped due to deadline violations are plotted versus the delay bounds, the service quality offered to different users, in terms of 95% delay, is about the same. Furthermore, the amount of packets dropped in the system due to deadline violations becomes very small. Moreover, this amount is distributed among all users in a fair manner. Like the CD-EDD, the VF-CD-EDD has the superiority since it achieves the smallest number of packets lost due to deadline violations.

Finally, we study the throughput characteristics of the aforementioned scheduling disciplines. Here we are interested in studying the overall throughput of the system as well as how the throughput is divided among users with different channel conditions, i.e. fairness in throughput sharing. The results of this experiment are illustrated in Figure 3-a for 100 milliseconds bound by plotting the overall throughput of the system versus the number of users using the simulation setup of the first experiment. When the system is operating with number of users less than the system capacity, the total throughput of the system equals the sum of the arrival rates. When the system is serving more users than the system capacity, we observe that, regardless of the delay bound, the total throughput achieved using the CD-EDD is higher than any other rule because this policy causes the smallest number of packet to be lost due to deadline expiry. Moreover, the total throughput achieved using any violations-fair discipline is less than the throughput achieved with the non-violations fair counterpart. This is because in order to achieve fairness in the ratio of packets dropped among different user, the violations-fair polices may prevent users with good channel conditions from transmitting their data for the sake of users with bad channel conditions (such channels support low transmission rates only). So the overall throughput achieved by the system will be lower than the case where the scheduling policy do not intend to make users with good channel condition drop some packet for the purpose of fairness.

In Figure 3-b, we compare the average throughput share of a single user against the actual throughput shares of both the best channel user and the worst channel user for 100 milliseconds delay bound for both the original disciplines and their violation fair counterparts. In this experiment, we use the same simulation



(a) The total throughput achieved.



(b) Throughput Fairness.

Figure 3. Throughput behavior at 100 m sec delay bound.

model used in the second experiment where the base station serves the 14 used above. As seen in these figures, the CD-EDD discipline achieves the greatest average throughput per user, besides, it keeps the actual throughput share as close as possible to that average. Note that the throughput shares of the best channel user and worst channel user are always close to each other for various delay bounds for CD-EDD scheduling. This means that the CD-EDD discipline is the most throughput fair policy that can guarantee delay bounds for real-time users. On the other hand, even though the violation fair disciplines leads to a slightly lower throughput per user as previously discussed, they ensure fairness in throughput sharing among all users regardless the delay bound. This is because in such disciplines, the number of packets dropped due to deadline expiry is almost equal for all users. We summarize the main results of our simulation experiments in Table 1.

Table 1. Simulation results summary

	CD-EDD	M-LWDF	EXP	VF-CD-EDD	VF-M-LWDF	VF-EXP
Delay bound guarantee	√	X	X	√	√	√
Independency on QoS	√	X	X	√	√	√
Total throughput	√√	√	X	Less than original Rules		
Delay fairness	√	Depend on QoS		√	√	√
Throughput fairness	√√	√	X	√	√	√
Violation fairness	√	X	X	√	√	√

6. CONCLUSIONS

This paper addresses the problem of scheduling real-time users over TDM-based wireless multimedia networks. We introduced the Channel Dependent Earliest-Due-Date first (CD-EDD) scheduling discipline, a discipline that provides statistical delay bound guarantees for time-sensitive traffic in networks with time-varying channels. Gains in throughput and realized delay are achieved by exploiting multi-user diversity techniques in which the scheduling decision takes into account the current channel state for each user in the system. By considering the packet loss due to deadline violation, we also presented a set of scheduling policies that achieve fairness in delays, throughput, and packet loss ratios among different users regardless of the value of the delay bound.

The proposed disciplines outperforms other existing polices in the sense that the services received by different real-time users, namely, delays, rates, and loss ratios, are fairly achieved for a wide of applications. The proposed policies have low computational complexity and are suitable for application in future broadband fixed or mobile wireless systems such as 802.16a and 802.20.

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