A Dynamic Pricing Model for Data Services in GPRS Networks

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Abstract**—GPRS data services are subject to severe performance degradation due to limited network resources. The technical approaches taken to alleviate the problem are not sufficient to encounter a complete range of incoming scenarios. In this paper, we define and study analytically a performance model for GPRS data services that takes into account prices that change dynamically, depending on the congestion in the system. The model is based on a Markov Modulated Poisson Process (MMPP), where the arrival rates are affected by a demand function. Performance metrics are also calculated. We believe that the proposed model captures the effect of dynamic pricing on the performance of GPRS data services in a realistic manner.**

I. INTRODUCTION

General Packet Radio Service (GPRS) is a bearer service based on GSM architecture that provides mobile subscribers with “always on” best-effort packet data services over GSM radio channels. With its packet-switched characteristic, GPRS enables mobile service providers to make more efficient use of the resources while providing mixed service capability for both real-time and non real-time applications. Issues related to allocation of available bandwidth for the particular types of service (i.e., voice or data), are currently being investigated extensively. Traditionally in GPRS, voice traffic has the right of priority and preemption over data traffic. Therefore, network resources for GPRS data services are scarce. During periods of congestion, the problem becomes critical, resulting in severe degradation of GPRS data services. Efficient allocation schemes are required to alleviate the problem.

There is enormous research going on that investigates the integration of mixed services, especially voice and data, proposing approaches to improve data services.

In [1], 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 [2], various algorithms for GPRS radio resource allocation are proposed. This work considers dynamic GPRS packet acceptance rate as well. 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. In [4], a Hybrid Radio Resource Allocation (HRRA) scheme is investigated. This work shows the performance of a GPRS system, when a dedicated number of GSM voice calls is used for GPRS data packet transfer.

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 [5]. Therefore, these schemes described earlier cannot guarantee quality of service, no matter how the parameters are adjusted [6].

To understand the nature of congestion, we have to study the network users’ behavior. It is well known that network users act independently and sometimes “selfishly”, regardless of the prevailing network traffic conditions. Therefore, even with advanced resource allocation schemes in place, it is hard to avoid congestion. As a result, congestion reduces the system utilization. Therefore, mechanisms that give users incentives to behave in ways that improve the overall utilization and performance of the network are needed. 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 [7]. 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 [8]. 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.

Since mobile networks evolve towards a multi-service environment where network resources are shared among different types of services, a real-time and/or dynamic pricing scheme should be used to encourage a more efficient use of the limited resources, for particular type of services, such as the mobile data services.

In this article, we propose a dynamic pricing scheme for data services in GPRS networks. Our approach to the problem takes into account the users' behavior towards real-time or dynamic pricing, in order to improve the performance of mobile data services. First, we identify a suitable queuing model for GPRS networks. We use a demand function to explain the effects of pricing in the arrival process, and hence the performance. In order to study the system in an analytic fashion, we alter the structure of the performance model to include the effect of dynamic prices. Based on this analysis we define performance measures analytically.

The paper is organized as follows: In section II, we describe the traditional dynamic pricing scheme used in both fixed and mobile networks. In section III, we present our proposed pricing model for GPRS data services and the approach we follow towards the analysis of performance. Section IV shows how performance measures can be calculated analytically. In section V, we draw the conclusion of our work.

II. BACKGROUND ON DYMAMIC PRICING

Currently, the service charge for telephone users is either fixed per call or flat. One of the advantages of these schemes is the simple billing and accounting processes [9, 10]. However, since users act independently and sometimes in a "selfish" manner, they utilize the system regardless of its traffic condition. Such pricing schemes do not provide incentives to users to avoid congestion during peak hours and cannot react effectively to the dynamics of the network. With dynamic pricing schemes, prices change depending on some criterions such as the traffic conditions. Users who require access to the network during peak hours and are able to afford higher prices, will be admitted to the network, while users who are not able to afford such prices are blocked. A nice property of dynamic pricing is that it is auto-regulating. There might be a situation when more and more users are willing to pay higher prices. In that case, the advantage of being admitted to the network disappears due to increasing congestion in the system. There is no need for the complex control mechanism.

Even though little has been published on dynamic pricing schemes for mobile networks, the study of dynamic pricing for fixed networks has been investigated already in the literature: the relationship between the increase in price and the reduction in the number of calls made by telephone users was studied by Cosgrove and Linhart [11]; congestion pricing for ATM networks was investigated by Peha [12] and significant work has been done in congestion control via pricing by Key et. al., Gibbens and Kelly [17,18].

These studies could be applied to cellular networks as well. For example, Hou et al. [6] has investigated the integration of dynamic pricing scheme to call admission control of the cellular networks. Sarayadar et al. [13] incorporated a pricing mechanism into the power control of wireless data networks in order to improve users' utility.

In terms of pricing for multi-service cellular networks such as GPRS and EDGE, network resources (channels or timeslots) are shared among voice and data services. Pricing of one type of service requires usage information of the other service in order to price the remaining resources appropriately.

In the next section, we propose a performance model for GPRS networks with pricing integration for data services. This constituted the main contribution of our work here. The model takes into account the integration of voice and data. The availability of data channels effects prices of the GPRS data services in a dynamic manner.

III. A DYNAMIC PRICING MODEL FOR GPRS DATA SERVICES

A. Model Description and Parameters

The model is applied to a pair of spectrum assigned in an integrated GSM/GPRS 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 the channel 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 where there is no contention mechanism and data calls are handled when channels are available.

Voice calls can be modeled as M/M/N/N [14] regulated by the erlang-B formula, where N is the number of service channels. The arrival of voice calls is modeled as a Poisson process with an arrival rate of λ_v and a service rate is 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 certain number of data users, M, and each of them has a data session. 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) [15]. 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

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

where i = 0,1,2,……,*M-1*.

The set of service rate of data users is

$$\mu_j = (N - j)\mu_d \qquad (2)$$

where j = 0,1,2,……,*N*

B. Dynamic Prices

In this paper, dynamic pricing will apply only to GPRS data services. Prices charged to data calls change according to the level of congestion in the system. If the number of channels available for data services decreases, the price charged to the data calls would increase. The pricing scheme will be initiated when the number of available traffic channels drops to a certain level that indicates a situation of congestion. Data users will be informed regarding charges and hence congestion, as the following call procedure describes:

Call procedure

1. Data users send request for data session through Packet Data Protocol (PDP) activation and wait for response from the system.
2. The status of system is identified. If the system is not congested, the data call request will be granted transmission.
3. If the system is congested, GPRS dynamic pricing is activated and the system will notify users the congestion level. Then, it will announce the price for granting the data call based on the congestion level, and ask users for their response, i.e., accept the price or cancel their call request.
4. If the answer is Yes, system will grant the transmission. Then, the amount charged for the transmission will be stored in the server.
5. For those users who deny the dynamic price, their call requests will be cancelled.

Note that by canceling the call requests of users who deny the dynamic prices, does not mean that the GPRS networks lose the “always on” characteristic. Users are still always able to perform data transmission. However, during the congestion time, users will be given a choice of price. It is up to the users to decide whether they want to perform data transmission at that time by agreeing to the network’s pricing requirement, or refuse to pay higher prices, by allowing the network to cancel their call requests.

The price that is broadcasted 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. We use the demand function that appears in [16] since it is used for different priority users, which fits our model. The demand function is as follows:

$$q = e^{-(\frac{p_h}{p_0}-1)^2} \qquad p_h \geq p_0 \qquad (3)$$

where p_0 is the nominal charge that is the price charged when system does not experience congestion, p_h is the price charged for granting transmission when system experiences congestion, and q is the percentage of users who are willing to pay the dynamic price.

Using a quadratic form, we can determine the dynamic price from (3) as follows:

$$p_h = p_0 + \frac{p_0\sqrt{-4\ln(q)}}{2} \qquad (4)$$

The percentage of users paying higher price (q) is an important parameter for our pricing model since it affects the arrival process of data calls during congestion.

From (2), we can determine the price charged to data users, according to the percentage of data users to whom the system can grant transmission. The arrival rate of data calls, when the system experiences congestion, is as follows:

$$\lambda_i^* = \lambda_i \cdot q_j \qquad (5)$$

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

$$q_j = (N - j)\Delta q \qquad (6)$$

where $j = L, L+1, \ldots, N$

Δq is the percentage change of users paying dynamic prices, when the Markov chain changes by one state, and L is a certain number of traffic channels that indicates congestion and therefore, the dynamic pricing scheme is applied.

C. State balance equations and performance parameters

Figure 1 illustrates the state diagram of MMPP, which is a two-dimensional Markov chain. The vertical states represent states of traffic channels used by either voice and data calls. The horizontal states represent states of active data users. The dynamic pricing will be initiated when L traffic channels has been used. At that point, the system is considered being congested. From Fig.1, when L channels are used, dynamic pricing is in place. The arrival rate of the system would be affected by the dynamic pricing scheme which results in changes of the arrival rate in the system as in (5). As the state of the system reaches N, the arrival rate of the system decreases as the price for granting access increases and results in a decrease in the number of data users who want to access the network at that time.

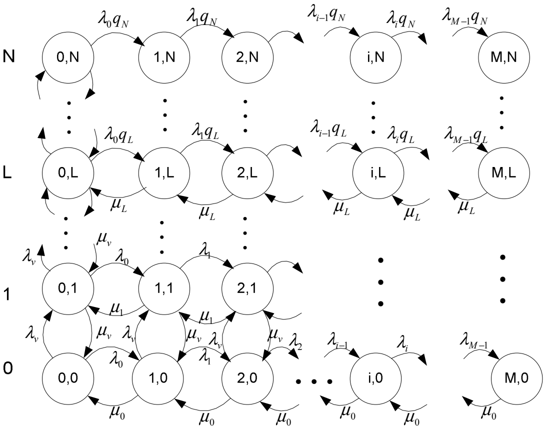

Fig. 1 State Diagram of MMPP with dynamic pricing scheme

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=L

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

For i=0 and j=N

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

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=L

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

For i=i and j=N

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

For i=M and j=0

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

For i=M and j=j

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

For i=M and j=L

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

For i=M and j=N

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

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

IV. PERFORMANCE METRICS

Matrix *K* can be constructed from the state balance equation described above, which has the following structure [15].

$$K=\begin{bmatrix} A_0 & V_0 & 0 & \dots & & & 0 \\ U_1 & A_1 & V_1 & 0 & \dots & & 0 \\ 0 & U_2 & A_2 & V_2 & 0 & \dots & \\ 0 & & & & & & V_{M-1} \\ 0 & \dots & & & 0 & U_M & A_M \end{bmatrix}$$

where A_j, U_j and V_j are submatrices of size NxN.

A_j can be found as follows.

$$A_0=\begin{bmatrix} \lambda_v+\lambda_0 & -\lambda_v & 0 & 0 & 0 & 0 \\ -\mu_v & \lambda_v+\lambda_0+1\mu_v & & \dots & \dots & \\ 0 & -2\mu_v & & & & \\ & 0 & & -\lambda_v & & \\ & & & \lambda_v+\lambda_0 q_L+L\mu_v & & \\ & & & -(L+1)\mu_v & & \\ & & & & & -\lambda_v \\ 0 & 0 & \dots & & & \lambda_0 q_N+N\mu_v \end{bmatrix}$$

$$A_i = \begin{bmatrix} \lambda_v+\lambda_i+\mu_0 & -\lambda_v & 0 & 0 & 0 & 0 \\ -\mu_V & \lambda_v+\lambda_i+1\mu_v+\mu_1 & \dots & & & \\ 0 & -2\mu_v & & & & \\ & 0 & & -\lambda_v & & \\ & & & \lambda_v+\lambda_i q_L+L\mu_v+\mu_L & & \\ & & & -(L+1)\mu_v & & \\ & & & & & -\lambda_v \\ 0 & 0 & \dots & & & \lambda_i q_N+N\mu_v \end{bmatrix}$$

$$A_M = \begin{bmatrix} \lambda_v+\mu_0 & -\lambda_v & 0 & 0 & 0 & 0 \\ -\mu_v & \lambda_v+1\mu_v+\mu_1 & \dots & & & \\ 0 & -2\mu_v & & & & \\ & 0 & & -\lambda_v & & \\ & & & \lambda_v+L\mu_v+\mu_L & & \\ & & & -(L+1)\mu_v & & \\ & & & & & -\lambda_v \\ 0 & 0 & \dots & & & N\mu_v \end{bmatrix}$$

Matrix U_i and V_i are given by

$$U_i = \begin{bmatrix} -\mu_0 & 0 & 0 & \dots & 0 \\ 0 & -\mu_1 & & & \dots \\ \dots & 0 & -\mu_2 & & \\ & & & -\mu_{M-1} & \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix}$$

$$V_i = \begin{bmatrix} -\lambda_0 & 0 & 0 & \dots & & 0 \\ 0 & -\lambda_1 & & & & \dots \\ \dots & 0 & \dots & & & \\ & & & -\lambda_{i-1}q_L & & \\ & & & & \dots & 0 \\ 0 & 0 & \dots & & 0 & -\lambda_{M-1}q_N \end{bmatrix}$$

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:

$$\text{Loss Probability} = \sum_{i=0}^{M} \underline{P_i} \tag{7}$$

$$\text{Average queue length} = L_{avg} = \sum_{i=1}^{M} i.\underline{P_i} \tag{8}$$

$$\text{Variance of the queue size} = \sum_{i=0}^{M} i^2 \underline{P_i} - L_{avg}^2 \tag{9}$$

$$\text{Average. waiting time in queue} = \frac{L_{avg}}{\lambda_d(M-L_{avg})} \tag{10}$$

In terms of revenue gained from our pricing model, this can be determined by the associated dynamic prices of certain percentage of users paying those prices (q_j). Details on revenue generated are currently being investigated.

V. CONCLUSION

In this paper, we have proposed a performance model for GPRS data services that combines dynamic pricing, as an additional strategy for encouraging a more efficient usage of limited network resources. The main contribution of our proposed model is an approach to integrate user behavior and real-time dynamic towards performance improvement of mobile data services. The work presented here is purely analytical. The steps followed to study the problem are summarized below:

1. We employ Markov Modulated Poisson Process (MMPP) as a performance model for GPRS networks since it captures the correlations between the inter-arrival times of multiple types of services as this is the case in GPRS networks.
2. A demand function for priority users is used to identify the user behavior towards dynamic pricing. This function affects the arrival process in the GPRS system.
3. The structure of MMPP is modified in accord with the change in the arrival process. We identified the sub-matrices that are used to construct the infinitesimal generating matrix of the MMPP.
4. Finally, the matrix is used to determine the performance parameters of our proposed model.

To summarize it, we study the MMPP model with demand driven (via pricing) arrival rates.

Currently, we are performing numerical tests and studying the results of our proposed model in terms of both performance improvement and revenue generated. We believe that the approach described here, together with our proposed model, could affect dynamic pricing and performance of GPRS data service, in a realistic manner.

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