

DYNAMIC PRICING WITH “ALTERNATIVES” FOR DATA SERVICES IN MOBILE NETWORKS

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ABSTRACT

Capacity of wireless data services offered by GPRS and EDGE is critically limited and cannot keep up with the rising demand. The technical approaches taken to alleviate the problem are not sufficient to encounter a complete range of incoming traffic scenarios. In this paper, we define and study analytically a performance model for wireless data services that combines the effect of pricing incentive as an additional strategy for encouraging a more efficient usage of limited network resources. We propose the novel pricing scheme, namely dynamic pricing with “Alternatives”, that not only provides the incentive for users to utilize network resource in the way that conforms to the network traffic condition but also potentially gains more user satisfaction by offering pricing preference. The performance results verify that the new pricing scheme significantly improves the system performance and potentially yields users’ satisfaction.

KEY WORDS

Priority pricing, Wireless pricing, Service differentiation, Incentive compatible.

1 Introduction

Recent cellular technologies such as GPRS and EDGE have revolutionized mobile services from voice-intensive services to multi-service. Mobile users are now not only using their mobile phone to make phone calls but also check emails, browse web pages, download music, etc. New applications have caused a significant increase in demand of data services in mobile networks. However, the capacity of GPRS and EDGE for data services are critically limited and cannot keep up with the rising demand. Network engineers have put a lot of effort on the channel allocation scheme and spectrum usage in order to allocate resources to users more efficiently [1]. However, due to voice traffic (which has the right of priority and preemption over data traffic in the GPRS and EDGE), the network could be overwhelmed by high volume of customers’ voice calls resulting in serious service degradation of data services. There is enormous research going on that investigates the integration of mixed services, especially voice and data, proposing approaches to improve data services. In [2], an analytical Markov

model was investigated to provide the number of packet data channel that should be allocated for GPRS under a given amount of traffic, for guaranteed quality of service. In [3], Mahdavi et al. have investigated a GPRS Markov-based model that performs complete sharing scheduling of real and non real-time services. Also, a novel expeditious computational algorithm for a GPRS model is proposed in their work.

The above network allocation schemes can improve the system performance within a certain dynamic range of incoming traffic. However, when the traffic arrival rate is temporarily very high, such as during the busy hours, the difference between peak and off-peak demand for services can be of a magnitude of 20 to 1 [4]. Therefore, these schemes described earlier cannot guarantee quality of service, no matter how the parameters are adjusted [5]. The fact that users are insensitive to network traffic condition allows us to determine other approaches that could influence the usage of data users to conform to level of network load. In commercial networks, pricing has been proved to be an effective mean to resolve the problem of scarce resource allocation. Network users are inherently price sensitive. Via prices, the network could send signals to the users, providing them with incentives that influence their behavior and decisions [6]. Pricing thus could become an effective mean to perform traffic management and congestion control. Such schemes are known as *dynamic pricing schemes*. In a dynamic pricing scheme, call prices change as demand fluctuates [7]. Prices rise in accordance with demand, deterring additional users from accessing the network or holding network resources for long periods, during congestion time. Therefore, such schemes create users’ incentive towards an efficient network usage.

Despite the beneficiary of dynamic pricing, it is hard to come up with a tariff that mobile users can accept since there is no guarantees (at the time of congestion) that users would get their services at their expected price [8, 10]. In this paper, we propose a pricing scheme that offers mobile users choices of pricing scheme (“alternatives”) by either performing data services with higher prices based on a dynamic pricing scheme or holding on to the conventional scheme (flat rate) with acceptable degradation in performance. We argue that, by offering mobile users choices in pricing schemes, they would be more satisfied than in a

case of traditional dynamic pricing scheme. The paper is organized as follows. In Section 2, we describe the drawbacks of dynamic pricing in mobile networks and introduce the concept of the proposed pricing scheme as a solution to the problem. In Section 3, our proposed model for dynamic pricing with “alternatives” is presented and the parameters involved are defined. Section 4 shows numerical results of our pricing model. In Section 5, we present the conclusion of our work.

2 Dynamic Pricing with “Alternatives”

We believe that mobile users are “selfish” (in terms of network usage) and price-sensitive. If we deploy dynamic pricing during the time of congestion, those users who will accept the dynamic prices (higher than normal) are the ones who are in immediate need for the service. As for the rest of the users, they would find the dynamic price unacceptable and leave the network. Some of them might try accessing the system again; some of them might not. As the system operates, the network will be less congested with the cost of dissatisfied users who cannot afford the dynamic prices. Therefore, mechanisms that appropriately handle this situation of users are needed.

In our proposed pricing scheme, namely *Dynamic Pricing with “Alternatives”*, we argue that, by offering the choices of pricing schemes, data users would be more accepting to the dynamic pricing. Network would be able to provide users with incentives that influence their decisions. The proposed scheme is similar to the Priority pricing scheme in [9] in the sense that users are allocated network resources based on their priority (or prices that they pay for the service). However, the proposed pricing scheme is different in that we guarantee certain amount of resource to low priority users (users paying flat prices or conventional users). Therefore, they would not be starved when there is large number of high priority users. It is true that we could lose some economic efficiency by guaranteeing some resource for low priority users but we could gain more acceptance of pricing scheme by offering the choices of pricing schemes (Dynamic or flat pricing). To ensure that users are deterred from using flat pricing as default, network would treat the users who choose dynamic pricing with superior quality compared to the users who choose flat pricing. We will explain in the next section the details of our proposed pricing scheme and how we can demonstrate the network performance of wireless data services.

3 A Dynamic Pricing Model with Alternatives for Wireless Data Services

The proposed pricing scheme is applied to the Markov Modulated Poisson Process (MMPP) which is suitable to describe the integration of mixed services. The model can be used to represent the next generation wireless networks, such as GPRS and EDGE. We first describe the model and

its parameters. Then, we describe how we can incorporate our proposed pricing scheme into the model.

3.1 Model Description and Parameters

The model is applied to each pair of spectrum assigned in a mobile data network. The arriving voice and data calls are modeled according to two mutually independent Poisson processes. Both of them are scheduled to share the same radio resource. We assume that each spectrum pair is slotted with some fixed slot duration and the number of slots is N . All N channels can be shared by both voice and data calls. However, voice calls have the right of priority and preemption over data calls. The data calls, which cannot immediately be transmitted, are queued at the source. In our model, we consider the downlink of the base station as a FIFO and data calls are handled when channels are available.

Voice calls can be modeled as M/M/N/N [11] regulated by the erlang-B formula, where N is the number of channels. The arrival of voice calls is modeled as a Poisson process with an arrival rate of λ_v and a service rate of μ_v . Packets from voice traffic have higher priority over data packets. If there is no channel available, the channel that is in use by data users will be reallocated to voice packets and will be released right after the voice call is terminated. For the data calls, each call request is processed and if it is accepted, the session for that data call is initiated. The data requested by the data users comes in bursts. We assume that our single cell has a maximum number of data users, M , and each of them has a data session to transmit. The inter-arrival time is exponential distributed with rate λ_d and burst length $1/\mu_d$.

Since arrival packets from both voice and data users share the same resources, they are correlated. We can model the employed traffic by using a Markov-modulated Poisson Process (MMPP) [12]. The MMPP has been extensively employed for modeling traffic processes with a time-varying arrival rate. Its main advantage is the ability to capture some of the important correlations between the inter-arrival times. In our model, we assume that if there are i data users in the queue, $M - i$ users are in reading mode. Therefore, the set of arrival rates of data users is

$$\lambda_i = (M - i)\lambda_d \quad (1)$$

where $i=1, 2, \dots, M - 1$.

The set of service rate of data users is

$$\mu_i = (N - i)\mu_d \quad (2)$$

where $j=0, 1, 2, \dots, N$.

3.2 Dynamic Prices

In this subsection of the paper, dynamic pricing with alternatives applies to data calls only. Since GPRS and EDGE networks provide best-effort data services, we measure the

congestion of data services by examining the number of data users in the system. The reason why we choose this parameter as the congestion indicator is explained at the end of this subsection. The pricing scheme will be initiated when the number of data users increases up to a certain level that indicates a situation of congestion (C users in the model). Data users will be informed regarding charges for the congestion period. The choice of prices being offered to users are either dynamic usage-based prices or flat-rate usage-based prices. The dynamic prices change according to network traffic condition while the flat-rate prices do not change during congestion time. When network experiences congestion, users will be offered the choices of the pricing scheme. Then, the system stores the records and notify AAA servers to charge users according to their pricing decisions. However, the system would still treat the traffic from both types of users without any difference until the number of data users reaches L users. At this point, only packets from priority users will be served. The packets from conventional users will be delayed until the number of data users in the system drops below L . We can see that when the number of data users is between C and L , the conventional users are still being served even though the system starts to congest. The conventional users pay lower prices but run the risk of being delayed whenever severe congestion occurs (number of data users more than L). Congestion indicator (C) is determined by network operators based on their traffic demand, revenue target, etc.. However, the threshold where the system starts relieving congestion (L) can be optimized based on prior statistics. In this paper, the derivation of optimal threshold L is not included. However, certain values of L have been used in the model to illustrate the effect of pricing scheme on the overall performance of the wireless networks as we show in the results section.

The dynamic prices that are offered to users when the system experiences congestion, can be derived from a demand function. The demand function describes the users' reaction to the price changes. In our case, the ratio between dynamic price and fixed price will determine the demand of each type of users. We use the demand function that appears in [13] since it is used for different priority users, which fits our model. The demand function is as follows:

$$q = e^{-\left(\frac{p_h}{p_o} - 1\right)^2}, p_h \geq p_o \quad (3)$$

where p_o is the flat-rate prices and p_h is the price charged to priority users. Therefore,

$$p_h = p_o + \frac{p_o \sqrt{-4 \ln(q)}}{2} \quad (4)$$

The percentage of users paying dynamic price (q) as described above would affect the arrival process of data calls during congestion. When the number of data users reaches L , only traffic from priority users will be served. Hence, the arrival rate of data calls from (1) becomes:

$$\lambda_i^* = \lambda_i \cdot q_i \quad (5)$$

where λ_i^* is the arrival rate of data users in a congested system when i data users are in the system, q_i is the percentage of users paying the dynamic price. q_i is determined by the system, based on the pricing policy. q_i can be simply set up as follows:

$$q_i = (M - i) \Delta q \quad (6)$$

where $i = L, L + 1, \dots, M$.

Δq is the percentage change of users paying dynamic prices, when the Markov chain changes by one state towards maximum number of data users, and L is threshold mentioned earlier.

The reasons we choose the number of data users as a congestion indicator rather than the number of available traffic channels can be explained as follows: most priority schemes for data services can starve the resource of low priority users if the number of available channels used as a congestion indicator. During congestion time, available network resource is extremely low. Most of incoming packets are placed in a queue waiting to be served. By using the traffic channels as the congestion indicator, network would allow only priority users to take advantage of the network resource; the conventional users are pushed back until the number of available traffic channels are met. The scheme does not react well to the arriving traffic and yields an excessive delay to conventional users. By using the number of users in system as the congestion indicator, the system can start serving conventional users at the first sight of congestion reduction (the number of users in the queue is reduced). Coupled with pricing, the proposed scheme can effectively resolve congestion situations and yield users' satisfaction. In this paper, for simplicity, we assume that each data users generate the same traffic pattern into the mobile networks.

3.3 State balance equations and performance parameters

Fig. 1 illustrates the state diagram of a MMPP, which is a two-dimensional Markov chain. The vertical states represent states of traffic channels used by either voice or data calls. The horizontal states represent states of active data users. The dynamic pricing will be initiated when C data users has been reached. At that point, the system is considered being congested. However, only until the number of data users reaches L , the system would relieve the congestion by serving only packets from priority users. From Fig. 1, when L data users are in the system, the arrival rate of the system would be affected by the dynamic pricing scheme with alternatives resulting in changes of the arrival rate in the system as in (5). As the state of the system reaches M , the arrival rate of the system would decrease due to the increase in the dynamic prices. Thus, we can expect fewer priority users during the congestion time.

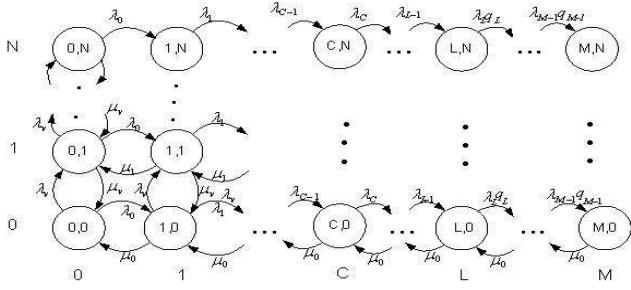


Figure 1. State Diagram of MMPP for dynamic pricing with alternatives.

From fig. 1, we can now set up the state balance equations as follows:

For $i = 0$ and $j = 0$

$$(\lambda_v + \lambda_0)P_{0,0} = \mu_v P_{0,1} + \mu_0 P_{1,0}$$

For $i = 0$ and $j = j$

$$(\lambda_v + \lambda_0 + j\mu_v)P_{0,j} = (j+1)\mu_v P_{0,j+1} + \mu_j P_{1,j} + \lambda_v P_{0,j-1}$$

For $i = 0$ and $j = N$

$$(\lambda_0 + N\mu_v)P_{0,N} = \lambda_v P_{0,N-1}$$

For $i = i$ and $j = 0$

$$(\lambda_v + \lambda_i + \mu_0)P_{i,0} = \mu_v P_{i,1} + \mu_0 P_{i+1,0} + \lambda_{i-1} P_{i-1,0}$$

For $i = i$ and $j = j$

$$(\lambda_v + \lambda_i + j\mu_v + \mu_j)P_{i,j} = (j+1)\mu_v P_{i,j+1} + \mu_j P_{i+1,j} + \lambda_v P_{i,j-1} + \lambda_{i-1} P_{i-1,j}$$

For $i = i$ and $j = N$

$$(\lambda_i + N\mu_v)P_{i,N} = \lambda_v P_{i,N-1} + \lambda_{i-1} P_{i-1,N}$$

For $i = L$ and $j = 0$

$$(\lambda_v + \lambda_L q_L + \mu_0)P_{L,0} = \mu_v P_{L,1} + \mu_0 P_{L+1,0} + \lambda_{L-1} P_{L-1,0}$$

For $i = L$ and $j = j$

$$(\lambda_v + \lambda_L q_L + j\mu_v + \mu_j)P_{L,j} = (j+1)\mu_v P_{L,j+1} + \mu_j P_{L+1,j} + \lambda_v P_{L,j-1} + \lambda_{L-1} P_{L-1,j}$$

For $i = L$ and $j = N$

$$(\lambda_L q_L + N\mu_v)P_{L,N} = \lambda_v P_{L,N-1} + \lambda_{L-1} P_{L-1,N}$$

For $i = M$ and $j = 0$

$$(\lambda_v + \mu_0)P_{M,0} = \mu_v P_{M,1} + \lambda_{M-1} q_{M-1} P_{M-1,0}$$

For $i = M$ and $j = j$

$$(\lambda_v + j\mu_v + \mu_j)P_{M,j} = (j+1)\mu_v P_{M,j+1} + \lambda_v P_{M,j-1} + \lambda_{M-1} q_{M-1} P_{M-1,j}$$

For $i = M$ and $j = N$

$$N\mu_v P_{M,N} = \lambda_v P_{M,N-1} + \lambda_{M-1} q_{M-1} P_{M-1,N}$$

From the state balance equations, we can obtain the steady-state probability of MMPP. Let $\underline{P} = [P_0, P_1, \dots, P_i, \dots, P_M]$ denote the state probability vector, where $P_i = [P_{i,0}, P_{i,1}, \dots, P_{i,N}]$. Then, \underline{P} can be found as the solution of the state equation $\underline{P} \cdot \underline{K} = 0$, along with the normalization condition where \underline{K} is the infinitesimal generating matrix of the MMPP, which is constructed from the state balance equation derived above and is the usual column vector of 1's. Matrix \underline{K} is a $r \times r$ matrix,

where $r = (M+1)N$ is the number of states. Matrix \underline{K} can be constructed from the state balance equation described above, which has the following structure [12].

$$\underline{K} = \begin{bmatrix} A_0 & V_0 & 0 & \dots & \dots & \dots & \dots & 0 \\ U_1 & A_1 & V_1 & 0 & \dots & \dots & \dots & \vdots \\ 0 & U_2 & A_2 & V_2 & 0 & \dots & \dots & \vdots \\ \vdots & \dots & \dots & \dots & \dots & \dots & \dots & 0 \\ \vdots & \dots & \dots & \dots & \dots & U_{M-1} & A_{M-1} & V_{M-1} \\ 0 & \dots & \dots & \dots & \dots & 0 & U_M & A_M \end{bmatrix} \quad (7)$$

where A_j , U_j and V_j are submatrices of size $N \times N$ derived from balance equations.

Given the state probability vector, \underline{P} , we can calculate performance parameters, such as loss probability, average queue length, the variance of the queue size and the average waiting time in the queue as follows:

$$\text{Loss Probability} = \sum_{i=0}^M \frac{P_i}{P} \quad (8)$$

$$\text{Average queue length} = L_{avg} = \sum_{i=1}^M i \frac{P_i}{P} \quad (9)$$

$$\text{Variance of the queue size} = \sum_{i=0}^M i^2 \frac{P_i}{P} - L_{avg}^2 \quad (10)$$

$$\text{Average waiting time in queue} = \frac{L_{avg}}{\lambda_d(M - L_{avg})} \quad (11)$$

4 Performance Analysis

In this section we evaluate the performance of the proposed dynamic pricing with alternative for Wireless data services. We observe that the proposed pricing model can significantly reduce the waiting time of data services which yields better quality of service. In Section 4.1 we describe in detail the basic assumptions and parameters used in the dynamic pricing model for GPRS data services and the result of our analysis is shown in Section 4.2.

4.1 Assumptions and parameters

We assume that the mobile base station handles circuit-switched voice calls and packetized data calls. The arrival rate of both incoming calls is Poisson and Exponentially distributed. The handoff calls into the system are handled differently at each base station. The handoff call handling is not included in this paper and will not follow the same procedures as the call initiated within the base station. The system queues are FCFS queues. The parameters used throughout our analysis are typical in the common practice of wireless networks. We assume that:

- There are 30 traffic channels (N) in total.

- The average call holding time for voice calls is exponentially distributed with mean 120 seconds.
- The average session time for data calls is exponentially distributed with mean 150 seconds.
- The parameter q used in the balance equations can be derived from (6) and Δq is $1/30$.
- The threshold L is the point where only traffic from priority users will be served. The arrival rate of data users will be affected by pricing incentive.
- Voice call blocking probability is 1 percent.

4.2 Numerical Results

One of the performance parameters that is crucial in wireless data services is the average queue waiting time. Since GPRS and EDGE are based on best-effort IP services, system performance is measured by the time that packets spend to actually reach the destination. During congestion time, packets are likely to spend most of their transmission time in queues. Average waiting time would mostly indicate the QoS of the system. Fig. 2 illustrates the average waiting time of the MMPP model as maximum number of data users allowed (M) in the system increases. The curve on top illustrates the average waiting time of the system when the threshold L equal to 30 which represents the scenario when we do not deploy any pricing scheme (L does not affect the arrival process). The other two lines represent the cases when L equals to 15 and 5 respectively. They represent high and low threshold respectively. As we allow more data users into the system, the average waiting time increases as expected. However, by deploying pricing, we can reduce the average waiting time in the queues improving the overall performance of the networks. The result is more significant when congestion threshold is stricter, i.e., small threshold. Regarding to the threshold C , it does not affect the performance of the mobile networks but it does affect the revenue generated from the services. The proposed scheme offers dynamic prices to users before the network actually take any actions. Thus, the low priority users would be informed of the network congestion and prepared for the service degradation. However, they would still be able to continue using the network as long as severe congestion does not occur, which is the purpose of our proposed scheme. For the priority users, we can see that the price incentive influences the usage of data users which directly affects the arrival rate of the system, resulting in decrease in the number of packets transmitted into the system and decrease in queue waiting time.

Fig. 3 illustrates the average queue waiting time when the maximum number of data users allowed in the system is fixed at 30. It shows how threshold L affects the average queue waiting time of data users. Note that when L equals 30, the average queue waiting time would be the same as

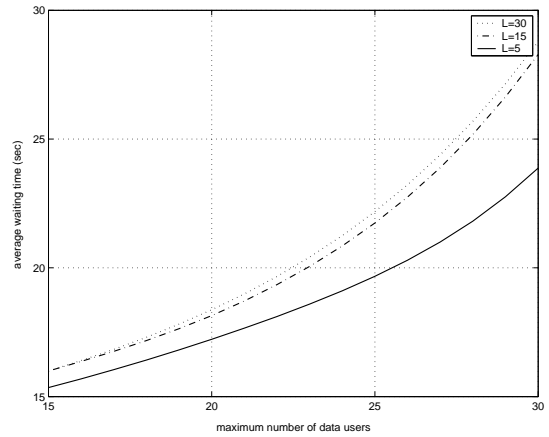


Figure 2. Average waiting time in queue for data users under dynamic pricing with alternatives.

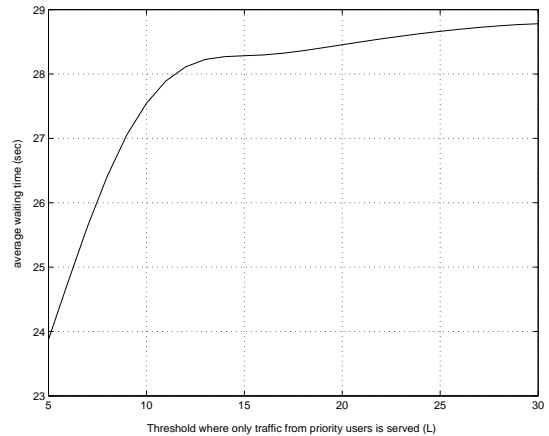


Figure 3. Average waiting time as threshold (L) increases ($M=30$).

that of the network without pricing incentive since maximum number of data users allowed also equal to 30. We can see that there is significant reduction of waiting time when threshold L drops from 13 to 5. Fig. 4 shows the variance of the queue size derived from (10) as threshold L increases. The smaller the threshold L is, the earlier the state that pricing incentive would affect the system, resulting in a reduction of the variance of number of users. We can see that, by introducing pricing incentives to data users, the fluctuation of incoming users would be reduced. In the other words, the proposed pricing scheme shapes the incoming traffic to match limited resources of the networks.

5 Conclusion

The main contribution of this paper is a performance model of mobile data services that combines the effect of pricing incentive as an additional strategy for encouraging efficient usage of limited network resources. We propose a novel

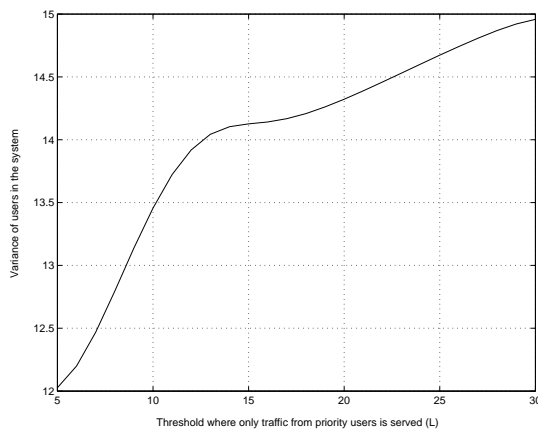


Figure 4. Variance of the queue size as threshold (L) increases ($M=30$).

pricing scheme that provides the incentive for users to utilize the network resource more efficiently. More importantly, due to this pricing scheme, more user satisfaction and revenue could be gained. Dynamic pricing with alternatives offers choices to data users. Mobile users are potentially more satisfied with the fact that they can choose whether they want to be served quickly by being priority users with high service charges or conventional users, who get the flat rate with some QoS degradation. The proposed scheme employs dynamic resource allocation according to the demand of each user group. Starvation of low priority users (conventional users) can be minimized. This reflects more fairness than the Priority Pricing scheme. The result from the performance model shows that, we can significantly improve network performance with our proposed pricing scheme. The system waiting time is reduced significantly. Since our proposed pricing scheme for packet-switched services employs the number of users in the system as congestion indicator, the network would react quickly to the congestion and retain its normal operation as soon as the congestion is resolved.

As described earlier, we assume that data users would generate the same traffic pattern into mobile networks. In reality, we know that this is not always the case. If the traffic pattern are very different among mobile users, the performance of our proposed pricing scheme that employs number of users as congestion indicator could be drastically changed. However, there are certain papers where authors have already conducted measurements of the real-time sessions of mobile networks such as GPRS and EDGE. In [14], Kilpi illustrates the cumulative session volume of a large number of GPRS sessions, giving an overview of typical GPRS sessions. The result shows that the typical GPRS sessions are small (hardly more than 1 MB). Therefore, as for GPRS and EDGE, we believe that our proposed pricing scheme with alternative would yield significant improvement as described above.

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