A Delay Bounded Approach for Streaming Services in CDMA Cellular Networks

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ABSTRACT

This paper considers the design of resource management schemes for cellular networks where mobile users are interested in receiving streaming media flows, and the cell utilizes a Discrete Sequence Code Division Multiple Access (DS-CDMA) air interface. Due to the relatively high data rate requirement of the streaming service, and the limiting effect of the multiple access interference (MAI) in CDMA networks, the cell may undergo overload conditions as the wireless channel path losses increase for any subset of users. In response, the base station is expected to delay, or perhaps forcibly terminate, some traffic streams.

To achieve acceptable performance, we examine the use of a novel admission control scheme that takes user mobility into consideration. The utilized scheme admits a traffic stream only if the estimated cell overload probability after a prescribed prediction interval does not exceed a specified threshold value. As well, we devise a packet scheduling algorithm that aims at minimizing the number of forced terminations of connections that exceed specified delay bounds. Performance of the proposed admission control scheme in conjunction with the devised scheduling procedure is analyzed using simulation. The obtained results show significant improvement of using the proposed methods over methods that don't take user mobility into account.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication

Keywords

resource management in 3G cellular networks, streaming QoS class, call admission control, packet scheduling algorithms

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1. INTRODUCTION

Third generation (3G) and newer generation (NG) wireless networks are best known for their capability in supporting mobile users with higher user bit rates through packet-switched connections, as well as conventional circuit-switched connections. The architecture of such networks is based on the use of the code-division multiple access (CDMA) air interface operating in a frequency-division duplex (FDD) mode, or a time-division duplex (TDD) mode (see, e.g., [2] for the CDMA-2000, and [3] for the UMTS/W-CDMA standards).

The ability to support advanced packet services at suitable rates has resulted in a growing interest in extending the current Internet's multimedia streaming services to mobile subscribers of such networks. Streaming services is considered a key enabling technology that allows multimedia content playback on wireless personal communication devices with limited energy and storage capabilities. Profitable deployment of such services, however, faces a number of technical challenges. Firstly, streamed multimedia traffic is delay sensitive, and require data transmission at relatively high rates, thereby consuming significant wireless system resources. Increasing a base station's transmission power to support high data rates increases the intra-cell and inter-cell multiple access interference (MAI). MAI has the effect of decreasing the available cell bandwidth, as well as increasing the possibility of running into cell overload conditions.

Moreover, provisioning streaming services in a dependable way requires maintaining session's quality (e.g. the allocated data rate) during both intra-cell and inter-cell user movements. Intra-cell user movements cause significant changes in the channel path loss between a mobile user and the serving base station while the user is possibly receiving a streaming flow. We note that for such mobile users, coverage by high speed wireless local area networks (WLANs) is hard to provision, hence users may rely solely on the services provided by a cellular network.

To date, the approaches proposed by different researchers for provisioning quality of service (QoS) in cellular networks to cope with such stringent constraints have emphasized the need to develop suitable call admission control (CAC), and scheduling mechanisms as the main tools to manage the scarce wireless resources. Our contribution in this paper follows parallel lines, and has the following specific facets: formalizing a resource management problem on delivering delay sensitive traffic to mobile users, adapting a novel predictive CAC procedure, discussed in [1], to the formalized problem, devising a packet scheduling heuristic that aims at minimizing the number of forced terminations given *deadline* constraints on delivering the admitted connections, and analyzing the performance resulting from the combined use of the above CAC, and scheduling algorithms using simulation. The utilized CAC procedure exploits a priori knowledge of user mobility patterns to estimate the cell overload probability after some prescribed prediction interval.

Existing work on resource management schemes for providing QoS guarantees to 3G/NG mobile users is currently growing at a vast pace. The following highlights some related results. In [5], the authors evaluate the performance of various scheduling algorithms for serving user requests on the downlink. The size of each request (e.g., file length of an HTTP request) is assumed to be known a priori. However, in contrast to our work here, channel conditions in [5] are assumed to be time-invariant during the entire period of serving any single request.

In [11] the authors consider dynamic bandwidth allocation for heterogeneous traffic on the uplink based on weighted fair scheduling. User requests and data rate allocation are done during well defined time slots. The devised scheme aims at achieving good utilization of the available bandwidth as well as fairness in allocating the bandwidth. The devised scheme can also guarantee delay bounds on a session's flow if the flow conforms to the parameters of a leaky bucket regulator, and the cell load allows the base station to allocate bandwidth more than the token arrival rate parameter.

The work of [10] uses a control theoretic approach for designing a CAC that dynamically adjusts the capacity of guard channels in CDMA cellular networks so as to maintain the handoff dropping rate at a target level. Simulation of voice dominated traffic is used to analyze performance. We note that the above approaches do not address the problem of serving the admitted flows at some data rate during the entire session time while taking mobility into account, as done in this work.

For cellular networks with fixed cell capacity, the work of [7] devises a combined CAC and adaptive bandwidth allocation scheme for serving streaming connections. The results of [7] deal with an adaptive multimedia networking framework where the bandwidth of an ongoing multimedia connection can by dynamically adjusted several times during the connection's lifetime. That is, the assigned data rates can be decreased (when overload conditions arise), or increased (when some connections terminate) dynamically. The devised CAC algorithm works by predicting the state of a cell (the number of active users, including handoff users) after some prediction time interval in the future. The CAC devised in [1], and utilized in this paper, generalizes the approach used in [7] to the more complex case of predicting the state of the cell in a CDMA environment. The work of [12] also considers the development of a rate adaptive framework for fixed capacity cellular networks.

The rest of the paper is organized as follows. Section 2 introduces the basic system models and important parameters used in the paper. Sections 3 and 4 outline the structure of the utilized CAC, and the devised scheduling scheme. Section 5 presents the obtained results, and section 6 concludes with a few remarks.

2. SYSTEM MODEL AND PARAMETERS

2.1 Cellular Network Model

Throughout the paper, we consider a UMTS-like cellular network architecture (see, e.g., [3]) operating in the frequency division duplex (FDD) mode where each user streaming flow is served by a dedicated data channel. The newly added functionality of the proposed CAC and scheduling modules are assumed to be embedded in the radio network control (RNC) part. Multimedia streaming requests are assumed to be served by servers located either on the Internet, or hosted by the public land mobile network (PLMN) provider, and attached to the gateway GPRS support node (GGSN) of the core network (CN) unit.

We assume that packets of each streaming connection experience most of the delays in the wireless network (queuing delays from the serving base station to the mobile user). As mentioned above, user mobility is assumed to be the primary reason for causing the required transmission power to exceed the total base station transmission power allocated for serving the streaming QoS class, and consequently the occurrence of queueing delays.

2.2 Admission Control and Scheduling Parameters

We adopt a framework where the streaming QoS class is characterized by a set $\{\mathcal{P}_T, R, t_{predict}, P_{admit}, t_{slot}, \alpha_{qos}\}$ of parameters, as explained below.

$\mathcal{P}_T$: the total base station transmission power allocated for serving all active connections of the streaming class.

R: a fixed data rate used for downlink transmission of a streaming connection's data over a transport channel.

$t_{predict}$: a CAC parameter used in computing the cell overload probability from a mobility transition diagram (cf. Section 3).

P_{admit}: a CAC probability parameter used in accepting new connections (cf. Section 3).

t_{slot}: a scheduler's parameter; the scheduler views time as a sequence of slots, each of length t_{slot} (e.g. 100 msec). The value of t_{slot} is chosen to be a multiple of the physical radio frame length. On the other hand, t_{slot} should not be set to a large value that allows the average large scale path loss to a user to change significantly (due to user mobility) during a single slot.

α_{qos}: a scheduler's parameter ($\alpha_{qos} \geq 0$) used to set an upper bound on the maximum acceptable processing (queuing + transmission) time experienced by any of the admitted connections.

To explain the role of α_{qos}, we introduce the following scheduling parameters for a connection with index i:

a_i: (arrival time) the slot number at the beginning of which the first group of $t_{slot} \times R$ encoded bits of the connection can be transmitted,

ℓ_i: (connection's length) the number of slots required to transmit all encoded bits in the stream to the intended user at the distinguished rate R,

c_i: (completion time): the last slot number used in serving the connection. (Thus, the total processing time of the connection at the base station is given by $1 + c_i - \ell_i$ slots.) and

d_i: an upper bound on the acceptable total processing time (in slot units) at the base station (i.e., an upper bound on the $1 + c_i - \ell_i$ quantity), given by

$$d_i = \lceil (1 + \alpha_{qos}) \ell_i \rceil \tag{1}$$

A few remarks about the above framework follow below. We assume that a mobile device requesting and receiving streaming connections is limited with respect to the energy and memory resources; hence, the choice of using a single serving data rate R to simplify communications.

In addition, due to the limited buffering capacity available to the mobile for compensating delay jitter during playback, frequent delays of user packets result in an unacceptable playback performance. If a connection i does not receive the required ℓ_i slots of service within the acceptable delay interval $[a_i, a_i + d_i - 1]$ then that connection is considered to be inadequately served. We further assume that such badly served connection is forcibly terminated by the base station without charging the user.

To account for the impact of such service termination policy on the network provider's revenue, we use the average *effective* throughput as one of the main performance measures; here, the average is taken over all traffic streams that have been successfully served to completion within the desired delay limits (that is, excluding the streams that have been forcibly terminated).

3. ADMISSION CONTROL

As mentioned above, the adopted QoS framework relies on the combined use of suitable CAC and scheduling algorithms. The CAC module is responsible for taking decisions on accepting/rejecting new incoming requests. Such decisions are taken based on the CAC's knowledge of aggregate user mobility patterns during a certain time interval of operation (e.g., rush hours). On the other hand, the scheduler takes short term decisions at the time scale of a single t_{slot} interval. In addition, the scheduler does not utilize any a priori knowledge of user mobility.

In this section we summarize the main aspects of the utilized CAC module; the presentation follows closely the description in [1].

3.1 Definitions and Notations

To describe the CAC scheme, we need the following definitions and notations.

Cell Decomposition. Due to the MAI in CDMA cells, it is insufficient to take the number of active streaming users in the cell as the only measure of cell load, rather a more detailed account of the base station transmission power requirements of different classes of users should be considered. The approach taken in [1] is based on classifying the active streaming users according to the amount of base station transmission power required to provide service at a specified data rate. The classification is based on the average large scale path loss experienced by each user.

To this end, the CAC scheme assumes that that each cell is partitioned into a fixed number r ($r \geq 2$) of regions, called *rings*. Each ring corresponds to a geographical area of the cell where the average large scale wireless path losses from the serving base station to each point of the ring fall within some predetermined range (e.g., [70 dB, 110 dB]). Different rings correspond to non overlapping regions with distinct path loss bounds, as illustrated in Fig. 1. In general, subdividing the cell into a large number of rings results in a more accurate model at the expense of increased computational requirements of the CAC scheme.

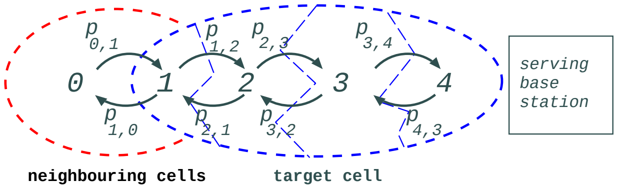

Figure 1: A target cell partitioned into four rings

Cell States. The state of the cell at any instant t is captured by an occupancy distribution sequence $N = (n_0, n_1, \cdots, n_r)$, where n_0 is the number of the streaming class users that may perform handoff to the target cell, and for $i \in [1, r]$, n_i is the number of active ring-i users in the target cell.

Cell Overload Probability. An occupancy distribution sequence N is an *overload* distribution if the base station cannot allocate sufficient transmission power to serve each mobile at the distinguished rate R, assuming that each mobile experiences the maximum observed average large scale path loss in its respective ring. The set of all overload distributions is denoted $\mathcal{OL}$.

Furthermore, given that the cell is in state N at sometime t, the *overload* probability, denoted $P_{N,\mathcal{OL}}$, is defined as the probability that the cell will be in some overload state at time $t + t_{predict}$.

Traffic and Mobility Models. User traffic and mobility in the cell (during the operation period of interest) is modeled using the following distributions. The arrival of streaming connection requests to the target cell is assumed to be Poisson with rate λ connections per second, and the time duration of each connection is exponentially distributed with average $1/\mu$ seconds.

For connections initiated in ring $i \in [1, r]$ of the target cell, we refer to the time duration the connection is served in that particular ring as ring-i *residence* time. After that time duration, the user may depart to another ring. The scheme assumes that ring-i residence time is exponentially distributed with average $1/\delta_i$.

Handoff traffic from neighbouring cells to the target cell is modelled using a similar setup: that is, the handoff traffic is viewed as coming from a new ring (denoted ring 0 in Fig. 1) lying outside the target cell. The scheme also assumes that ring-0 residence time is exponentially distributed with average $1/\delta_0$ (δ_0 is the handoff rate from the neighbouring cells to the target cell).

Transition Probabilities. User movement across rings during a certain epoch of the day is modeled by a transition diagram where rings and transitions are represented by nodes and directed edges, respectively. Here, $p_{i,j}$, $i \neq j$, $i, j \in [0, r]$, denotes the probability that an active user moves from ring i to ring j after spending the residence time mentioned above. The transition probabilities out of any ring $i \in [1, r]$ satisfies $\sum_{i \neq j} p_{i,j} = 1$. For the special case of $i = 0$ (i.e., for ring 0 representing the neighbouring cells), we have $\sum_{j=1}^{r} p_{0,j} \leq 1$.

Ring Residence and Departure Probabilities. The probability that a test connection initiated in ring i at time

t will continue to be served in the same ring during the prescribed prediction interval $t_{predict}$ is denoted $p_{r,i}$; thus, $p_{r,i} = e^{-(\mu+\delta_i)t_{predict}}$. In addition, the probability that a test connection initiated in ring i will depart to another ring during the next $t_{predict}$ time units is denoted $p_{d,i}$ ($p_{d,i} = 1 - e^{-\delta_i t_{predict}}$). Thus, corresponding to each (i,j) transition in the mobility diagram, the product $p_{d,i}p_{i,j}$ is the probability that a test connection initiated in ring i will depart to ring j during the next $t_{predict}$ time units.

3.2 Physical Layer Constraints

The CAC scheme devised in [1] combines a SINR-based admission control scheme (see, e.g., [4]) with a mechanism to predict the state of the target cell after a prescribed prediction interval $t_{predict}$. The main physical layer constraints that the scheme applies are described below.

Given an occupancy distribution N associated with a set $M = \{1, 2, \ldots, m\}$ of users in the target cell (i.e., $m = \sum_{i=1}^{r} n_i$), determining whether N is an overload distribution requires that the RNC estimates the minimum amount of base station transmission power that should be allocated to serve each user. We denote such vector of required transmission power levels by $\mathbf{P_{tx}} = (P_{tx,1}, P_{tx,2}, \ldots, P_{tx,m})$. Determining $\mathbf{P_{tx}}$ (if one exists) is carried out by solving a linear system of equations where the equation associated with mobile receiver $u \in M$ has the following form (see, for example, [4, 9, 13])

$$E_b/I_0 = \frac{(W/R_u)(P_{tx,u}/L_u)}{\gamma\, I_{intra\_cell} \;+\; I_{inter\_cell} \;+\; \eta_0 W}. \tag{2}$$

The following list explains the parameters used:

E_b/I_0**:** a target bit energy to interference and noise ratio that should be achieved at each receiver (e.g., 7 dB),

W**:** the chip rate of the CDMA air interface,

R_u**:** the transmission data rate to mobile u,

$P_{tx,u}$**:** the amount of serving base station transmission power allocated to mobile u,

L_u**:** the average path loss from the base station of the target cell to mobile u,

γ**:** a fraction accounting for the loss of orthogonality due to multipath,

I_{intra_cell}**:** the interference power received by mobile u from the serving base station,

I_{inter_cell}**:** the total interference power received by mobile u from the neighbouring base stations, and

η_0**:** the noise power spectral density at the mobile.

A positive solution $\mathbf{P_{tx}}$ of the resulting system of equations is a feasible power allocation if it does not violate the base station capacity constraint:

$$\sum_{u=1}^{m} P_{tx,u} \leq \mathcal{P}_T. \tag{3}$$

3.3 Admission Procedure

Given the above framework, the scheme is adapted to our current problem as follows.

1. Upon arrival of a new streaming connection request, the CAC computes the occupancy distribution vector N that results if the newly arrived request is admitted. The RNC then tests whether there exists a feasible power allocation $\mathbf{P_{tx}}$ to serve all in-cell connections of the distribution N at data rate R.

2. If there is no feasible allocation, the base station rejects the request.

3. Else (if a feasible solution exists), the procedure described in [1] is used to decide whether the following admission condition is satisfied:

   $$P_{N,\mathcal{OL}} \leq P_{admit} \tag{4}$$

   where P_{admit} is a QoS admission control probability for the streaming class set by the network provider. Finally, the RNC admits the request if condition (4) is satisfied.

4. SCHEDULING DISCIPLINE

As mentioned above, the scheduler views time as a sequence of slots of length t_{slot} each. During each slot, the scheduler selects a subset of connections for downlink transmission at the prescribed rate R, subject to the power constraint (3). We also assume the functionality of the scheduler is decoupled from that of the CAC, and the scheduler does not utilize any a priori knowledge about user mobility patterns.

Given the above framework, one way of defining an *ideal* scheduler is as follows: given a set of n already admitted connections $\{1, 2, \cdots, n\}$, the average radio path loss to each respective user, the remaining required service time of each connection ℓ'_i (slots), and the remaining acceptable delay time d'_i (slots), $d'_i \geq \ell'_i$, we ask for a scheduler that minimizes the number of forced terminations. A few remarks about the above combinatorial optimization problem now follow.

1. An optimal scheduler is necessarily *preemptive*; that is, the scheduler may assign non-adjacent slots for serving a connection (however, no connection is permitted to be preempted within any single slot). For example, if the base station can serve at most two users in any slot, and the system has three identical connections with $\ell' = 2$, and $d' = 3$ then an optimal scheduler achieving zero forced termination is only possible by preempting some connection for one slot.

2. If the target cell has a fixed capacity, and each connection requires the same amount of the base station transmission power during each scheduling slot (which is not always the case for CDMA cells), then the *feasibility* problem that asks whether all admitted connections can be scheduled with no forced termination can be solved efficiently using a reduction to network flows (see, e.g., [8]).

In light of the computational intractability of many scheduling problems, we investigate the performance of a simple *priority* based scheduling algorithm (see, e.g., [6] for an

Table 1: Simulation parameters

Parameter	Value	Unit
Base station power budget	25	watts
Chipping rate	4.096	Mcps
Noise spectral density (η_0)	-174	dBm
Orthogonality factor (γ)	0.2	
Convolutional coding rate	1/3	
E_b/I_0 requirement	7	dB
Log-normal shadowing exponent (n)	4	
Log-normal shadowing standard deviation (σ)	4	dB
Cell radius	1000	m
R (encoded data rate)	128	Kbps
Average streaming connection duration ($1/\mu$)	200	sec
Average ring residence time ($1/\delta_i$)	100	sec
CAC Prediction interval ($t_{predict}$)	6	sec
Admission probability (P_{admit})	0.1	

overview of the use of some priority rules in scheduling). The proposed algorithm attempts to minimize the number of forced terminations by assigning higher scheduling priorities to connections with low d'_i/ℓ'_i ratios:

Scheduling Algorithm: At the beginning of each scheduling slot, sort the connections in a nondecreasing order of their d'_i/ℓ'_i ratios then schedule for transmission in the current slot as many connections as possible according to the ordered list.

5. SIMULATION RESULTS

In this section we compare the performance of the utilized predictive CAC scheme against a conventional *number based* admission control scheme. Both CAC schemes are used in conjunction with the devised scheduling algorithm. The number based scheme treats the cell as having a fixed capacity equivalent to the number of users n that can each be served at the distinguished rate R while experiencing a specified average path loss value. In our simulation setting, the specified path loss corresponds to the predicted average path loss at distance equal to half the cell radius from the serving base station. Using the cell and air interface parameters used in the simulation, n is set to 30 users. The number based CAC rejects a new connection only if n connections are currently being served.

The simulation study assumes a target cell divided into $r = 4$ rings, with transitions as illustrated in Fig. 1. Table 1 summarizes the main simulation parameters.

To present the results, we first recall that the prediction methodology used in the proposed CAC aims at avoiding situations where the base station runs out of downlink transmission power as the distribution of users change in the target cell. To illustrate the effectiveness of the proposed CAC in this aspect, we examine the forced termination probability. Figure 2 shows that the predictive CAC consistently outperforms the number based CAC in this respect. In particular, we note that the built in lookahead mechanism of the predictive CAC limits the termination probability to less than 0.3 at the highest tested offered load value (22 Erlang). In contrast, the number based CAC scheme may result in more than 70% of terminated calls. The above observed result is a consequence of the rather cautious behaviour of the predictive CAC of not accepting as many connections as the number based CAC, as illustrated in Figure 3. In particular, the figure shows that the number based CAC accepts almost all incoming connection requests, whereas the predictive CAC may reject 20%, or more, requests. The numerical results shown above raise an interesting question of whether the proposed CAC achieves higher effective throughput than the number based CAC (given that the latter tends to accept more connections than the former). Figure 4 answers the above question in a positive way, by showing that the proposed CAC consistently achieves higher effective throughput. We also remark that the performance of the two schemes have been further analyzed with respect to two additional measures: (a) the average base station energy incurred in transmitting connections that have been successfully served to completion, and (b) the average base station energy wasted on forcibly terminated streams.

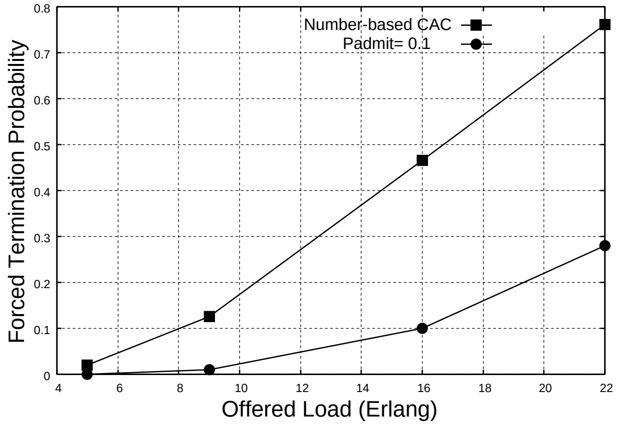

Figure 2: Forced termination probability.

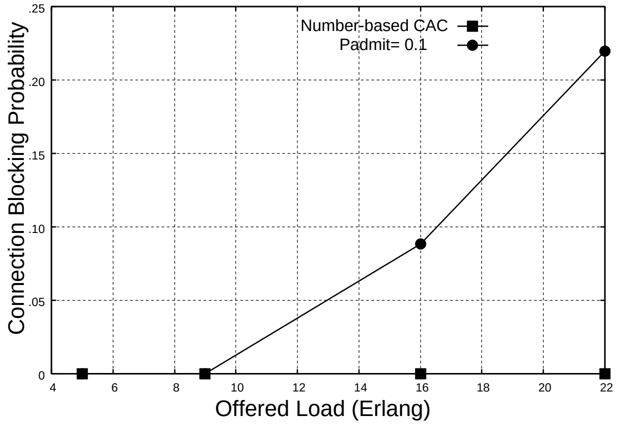

Figure 3: Connection blocking probability.

The obtained results show that the proposed scheme achieves the above superior effective throughput while achieving more savings in the average base station energy consumption, compared to the use of the number based CAC algorithm. The proposed scheme also achieves negligible average wasted energy. Such reduced wasted energy is important from a network provider's view point since it results in reduced daily operating costs for maintaining and running the communication system.

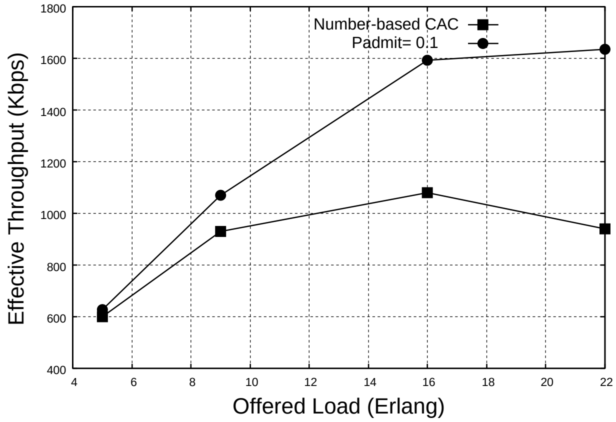

Figure 4: Average effective throughput.

6. CONCLUDING REMARKS

In this paper, we explored a fundamental problem that arises in provisioning the class of streaming services to mobile users in 3G networks employing a CDMA air interface. We devised a predictive admission control procedure, and a scheduling procedure that collectively strive to maintain the total delay incurred by a stream in the wireless network within a prescribed bound. The obtained simulation results show that the proposed admission control scheme achieves superior performance in terms of minimizing the forced termination probability and maximizing the effective network throughput. Future work includes investigating the performance of the proposed schemes in other possible user and traffic scenarios, as well developing effective scheduling algorithms for the formalized delay bounded problem.

7. ACKNOWLEDGMENT

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