# Call Admission Control and Dynamic Pricing in a GSM/GPRS Cellular Network

by

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# Declaration

I declare that the work described in this dissertation is, except where otherwise stated, entirely my own work and has not been submitted as an exercise for a degree at this or any other university.

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# Abstract

In the past decade, the wireless communications market has experienced tremendous growth, and this growth is likely to continue in the near future. In addition to an increase in the number of users, ever more demanding applications will appear, resulting in ever greater resource requirements. The limited radio frequency spectrum available can no longer support this increasing demand, and the required quality of service will no longer be attainable if an efficient solution is not found.

The easiest approach to solve this problem is to increase the capacity of the network, but this is uneconomic and not really practical. Indeed, at their current size, the networks are already under utilized most of the time, even if they can not accept every incoming call during congested peak periods. Increasing their capacity still further may solve the congestion problem for a while, but at the cost of an even higher global under utilization of resources. Other solutions have emerged to alleviate this problem, but none of them is really effective when the degree of congestion becomes too high.

An alternative solution is to keep the current network capacity and to make the users' demand fit this limited capacity. This is the basic principle which leads to dynamic pricing: the price of making a call depends on the network load, it can be very high when congestion occurs or very low to encourage users to make calls during off-peak periods. As a result, the congestion is decreased while the overall utilization of the communications channels is improved. Dynamic pricing has already been applied successfully in several domains, but has only recently been considered for use in cellular networks. This project aims to look at how the different solutions mentioned above perform to solve the problem of congestion in the case of both GSM and GSM/GPRS networks, and in particular, at whether or not a combination of dynamic pricing and more traditional approaches can give better results. For this purpose, a detailed traffic model for both GSM and GPRS networks is given and implemented in an event-driven simulator. The effect of several dynamic pricing and admission control combinations is then analysed, and the importance of some incoming traffic parameters is highlighted.

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Chapter 1

# Introduction

## 1.1 Context

In the past decade, the wireless communications market has experienced tremendous growth, and this growth is likely to continue in the near future. In addition to an increase in the number of users, ever more demanding applications will appear, resulting in ever greater resource requirements. The problem for wireless networks is that the available radio frequency spectrum is limited, and can no longer support this increasing demand. The original approach used to solve this problem was to increase the capacity of the network using cell splitting and frequency reuse [78], or overlapping cell layers [79]. But this can not continue indefinitely. Nowadays, the number of cells in large cities has almost reached its maximum, and reducing the size of the cells still further would add more technical overheads than capacity benefits. Moreover, during off-peak periods, it would increase the amount of unused resources, which is uneconomic from the operators' points of view and is, thus, to be avoided.

Since it is no longer possible to make the network capacity fit the demand during peak periods, alternative solutions have to be found to achieve a better utilization of this limited capacity. One of these is to manage the incoming calls more efficiently, in order to guarantee a satisfactory level of quality of service (QoS). This can be achieved using one of the call admission control (CAC) schemes developed over the past few years [37-45]. The role of a CAC scheme is to decide whether a call should be allowed to enter the system or not, by taking into account different QoS parameters. In mobile networks this decision is made more difficult by the existence of two types of call: new calls which wish to connect to the network and handoff calls that started in one cell and are willing to continue in another. Since it is more annoying from a user's point of view to lose an ongoing call than to see a connection attempt refused, most of the schemes are designed to favour handoff calls whilst keeping the tradeoff between handoff and new call blocking at its optimal value. A second solution is to use more efficient algorithms to manage the number of available channels, only allocating them to the cells which require them, instead of giving all cells the same number of channels regardless of the number of users they have to cope with. This has given rise to dynamic and hybrid channel allocation schemes [28].

Even if the previously mentioned techniques can improve the users' level of satisfaction when the network is not congested, it has been proven that their performance starts declining as soon as the number of users exceeds a certain limit. This means that there is a need to avoid congestion by making demand fit the available capacity, since the opposite is impossible in some cases. Because a user tends to act selfishly, using the maximum available resources even if it decreases other users' level of satisfaction, the only possible solution is to use price as a mechanism to give incentives to make a call or not. This leads to real-time or dynamic pricing: the price per unit of time will change in real-time according to network load. A high price during periods of congestion will make some users postpone their calls or shorten them. Similarly, they can try to move to another cell to obtain a cheaper price. On the contrary, a very low price could encourage the users to make their calls at times they did not want to originally. The overall result will be a better distribution of the calls during the day, a reduction of peak time congestion and a better utilization of the resources during off-peak times. This is an important step forward from the pricing strategy used by most mobile telephony operators, who charge different prices during periods that they think will be over or under loaded, but who do not take the actual network load into consideration.

Dynamic pricing, albeit having being used for a long time for regulating the traffic on packet-based networks, such as the Internet, is only emerging now as a potential solution to congestion problems in cellular networks. Economic and user behaviour studies, as well as technical ones, have to be made prior to its use to determine the best pricing functions to use in order to achieve the best possible results. This type of pricing could then be applied to cellular networks in addition to existing techniques, where its effects as a traffic regulator are much needed.

## 1.2 Project Goal

Although CAC schemes and dynamic pricing were designed for the same purpose, little work has been carried out on their combined effects as a resource manager. The principal study, [8], is more focused on dynamic pricing and the call admission control scheme it uses is relatively simple. Hence, it does not explore all the possible benefits a well designed CAC scheme has to offer. Therefore, it would be worthwhile and beneficial to explore how different CAC schemes manage to improve the network utilization, and how well they can be combined with dynamic pricing. This could permit direct comparison and allow for the determination of the best scheme, as well as presenting how dynamic pricing can provide even greater results. This is one goal of this project.

With the current trend towards an ever growing use of mobile networks for purposes other than simple voice calls, there is a need to understand how dynamic pricing would behave in the case of packet-based cellular networks, since these may be used in the future. This is a second goal of this project: to explore how incoming traffic properties, mixing both GSM and GPRS calls, could impact on network performance, and to seek the best values for key parameters.

Finally, a third goal of this project is to continue the work begun in [50], where an accurate model of a GSM/GPRS cellular network was established by surveying the associated literature. This model needs to be deepened to incorporate new applications using GPRS technology, such as file or e-mail transfer. By integrating such improvements, the simulator built for [50] will be made more powerful in the sense that it will have more features and that it will allow the user to have access to more experimental settings.

## 1.3 Contribution to Knowledge

For this work, the main studies on GSM and GPRS network modelling have been analyzed and compared in order to determine which is most suited as a model for a cellular network which includes e-mail and file transfer. The chosen model may now be used for further studies where an accurate model is required, or used as a basis on which other technologies or applications models can be built.

Different combinations of call admission control schemes and dynamic pricing have been studied through simulation, and their comparative benefits analyzed using two important metrics: the total revenue and the total utility generated over a day.

Finally, the importance of some of the incoming traffic parameters has been outlined and their optimal values considered from the perspective of performance.

Together these should lead to a better understanding of how dynamic pricing behaves and how it could be used in current cellular mobile networks.

## 1.4 Dissertation Outline

In the following chapter, recent research studies on dynamic pricing are reviewed. This includes detailed descriptions of the small number of dynamic pricing algorithms that have been proposed for cellular networks, along with a recapitulation of the results obtained when these are applied to other technologies. In chapter 3, existing call admission control and channel assignment schemes are presented. Chapter 4 is a presentation of the existing work from which the network model used by the simulator was derived. The simulator built for this work is then described in chapter 5, together with the GPRS traffic model adopted. Finally, the experiments carried out using the simulator and the results obtained are presented in chapter 6, before the conclusions drawn are discussed in chapter 7.

## Chapter 2

# State of the Art in Dynamic Pricing

In this chapter, we review the different dynamic pricing schemes proposed in the literature for different technologies with a particular focus on mobile networks. Dynamic pricing in cellular networks has only recently become a research domain, and not many comprehensive studies have been completed. Indeed, only three significantly different approaches have been identified in the literature. The first of these has been proposed by Fitkov-Norris and Khanifar, the second by Hou, Yang and Papavassiliou and the last by Viterbo and Chiasserini. In marked contrast, dynamic pricing for packet based networks such as the Internet has been a centre of research interest for quite some time, and numerous studies have been undertaken [14-17]. Some of the most relevant ones to this work will be described herein. Finally, conclusions drawn about dynamic pricing in other contexts like electricity, fixed telephony or E-Commerce will be detailed and similarities with mobile networks will be outlined.

## 2.1 Dynamic Pricing in Mobile Networks

### 2.1.1 A Self-regulated Dynamic Pricing Algorithm for GSM/GPRS Networks

### *2.1.1.1 Presentation*

In [1-4] Fitkov-Norris and Khanifar introduce one of the first dynamic pricing algorithms for mobile networks. The basic algorithm appears rather simple, but is based on a number of well accepted principles. Among these is the fact that as price increases users tend to both shorten the duration of their calls and reduce the number of calls made. Therefore, pricing strategy is a very powerful tool for maintaining the network load (which is a function of the average call holding time and the call inter-arrival times) at a predefined level where the degree of user satisfaction is considered acceptable. However, the nature of mobile networks makes it necessary for even the simplest algorithm to take into account parameters such as the price elasticity on demand or the impact of pricing on mobility, resulting in complex equations from even a simple starting point.

The algorithm itself is self-regulated: it uses a number of predefined parameters and regularly checks the conformity of the actual load of the system to these parameters. If it is decided that the network requires a price adjustment, a tariff increment ΔP is calculated and the price is updated. ΔP can be positive or negative. If it is positive, then the load on the system is too high, and the users' degree of satisfaction may suffer as a consequence. The newly introduced higher price will act as an incentive for new users to wait for a while before making their calls, thus reducing the traffic load. On the contrary, if ΔP is negative, it means that the resource is not optimally used, and that a part of the network is available. A lower price should encourage the consumers to make their calls. The speed at which this price update is made determines the level of self-regulation of the system.

A representation of the basic algorithm can be seen in figure 1 below. The complete algorithm including both GSM and GPRS traffic is given in figure 2. GSM and GPRS traffic are different (see chapter 4). Hence, it can not seem obvious how the same pricing algorithm may be applied to both of them. Fitkov-Norris and Khanifar argue that this is possible because GSM and GPRS share the same pool of resources. Whereas GSM (voice) calls can only use one channel at a time, the advantage of GPRS is that the bandwidth can be greatly increased by the allocation of several timeslots to one call. The pricing strategy should consequently be based on the bandwidth used. If the nominal price for the usage of one channel for a particular duration is known, it is possible to calculate the corresponding price for calls with multiple channels.

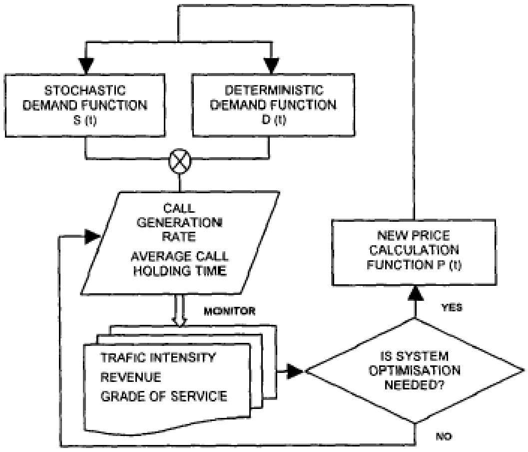


**Figure 1 : Basic Algorithm**

### *2.1.1.2 Implementation*

According to the authors, the most suitable position for implementation of the algorithm will be in the Base Station Controller (BSC). They provide three major justifications for their choice. The first is that the BSC already collects the information used by the algorithm (revenue, number of calls blocked, etc.) without using it. The second is that the calculation of the algorithm in real time requires sufficient processing power, which can be found in the BSC. Finally, the positioning of the algorithm in the BSC would minimize the increase in the control traffic overhead in the network.

Once the price calculation is finished, the result can be broadcast to the mobile stations in the target cell using the Broadcast Control Channel, since this channel is only listened to by the Mobile Stations in that particular cell and has a free slot on the downlink.

### *2.1.1.3 Algorithm Details*

Up to now, only a general description of the algorithm behaviour has been given along with a possible implementation strategy. In this subsection, the user behaviour model is detailed and the pricing scheme presented.

#### 2.1.1.3.1 User behaviour model

##### *Call Generation Rate*

The user demand is modelled as a combination of a deterministic function D(t), a function of the time of day which can be predicted fairly accurately, and a random demand S(t) caused, for example, by emergencies.

D(t) is modelled using a Markov-modulated traffic model [5]. The call inter-arrival times are determined by the generation rate, which is a function of the time of the day. The probability of K arrivals in interval of length *t* is given by:

$$P_K(\lambda t) = \frac{(\lambda t)^K}{K!} e^{-\lambda t} \quad (1)$$

### *Effect of price on demand*

The effect of price on demand is modelled using an exponential function:

$$Q_X = A.e^{-\beta P_{QX}} \quad (2)$$

Where:

- $Q_X$ is the quantity demanded of good X,
- $P_{QX}$ is the price of good X,
- A is the demand shift constant,
- $\beta$ is the demand elasticity coefficient.

This equation is a simplification of the actual function used. In reality, two additional parameters are taken into account.

- The demand shift constant A captures the change in demand due to the effect of the time of day. It uses historical data and will, therefore, change in time. Since pricing bias is already present in the historic data due to the pricing schemes in place, the model is corrected by taking the difference between the peak or off-peak price in the real system and the dynamic price in the modelled system.
- If the dynamic price drops below the historic off-peak price, a fixed line substitution effect is taken into account using an exponential function.

The modified version of equation 2 is, therefore,

$$Q_X = A(t).e^{-\beta(P_{bias} - P_{dynamic})} + E(P_{bias} - P_{dynamic})^{-\beta} \quad (3)$$

where E is the off-peak shift constant.

### *Effect of price on mobility*

Regretfully, this information is not available for telecommunications, because no study about it has been carried out. Hence an alternative approach had to be used. The gravity model has been borrowed from economics for use in this algorithm. Wilson originally employed it to determine the most probable distribution of the number of trips between two regions depending on the attractiveness of the destinations [6]. The translation of this model to the mobile network scenario is very straightforward, so the adaptation of the model was an easy task.

The resulting model is given by the following formula:

$$\psi_{ij} = K.O_i.O_j\left(\frac{1}{d_{ij}}\right)$$

where:

- K is a constant
- $\psi_{ij}$ is the total number of calls between cells i and j.
- $d_{ij}$ is the price of the calls.
- $O_i$ is the total number of users in cell i.

The drawback of this formula is that it is not linear: if the number of users doubles in cell i and in cell j, the number of expected calls will quadruple; therefore corrective constants $A_i$ and $B_j$ need to be introduced. The gravity model is thus modified to:

$$\psi_{ij} = A_i.B_j.O_i.O_j.f(d_{ij})$$

with:

$$A_i = \frac{1}{\sum_j B_j.O_j.f(d_{ij})} \qquad B_j = \frac{1}{\sum_i A_i.O_i.f(d_{ij})}$$

where $f(d_{ij})$ is the pricing function.

#### 2.1.1.3.2 Pricing

In a dynamically priced network, the shape of the pricing function is the most important parameter, as it influences the demand function and consequently the total revenue and utility of the network.

In [4], two pricing functions, linear and non-linear, have been tested. In [2], a more complex function is introduced. This is the solution of the following minimization problem:

$$Min\left(\int_0^{Q\max}(P_{\min}+P(q)).dq\right) \text{ subject to } \sqrt{1+p(q)'^2}\,dq = M$$

The solution is of the form: $P(q) = K - P_{\min} - \sqrt{\lambda^2-(h-q)^2}$

It is also possible to adapt the pricing strategy to the desired goals. Therefore, a pricing function which aims at optimizing the revenue or the total utility can be designed. It should be noted that there is a natural trade-off between these design strategies.

#### 2.1.1.3.3 Results

This dynamic pricing strategy has been tested through simulation [1-2]. The results show that the total revenue generated is significantly higher than that generated with existing pricing schemes and that the rate of call blocking is much lower than with the current schemes (the overall reduction is as high as 30%). It is thus shown that dynamic pricing is a very efficient tool for regulating the network load and, moreover, has other significant advantages.

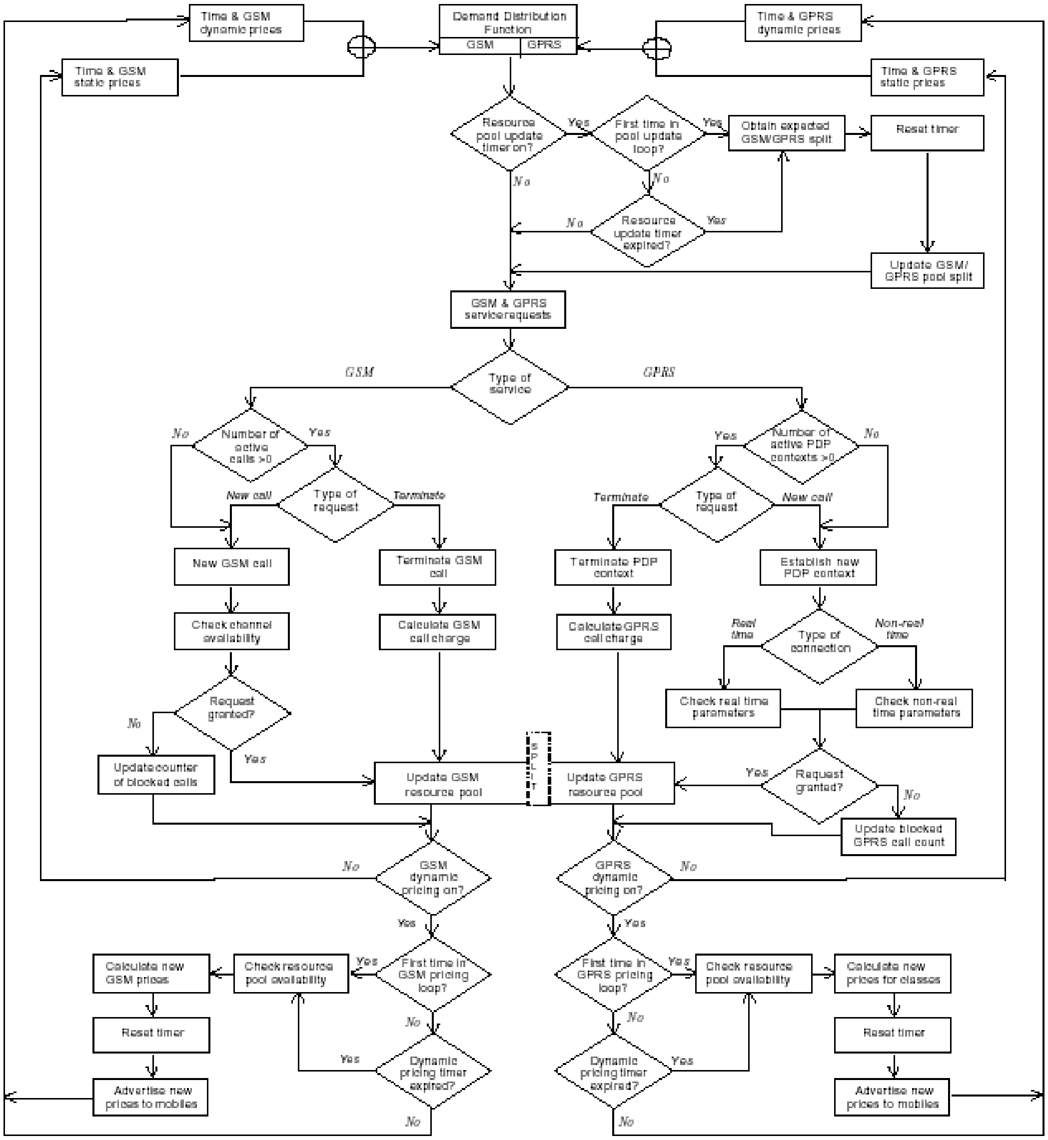


Figure 2 : Complete Algorithm

## 2.1.2 Integration of Pricing with Call Admission Control for Wireless Networks

### *2.1.2.1 Scheme Proposed*

In [7-8], Hou, Yang and Papavassiliou present a new dynamic pricing scheme for cellular networks. The main improvement, in comparison to the scheme described above, is that it introduces the notion of call admission control. Whereas the previous scheme did not consider the difference between new calls and handoff calls (calls started in a cell but which will be continued in another cell because the user is moving), this one does. Numerous call admission control strategies exist, as will be explained in the next chapter, most of them designed to manage the natural trade-off between new calls and handoff calls in a cell: if the decision is made to give the priority to handoff calls for example, it will consequently increase the probability that new calls are blocked, and vice-versa.

Hou et al. argue that traditional CAC schemes are not sufficient, because they can not ensure a good quality of service when the network is congested. When the number of ongoing calls becomes too high then, no matter what CAC scheme is used, the probability that new calls or incoming handoff calls are blocked becomes too high to give the users a good level of satisfaction. In that context, the introduction of pricing as a new dimension to call admission control is a way to maintain the resource utilization to an optimal level, whilst ensuring a predefined quality of service (or utility). Their research focuses on optimizing the resource utilization rather than the total revenue. However, the two are linked since the price is set at the maximum price for which all the resources are used.

### *2.1.2.2 Definition of the Optimal Call Arrival Rate*

In [7], it is proved analytically that, for a given network (with a predefined set of parameters such as the number of channels per cell, and a chosen CAC scheme) and under further assumptions about the shape of the utility function, there exists a call arrival rate which maximizes the total utility. The total utility is the sum of the utility of the individual users, the latter being a representation of the users' welfare. In this case, it is a function of a weighted sum of the new call blocking probability and the handoff call blocking probability. The coefficient associated with handoff calls is more important, as it is more damaging for a user to lose an ongoing call than to be unable to establish a new call. Therefore, the aim of the pricing scheme is to maintain the arrival rate as close as possible to this optimal arrival rate.

### *2.1.2.3 Experimental Settings*

#### 2.1.2.3.1 System Structure

The system is composed of two independent blocks, the pricing block and the CAC block. A Guard Channel CAC scheme is used; as will be explained in the next chapter, this gives priority to handoff calls by blocking new calls if the number of available channels is less than the designated number of guard channels and by blocking handoff calls only if all channels are occupied.

The system is described in figure 3 below.

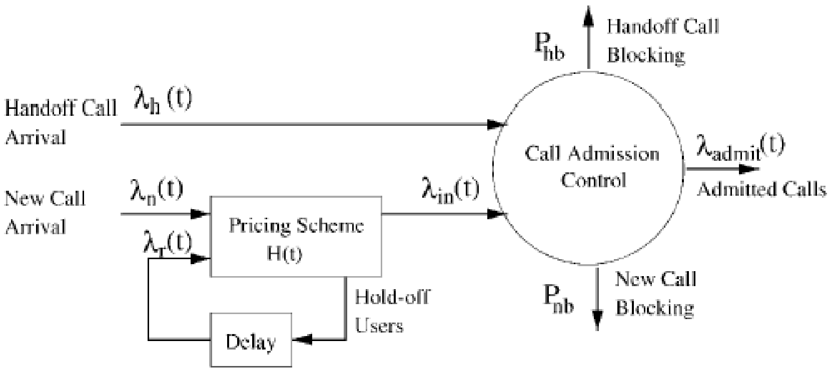


**Figure 3 : System structure for Hou et al.'s algorithm**

When a user attempts to establish a connection, the new call is first considered by the pricing block, and the user given the current price. If the price is accepted, the call is forwarded to the CAC block, where it can be either accepted or rejected, depending on the prevailing network load. If the price is too high, the user can either leave or retry after a delay.

#### 2.1.2.3.2 Pricing Strategy

The price charged to the user depends on the network load, as expected in a dynamically priced network. However, contrary to the pricing scheme proposed by Fitkov-Norris and Khanifar, the main concern is the user utility; the price can not become very low as a means to encourage the user to make more calls when the network is under-utilized. Consequently, the pricing strategy is as follows: when the incoming rate λ is less than the optimal rate λ*, a constant price $p_0$ is charged. When it becomes more than λ*, a dynamically calculated price p(t) is charged.

#### 2.1.2.3.3 Demand Modelling

The demand function is that introduced in [9]:

$$D[p(t)] = e^{-(\frac{p(t)}{p_0}-1)^2} \quad \text{for } p(t) \geq p_0$$

D[p(t)] represents the percentage of users who will accept the current price. Since D[ $p_0$ ] = 1, it means that $p_0$ is accepted by everyone.

#### 2.1.2.3.4 Pricing Function

The price p(t) to be charged at a particular time t is given by the following function, which is a function of the new call arrival rate, the retry call arrival rate as represented in figure 3 above, and the optimal call arrival rate.

$$p(t) = D^{-1}\left( \min(\frac{\lambda_n^*}{\lambda_n(t) + \lambda_r(t)}, 1) \right)$$

#### 2.1.2.3.5 Utility Function

The utility function needs to be a good representation of how the network load impacts on the users' welfare. It is obvious that it must be a decreasing function of the global blocking probability, but a lot of different shapes are acceptable. Two main approaches can be used. The first corresponds to a system with hard QoS requirements, whereas the second corresponds to a system with softer ones.

A utility function of the first type can for example be:

$$U_1 = 1 - e^{30(Pb-0.1)} \text{ for } 0 \leq \text{Pb} \leq 0.01 \text{ and 0 otherwise}$$

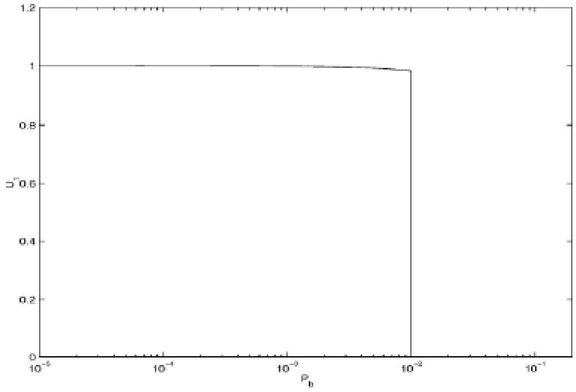


**Figure 4 : Utility function with hard QoS requirements**

A utility of the second type can be:

$$U_2 = \max(1 - e^{30.(Pb-0.1)}, 0)$$

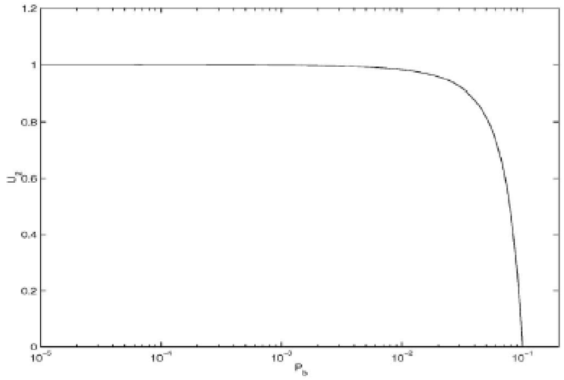


**Figure 5 : Utility function with soft QoS requirements**

The former is used in the original study [8].

### *2.1.2.4 Results*

This model has also been evaluated through simulation. The call arrival rate is described by a Poisson Process and the call holding time follows a negative exponential distribution. Contrary to the experiments carried out by Fitkov-Norris and Khanifar, the call duration is independent from the price.

Different user behaviours were considered, with regards to the percentage of users that retry after being blocked at the pricing level and at the CAC level. The results were also compared with the case where no pricing block was implemented.

It was shown that the proposed system, which integrates CAC and dynamic pricing, succeeds where traditional CAC schemes fail, that it to say, in guaranteeing a predefined level of QoS even during the peak periods. Moreover, both the total user utility and the operator revenue are significantly increased.

### 2.1.3 Dynamic Pricing for Connection-oriented Services in Wireless Networks

#### *2.1.3.1 Presentation*

In [10, 11], yet another approach to dynamic pricing in connection-oriented mobile networks is presented. The main goal of this research is to maximize the total revenue by finding an optimal pricing function.

The call duration is modelled as a function of the service price, and the user demand as a decreasing exponential function of both the call price per unit of time and the call blocking probability, which is the Quality of Service metric they selected.

In addition, because customers like transparency, the price follows an imposed linear dynamic. Standard Markovian techniques are used to represent the system evolution and to determine the optimal pricing function.

#### *2.1.3.2 System Model*

##### 2.1.3.2.1 Demand Modelling

A standard econometric model is used for the demand function:

$$D(p,Q) = e^{(-\alpha p+\beta Q)}$$

where p is the price per unit of time and Q is the Quality of service. Here, the quality of service is said to be the probability of call success, that is Q = 1 - Pb where Pb is the probability of a call being blocked. The parameters α and β characterize the user population behaviour and must be identified by adequate market research.

This model takes into account common user behaviour: the users' demand function drops as the price per time unit increases and the quality of service decreases.

If the system is supposed to have N communication channels, it may be represented by a birth-death Markov chain where each state i = 0, … N represents the number of ongoing calls.

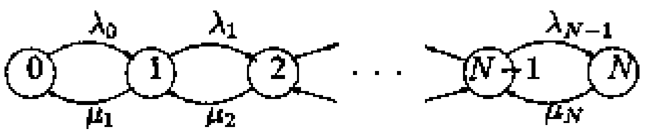


**Figure 6 : Birth-death Markov chain**

$\lambda_i$ is the call arrival rate when the system is in state i, and $\mu_i$ is the average call termination rate when the system is in state i. $p = (p_0, p_1, ..., p_{N-1})$ is the price vector representing the cost per time unit of a call started when the system is in state i. The objective is to determine the optimal price vector which will maximize the total revenue while reducing the blocking probability.

Applying standard Markovian techniques to the Markov chain given above, the steady state solution is given by the following probability vector $(\pi_0, \pi_1, ..., \pi_N)$ where

$$\pi_0 = \left( \sum_{k=0}^{N} \prod_{j=1}^{k} \frac{\lambda_{j-1}}{\mu_j} \right)^{-1} \quad \text{and} \quad \pi_i = \pi_0 . \prod_{j=1}^{i} \frac{\lambda_{j-1}}{\mu_j}$$

The blocking probability can be deduced as being equal to $\pi_N$. Knowing the price vector and the probability vector given above, it is easy to calculate the total revenue generated while maintaining the blocking probability at a satisfactory level. The optimization problem is now only a very complex mathematical problem.

### *2.1.3.3 Results*

The results have been obtained for different user populations (by varying the coefficients α and β) and compared to a flat pricing strategy where a constant price for the network usage is fixed. It is shown that when the traffic load is very low, the dynamic pricing strategy may lead to a slight loss of revenue. However, as soon as the traffic load increases, the dynamic strategy behaves much better and results in a huge increase of revenue (more than 25%). It is also noted that α and β have little impact on the results.

#### *2.1.3.4 Future work*

The first part of the research study, as presented above, only considers connection-oriented communications. A future objective of Viterbo and Chiasserini is to apply the same Markovian techniques to packet-based networks. They want to consider third generation mobile communications, where different classes of users can be introduced given their desired information bit rate and actual bandwidth occupancy. They propose not to use the basic idea, which would be to charge the user according to B (bandwidth used) and to the traffic load. Instead, they intend to apply a different pricing strategy to each user class.

The same demand function as for the connection oriented systems is used for each user in each class, and then multi-dimensional Markovian techniques are used to solve the problem.

### 2.1.4 Models for 3G/4G Network Pricing

Wallenius and Hamalainen presented models for 3G/4G service pricing including QoS guarantees [12].

Two types of pricing for the different 3GPP ($3^{rd}$ Generation Partnership Project) [13] traffic classes are introduced. For real-time connections, which are always given a whole traffic channel, it is possible to charge based on the duration and on the number of bits transmitted. For non real-time interactive and background classes, however, a pricing function of the reserved bandwidth is considered more suitable.

Because linear pricing functions for QoS provision can result in huge disparities between connections with high requirements (multimedia) and connections with low ones (voice), a linearity factor is introduced.

The price is then as follows: $P_b = A_{ij}(e - e^{-B.x}).T_l$

Where:

- $P_b$ is the unit of price of the call
- $A_{ij}$ is the linear price factor for each traffic and subscriber class

- $T_l$ is the traffic load
- B is a linearity parameter
- x is one of the QoS attributes, which can be either bandwidth, end to end delay or bit error rate

## 2.2 Dynamic Pricing in Other Industries

### 2.2.1 Internet/ATM

Contrary to the case of Mobile Networks, dynamic pricing as a means of congestion avoidance has been investigated in detail for packet-based networks, such as the Internet or ATM.

There are two main methods to dynamically price the Internet. You can make the users pay according to prices they bid for available bandwidth, or make them pay according to the congestion they cause to other users. The first is called Smart-Market, the second Shadow-pricing. The two approaches are linked, because the more bandwidth you use, the more congestion you create for other users. Nevertheless, the pricing function used is different. In particular, it is different to the pricing of circuit-switching applications, where the price is based on duration. In the case of packet-based networks, it is based on the number of packets sent.

#### *2.2.1.1 Smart-market*

The Smart-Market approach was introduced by Varian and MacKie-Mason in [14]. It is based on simple observations on how the Internet currently works: the standard pricing is independent of the bandwidth actually used by consumers. The higher the maximum bandwidth you have, the higher the price is, but the price doesn't change when the network is congested. In [14], the authors propose an efficient pricing structure to manage congestion, encourage network growth, and utilise resources in the most profitable manner.

Today, the two ways to fight congestion of Internet traffic are by dropping packets and by delaying them. For example, it is very likely that during congestion periods, the packet generated by one user can lead to the packet of another user being dropped. However, the first user has not to pay for the loss experienced by the other.

The Smart-Market approach is different: the price to send a packet changes minute by minute based on the congestion of the network. Each packet has a bid field, indicating how much the user is willing to pay to send it. Non-important packets such as e-mail packets will have a low bid price, and real time application packets will have a high one. At any time, the network only accepts and charges the packets with a bid superior to the current cut-off price, dynamically calculated based on congestion measures. The others are rejected or queued in buffers.

This could be quite easy to implement: a basis bid could be assigned to every packet with this price being overridden for special applications.

One thing to notice is that users don't pay the price they bid. They always pay a lower price, equal to the network clearing price, which can also be calculated in real-time. It is fundamentally different from standard priority based systems such as the postal service, when you can pay high prices even if lower prices would have achieved the same results.

This method, even if simple to implement, has one major drawback. Packets with low bids can be delayed for a very long time. The bid field also takes extra-space, and having more information to transmit, is not a very efficient way to reduce congestion.

#### *2.2.1.2 Shadow-pricing*

The concept of shadow-pricing is one of the most studied concepts for dynamic pricing in packet-based networks. Users pay for the amount of congestion that their packets impose on others. Many different small variations of the basic idea have been proposed, but they are all based on the work by Gibbens and Kelly [15].

The idea is to give the users sufficient information to make the right decision as to whether to submit packets or not. It is achieved using marks. A mark corresponds to a fixed price that the user will have to pay for the packet. Marks are issued when resources are congested. When a user receives a mark, he knows that the resource is congested and that he will have to pay for each packet he sends: he can then decide to wait until the network becomes less congested. The problem is that users don't know the price of the mark before they receive it; it is retrospective.

The shadow price is defined by the marginal increment in expected cost (packet loss) at the resource for a marginal increment in load. It is a measure of the impact of sending one packet on the quality of service experienced by the other users.

They show that, for Poisson statistics, the marking of every packet when a resource is overloaded produces an expected charge per unit of flow which is precisely equal to the shadow price at the resource. Therefore, on average, the more congested the network is, the more expensive it will be to send a packet.

### *2.2.1.3 Other methods for pricing in the Internet*

#### 2.2.1.3.1 Priority based Pricing

In [16], another pricing scheme based on priority is proposed. With the increasing demand for different levels of quality of service, it is argued that an efficient pricing scheme should take this trend into account. Services with a higher priority can impose delays on services with lower priorities, so their cost is higher. When the arrival rate increases for a priority class the corresponding price increases as well, and so do the prices for the other classes. Indeed, the higher priority a class has, the more expensive it will be to use it, and the system must respect this rule at all time. The users know this and can make decisions on the class of service required based on this principle.

#### 2.2.1.3.2 Paris-Metro Pricing

The famous Paris-Metro pricing was introduced in [17]. Although this method is not really a dynamic-pricing scheme, dynamic pricing can be incorporated into it. Indeed, it is more a conceptual idea than an actual implementation. The idea is to split the available bandwidth into a small number of channels (presumably two) and to assign them a different price. The traffic then regulates itself. When the network load is very low, it is very likely that the users will use the lowest price, which will cause the corresponding channel to become overloaded. As a result, the users can decide that it is worthwhile to pay more for better quality of service. When the traffic becomes too congested in the most expensive channel, it may not be suitable to pay this price anymore, and maybe a lower price would achieve the same quality of service. Users then decide to go back to lower channels, which decreases the load in higher channels, etc.

The whole network works on best-effort, there is no quality of service guaranteed. It is even conceptually possible to get poorer performance with higher price.

### 2.2.2 Fixed Telephony

The implications of dynamic pricing on demand regulation in fixed line telecommunications have been investigated by Cosgrove and Linhart [18]. They observed a positive correlation between the increase in price and the reduction in the number of calls made by customers.

Koschat et al. [19] constructed a theoretical model taking into account the systematic and stochastic components of demand and studied optimal real-time tariffs for telephone calls. The model highlighted the potential advantages of real-time pricing for fixed telephony.

Some practical pricing experiments have been carried out in students' dormitories [20]. Shih, Katzand and Joseph conclude that a simple congestion pricing scheme that charges depending on the number of people calling does not influence call duration. This argument was used in the study by Hou, Yang and Papavassiliou to justify their choice to use constant call durations.

### 2.2.3 Electricity

Dynamic pricing for electricity has been considered and applied for a very many years. A lot of studies have been published including [21-25]. In general, the response of industrial and residential customers to real-time pricing was variable and complex but led to reduced bills for the majority of users.

In [26], the goal is to generate fair prices for customers, including the embedded and running costs. Many factors have to be taken into consideration, such as external temperature, wind, etc. The idea is to encourage the users to change their demand pattern if they know that they will have to pay more during the peak period, which results in an equalization of the demand during the whole day.

### 2.2.4 E-Commerce

The nature of the Internet gives the sellers a good way to rapidly change their prices according to customer demand. Moreover, because it is really easy for a customer to change the website he is surfing on and to find the best value for the lowest price, the sellers need to take a decrease in customer demand into account almost immediately, if they don't want to lose money. The price is, therefore, dynamic.

The web, and all the opportunities it gives, has made it a privileged sector for experiments about on-line sales and the results will be later transferred to more traditional market places.

[27] explains that dynamic pricing is already used in the electronic and airline industries, and that the sales made using this type of pricing reached $843 billion industry-wide in 2002.

### 2.2.5 Market

The evolution of the price of shares on the stock-market has been understood for a very long time and analogies with the pricing of telecommunications networks are possible. Indeed, both prices are based on demand and supply, and in both cases, the evolution of customer demand tend to increase when the price decreases, and vice versa.

## 2.3 Conclusions

In many industries it has been shown that dynamic pricing has many advantages over flat-pricing, especially because it doesn't have to make assumptions about customer behaviour: it can, on the contrary, react in real-time. At the cost of a slight increase in the price calculation process requirements, it is possible to achieve better resource utilisation along with higher revenue and a price which is fairer to the customers.

In the special case of cellular networks, only a few significant studies have been made, with the same results as in the general case. Amongst these, only the study by Hou et al. considered the integration of CAC with dynamic pricing. This project focuses on the impact on different call admission control schemes and will use their study as a basis for the experimental settings. Nevertheless, the impact of the call holding time on the total revenue and utility has been investigated in [50]; the results show that this parameter is of huge importance. Because it does not seem very relevant to use a call holding time independent of the price, this assumption will be relaxed in the following study.

Chapter 3

# Channel Allocation and Call Admission Control

Technological advances and rapid development of handheld wireless terminals have facilitated the rapid growth of wireless communications and mobile computing. Considering the current trends in the telecommunications industry, this growth is likely to continue in the future. Therefore, an efficient reuse of the scarce radio spectrum is needed to satisfy the bandwidth requirements of multimedia applications. The first section of this chapter will give an overview of the different channel allocation schemes which are used in real mobile networks. The chosen scheme has a direct consequence on the overall performance, which explains why so much effort has been put into trying to find ever-better resource allocation techniques.

The inherent mobility of wireless terminals adds a new level of complexity to standard resource allocation. Indeed, two types of calls are sharing the channels allocated to a cell: the new calls and the handoff calls. New calls are those initiated by mobile users in the current cell; while handoff calls are those initiated in other cells and handed over to the current cell. The major Quality of Service metrics for mobile communications, the call blocking probability and the call dropping probability, depend on how the number of channels is shared between those two types of calls; that is the Call Admission Control scheme in use. The second part of this chapter will present different existing CAC schemes; such schemes form one of the most active fields of research in the whole wireless communications domain.

## 3.1 Channel Allocation

In [28], a detailed survey of the different channel allocation strategies is presented. The channel allocation can be fixed, dynamic or hybrid, depending on how the resources are shared among the different cells in the network. However, whatever scheme is used, there is a rule which needs to be respected, due to the nature of mobile communications. To avoid interference between calls, the same frequency can not be reused in another cell within a “co-channel reuse distance” $\sigma$.

### 3.1.1 Fixed Channel Allocation

In the Fixed Channel Allocation Strategy (FCA), a set of nominal channels is permanently allocated to each cell for its exclusive use.

The total number of available channels is divided into a number of sets and the minimum number of channel sets (N) required to serve the entire coverage area is related to the reuse distance σ as follows [29, 30]:

$$N = (1/3).\sigma^2$$

Figure 7 below shows the allocation of channels sets for N=3 (a) and N=7 (b).

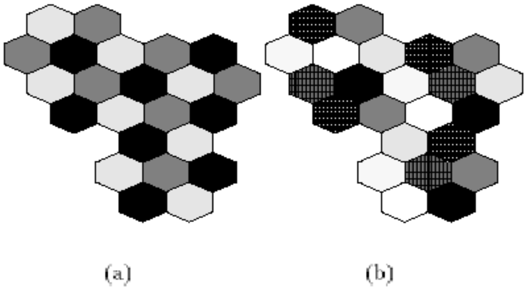


**Figure 7 : Channel allocation for N=3 and N=7**

In the basic FCA scheme [31], the number of channels allocated to each cell is the same. It is of course possible to adapt the number of channels allocated to the traffic conditions encountered by the cells. This can be done using historical data. The performance can be greatly improved if the allocation is done efficiently, but there is also an associated risk: if the traffic conditions change over time, it is possible that the allocation becomes non-adapted, resulting in extremely poor performance.

One improvement to the FCA scheme is done by channel borrowing. When a heavily-loaded cell can no longer serve incoming calls (handoff or new calls), it can try to borrow a channel from a neighbouring cell, always respecting the minimal distance σ. This results in what is called channel locking: when a channel is borrowed, several other cells are prohibited from borrowing it (figure 8 below). The blocking probabilities got using channel-borrowing are lower than the ones with FCA. As with other parts of channel allocation, a lot of research has been conducted into channel borrowing, and small differences have been proposed. For example, the channel can be borrowed from a non-adjacent cell [32,33], it can be done from the richest cell (the cell with the most number of available channels), or it can simply be the first channel found. It is also possible to make only a portion of the channels available for borrowing; this is called Hybrid Channel Borrowing [34, 35].

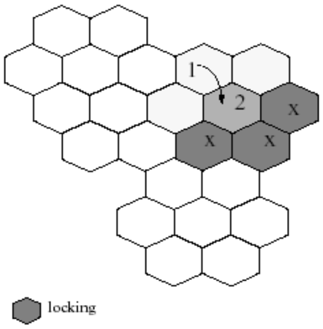


**Figure 8 : Channel locking**

### 3.1.2 Dynamic Channel Allocation

Due to the short term temporal and spatial variations of traffic in cellular systems, FCA schemes are not able to attain high channel efficiency. To overcome this, Dynamic Channel Allocation (DCA) schemes have been studied. In contrast to FCA, there is no fixed relationship between channels and cells in DCA. All channels are kept in a central pool and are assigned dynamically to radio cells as new calls arrive in the system [76, 77]. After a call is terminated, the channel is returned to the common pool.

In DCA, a channel is eligible for use in any cell provided that signal interference constraints are satisfied. Since, in general, more than one channel might be available in the central pool to be assigned to a cell that requires a channel; some strategy must be applied to select the assigned channel [36]. The main differences between the strategies are related to how this choice is made. It is often associated with a cost function.

### 3.1.3 Hybrid Channel Allocation

To combine the advantages of both FCA and DCA, hybrid channel allocation has been proposed [30, 34]. In Hybrid Channel Allocation schemes, the set of available channels is split into fixed and dynamic sets. The fixed set contains a number of nominal channels that are assigned to cells as in the FCA schemes and in all cases are to be preferred for use in their respective cells. The second set of channels is shared by all users in the system to increase flexibility. When a call requires service from a cell where all of the associated nominal channels are busy, then a channel from the dynamic set is assigned to the call. The dynamic set is managed by a DCA scheme.

## 3.2 Call Admission Control

All the allocation schemes presented above did not take into account the effect of handoff calls in the performance of the system. In general, call hand-off is caused by the degradation of the radio link, either because there is some change in the environment, or because the user is moving and needs to change base station to keep sufficient transmission power.

From the user point of view, it is more frustrating to lose a call that has already begun than to be prevented from establishing a new call. The user welfare will consequently be increased if special care is given to handoff calls; even if it increases the blocking probability of new calls. For this reason, many call admission control schemes that manage the tradeoff between handoff and new calls have been proposed, each of which tries to give priority to handoff calls. In this section, a selection of existing schemes will be presented, starting with some simple handoff priority schemes, and continuing with more sophisticated ones.

### 3.2.1 Simple CAC Schemes

#### *3.2.1.1 Guard Channels*

Among all the CAC schemes, the Guard Channel scheme is the nearest to a standard, since it is used commonly for experiments and has been subject to numerous studies over the past two decades [37-40]. The guard channel approach offers a generic means of increasing the chances of handoff call success, simply by allocating a number of channels exclusively for them. Although it is possible to decide statically which channels will be guard channels and which will not, the general meaning of guard channel call admission control does not refer to the static case. On the contrary, even if the number of guard channels is fixed, the channels themselves are not.

What it means is that, if there are N channels of communication in the cell from which G are guard channels, a new call will be accepted only if the number of available channels is superior to G, whereas hand-off calls will be accepted as long as at least one channel is available.

The number of guard channels for a given network is extremely important. It is very easy to understand how this parameter impacts on the overall performance. If all channels are guard channels, it is impossible to start a new call, but the probability that a handoff call will be blocked is very low. In the opposite case, if no channel is allocated exclusively for handoff calls, both types of calls will be treated equally, neglecting the relative importance of the handoff calls. In [41], the number of guard channels is adjusted automatically in real time to minimize the loss probability of handoff calls, so that the trade-off problem is solved automatically.

### *3.2.1.2 Queuing Schemes*

Along with guard channels, the queuing of calls is the second major scheme for handoff prioritization. Different queuing schemes exist.

#### 3.2.1.2.1 Queuing of handoff calls

This has been studied in [43]. The handoff calls are queued and no new calls are handled before the handoff calls in the queue are. Hence, this is a stricter scheme than the guard channel ones. The handoff calls can be queued because of the overlapping zone where two or more base stations in neighbouring cells can work at the same time. Of course, it is not possible for a call to wait indefinitely; it is necessary to impose a time limit, which will have been determined by analysis of the average time that users stay in the overlapping area. Because the size of the buffers for queuing is limited, handoff calls can be blocked before being queued.

#### 3.2.1.2.2 Queuing of new calls

It seems more natural to queue new calls given the fact that they are almost insensitive to delay. In [42], a method was proposed which involved the introduction of guard channels and the queuing of new calls. The results showed that the blocking of handoff calls decreases much faster than the queuing probability of new calls increases.

#### 3.2.1.2.3 Queuing of both types of calls

It is also possible to queue both types of calls, and then decide to give a higher probability of service to the handoff calls present in the queue.

Of course, to achieve better performance, the guard channel schemes and queuing schemes can be combined [44, 45]. However, it is important to bear in mind that the more complex and efficient a scheme is, the more computational power and time it requires to be applied. In the next section, examples of very complex CAC schemes are presented, taking into account the mobility of the users to adapt in real-time to the environment.

### *3.2.1.3 New calls bounding scheme*

As mentioned previously, each CAC scheme suffers when congestion occurs, because it is not possible to maintain both the new call and the handoff call blocking probabilities at a low level when the number of incoming calls increases dramatically. A very powerful scheme would be to avoid too many incoming calls. Because new calls in a cell are likely to become hand-off calls in the neighbouring cells, it seems a good idea to restrict the number of new calls in a cell, to avoid future congestion in its neighbouring cells.

In [46], this concept is used. The presented scheme works as follows:

$$P_{new} = \begin{cases} 1 & B_{usednew} \le N_{bnd} \ \& \ B_{used} \le C - B_{new} \\ 0 & otherwise \end{cases}$$

where :

- $B_{usednew}$ is the number of channels that is used by new calls.
- $N_{bnd}$ is a given bound for new calls.
- $B_{used}$ is the number of channels currently used.
- $B_{new}$ is the number of channels required by the incoming new call.

### 3.2.2 Advanced CAC Schemes

All the schemes presented in the previous sections were basic in the sense that they did not consider the mobility of the user. Information theory shows that it is theoretically possible to get better results by using mobility information in addition to traffic information. Therefore, the majority of the schemes presented in this section are improvements on previous ones, but use either guard channels or queuing as a basis.

One of the major advantages provided by mobility information over traditional CAC schemes is "channel-reservation". The concept is simple: if you can inform a cell that you will require one of its channels at a precise moment of time, the target cell can do its utmost to ensure that this channel will be available for you when you arrive. However, because channel-reservation is a waste of resource (a reserved-channel remains idle until the arrival of the call), an efficient reservation-based scheme should make the reservation at the latest possible moment. So it is necessary to have the most accurate possible knowledge on when the call is to arrive, and consequently, when the reservation is to be made. This precise knowledge is not easy to obtain in real systems, because complete user behaviour is unpredictable. Nevertheless, a complete knowledge is not necessary. The study of the reception power from different base stations, the analysis of the user population mobility pattern or of GPS information are many different ways of obtaining user behaviour information which have been studied in the literature.

In the following, a set of interesting proposals is discussed. These provide an overview of how different strategies relating to mobility information can be used to improve the reservation of resources for CAC schemes.

#### *3.2.2.1 Influence curves*

In [46], the mathematical concept of influence curves is introduced to take the mobility pattern into consideration. It is based on the following observations:

- A user is more likely to request a handoff in the far future than in the near future once he enters a cell. This implies that the handoff probability (the probability that a call needs at least one handoff during remaining call life) is a function of the time elapses after a call enters a cell.

- After dwelling in a cell for the same length of time, a high-speed user (for example a user in a car) is more likely to request a handoff than a low-speed user (a pedestrian) is, which implies that the handoff probability is also related to the speed class of a user.

Because of call hand-off, the traffic in different cells is no longer independent. A call in a cell not only uses a channel in this cell, but also exerts an influence on the neighbouring cells (with different probabilities), because it is likely to hand-off to one of those cells in the future.

From the aforementioned observations it can be concluded that the extent of such influence can be characterized by both the elapsed time and velocity class.

If $f_h(t)$ and $f_l(t)$ represent the cell-dwell-time probability density functions of the high-speed users and the low-speed users, respectively, the probability that a high-speed user entering a cell will require a hand-off after time T is:

$$L_h(t,T) = \int_0^{T-t} f_h(\tau).d\tau$$

Similarly, we can obtain $L_l(t,T)$. Let $\alpha_{i,j}$ be the directional factor, i.e., the probability that the hand-off target cell is cell j when the call is being served in cell i. If no further information is available, all the factors will be equal to 1/6. Of course, in particular places, the factor can be different; for example this is the case on motorways, where all users on one side go into the same direction.

The influence curve characterizing the influence exerted on cell j at time T by an ongoing high-speed call which enters the cell i at time T is:

$$I(i,j,t,T) = \alpha_{i,j} L_h(t,T)$$

Using the influence curve for every ongoing call, we can further determine the number of channels it is necessary to reserve in each cell, as a portion of the total influence, this latter being the sum of the influence curve for all ongoing calls in cell i.

### *3.2.2.2 Shadow cluster*

In [47], the famous notion of Shadow cluster for channel reservation is introduced. This is a general concept, which can be exploited at different levels given the degree of information available regarding the users mobility.

It can be represented as in figure 9 below. The shadow is stronger where more reservations need to be made, that is in the neighbouring cells which the mobile station is the most likely to move into, according to its current mobility. In the cells in the path of the mobile station, reservations can be made to a lesser extent, even in the cells which are not directly in contact with the current one.

When the mobile station moves, its shadow moves as well, the resources reservations and cancellations being made in real-time.

The base station of a cell is responsible for informing other base stations of the probability that a mobile station under its control will require one of their channels in the future. Given this probability, the target base station can decide whether to actually reserve a channel or not.

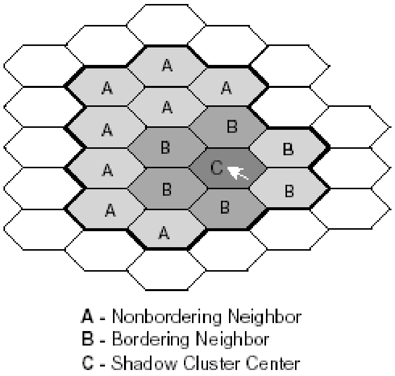


**Figure 9 : Shadow cluster**

### *3.2.2.3 Predictive Channel Reservation*

The position of the mobile station in the network is also used in [48], where the notion of "threshold distance" is used to define the size of channel reservation area. The PCR scheme makes predictive channel reservations for each mobile station (MS) based on its current position (calculated with GPS data) and orientation. The threshold distance is defined as the radius of a circle which is co-centered with a cell, and this circle is smaller than the cell's coverage area

(Figure 10 below). The area between these two circles is called the channel reservation area. When a mobile station enters the reservation area of a cell from the inner part of that cell, and at the same time, is heading to a new cell, a reservation request will be sent to that new cell's base station.

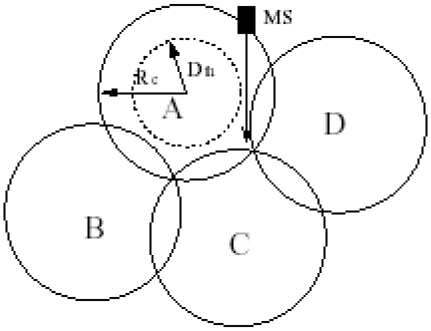


**Figure 10 : Notion of threshold distance**

### *3.2.2.4 Adaptive Channel Reservation*

In [49], it is argued that the Predictive Channel Reservation scheme has some problems, including the following: the threshold distance is the same for all users, regardless of their speed. Hence, the time the base station will have to make the reservations can vary a lot between two different incoming calls. Another problem can be seen in figure 10, where the mobile station in the reservation area of the cell A, is heading to cell C. Although a reservation is requested, there is a lot of time before the mobile station will actually enter into the cell C, which means that the resource will be idle for a long time. This results in an under-utilization of the wireless resources, which is to be absolutely avoided.

To overcome this, the Adaptive Channel Reservation scheme is introduced. This is not based on a threshold distance, but rather on a constant threshold time $T_{th}$. According to each mobile station's current moving speed, orientation and location information, base stations can predict the time within which the mobile station will reach the boundary of its next target cell. This is represented in figure 11 below, where the mobile station is moving with velocity V towards cell A. The velocity V can be decomposed into two orthogonal component vectors, $V_1$ and $V_2$, where $V_1$ is the velocity component of this mobile station towards the centre of cell A. From $V_1$ and $R_{MS}$

(the distance between the mobile station and the centre of cell A), we can estimate the time T by which the mobile station will reach the boundary of cell A by:

$$T = \frac{R_{MS} - R_C}{V_1} \quad \text{where } R_C \text{ is the radius of the cell.}$$

Knowing T and $T_{th}$, it is possible to make the decision on whether or not it is necessary to make a reservation.

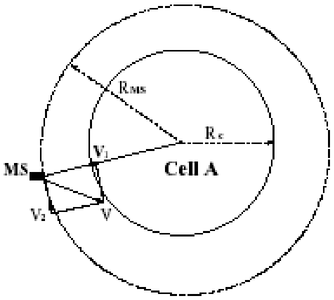


**Figure 11 : Adaptive channel reservation**

## 3.3 Conclusion

In this chapter, some of the existing schemes for channel allocation and call admission control have been presented. As the more advanced schemes, which use GPS data, mature, they may be increasingly used in the future as mobile terminal technology progresses. The goal of call admission control is to balance the trade-off between the new and handoff call blocking probabilities, and it has consequently a great impact on user utility. Call Admission Control and dynamic pricing have almost the same goal, and as shown in [7], their combined effect can be even more efficient. For this reason, it seems particularly interesting to look at the effect of different schemes in a dynamically priced mobile network. This is one of the objectives of this project.

## Chapter 4

# GSM/GPRS Network Modelling

This project mainly focuses on analyzing the effects of different call admission control and channel assignment schemes on a dynamically priced GSM/GPRS network. However, it is also one of its objectives to continue the work started in [50], where a simulator for GSM/GPRS network was built. In particular, the GPRS traffic model needs to be extended to be more realistic and to take account of different types of applications: Web traffic, E-mail and file transfers.

In this chapter, a quick recapitulation of the GSM [51] and GPRS [52] technologies and how they interact will be given, so that the experimental settings which will be used in the following may be justified. It is not intended to provide a very detailed description of GSM and GPRS; these are very complicated technologies and would require much deeper exposition than is possible in this dissertation. Finally, existing proposals for GSM and GPRS traffic modelling will be presented along with the choices made for this project.

## 4.1 GSM and GPRS Technologies

### 4.1.1 GSM

The origin of the “Global System for Mobile communications” (GSM) goes back to the year 1982. At that time, the European countries decided to develop and adopt a common norm for the passage from analog cellular networks to digital technologies. The digital technologies are more efficient than analog ones in their use of the spectrum; they can also offer more functionality and security.

#### *4.1.1.1 Concept of cellular networks*

GSM, as in other radio telephony systems, uses a radio link between the phone network and the mobile terminals. The transmission between these two entities must be of sufficient quality; this is why a number of base stations (transmitters) have to be installed at different places in order to cover the entire network area. The notion of cell, and thus of cellular networks, appears with these base stations. A cell is the area where a mobile phone can establish a connection with a particular base station. They are often represented by hexagons, because a hexagon is a good shape to regularly cover a whole area, but they don't actually have that form. Indeed, in reality, the shape of a cell is more of an irregular circle, the irregularities being due to the obstacles around the base stations, buildings for example. The size of the cell depends on the transmission power of the base station. Huge cells are used in rural zones, whereas smaller cells are used in city centres. As will be explained below, the number of frequencies allocated to GSM is restricted. For this reason, they have to be reused among cells to increase capacity, which results in networks with similar aspects to the one presented in figure 7. The number of cells using all the available frequency band is called a cluster. Frequent clusters have 4, 7, 12 or 21 cells.

#### *4.1.1.2 GSM frequencies sharing*

Two frequency bands of 25 MHz have been allocated for the GSM system in the 900 MHz frequency band. They correspond to the downlink and uplink. Each communication channel is 200 kHz wide and it is thus possible to split the available bandwidth into 125 duplex links. However, only 124 are effectively usable, since the 125th channel is used for signalling. The number of channels then must be equally shared among the phone operators.

In addition to the frequency multiplexing presented above (FDMA), temporal multiplexing (TDMA) is also used to increase the capacity of GSM links. Each channel is divided into eight time slots, and each user is only given one time slot for its communication. It means that each user can only use the link for one eighth of the time.

Considering all the information mentioned above, a cluster of seven cells and three operators, it is possible to give a rough calculation of the number of calls N that can simultaneously happen in a cell:

$$N = \frac{124 * 8}{7 * 3} \approx 47$$

*This is the value that will be used in the simulator for the number of channels inside each cell.*

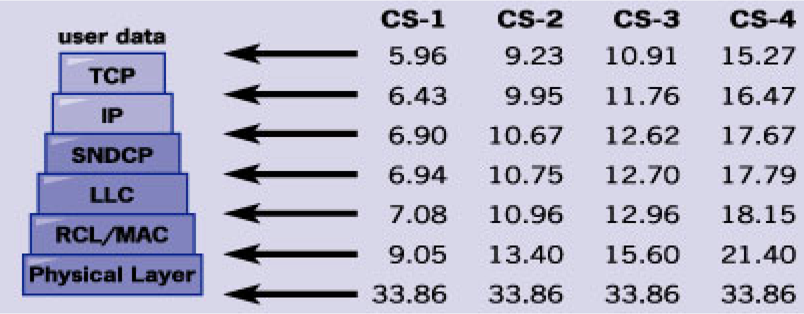
### 4.1.2 GPRS

The tremendous growth in demand for mobile communications has very quickly shown the limitations of GSM in face of the ever increasing amount of data to be transmitted. One of the major reasons is that GSM is a circuit-orientated technology, which means that once a call is established, one channel is exclusively allocated for this communication for its full duration, even when neither of the correspondents is talking. This results in a very poor utilization of the bandwidth.

To overcome this, the General Packet Radio Service using a packet-based technology was introduced, reusing the GSM infrastructures. With GPRS, it is possible to achieve much better throughput than GSM and better resource utilization. Indeed, a user only uses the link when he really needs to, and releases it automatically as soon as possible. As a consequence, GPRS is suitable for more types of applications, such as file transfer or web-traffic.

Unlike GSM, more than one time slot can be allocated for one call in GPRS (up to eight), which explains why the maximum theoretical throughput is so high.

Because the bottleneck is the radio interface, new coding schemes for the radio channel have been found, increasing the throughput from 13.4 to 21.4 kbits/s. These results are illustrated in figure 12 below [53], which represents the different throughputs (in kbits/s) at different layers of the stack.



| user data | CS-1 | CS-2 | CS-3 | CS-4 |
|---|---|---|---|---|
| TCP | 5.96 | 9.23 | 10.91 | 15.27 |
| IP | 6.43 | 9.95 | 11.76 | 16.47 |
| SNDCP | 6.90 | 10.67 | 12.62 | 17.67 |
| LLC | 6.94 | 10.75 | 12.70 | 17.79 |
| RCL/MAC | 7.08 | 10.96 | 12.96 | 18.15 |
| Physical Layer | 9.05 | 13.40 | 15.60 | 21.40 |
|  | 33.86 | 33.86 | 33.86 | 33.86 |

**Figure 12 : Throughputs for GPRS in kbits/s**

Because one user can be given eight time slots, each of them corresponding to a maximum throughput of 21.4 kbits/s, the global maximum throughput that can be achieved is 171.2 kbits/s. However, this theoretical value is almost never reached in the reality. The reason is that it would require that a particular user gets the eight time slots available, which is possible only when the network is not congested. Moreover, even if GPRS technology can manage up to eight time slots, current mobile phones can not. Most of them can only manage four time slots for the downlink and one time slot for the uplink. They are also limited in the sense that they often don’t use the highest coding schemes (CS-3 and CS-4), which are too prone to errors.

*Therefore, for this project, we will only consider the allocation of one to four time slots (corresponding to one to four channels) for each call, and a throughput of 10 kbits/s for each channel, which is a common value used in the literature.*

### 4.1.3 Resources allocations between GSM and GPRS

Because GSM and GPRS calls share the same resources, there is a need to manage the way they can have access to these resources. Because voice calls (GSM) are supposed to be more important than data calls, the problem is very similar to the one with new calls and hand-off calls, which was discussed in chapter 3. The same strategies can be adapted to this problem, for example the queuing of the two types of calls with or without priority. Similarly, channels can be specifically allocated for GPRS, or on the contrary the allocation can be made dynamically.

In [54], another scheme is presented. It is call “Dynamic Channel Stealing” and permits a GPRS call to temporarily use the channel allocated to an inactive voice call.

## 4.2 Cellular Network Modelling

The different strategies employed in the literature to represent a cellular network are now presented. Because the results depend on this representation, it is a crucial parameter which needs to be considered seriously. The problem is that it is not realistically feasible to simulate a full network, since it would require a huge amount of computational power. It is thus necessary to use a smaller representation, which keeps the salient characteristics of a global one.

### 4.2.1 Basic Approach

The basic approach consists of considering only one cell, and to model the arrival of handoff calls using a mathematical formula. In [55], this solution is used and the following handoff call traffic model is proposed:

$$\lambda_h = \frac{\eta.(1-P_{nb})}{\mu+\eta.P_{hb}}.\lambda_{in}$$

where

- $\lambda_h$ is the hand-off call arrival rate,
- $\lambda_{in}$ is the new call arrival rate in the admission block,
- $P_{nb}$ is the new call blocking probability in the admission block,
- $P_{hb}$ is the hand-off call blocking probability in the admission block,
- $1/\eta$ is the mean cell dwell time,
- $1/\mu$ is the mean call holding time.

### 4.2.2 Classic Approach

The classic approach is to define a scenario consisting of a cell surrounded by one or, preferably, two rings of interfering cells [56, 57]. With this representation, statistics can only be collected for the central cell, since the other cell are not surrounded by the same number of cells and consequently do not suffer from the same interference. This means that only 1/19 or about 5% (in the case of two rings) of the simulation results are used. It represents an important loss of data, which has to be avoided, even if the results obtained for the central cell are satisfactory.

### 4.2.3 Refined Approaches

In [58, 59], another approach is proposed. Because the problem with previous approaches was that the data collected for the border cells was useless, the strategy is to get rid of these cells. In order to achieve this, the so called "wrap-around" scenarios have been proposed. There are two ways to represent it. The first is given in figure 13, the second in figure 14. In figure 13, the cells simply continue on the other side of the map. In figure 14, it can be compared to a foot ball, where cells are bound to each other, resulting in a sphere.

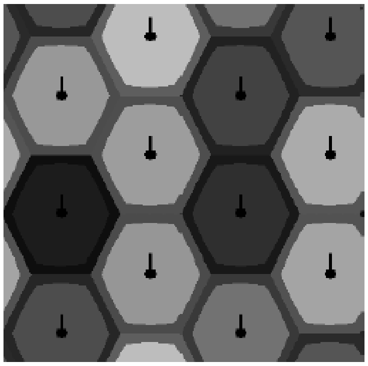


Figure 13 : Refined approach model 1

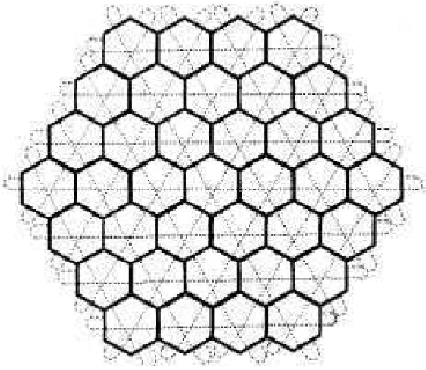


Figure 14 : Refined approach model 2

In [50], experiments were made to compare the results obtained using the last approach and the first one. It showed that both approaches produce similar results. For this reason, it was argued that it was not necessary to use a wrap around model with a large number of cells.

*Therefore, for this project, a wrap around model consisting of seven cells will be used.*

## 4.3 Traffic Modelling

This section aims to justify the GSM and GPRS traffic models chosen for this study. For this purpose, a brief overview of some existing proposals will be presented [60]. In particular attention will be given to empirical measurements rather than purely theoretical studies.

### 4.3.1 GSM

The behaviour of voice users has been widely studied in the past. Traditional phone users and mobile phone users have the same characteristics; it is hence possible to transfer the well-known results from the first technology to the second. Indeed, in both cases, the communication comprises a sequence of active phases (when the user is actually talking) and inactive phases (when he is listening to his counterpart). For this reason, the traffic generated by these users is usually characterized by an ON/OFF process. The only relevant parameters for this type of traffic are the mean inter-arrival time between consecutive connections, and the mean connection duration. It is widely accepted that exponential distributions should be used for both parameters, resulting in a Poisson process description for voice users.

*This standard will be adopted for this project, the arrival of GSM calls being represented by a Poisson Process. The call arrival time is varied with the time of the day, as given in figure 15 below.*

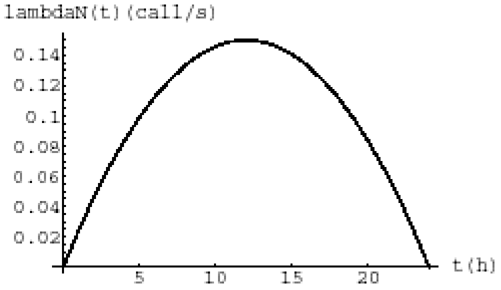


**Figure 15 : Incoming traffic as a function of the time of day**

### 4.3.2 GPRS

Although the modelling of GSM traffic is rather straightforward, the traffic generated by GPRS is highly dependent on the application involved. Because most of these applications have a high burstiness, the simple Poisson process description is no longer sufficient. Before giving more details about how the different applications are represented, it is necessary to look at which applications need realistically be considered for mobile phones. Vicari [61] investigated the behaviour of dial-in users. Figure 16 below shows the traffic share of the most important applications for access speeds between 9.6 kbits/s and 64 kbits/s.

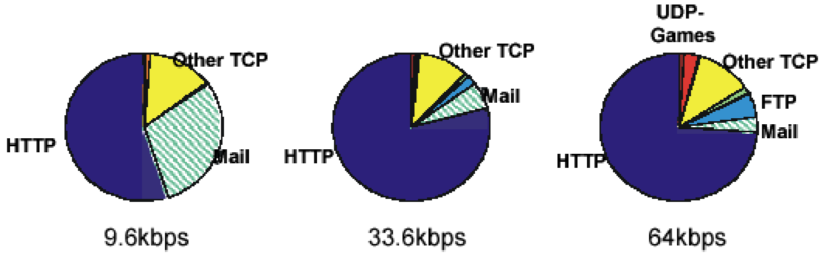


**Figure 16 : Traffic repartition for dial-in users**

As mentioned in the previous section, the throughput experienced by GPRS traffic can change with network congestion. However, the average current throughput is around 30 kbits/s. Therefore, it seems relevant to use the results obtained for 33.6 kbits/s. At that throughput, the principal traffic is web based, while other relevant applications are E-mail and File transfer. The other applications each occupy a very small part and consist of games, telnet, etc., which are only relevant for dial-in users but are not applicable to GPRS.

*For this project, the GPRS traffic will therefore be made up of the following: 80% Web, 15% E-mail and 5 % file transfer. A small readjustment had to be made to adapt the results obtained by Vicari to GPRS (removal of other traffic types). The use of these applications is interesting because they correspond to three types of applications: interactive, best-effort and background, respectively [13].*

### *4.3.2.1 Web Traffic*

#### 4.3.2.1.1 Measurement based proposals

Nowadays, the Web is the most important application used by the Internet community, and many attempts to model its traffic have been proposed in the past decade. A web document is made of HTML code (the main object) and additional other objects such as images or java code (inline objects). For the transfer to be completed, every object has to be downloaded. Recent versions of web browsers allow a user to download several objects simultaneously, by establishing multiple connections. However, for this project, we will consider that all objects are downloaded individually. It seems a more realistic view of web traffic for GPRS, which has to operate in a wireless environment with a more restricted spectrum than typical wire lines.

There are three main ways to get information about web traffic. The first is the analysis of server logs, which has been used in [62]. This does not permit the establishment of a model for a single user so it is not relevant for this study. The second method is the analysis of client logs, used in [63, 64]. Even if the results are relevant, the studies are of sufficient age that their reliability is questionable. Packet traces are the main method that is almost always used today [65-69]: the analysis of packets gives information about the application in use, from which it is possible to deduce an appropriate model.

The different studies of the third type mentioned above can be separated into two categories. The first type [67, 68] separates the traces into sessions and sub-sessions and proposes distributions for both the inter-arrival times of sessions and the duration of a session. The others only consider an unlimited session. The main studies of both types will be presented below.

In [67], a subsession is described as the time period during which a user actively uses the Internet. Vicari found that a typical subsession is made of 19.6 web pages on average, each of them consisting of four objects on average. The size of the global web document and the time between web requests are modelled by Pareto distributions.

In [68], a more detailed model is provided, consisting of three levels, the session level, the page level, and the packet level. The session inter-arrival time is then modelled by a Poisson process, whereas the number of pages downloaded per session is represented by a lognormal distribution. Page size is found to be Pareto distributed. The reading time between two consecutive sessions is said to be Gamma distributed (mean 30s, standard deviation 140s).

Among the models using an ON/OFF process, the studies carried out by Deng in [65], by Mah in [66] and by Choi and Limb in [69] are the most interesting ones.

Deng considered the simplest ON/OFF model, where the ON phase is the time during the download processes and the OFF phase is the “viewing time” of the downloaded document. Distributions for the three main parameters (duration of the ON period, duration of the OFF period and inter-arrival time of web requests during the ON phase) were found, respectively Pareto for the first and Weibull for the others.

Mah's model is a little more sophisticated, since his OFF period is not only the time a user views the downloaded page, but also the time between two sessions. The major advantage of this study over the previous one is that Mah gives distributions for the size of objects in the web page. However, their number is only given via median and mean, which are not easily used for simulation studies.

Finally, the model presented in [69] is the most interesting. It is represented in Figure 17 below. As can be seen in this figure, three different layers are considered. The ON/OFF model corresponds to the arrival of web requests. The OFF time is said to be Weibull distributed whereas the ON time depends on the size of the document to download. A division of the document into one main and several inline documents is used. The object sizes are found to be lognormal distributed (mean 10 kB and 7.7 kB), and the number of inline objects is found to be gamma distributed (mean 5.5). Choi and Limb considered the recent versions of web-browsers where several connections can be established simultaneously.

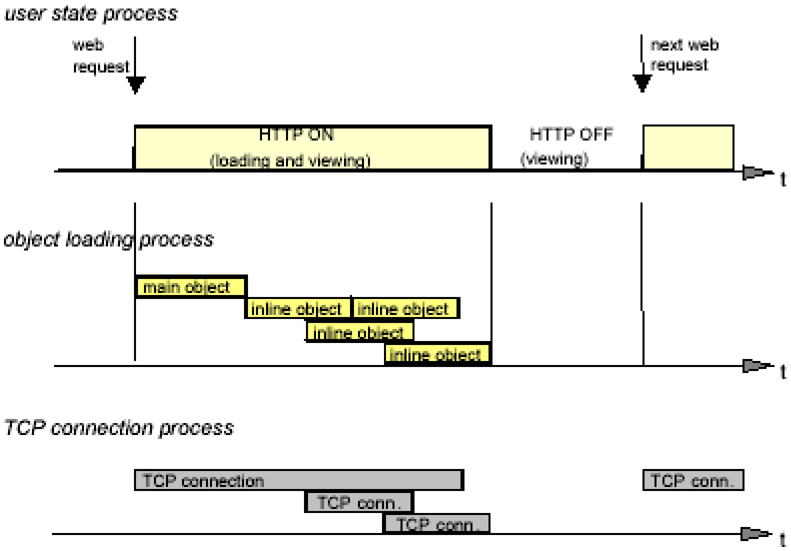


**Figure 17 : Model of Choi and Limb for Web traffic**

#### 4.3.2.1.2 Models proposed by standards

All the models presented in the previous sections are based on actual measurements. In contrast, the Web-traffic models proposed for UMTS [70] and cdma2000 [71] are only theoretical but are recommended for performance analysis. For example, in [70], the page size is represented using a truncated Pareto distribution and the number of pages per session by a Geometric distribution of mean 5. The inter-session time is represented using a Poisson process, and the viewing time using a Geometric distribution of mean 412 s.

#### 4.3.2.1.3 Model used for this project

As far as possible, it has been decided for this project to use empirical values for the different important parameters of Web-traffic. Among the different studies presented, the one made by Choi and Limb is the most relevant. Therefore, the results presented in [69] will be used. However, because some required parameters are missing in this study, the number of pages per session and the inter-session time will be taken from the UMTS recommendation.

A recapitulation of the GPRS Web-traffic model is given in table 1 below.

| Parameter | Distribution | Literature source |
|---|---|---|
| Main object size | Lognormal<br>mean 10 kB<br>stddev 25 kB | Choi and Limb |
| Inline object size | Lognormal<br>mean 7.7 kB.<br>stddev 126 kB | Choi and Limb |
| Number of inline objects | Gamma<br>mean 5.5<br>stddev 11.4 | Choi and Limb |
| Viewing time | Gamma<br>mean 30s<br>stddev 140s | Reyes |
| Inter-session time | Poisson arrival process | UMTS |
| Number of pages per session | Geometric<br>mean 5 | UMTS |

**Table 1 : Model used for Web Traffic**

### *4.3.2.2 Email and file transfer traffic modelling*

Although web-traffic is made up of a sequence of sessions, where a user downloads a document and then reads it, E-Mail and file transfer traffic is different. These only consist of one “session”, where the user sends the file he has to send. The only difference between the two types of traffic is the size of the file to transmit.

#### 4.3.2.2.1 E-Mail

The number of studies concerning E-Mail traffic [60, 72-74] is much smaller than for Web-traffic.

In [73], the analysis of a sample of 1760 E-mails shows an average size of 77.9 kB with a standard variation of 337.6 kB. In [60], the result of the analysis of the E-Mail collection of a sample of users at the University of Würzburg is presented. The average E-Mail size is found to be 22.7 kB with standard deviation of 200.3 kB. In [72], a different approach is given. The E-mails, of size smaller than 300 bytes are considered to be errors and are not taken into account. The minimum size for an E-Mail is hence 300 bytes. The remaining messages are separated into two categories, each of which follows a lognormal distribution of mean 1.7 kB and 15.7 kB respectively.

Finally, in [74], an attempt to model the E-Mail size using a Cauchy distribution is made. It is defined by the following density function, with $\alpha = 0.8$ and $\beta = 1.0$.

$$f(x) = \left( \pi.\beta.\left[ 1 + \left( \frac{x-\alpha}{\beta} \right)^2 \right] \right)^{-1}$$

This results in a mean size of 2.7 kB with standard deviation of 17.7 kB.

As can be seen with the figures given above, there is no real common value for the E-Mail size distribution. Nevertheless, the results in [74] and in [72] seems to underestimate their size whereas it is overestimated in [73]. For this reason, the middle value found in [60] seems to be the most appropriate.

*Because imposing a smallest size seems to be a good idea, it has been decided to adopt the following E-Mail representation for this project: The E-Mail size will follow a geometrical distribution of mean 23 kB, with a smallest possible size of 300 bytes. This geometrical distribution was used in [75] and produced valid results in that study.*

#### 4.3.2.2.2 File Transfer

The average size of the files transmitted by GPRS is very difficult to estimate. Two important facts need to be taken into account. The first is that, given the low throughput of GPRS, important files will not be sent using this medium. The second is that FTP transfer is very rare because of the importance of HTTP file transfers. However, a study of the average size of file transferred was made in [72] and it was found to have an average of 4 kB. This is about the size of a JPEG image, and thus this value will be used in the simulator. The same decision was made in [75].

*File transfer will be considered to follow a geometric distribution of mean 4 kB.*

## 4.4 Call duration and cell dwell times

The GSM call holding time (total call duration) and cell dwell time (time a mobile host stays in a cell) are modelled using a geometrical distribution. Contrary to the study made in [8], they are assumed to be dependent on the price. They are however independent of time. When a call is generated, both its call holding time and cell dwell time are generated and the minimum of these two is used to determine a suitable event trigger to associate with the call.

*In this project, except where otherwise stated, the call duration is assumed to be exponentially distributed with a duration decreasing with price:*

$$\tau(p) = \tau_0 . e^{0.4.(1-\frac{p}{p_0})}$$

where $\tau_0$ is the call duration of a call following a constant distribution, and $p_0$ is the normal price.

## 4.5 Conclusion

Along with a presentation of different GPRS traffic representations, this chapter has given the different settings which will be used for the experiments carried out in this work. The choices were made using the most relevant and appropriate results obtained by different studies. It should be noted that in some cases the differences between similar studies were significant and, where necessary, the average results have been used.

## Chapter 5

# Simulator

Given the complexity of the different pricing algorithms presented in chapter 2 , and the wide variety of available call admission control schemes, the use of a simulator was considered a necessity in order to achieve the goals of this project. Therefore, the simulator built for the work presented in [50] has been used, improved and extended. The same developing tool (IntelliJ IDEA 3.0.1) has been kept, so has the java programming language.

In this chapter, a description of the main characteristics of the simulator will be given along with the improvements made and the new features added to it.

## 5.1 Design of the Simulator

### 5.1.1 Type of Simulator

The simulator is a discrete event, event-driven simulator. Discrete event means that the effects of every particular event are taken into consideration, which is not the case in simulators where the average effect of several combined events is used instead. Event-driven means that the simulator clock advances from one event time to the next event time, and that there is no fixed time increment.

This choice of simulator has repercussions on its performance, and also gives rise to inherent limitations. Indeed, because it is a necessity to model every event, it is not possible to create an unlimited number of them. For example, it is not realistically feasible to put an event in a queue and to make it wait until another condition is fulfilled, with an expectation that it will stop waiting as soon as the condition is fulfilled. That would require a huge number of similar events with very close execution times in order to maintain the illusion of continuous time. As memory is limited, this solution is to be avoided, and the simulation time has to be split into larger slots.

### 5.1.2 Level of Abstraction

The main goal of the simulator is to provide a computational aid for studying the influence of call admission control and dynamic pricing in a GSM/GPRS network. The performance of GPRS traffic is not a centre of interest here, so it is not necessary to track the behaviour of every packet. It is sufficient to know how the system will behave at the call level, so this is the level of abstraction which has been used.

### 5.1.3 Functioning of the Simulator

A simplified class diagram of the structure of the simulator is given in figure 18 below.

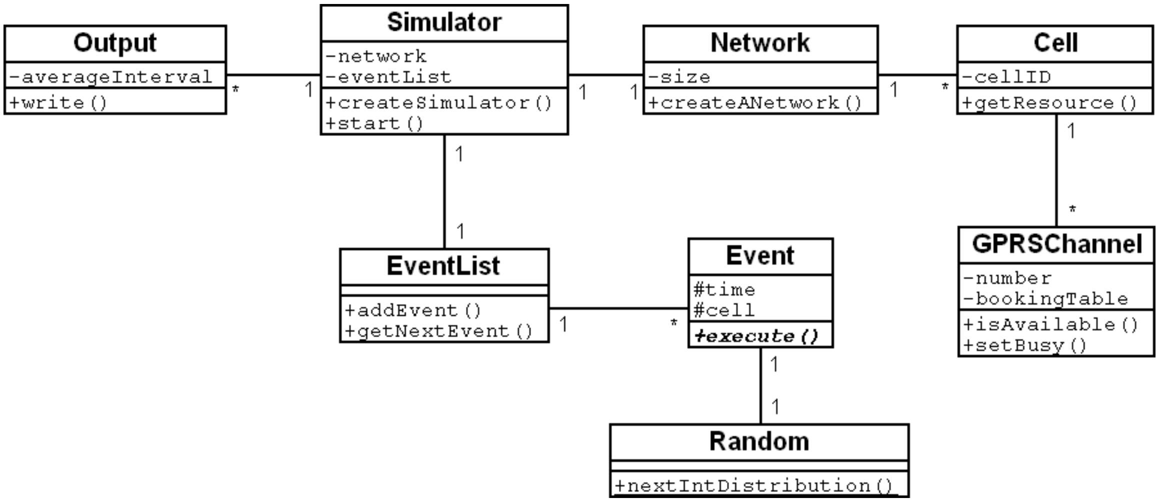


**Figure 18 : Simplified class diagram**

The main class is the class *Simulator*. An instance of *Simulator* is associated with an instance of the *Network* class, which represents the set of cells used for the simulation. The number of *Cells* to be generated in the network is given by the network *size* attribute, which is a simulation parameter specified by the user.

One of the most important classes is the class *Cell*, representing one cell of the network. Each cell manages its own set of channels (it integrates the call admission control block), calculates its own revenue and utility, and updates its own dynamic pricing. When GPRS traffic is used, a number of *GPRSChannel* instances are created for every cell and bound to them. The role and behaviour of the *GPRSChannel* class will be explained later.

When the simulator is initialized, an *EventList* is created to manage the different events. The events are stored and sorted by increasing execution times. When the simulation starts, the first event is executed (by calling its *execute* () method) and removed from the list, and then the second is handled, etc. The same process is repeated until the event list is empty or the next event time is greater than the total simulation time. When the simulation is finished, the *Output* class is used to average the results and to write them into text files, for later analysis.

The *Random* class is used to generate the event execution times, as well as the GPRS call characteristics such as the number of sessions or the different reading times. Number-generation functions following the different required distributions are available. The new distributions added for this particular project use the same package as the previous ones (package *cern.jet.random*), in order to maintain stability and to reduce the risks of small incompatibilities.

Another class of major importance is the *Event* class, since events are the basis of all event-driven simulators. An event is bound to the cell where it has to execute. The *Event* class is an abstract superclass. The event hierarchy is presented in figure 19 below.

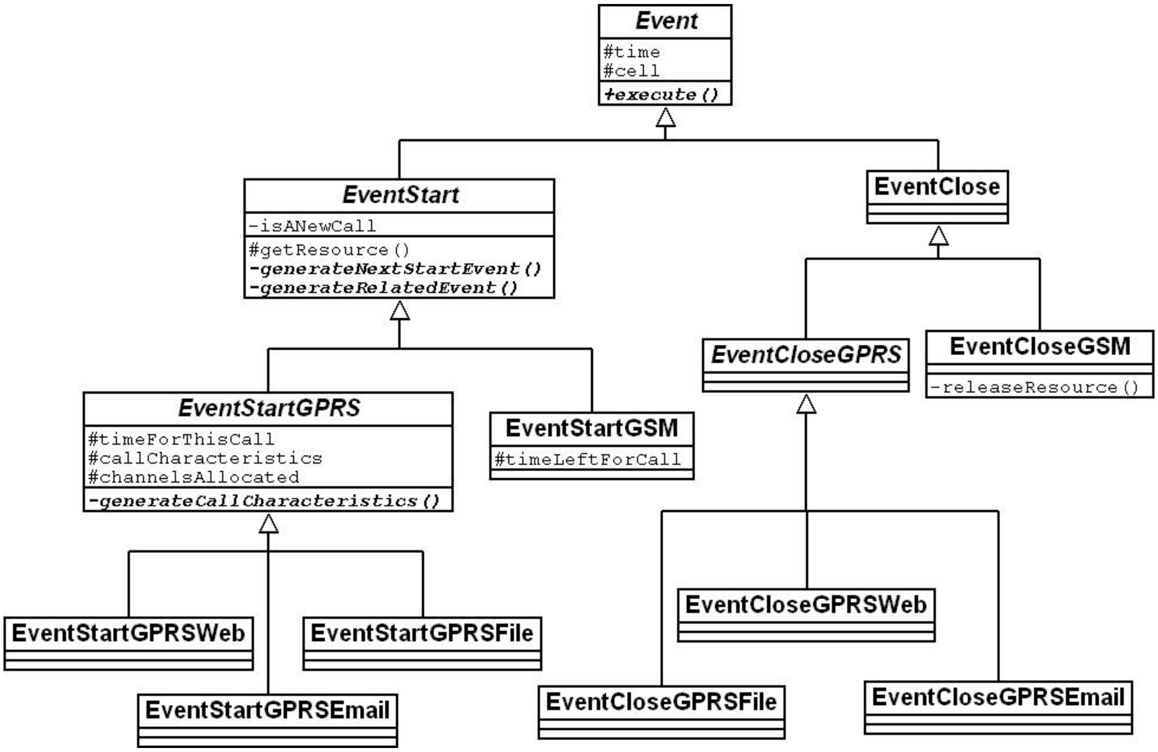


**Figure 19 : Event hierarchy**

The two different types of events are *EventStart* and *EventClose*, which correspond to the start and to the end of a GSM call or of a GPRS session. Because GSM calls and GPRS sessions do not behave the same, it has been necessary to create different subclasses, resulting in the classes

*EventStartGPRS, EventStartGSM, EventCloseGPRS and EventCloseGSM*. In addition, in the case of GPRS, the three considered types of sessions (Web session, File and Email) have their own subclasses, as can be seen in the figure.

The initial *EventStarts* are created at the very beginning of the simulation. If GSM traffic is used, one *EventStartGSM* is created for each cell. If GPRS traffic is used, a function from the Random class is used to determine the type of the GPRS session, prior to the creation of the corresponding *EventStart*. They are then put in queue in the *EventList*. When they are to be executed, their *getResource( )* method is called. This method will behave differently depending on whether the event is a GSM call or a GPRS session. In the case of a GSM call, it will look at the number of available channels (including the possible borrowing of a channel from another cell if this call admission control scheme has been selected), and then decide to accept or to block the call accordingly. In the case of a GPRS session, it will first make an attempt to get a number of available channels (updating the *channelsAllocated* attribute of *EventStartGPRS*), which will be between zero and four, zero corresponding to a blocked call. Then, the call characteristics will be used in order to handle the call successfully, using the different channels got in the previous step. This will be described briefly in the next section, when the GPRS traffic is considered.

When deciding whether a call is to be accepted or blocked, the cell also updates its own characteristics, such as the number of accepted calls, the number of blocked calls for handoff and new calls, and the total utility generated by the cell. Then, every five minutes, it uses those values to update the price which will be used when the dynamic pricing function is activated.

## 5.2 GPRS Traffic

### 5.2.1 Introduction

As mentioned in chapter 4, GSM and GPRS traffic are fundamentally different. The simple simulator model used for the GSM calls, where an available channel will remain available for the whole call duration, can not be applied to GPRS sessions.

Another point of interest is the duration of a particular call, which is needed when the price is based on the call duration. This is straightforward for GSM calls: the call duration is calculated during the creation of the corresponding *EventStartGSM* event, and the price is computed when the related *EventCloseGSM* event is executed. When GPRS sessions are considered, this is not possible. Indeed, the call duration can not be known directly at the initialization of the call, because it depends on the state of the GPRS channels. For example, the more congested a channel is, the longer it will take to transmit a file.

The GPRS traffic model used in the simulator has been completely rewritten for this project, mainly to facilitate multiplexing. In the new simulator, a call will release the channels it has during the viewing times of a web session. During those times, the channels will be available for use by other calls. This is not quite the real GPRS model, where the bookings of the channels are managed in real time considering the different sessions happening at the same time, but it is closer to reality than the model formerly used. It was not possible, given the limitations of the chosen type of simulator, to implement the real model. This would have required calls to wait until another call has finished transmitting, which, as mentioned previously, is not possible. Instead, a simplified model has been used, which is presented below.

### 5.2.2 Representation of a GPRS Call

Three types of GPRS sessions have been considered for this project. However, it is possible to use only one global representation. The *callCharacteristics* attribute of every *EventStartGPRS* instance contains all the information about the call. Its representation inside the simulator is given in figure 20 below.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Call Type | Type of first session | Number of pages | Size of first page | Duration of first viewing-time | Size of second page | Duration of second viewing Time | Size of third page |

**Figure 20 : Representation of a GPRS call**

The call type refers to “WEB”, “FILE” or “EMAIL”, whereas the type of first session is either “SESSION”, or “VIEWING-TIME”. The number of pages is the number of web pages that the web session will download when the call is a web session. This is set to one for emails and file transfers. Finally, the sequence of sizes and viewing times depend on this number, but will always finish by a size, since once the last page is downloaded, it is read after disconnecting from the network.

During the execution of the *getResource()* method for a GPRS call, a number of channels is allocated to the call, then the *callCharacteristics* attribute is used in order to book the different *GPRSChannels*. For this purpose, each GPRS channel owns a *bookingTable* attribute, which represents a succession of one second time slots for the experiment duration. This means that the duration of the call is second based. Even if a call would only require 0.2 seconds, the full second will be booked, and thus paid for. When a GPRS call wants to book a channel, it has to deal with different parameters. The first is that it may encounter partially booked channels where the different channels may have been booked by other calls. The second is that it has to book the different channels in parallel, since it would not be right to book one channel for nine seconds and another for only two seconds. Finally, it has to respect the cell dwell time, which is the maximum amount of time that the call can spend in the cell. In order to do that, it has to maintain the *callCharacteristics* attribute so that it may be transmitted when the corresponding handoff call is generated.

In this model, the priority is thus given to the first arriving call, since the next call will have to cope with an already partially booked channel.

A simple example of the handling of a GPRS call is presented in figure 21 below. The call has been given three different channels (represented by a row of the table) and is supposed to be a web session with only two pages to download. The size of the first session is of nine time slots duration followed by a viewing time of six seconds. The last session represents a transmission time of six time slots. The upper part of the figure represents the states of the channels before the handling of the call, and the lower part their states after.

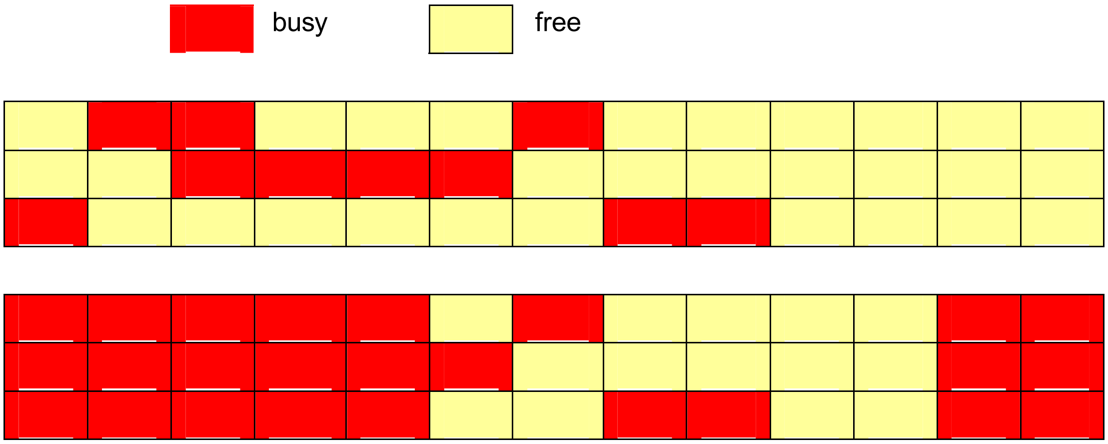


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**Figure 21 : State of channels before and after GPRS call**

We see that no changes are made during the six seconds of viewing time, and that the correct number of time slots is reserved elsewhere.

## 5.3 Features of the Simulator

The proposed simulator includes a number of different features, which makes it possible to carry out a large range of experiments. First, the experiments can be realized in steady state or in real traffic conditions. Then, different call admission control schemes can be selected (queuing of new calls, queuing of handoff calls, guard channels schemes, channel borrowing with and without locking, dynamic and hybrid channel allocation), individually or in combination. Finally, different traffic parameters such as the GSM traffic-rate for the overall traffic, the proportion of the different types of GPRS sessions, as well as the users' behaviour can be defined.

The simulator can be used in two different modes, unicellular and multi-cellular. In the case of the multi-cellular model, the size of the network can be specified. Although those two different models require a completely different way of functioning, this is completely transparent to the user.

All the different properties are regrouped in a java property file. During the execution, the different properties are then loaded from this file and are provided to the classes as needed.

## 5.4 Simulator Validation

The parts of the simulator built last year had been extensively tested to ensure their good functioning. The same approach has been used for the new features. The validity of the different statistical distribution has been verified before use. The GPRS traffic model has been tested on simple test cases to ensure that it behaves as expected even for complicated situations. Before launching the real experiments, simple ones have been carried out to ensure the coherence of the results with what was expected. The unicellular model will not be used for this project, nevertheless the concordance of its results with the other model has been checked.

## 5.5 Conclusion

In this chapter, the main characteristics of the simulation tool used for this project have been outlined. A brief description of how it behaves has been given, along with a presentation of its features and its limitations. The model used for GPRS traffic has also been presented and illustrated by a simple example. In the following chapter, different experiments about call admission control and dynamic pricing are carried out using the simulator, and the statistics generated are then analyzed and the results presented.

## Chapter 6

# Experiments and Results

This study has three objectives: to compare different simple call admission control schemes (presented in chapter 3), to look at the impact of different factors which may influence the results when GPRS traffic is included, and to look at the influence of dynamic pricing. In this section, the simulator described in the previous chapter is used to carry out experiments. The results are then presented and analyzed.

The experiments conducted fall into two distinct groups: one where dynamic pricing is not used and the other where it is. The first represents the simple case, where nothing is done to regulate the traffic. The second permits the exploration of the influence of dynamic pricing.

It has been decided to obtain two different types of results for each experiment pertaining to the CAC schemes. First, the total revenue and utility generated during a day are needed for a direct comparison of the schemes. But, since it would have been very restrictive to only use the simulator for those two values, one or more additional metrics will be gathered for every case. These will be explained individually in the following sections.

Every result presented is an average of at least fifty full-length simulation runs and of three hundred simulation runs in most cases.

The utility and pricing functions used in the simulator are the ones mentioned earlier in this dissertation, and the user behaviour has been set to the most elaborate case presented in [8], that is to say the case where one third of the blocked users retry after twenty minutes and one third of the users who find the proposed price too high retry after the same amount of time.

It should be noted that the unit used for the revenue is as follows: 100 corresponds to the price to make a GSM call of duration one second.

## 6.1 Steady State

### 6.1.1 Experiment

To study the behaviour of the simulator in steady state is not exactly part of this project, but it is very useful to get a better understanding of how it really works. Moreover, this experiment is a prerequisite to all following experiments, since, as mentioned in chapter 2, the optimal arrival rate is the crucial factor in the whole dynamic pricing strategy.

Thus, for every particular experiment, it is necessary to determine beforehand the corresponding $\lambda^*$ by performing one experiment in the steady state.

### 6.1.2 Results

The results obtained where there is no guard channel are given in the figure 22 below. The shape of the graph is characteristic of this particular type of experiment. We see that in this case $\lambda^*$ is found to be 0.13. For values of lambda smaller than 0.13, the increase of the utility is almost linear, whereas this is no longer the case when lambda exceeds 0.13. This is understandable: for $\lambda < \lambda^*$, the network is under-utilized, so the rate of blocked calls remains quite small. Therefore, if $\lambda$ doubles, the number of accepted calls will almost double as well, and this will result in a double of the total utility.

In contrast, as soon as $\lambda$ starts to exceed $\lambda^*$, there is congestion, the network can no longer cope with the number of incoming calls. The level of congestion increases faster than $\lambda$, and the graph is no longer linear.

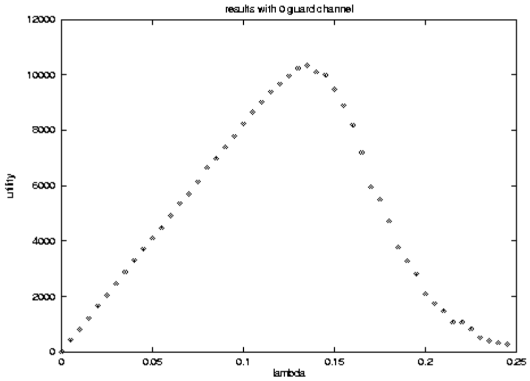

**Figure 22 : Utility as a function of time in the Steady State**

## 6.2 Guard Channels

### 6.2.1 Experiment

As mentioned in the chapter 2, the guard channel scheme is the nearest call admission control scheme to a standard. Its principle is simple: handoff calls have access to more channels than new calls. It has also been mentioned above that one of the challenges is to establish the optimal number of guard channels for the network. For this reason, this experiment aims to look at the influence of N (the number of guard channels) on the total revenue and utility generated over a day under the given experimental conditions.

### 6.2.2 Results

The variation of total utility and total revenue with N are presented in the two figures below (figure 23 and 24). In each figure, both cases, with and without pricing are displayed simultaneously.

What can be seen first is that both figures have similarities. Indeed, for both revenue and utility, the two graphs decrease with N. It means that the loss of utility and revenue triggered by an increase of N, when fewer new calls can be admitted, is higher than the corresponding gain due to a lower loss rate of handoff calls. This first result may seem a little unexpected, since it suggests that the presence of guard channels is not a good thing for the global results. However, one must bear in mind that the guard channels scheme, as other call admission control schemes, has been designed to cope with congestion. Even if it achieves its aims during periods of high congestion, it is likely that its influence on a full day of traffic, with large amounts of time when the network is not congested, can hardly be seen.

To validate this, another experiment has been carried out in steady state, with a constant value of $\lambda$ equal to 0.3, which corresponds to a moderate level of congestion. The results show that for this value, the optimal value for N is 1 (N set to 2 also gives better results than when it is set to 0). It is also very likely than it would have been higher for a greater value of $\lambda$. This is a good proof that a network with guard channels performs well when there is congestion.

The second point of interest is the influence of pricing. As can be seen, it is different for revenue then for utility. For utility, the growth is spectacular: the maximum grows from 1600 to 10500. This means that dynamic pricing is very efficient in fulfilling its function as a regulator of incoming traffic, resulting in really low rate of blocked calls, and thus a very high utility. On the contrary, the revenue generated using dynamic pricing is lower than the one generated without it, although both maxima are almost the same. This is not due to dynamic pricing itself, but it is due to one experimental assumption: the call duration is said to be dependant upon the price, and it decreases faster than the price increases.

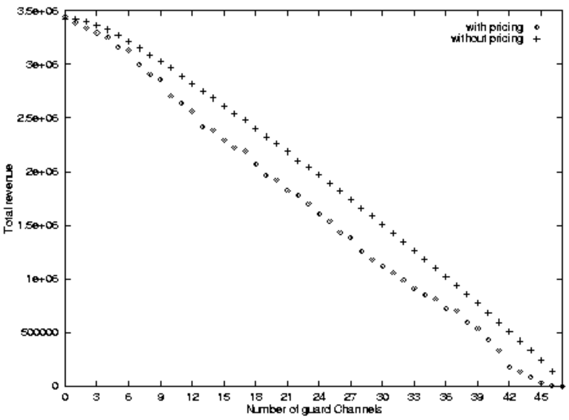

**Figure 23 : Revenue as a function of N**

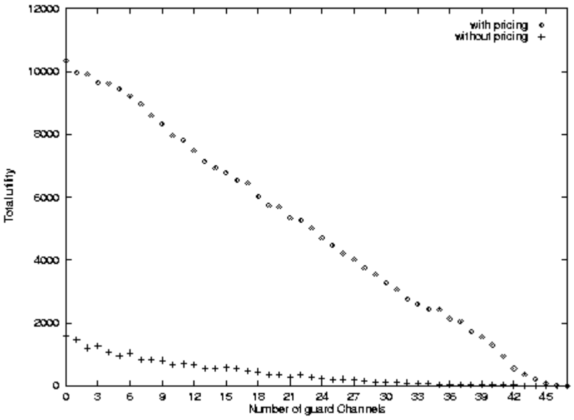

**Figure 24 : Utility as a function of N**

An additional experiment has been carried out. Instead of deciding on a fixed number of guard channels at the beginning of the simulation, the simulator had to adapt this number to the traffic conditions, in order to maintain a handoff call blocking probability below 0.005. With pricing, N constantly remained equal to 0, which means than the limit value was never reached. It once again shows the power of pricing as a traffic regulator. Without pricing, this is not the case and the results are presented in figure 25 below. We see than the shape of the graph is very close to the shape of the incoming traffic rate, with a maximum of 6.2 guard channels in average. At the beginning and at the end of the day, N remains equal to 0 for a small period of time, because there are so few incoming calls that there is no congestion at all.

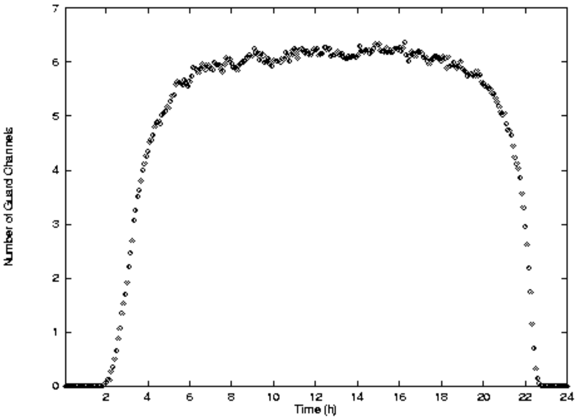

**Figure 25 : N as a function of time**

### 6.2.3 Conclusion

This first set of experiments has shown two important results. The first is that the introduction of pricing has very significant effects on the total utility, which is not a surprise when we recall that the whole pricing strategy is intended to optimize it. The second important result is that under the chosen experimental settings, it is preferable not to use any guard channels, since this triggers a loss of revenue and of utility. Therefore, for the rest of the experiments, no guard channels will be used.

## 6.3 Queuing Schemes

### 6.3.1 Experiment

In the previous section, the calls had only one opportunity to enter the system. If no resources were available, they were immediately blocked. On the contrary, in this section, queues are introduced. Three schemes are studied. In the first, new calls are queued: they are allowed to wait in a buffer for twenty seconds and to make an attempt to enter every second. The second is the equivalent for handoff calls, but they can only wait for ten seconds for a maximum of ten connection attempts, since they are more sensitive to delay. The last one is the combination of the queuing of both new calls and handoff calls.

In addition to total revenue and utility generated, the variation of the percentages of calls which need to be queued with the time of day, and the average number of attempts required before acceptance are also studied.

### 6.3.2 Results

Without pricing, the queuing of both gives a total utility of 4,733 and a total value of 3,429,149 for the revenue. The queuing of new calls gives a total utility of 14,766 and a value of 3,428,062 for the revenue. Finally, the queuing of handoff calls gives a total utility of 15748 for 3,421,141 of revenue.

With pricing, the values become, for utility and revenue respectively: 14,409 and 4,697,746 for the queuing of both, 19,018 and 4,987,706 for the queuing of new calls and finally 18,021 and 4,955,562 for the queuing of handoff calls.

The first thing to notice is that the results obtained for the total utility are significantly higher than the ones obtained without queuing. It would, of course, not be realistic to say that the queuing schemes are much better than the guard channel ones. Indeed, the different figures are not directly comparable, since it was obvious that with up to twenty tries for new calls for example, their chance of being accepted was much higher than with only one attempt. In addition, this scheme requires a more complex infrastructure, with the introduction of sufficiently large buffers and with the management of the time spent queuing by the different calls.

The second is that it seems more efficient to queue only one type of calls than both of them. It is not really difficult to understand why. When both types are queued, this results in a large queue, with many new calls and handoff calls. Finally, the maximum time spent queuing excepted, it is similar to the case of a system without a queuing scheme, but with a different incoming call rate (which is higher but which has also not exactly the same shape with the time of the day). It also seems preferable to queue handoff calls rather than new calls. This is due to the utility function, where the loss of one handoff call is twice as important as the loss of a new call.

Concerning the revenue, the values are very similar to the ones obtained in the previous case, which confirms the first idea that this is almost the maximum value without pricing, (around 3,500,000).

The introduction of pricing has again had a very positive effect. The utility increases significantly, even if the growth is smaller than for the simple guard channels scheme, and is not that far from the theoretical maximum (found to be 23,000 under these experimental settings). The maximum is now obtained for the queuing of new calls, but the difference between this and the value for the queuing of handoff is still small. The queuing of both call types gives much better results with the introduction of pricing, even if it is still not as good as the others. The revenue also increases significantly, to almost reach 5,000,000 (again not far from the maximum of 5,200,000). This shows that the combination of a less restrictive admission scheme and traffic regulation by dynamic pricing really is very effective.

The variation in the percentages of new and handoff calls which need to be queued (that is to say which are not admitted at their first attempt) for the first two cases are presented in figure 26 below. The figure 27 represents the same characteristics for the queuing of both call types. Figures 28 and 29 represent the average number of attempts before acceptance for the different types of calls.

In figure 26, we can see that on average new calls are queued more often than handoff calls, which can be explained easily because there are more new calls than handoff calls in the system. What we see as well is that without pricing, the two graphs have a regular shape (with a maximum of 65% for new calls and 32 % for handoff calls), which is not the case with pricing. Indeed, in the latter case, the two graphs have two separate parts. In the first part, corresponding to the beginning and to the end of the day, the results are almost the same as the ones without pricing (because the pricing function is not activated yet). However, this is not true for the second part, which corresponds to the middle of the day, where the pricing scheme has come into effect. The graph stops increasing, to remain at a quite low level (around 10 to 20 %). We can also notice than the differences between handoff and new calls have almost disappeared. The small dissymmetry between the two spikes on the left and on the right is due to the difference in the call duration. Before the first spike, there is no pricing, so the calls last in average longer than the ones before the second spike, where the pricing scheme is active.

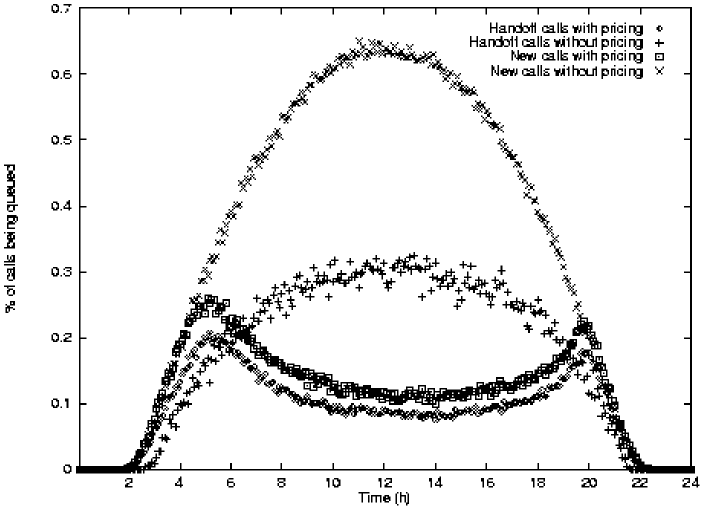

**Figure 26 : Percentages of calls queued as a function of time**

In figure 27, we can see that the four graphs can almost exactly be represented by two graphs only. Indeed, because there is no difference between new and handoff calls with regard to the way they are put into the queue, their relative graphs are extremely close. On the graph corresponding to the case without pricing, we see that it has a regular shape, with a maximum of 65%. With pricing, the values become almost equal to 0, while again two small spikes occur at the beginning and at the end of the day.

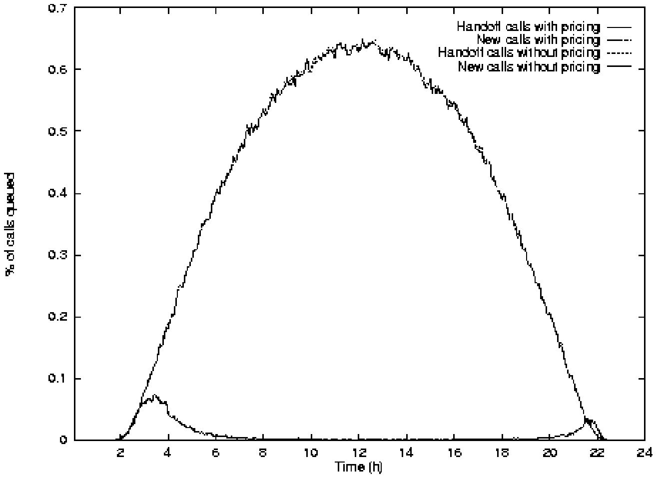

**Figure 27 : Percentages of calls being queued as a function of time 2**

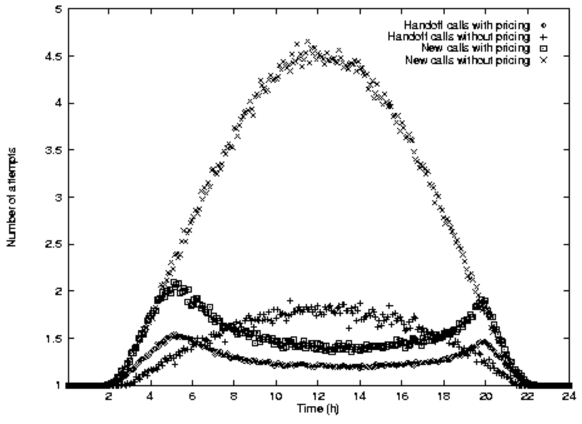

**Figure 28 : Number of attempts before treatment as a function of time**

In figure 28 above, representing the average number of attempts before connection in the cases of the queuing of new calls and of handoff calls, we can see that the graphs almost look the same as the ones representing the percentage of calls being queued. The comments made previously are consequently, still appropriate. Nevertheless, there is one difference in the case without pricing, where we see that the differences between new and handoff calls is much more significant in this case.

In figure 29 below, we see that even if the curves corresponding to new calls and handoff calls are similar, new calls make on average 2.5 attempts more than handoff. This is a consequence of the difference in the maximum time spent in the queue by the two types of calls. However, as soon as pricing is introduced, there is no more difference, and we see that almost all calls are connected at the first attempt.

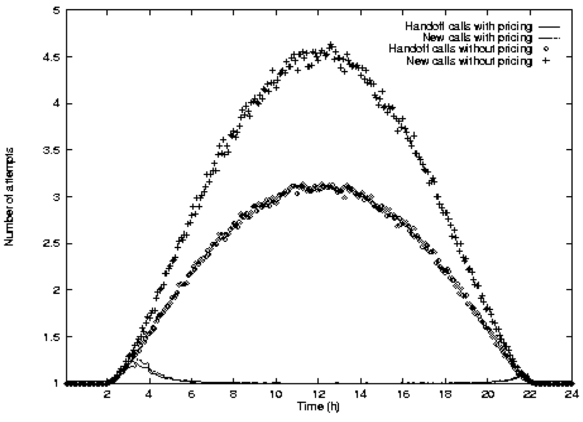

**Figure 29 : Number of attempts before treatment as a function of time 2**

### 6.3.3 Conclusion

The analysis of the different graphs presented above has shown that the introduction of a queuing scheme can improve the performance of the system, at the expense of a more complex infrastructure. The average number of attempts for the different schemes suggests that the limit of twenty seconds in the queue for new calls is too high, and that ten seconds may have been sufficient. The dynamic pricing also permits an increase in the revenue and the utility, but makes the queues almost redundant. Moreover, the results are better when dynamic pricing is used in addition to queuing rather than when it is used in isolation.

## 6.4 Channel Borrowing

### 6.4.1 Experiment

In the last section, we saw that the introduction of queuing has a positive effect on the total utility and revenue generated. However, it is not possible to make a direct comparison with the simple case where every call has only one chance to be accepted. In this section, this one-chance-only property is reintroduced. The difference here is that when a cell has no channel left, it can try to borrow one from one of its neighbouring cells.

In addition to utility and revenue, the number of channels borrowed and lent at different times of the day is studied. Two different experiments have been carried out here. The first involves simple channel borrowing without locking. The second introduces locking, which is necessary in real systems to take the interferences generated by the calls into consideration.

### 6.4.2 Results

For utility and revenue, the results are as follows: without pricing, the experiment without locking gives a utility of 2,118 and 3,981,648 for revenue. With pricing, those values become 13,144 and 4,338,099. When locking is considered, the experiment without pricing gives a utility of 1,332 for 2,862,247 of revenue. Those figures become 10,698 and 3,577,583 with pricing.

The introduction of channel borrowing permits a better utilization of the global resources of the system, and it can be seen in the utility, which is better than in the simple case. The same is true for the revenue, however it remains lower than in the queuing schemes case. The introduction of locking has, as expected, had a very negative effect. As mentioned previously, the borrowing of one channel leads to the loss of more than one channel due to interference. The results seem coherent with this fact.

The number of channels borrowed and lent in the case of borrowing without locking is now studied using figure 30 below.

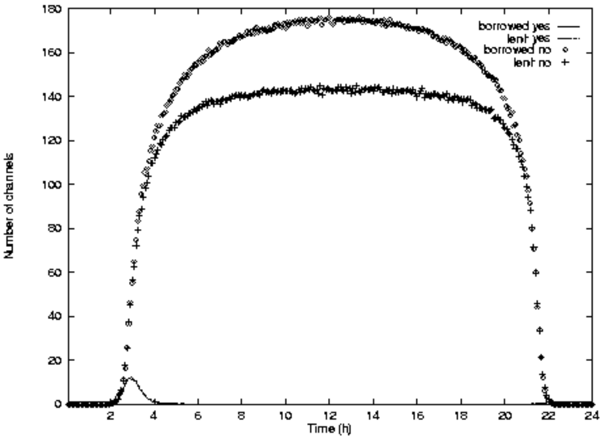

**Figure 30 : Number of channels borrowed and lent as a function of time**

Without pricing, the two graphs have almost the same shape as the incoming call traffic. The number of borrowed channels reaches a maximum of 175, whereas the number of lent channels is never greater than 140. This result is surprising, because it would have been expected to see both of those figures being equal. This is due to the overlapping model used for this experiment (only seven cells are considered). Indeed, even if the central cell really has six different neighbours, this is not the case for the other cells which only have four different ones.

As soon as pricing is introduced, it is no longer necessary to borrow channels from the other cells; the cells' own channels are sufficient to cope with the incoming traffic. The same spikes at the beginning and at the end of the day can be observed, for the same reasons as before.

The case with locking is now presented in figure 31 below. The focus of interest here is the differences between the number of locked and borrowed channels. Since the number of lent channels is very close to the number of borrowed channels, it has not been shown. As expected, the number of locked channels is always higher than the number of borrowed ones, which explains the loss of utility and revenue. In a network without model restrictions, one graph would have almost exactly been the double of the other. Another point of interest is to note that the two graphs reach a plateau quite quickly and stay there for a long time.

With pricing, since it is not useful to borrow channels, it is thus not useful to lock ones, which explains why both graphs always stay close to zero.

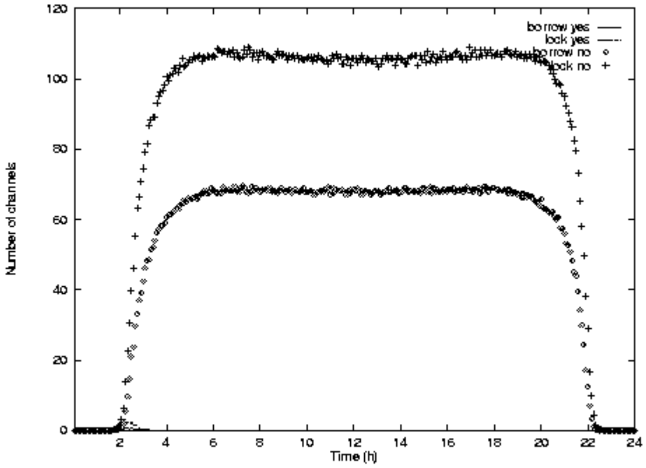

**Figure 31 : Number of channels borrowed and locked as a function of time**

### 6.4.3 Conclusion

Channel borrowing allows a cell to increase its number of channels when it really needs to, and to lend one of its unused channels to other cells. As a consequence, more calls can be treated, and the utility is higher. A really good study would have required a more accurate network model than the simple overlapping model used here, but due to time restrictions it was not possible to implement this. The introduction of locking has negative effects, but it is a necessary restriction in real systems. The final thing to bear in mind is that with the model considered here, where the traffic is homogenous among the different cells, channel borrowing is not as powerful as it is in systems where some channels are much more loaded than others.

## 6.5 Dynamic and Hybrid Channel Assignment (DCA & HCA)

### 6.5.1 Experiment

The experiment presented in the section above used channel borrowing as a means to improve utilization of the global resources of the network. In this section, we take another step in this direction by incorporating dynamic and hybrid channel allocation, as introduced in chapter 3. With dynamic channel allocation, there is no channel assigned specifically to one call, but rather a pool of channels available for sharing among the different cells. When one cell needs to use a channel, it just takes one from the pool if it is available and then gives it back when the call is finished. Hybrid channel allocation is a combination of fixed and dynamic channel allocation. For the DCA experiment, a pool of 329 channels has been used (corresponding to 47 * 7), whereas for the HCA, the pool had a size of 161 channels for 24 channels left in each cell (this corresponds to 50 % of the total number of channels of the system available in the pool).

### 6.5.2 Results

The dynamic channel assignment scheme used without pricing gives a total utility of 1,762 for 3,600,402 of revenue; the figures become 12,655 and 4,192,565 with pricing. The hybrid channel assignment gives 1,816 and 3,490,733 without pricing and 12,696 and 4,196,586 with.

The general result observed for pricing is verified once again: it increases both utility and revenue, and it makes the different call admission control schemes (here DCA and FCA) almost identical. Without pricing, we see that hybrid channel assignment gives a better utility but creates a little less revenue than dynamic channel assignment. Finally, even the HCA scheme does not give as good results as the channel borrowing scheme. This can be understood quite easily: in the case of channel borrowing, the results presented earlier showed that the average number of borrowed channels was higher than the average number of lent ones, which results in an overall increase of the total number of channels, becoming on average higher than 47. As a consequence, more calls could be handled. With DCA and HCA, the division is made equally, resulting in an average number of exactly 47 channels. Moreover, in the case of HCA, a cell can not have less than 24 channels, which is not the case for the DCA.

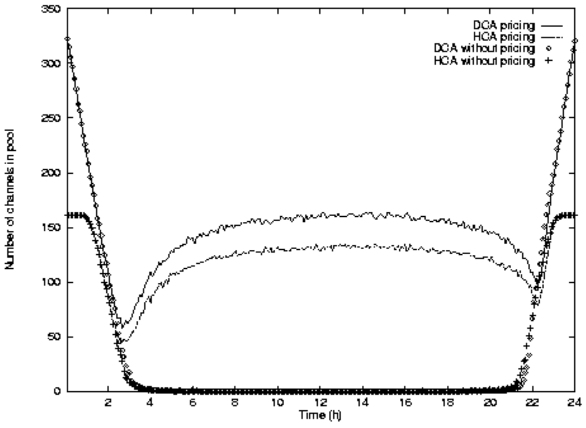

**Figure 32 : Number of channels in pool as a function of time**

The variation of the number of available channels in the pool for HCA and DCA, with and without pricing, is presented in figure 32 above. The results are similar for the two schemes. Without pricing, the number of available channels decreases regularly from the origin to zero, where it stays for most of the day, which means that there is congestion and that all channels are needed. We can see however, that for HCA, this number remains constant and equal to 161 for a short period of time at the beginning and at the end of the day. This corresponds to periods with very low incoming traffic, where the 23 channels assigned to each cell are enough to cope with all incoming calls, without having to request a channel from the dynamic pool.

With pricing, the behaviour of the system is comparable to that which we saw for the previous experiments. During the periods where there is no congestion, when the pricing has not come into effect, it behaves exactly as in the experiment without pricing, but it never reaches zero. Indeed, when congestion occurs, the price starts to regulate the traffic, resulting in less new incoming calls. All channels don’t need to be used at the same time anymore, and so the number of available channels starts to increase. The number of available channels is at its maximum at the middle of the day, where the price is at its highest, which is what was expected. At the end of the day, there is no more congestion, the pricing stops, and the graph starts to follow the one of the case without pricing again.

A complementary metric has been considered in the case of HCA: the proportion of calls which have been treated using the channels in the dynamic pool (presented in figure 33 below). Without pricing we see that this number, after having stayed for a while at zero when there is no congestion, increases regularly until it reaches the value of 50%. This is logical when we recall that there are 50 % of the channels in the pool. At the end of the day, the behaviour is the opposite; it decreases to zero again, where it stays for almost the same duration.

With pricing, this percentage never reaches 50 %, because as soon as it reaches 45 %, the pricing scheme makes it decrease to a final value of 18%, before it starts to increase again to 35%, until the pricing stops, triggering the channels in the pool to be increasingly less used.

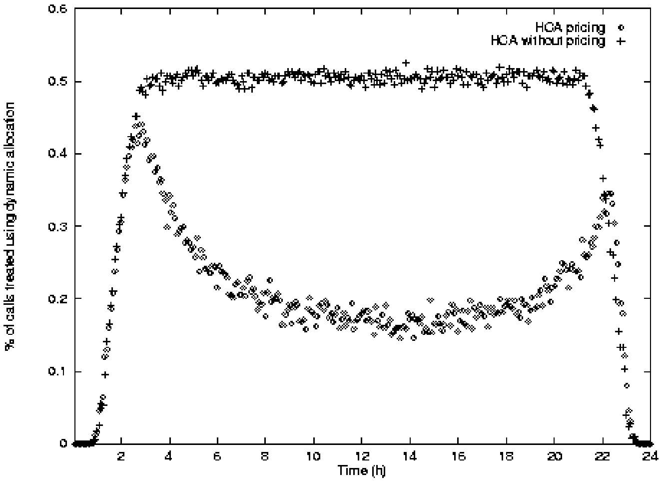

**Figure 33 : % of calls using channels in pool as a function of time**

### 6.5.3 Conclusion

Dynamic channel assignment represents a good improvement on the basic system, but it is not as efficient as channel borrowing. When pricing is introduced, the performances are again significantly increased, and all channels are not used at the same time. This allows the system to ensure that there will always be one channel available for an incoming call, new or handoff, and this leads to the optimization of the utility.

## 6.6 Conclusion About the Experiments Carried Out Considering GSM Only

The table below summarizes the values obtained for the utility and for the revenue for the different experiments presented above.

| Scheme | Utility no | Revenue no | Utility yes | Revenue yes |
|---|---|---|---|---|
| **0 Guard Channel** | 1,600 | 3,450,000 | 10,500 | 3,450,000 |
| **Queuing of New calls** | 14,766 | 3,428,062 | 19,018 | 4,987,706 |
| **Queuing of Handoff calls** | 15,748 | 3,421,141 | 18,021 | 4,955,562 |
| **Queuing of both** | 4,733 | 3,429,149 | 14,409 | 4,697,746 |
| **Channel Borrowing without locking** | 2,118 | 3,981,648 | 13,144 | 4,338,099 |
| **Channel Borrowing with locking** | 1,332 | 2,862,247 | 10,698 | 3,577,583 |
| **DCA** | 1,762 | 3,600,402 | 12,655 | 4,192,565 |
| **HCA** | 1,816 | 3,490,733 | 12,696 | 4,196,586 |

**Table 2 : Results for the experiments carried out with GSM only**

In this table, what is remarkable is that the introduction of pricing always has a positive effect on the total utility, and almost always on the total revenue. However, it is always the total utility that is considerably increased. The best results with and without pricing are always obtained by the queuing schemes, which is not surprising as mentioned above. We see that the channel borrowing without locking also gives good results.

Another point of interest is to notice that the different schemes studied are very efficient at improving the utility, in which they are all (channel borrowing with locking excepted), better than the simple case, but they don’t improve the revenue significantly when there is no pricing. This is due to a simple fact: the maximum theoretical revenue is obtained when all the channels are always busy, which requires a good resource management. Since traditional CAC schemes can not cope with congestion efficiently, the resource utilization is not maximized when there is no pricing. However, when the pricing is used to make the traffic smoother, they start to become very efficient and succeed in increasing the total revenue as well.

Two final experiments have been carried out, to see whether or not it is possible to get better results than the ones obtained by the queuing of new calls and handoff calls.

First, the combination of handoff call queuing and channel borrowing gives a utility of 19,819 and 3,976,704 for revenue. In this case, it was not necessary to introduce pricing, since the optimal value found for lambda was higher than the maximal arrival rate of 0.45 calls per second. The utility is the best obtained so far, but this is not the case for the revenue.

Next, the combination of handoff call queuing and HCA has been studied. Without pricing, the results give a utility of 17,615 and revenue 3,485,772; these figures become 19,251 and 4,522,484 with pricing. The results are better than the ones obtained without combination, but not as good as when using the combination of channel borrowing and handoff call queuing.

Finally, it seems possible to improve upon the best utility obtained in the experiments presented above, but only at the cost of introducing a more complex scheme. This is a general observation: in order to get good results, very elaborate schemes have to be applied. Pricing, however, does not really respect this rule: it is very simple, does not require more infrastructure, but gives excellent results. Its effect on incoming traffic makes it possible to cope with every traffic type, even in highly congested periods.

All results obtained for dynamic and hybrid channel assignment, and for channel borrowing, are for the simplified model used for the network by the simulator. Further refinement of this model, which was beyond the scope of this study, may yield yet more accurate results.

## 6.7 Inclusion of GPRS Traffic

In all experiments conducted previously, only GSM traffic was considered. Indeed, most of the schemes were designed for connection-oriented communications, and did not apply directly to GPRS calls. In the following section, we consider a mix of both GSM and GPRS traffic. The experiments conducted will have a different focus to the previous ones, and will not look in detail at the call admission control schemes. Rather they will look at different properties of GPRS traffic to study the impact of new parameters on the global results, such as the pricing scheme used or the division of calls between GSM and GPRS.

It has been decided to use 85 % GSM calls and only 15 % GPRS calls in the basic case, since it seems to be a realistic division of the incoming traffic. A static channel allocation scheme has been used. That is to say, the GPRS calls have their own channels, and so have the GSM calls. No call of one type can use a channel reserved for another type. To respect the division of calls, the total number of channels in each cell (47) has been split accordingly. As a result, there are 40 GSM channels and 7 GPRS channels in each cell.

### 6.7.1 Influence of the Pricing Scheme

#### *6.7.1.1 Experiment*

The major difference between GSM and GPRS traffic is that GPRS is a packet-based technology, which makes it more flexible when congestion occurs. In the improbable case where a user would be the only one to use the network resources, its performance can be very high and a lot of data can be transmitted in a short amount of time (the average number of channels allocated for each call will be high and each channel will be lowly loaded, resulting in almost no delay during the transmission). On the contrary, when the network is overloaded, each packet can have to face high latency, giving poor performance. This packet-based aspect of GPRS traffic also gives the operators different choices for its pricing, where previously they had to price a GSM call based on its duration. Indeed, they can decide to make a user pay based on the transmission time required for the GPRS session, or based on the total data size transmitted.

Duration based pricing can be seen as a kind of dynamic pricing, since the lower the level of congestion is, the cheaper it will be. However, very accurate management of the traffic load would be required to let the user have an idea of the price he will have to pay to transmit his data and let him make his choice. On the contrary, the size based pricing is fairer to the user. He knows the price he will have to pay depends on the total data size he wants to transmit and is not a function of complex traffic parameters. Even when dynamic pricing is introduced, this remains true. The price to transmit a given size will change with the network load, but the final cost of a call will still be computed using the size transmitted.

Using the simulator and the parameters defined previously, the impact of three types of charging on the cumulative revenue generated during the day has been studied. The results are given in the next section. The three types of pricing considered are the following: first, a duration-based pricing, where the user pays for the time he uses the network to transmit. Second, another type of duration-based pricing, where the user pays for all the time he is in the system, including the time when he is reading downloaded documents and is not actually transmitting. Finally, a size based pricing. To make comparison possible among the different schemes, the size and duration based pricing are linked as follows: the size based price for a transmission of N bits is equal to the duration based price that it would have cost to transmit those N bits had the call only been allocated one channel.

### *6.7.1.2 Results*

The result of the experiment when there is no dynamic pricing is given in figure 34, whereas the case with dynamic pricing is presented in figure 35.

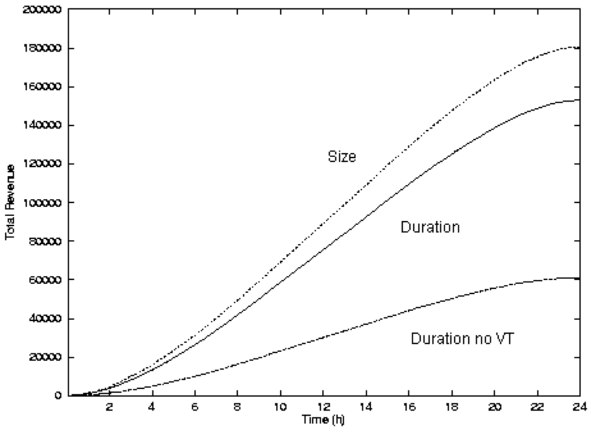

**Figure 34 : Revenue as a function of time without pricing**

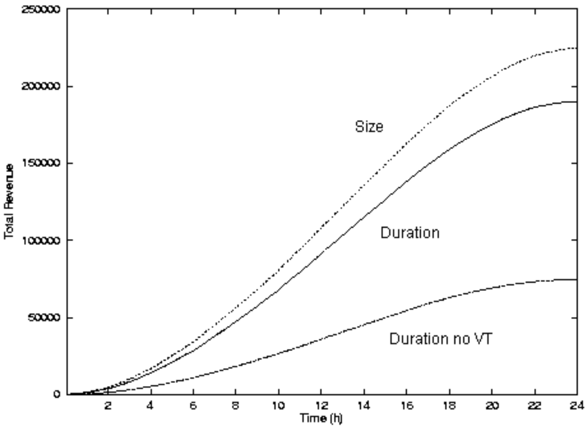

**Figure 35 : Variation of revenue over a day with pricing**

Both graphs have a very similar shape. In each case, we see that the size based pricing generates more revenue than duration based. In addition, it can be noted that once the viewing times are removed, the duration based pricing gives a much lower final result. This is due to the fact that the viewing times are on average longer than the times needed to download the corresponding web pages.

The introduction of dynamic pricing has a positive effect on the revenue, since we see that the maximum grows from 180,000 to 225,000. What was true for GSM is hence still true for GPRS: dynamic pricing makes the incoming traffic smoother and results in a better utilization of the resources.

From the graphs above, we see that the revenue generated using size-based pricing is about three times higher than that generated using duration based pricing when the viewing times are not considered. This seems to indicate that the GPRS channels are not heavily loaded and that the transmissions can consequently be made quickly. To verify this assumption, another experiment has been carried out: figure 36 presents the average number of GPRS channels given to a call as a function of the time of the day.

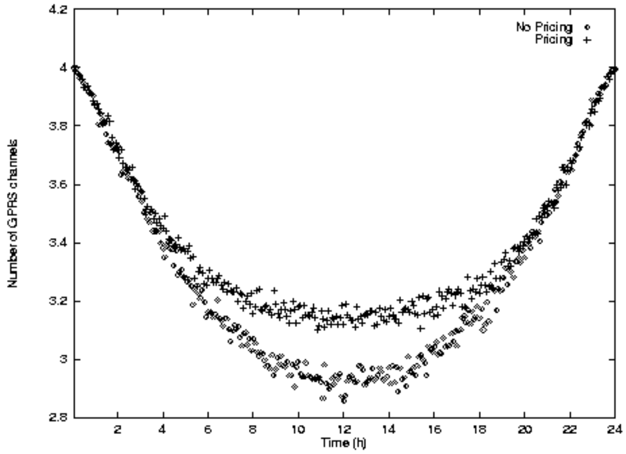

**Figure 36 : Average number of channels allocated as a function of time**

In this figure we see that this number always remains high, between 4 to 2.9 when there is no dynamic pricing, and from 4 to 3.2 when there is. This explains the low revenue generated by the duration based schemes. On first sight, it can seem surprising that the GPRS channels never suffer from congestion, since their number is proportional to the incoming traffic division between GSM and GPRS. However, the main difference is that for the same number of calls, GPRS will result in a lower congestion. Indeed, the duration of a GPRS session is much shorter than that of a GSM call.

### 6.7.2 Influence of Incoming Traffic Division

#### *6.7.2.1 Experiment*

The previous experiment showed that with 85 % GSM calls, the GPRS channels were under utilized, resulting in a loss of revenue. At the same time, other results gathered during the same experiment showed that GSM channels suffered from congestion during the peak times of the day. This means that the call division is not made efficiently. Different strategies can be tried to solve this problem. First, the average size of a GPRS session can be increased, but it is a very complicated process dependent on user behaviour and is not really applicable here. Second, the same division of calls can be used but the number of GPRS channels can be decreased. Finally, the same number of GPRS channels can be kept but the proportion of GPRS calls can be increased. This last strategy will be studied first. In the following, we will consider the influence of the percentage of GPRS calls (varying from 5% to 95%) on the total revenue and utility.

#### *6.7.2.2 Results*

Figure 37 below represents the variation of the total revenue for GSM and GPRS as a function of the percentage of GPRS calls, in the case where no dynamic pricing is used.

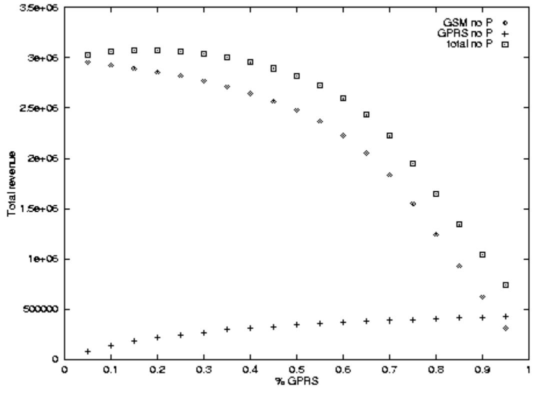

**Figure 37 : Revenue as a function of % GPRS without pricing**

What we see first is that the revenue generated by GPRS calls always increases, while the one generated by GSM calls decreases, which conforms to expectations. However, while GPRS revenue increases regularly, the GSM decrease can be split into two phases. Low values of % GPRS, from 5% to 35%, correspond to a slow decrease, after which the decrease becomes quicker and the graph starts to converge to zero. This dissymmetry between the two graphs means that the total revenue generated, including both GSM and GPRS, has a maximum for a percentage of GPRS calls equal to 17%. This is not far from the value which was chosen as a basis for the experiments.

The results when dynamic pricing is introduced are given in figure 38. In this figure, we note that the graph corresponding to GPRS has almost the same shape as in the previous case, if anything it increases slightly faster to reach a higher final value. On the contrary, the shape for the GSM graph is completely different, since it always decreases quickly and in an almost linear fashion, even if the average value is higher with dynamic pricing. As a result, the total revenue generated continually decreases when the percentage of GPRS calls increases. The reason for this is simple: the dynamic pricing ensures that no more calls than wanted will enter into the system. The capacity of the system is limited, so this number is not infinite. When there is no pricing, as in the previous case, the increase in the number of incoming calls does not increase the revenue significantly, because this capacity is almost attained. On the contrary, with dynamic pricing, even when the network capacity is reached, the revenue continues to increase as a result of the increase in price.

We see that as far as the revenue is concerned, two different approaches have to be considered. Without pricing, it is better to try to maintain the proportion of GPRS call at about 15 or 20%. However, if dynamic pricing is used, better results will be achieved when there are as few GPRS calls as possible.

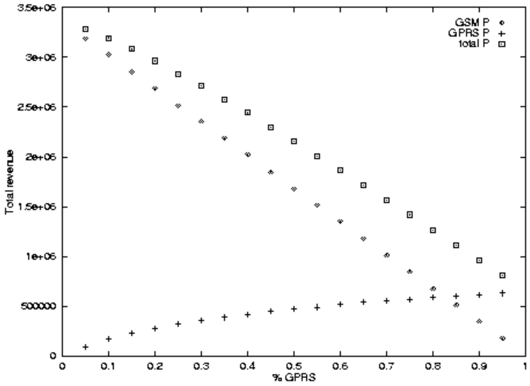

**Figure 38 : Total revenue as a function of % GPRS with pricing**

We will now look at the variations concerning the total utility generated over a day. The results are given in figure 38 above.

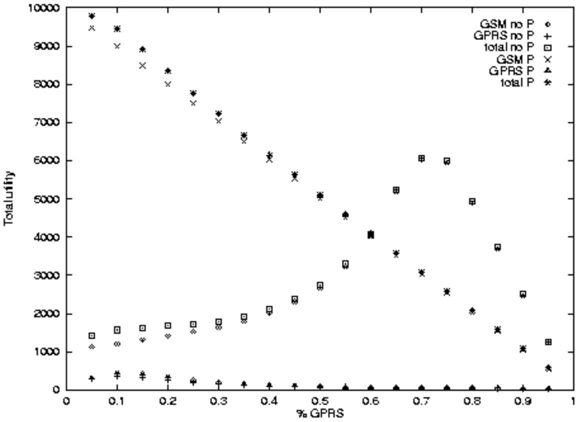

**Figure 39 : Utility as a function of % GPRS calls**

The differences between the cases with and without pricing are, once again, huge. Without pricing, both GSM and GPRS users' utility attain a maximum. For GSM, it is obtained for about 70% of GPRS calls, whereas the maximum for GPRS is obtained for only 10% of GPRS calls. The GSM utility is so much bigger than the GPRS one that the total utility almost exactly follows the GSM graph. It is not surprising that this latter graph has such a maximum. It is the same reason as given for the existence of $\lambda^*$ in steady state. When the proportion of GPRS calls is smaller than 70%, the number of GSM calls is too high for the network to cope with. On the contrary, when this value becomes higher than 70%, the capacity of the network is not completely used. The maximum observed corresponds to the point where this compromise is managed the most efficiently.

When dynamic pricing is introduced, the results are exactly the same for the revenue; that is to say that the values are higher than in the case without pricing, that the GPRS graph is not really affected by the introduction of pricing, whereas the GSM one becomes regularly decreasing, and that the graph concerning the total utility also decreases regularly.

As a result of all those experiments, we can say that the introduction of pricing, in addition to its usual increase of both revenue and utility, also makes their variation with the percentage of GPRS calls similar. Reducing the proportion of GPRS calls will increase both revenue and utility. On the contrary, when there is no dynamic pricing, it is not possible to maximize both parameters at the same time (under the considered experimental conditions), and so a choice has to be made.

As mentioned before, to make the percentage of GPRS calls vary while keeping seven GPRS channels was only one of the two possible ways we consider to make better use of the network resources. The other, which is to keep 85% of GSM traffic and to make the number of GPRS channels change, will be presented in the following section.

### 6.7.3 Influence of the Number of GPRS Channels

#### *6.7.3.1 Experiment*

For this experiment, the number of GPRS channels has been increased from one to seven, whilst maintaining the total number of channels equal to 47.

The last experiment suggested that, on average, the higher the proportion of GPRS calls was, the lower the revenue and utility were. With this experiment, this proportion will remain equal to

85%, but the capacity allocated to either type of call will change, hence increasingly advantaging GSM calls over GPRS ones. We will see whether GSM traffic maintains its position as a better source of revenue and utility than GPRS traffic.

### *6.7.3.2 Results*

The variation of the total revenue in the case where no dynamic pricing is used is presented in figure 40 below.

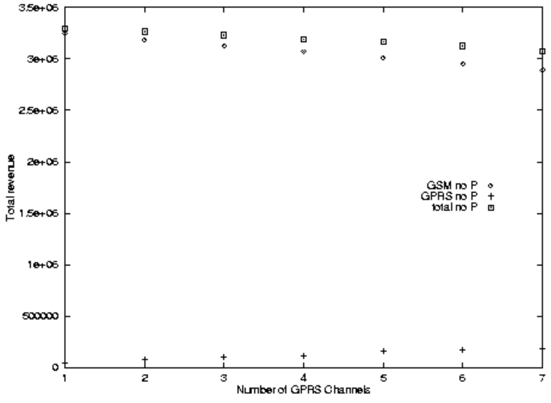

**Figure 40 : Total revenue with number of GPRS channels without pricing**

What can be seen is that when the number of GPRS channels is increased, the revenue generated by GPRS traffic increases and the revenue generated by GSM traffic decreases. The increase in the GPRS revenue being slower than the decrease in the GSM one means that the total revenue decreases slightly. However, the decrease is not as large as it was in the previous experiments.

Another notable fact is that even if the decrease in the GSM revenue is regular, this is not the case for the increase GPRS traffic. Indeed, there is a significant increase between 4 and 5, whereas it is much slower between (1 and 4) and (5 and 7). The same phenomenon can be seen in figure 41 representing the total utility when there is no dynamic pricing, where the variations are more visible due to the smaller scale.

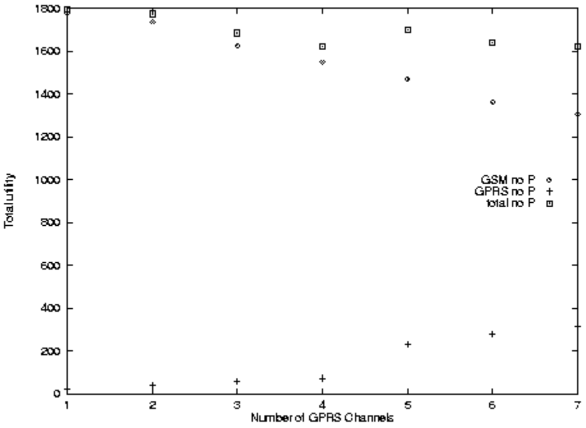

Figure 41 : Total utility with number of GPRS channels without pricing

In this figure, it can be clearly seen that the introduction of a fifth GPRS channel has a huge effect on the total utility generated by GPRS traffic. This increase is even bigger than the loss of GSM utility generated at the same time, so that the total utility is higher for five GPRS channels than for four. The best value remains nevertheless obtained when the number of GPRS channels is as low as possible, that is to say one in this case.

Those results suggest that a similar increase would have appeared for the introduction of the ninth or thirteenth channel. Indeed, it is due to the fact that a GPRS call can be allocated four GPRS channels if they are available. Consequently, where there are only four GPRS channels, an incoming call could be given all the GPRS channels of the cell. Another GPRS call, arriving immediately after this call, would hence be blocked, and would make the utility lower. On the contrary, when there are five GPRS channels, a second call can be accepted even if four channels had been given to a previous call. This is the reason for the abrupt increase in the GPRS total utility graph. With the GPRS traffic considered in this study, it is therefore a good idea to use either one, five or nine GPRS channels. Since only one channel would not be enough to satisfy GPRS users, this solution is to be avoided, even if it means getting less total revenue and utility. To avoid losing too much revenue, the number of five GPRS channels (for 42 GSM ones) seems to be the best solution when there are 85% of GSM calls in the incoming traffic.

The introduction of dynamic pricing has a very similar effect to all previously presented results. The revenue and utility are increased, but the shapes of the graphs remain almost the same for this particular experiment than in the case without dynamic pricing: the total utility and revenue decrease when the number of GPRS channels is increased, except for utility when the fifth channel is introduced. For this reason, the corresponding graphs are not presented here.

The maximum number of channels allocated for one GPRS call (here four), seems to have a big influence on the total utility and revenue. For this reason, it would be very interesting to see exactly how this parameter impacts on the considered values. This last experiment has been carried out and the results presented below.

### 6.7.4 Influence of the Maximum Number of GPRS Channels per Call

#### *6.7.4.1 Experiment*

It is a convention for the GPRS traffic with current mobile phones that a maximum of four channels can be allocated to a single call, if the network load permits. This is why this value has been used for this project. However, the results of the previous section showed that this maximum number has repercussions on the total utility and revenue generated. To further our knowledge about the precise effect of this parameter, this maximum number has been increased from one to four, and the results obtained are presented in figures 42 and 43 below.

#### *6.7.4.2 Results*

Figure 42 presents the variation of the total revenue for the GPRS traffic.

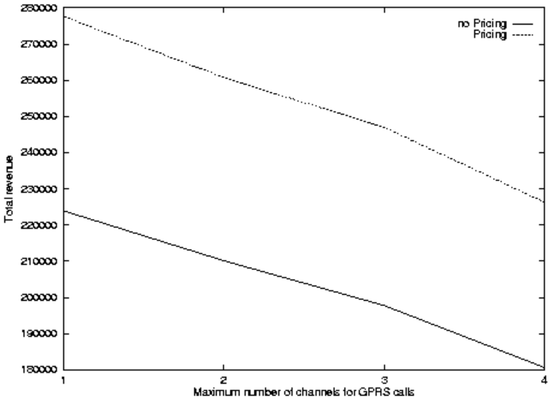

**Figure 42 : Total revenue as a function of the maximum number of channels per call, without pricing**

This figure shows that the total revenue decreases when the maximum number of channels allocated to one GPRS call increases. The decrease is more marked between three and four than between one and three. The two graphs corresponding to the cases with and without dynamic pricing are very similar, almost parallel, even if dynamic pricing gives better results, as usual.

The corresponding graph for utility is given in figure 43. The observations are the same, even if the two graphs are no longer exactly parallel. We can see that in proportion, the effects are greater on the utility than the revenue. Where the total revenue is on average decreased by 20% when the maximum number of channels allocated increases from one to four, the total utility is decreased by 65% during the same time.

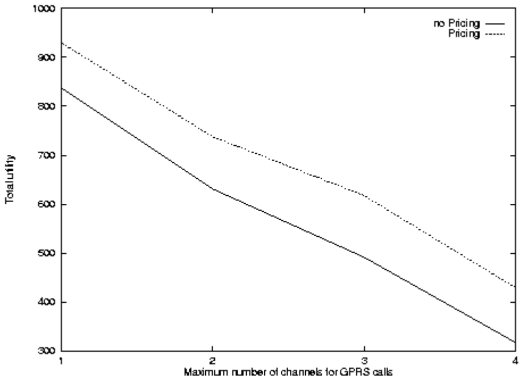

**Figure 43 : Total revenue as a function of the maximum number of channels per call, with pricing**

### *6.7.4.3 Conclusion*

The impact of the maximum number of channels allocated to one GPRS call, anticipated by the results presented in the previous section, has been confirmed. It has been shown that the revenue and utility are lower with the chosen model for GPRS traffic that they would have been with a simpler model where one call could only be allocated one channel, as it is for the GSM traffic. This result was crucial for all experiments concerning the division of GSM and GPRS traffic, since it explains why it was always better, as far as total utility and revenue were concerned, to privilege GSM calls over GPRS ones. But this was not easy to predict beforehand. Indeed, when this parameter is high, a single call may use almost all the available bandwidth, but in compensation, it will last a shorter length of time. On the contrary, if a call can only use one channel at a time, other calls can be treated simultaneously, but they will last longer. There is hence a compromise to find between the duration of the calls and the use of bandwidth. The results obtained suggest that it is more efficient to favour the use of bandwidth. Because the proportion of GPRS calls is likely to increase in the future, a strategy has to be found to counter the loss of revenue that the results suggest. The easiest solution is to charge the GPRS sessions more than the GSM ones.

Another way to see this result is that the total utility is not dependant on the individual call utilities: from a single user point of view, it is better to use all available channels if possible even if all other calls and the total utility have to suffer as a consequence, since its own welfare will be increased. On the contrary, from a global point of view, it is better to reduce the individual users' welfare to maximize the total utility. This is a common result for networks with limited capacity: the maximizations of individual and global welfares require different techniques and are often not compatible.

### 6.7.5 Conclusion About the Experiments Carried Out With GPRS

The first experiment carried out showed that more revenue is generated if users are charged based on the size of data they want to transmit rather than on the duration of their calls. Further analysis showed that this was due to the fact that under the experimental conditions the GPRS channels were not used at their maximum capacity. Other experiments were then carried out in order to try to use those channels more efficiently. What this showed is that without pricing, it is not always possible to maximize both utility and revenue, and that a compromise has to be found. However, when pricing is introduced, both graphs have a similar shape, decreasing when the proportion of GSM calls treated by the system decreases. Because the pricing for GPRS was designed to be fair in comparison to the GSM one, a final experiment was carried out to understand why GPRS calls always generated less revenue. It was shown that this is because a GPRS call can use up to four channels at a time, whereas GSM calls are limited to one. From the different results obtained, optimal values for key parameters under the experimental conditions were found, while it was shown that several compromises need to be made.

## 6.8 Conclusion

In this chapter, the simulator has been used to look at the impact of different call admission control schemes on the total utility and revenue generated over a day. It has been shown that the use of a good CAC scheme can improve the performance of the system. In addition, the introduction of dynamic pricing always leads to increased utility, and often to increased revenue as well, even if the two values are not always linked.

Dynamic pricing manages to achieve these results by regulating the traffic during congested periods, making it smoother. Therefore, because of its simplicity, it seems to be an excellent alternative to complex CAC schemes as a way to improve resource utilization, even though it is even more efficient when not used alone, but rather as a complement to call admission control.

Finally, the effects of the introduction of GPRS traffic have been studied, and conclusions about the pricing strategy and the incoming traffic division have been given.

Chapter 7

# Conclusions

The introduction put forward the need for good management of the scarce resources available for wireless communications. Three possibilities were considered: to increase the capacity of the network, to achieve an optimal resources division among the different cells through channel assignment and call admission control schemes, and to make the demand fit the available capacity through dynamic pricing.

CAC and channel assignment have been the subject of many studies, but this can not be said of dynamic pricing, especially for cellular networks. In addition, although both CAC and dynamic pricing have the same goal, no research study has been carried out to look at their combined effects. The work presented by Hou et al. in [8] introduced a call admission control block and distinguished between new and handoff calls, but they only considered the simple guard channels scheme. The dynamic pricing function they proposed, however, contained no limitation about the type of cellular network and can be applied in combination with any CAC scheme.

The main goal of this project was to deepen the knowledge of how CAC and dynamic pricing can interact in order to give better results. It also sought to extend the work started in [50], where a first model for a GSM/GPRS network and a first simulator were designed to study the impact of some parameters of the pricing function described by Hou et al. The results obtained in that study have been used; the network model and simulator have been refined, and new results have been gathered to look at what the consequences of the unavoidable growth of GPRS traffic may be.

## 7.1 Achievements

First, the state of the art on dynamic pricing has been presented in chapter 2, with a particular focus on its application to cellular networks. Three principal studies with different pricing methods were identified, but they all converged towards the same idea that dynamic pricing was a very powerful tool to increase the revenue and the utility. The same conclusion has been reached by numerous studies about dynamic pricing in other industries.

In chapter 3, different call admission control schemes were considered. In cellular networks, most of these are designed to manage the tradeoff between the new call and handoff call blocking probabilities in the most efficient manner possible. Both the past and future research directions of this field were explored from the simple guard channel scheme to the advanced schemes using real time GPS data.

In chapter 4, the different approaches which may be used to model a GSM/GPRS network have been described. After a quick recapitulation of the experimental settings from [50] that were reused for this project, more details have been given on the expected composition of GPRS traffic. Existing standards such as UMTS or cdma2000 are not based on real measurement results and empirical studies have been preferred here. Many different experiments have been carried out to try to determine the most reliable description of web, e-mail or file transfer traffic. However, most of these are either out of date or unsuitable to the project requirements. Therefore, for each of the three types of GPRS traffic that have been considered, the model adopted is a combination of the best methodologies given in the literature.

In chapter 5, the simulator built in [50] has been briefly described, focusing more on the new features which have been added. In particular, the new GPRS traffic model implemented has been presented and illustrated by a simple example. One of its major improvements is that it allows for multiplexing of data.

In chapter 6, the experiments carried out have been described in detail. First, different CAC and channel allocation schemes have been implemented and the results have been analyzed, with and without dynamic pricing.

The conclusion was that dynamic pricing is a simple solution in the sense that it does not require any new infrastructure, but that it is a very powerful tool to reduce congestion and thus to achieve better utility, and often better revenue as well. The effects were very significant, not only for the total revenue and utility, but also for different parameters such as the call queuing time or the number of available channels in the central pool in the case of dynamic channel allocation. For some experiments, it was even shown that the introduction of dynamic pricing alone was sufficient, and that the call admission control block did not need to be used to its maximum potential to be effective. These results, added to the previous results obtained by other research (see chapter 2), mean than the efficiency of dynamic pricing as a resource manager is beyond doubt for GSM networks. Moreover, it has advantages for both operators and users. The operators can achieve a better utilization of the resources and generate more revenue, while the users see their utility greatly increased. Since both new and handoff calls benefit from dynamic pricing, the user mobility, which is one of the main sources of potential problems, can now be achieved with much lower risk of communication drop prior to connection termination.

These experiments also enabled the comparison of different CAC schemes. It was shown that almost all of them can improve the basic results, with different levels of success. The best results were obtained by queuing schemes, but it was argued that this type of CAC scheme was not directly comparable to the others, where the users only have one opportunity to establish a communication. Among the other schemes studied, channel borrowing and to a smaller extent dynamic channel assignment improved the results obtained by the basic scheme significantly. The importance of a good CAC scheme design was highlighted by the differences between the different schemes. It was however mentioned that, dynamic pricing excluded, the best CAC schemes were also the most demanding with regard to computational requirements or infrastructure, but that it was certainly worth making this investment.

Finally, it was proved that a combination of the best CAC schemes and dynamic pricing gave even better results.

With the introduction of GPRS traffic, the first experiment carried out was to look at the effects of different pricing strategies. The results suggested that, under the experimental settings, the GPRS channels were under utilized and that the incoming traffic division could be improved. The new goal of looking at the influence of GPRS parameters was hence added to this project. It was shown that the choices made for the traffic division between GSM and GPRS calls, as well as the chosen number of GPRS channels, had significant repercussions on both total utility and revenue, and that these values must be determined carefully when dimensioning a real network. Finally, the nature of GPRS traffic, which allows a user to get more than one channel for his call when possible, was shown to generate less revenue and utility than the simple GSM traffic. Consequently, it was suggested that a higher price or a different pricing function should be used for GPRS sessions. Even for GPRS traffic, which is completely different from GSM, it has been shown that dynamic pricing could improve the performance of the network, even if its effects are a little less spectacular than when GSM is considered in isolation. This suggests that the introduction of dynamic pricing could be done on current networks, and that it may not be a very difficult task to adapt the pricing strategy later when new application types appear, adapting the advantages of dynamic pricing to the newly introduced traffic types.

## 7.2 Obstacles Overcome

The first difficulty that had to be faced was the choice of the most relevant call admission control schemes. So many schemes have been proposed that it was not easy to select the most representative ones. Another difficult task was to determine appropriate values for GPRS traffic parameters, and then to find efficient corresponding distribution java packages.

To understand in detail how the simulator built for the study presented in [50] worked, to then be able to use it and to extend it was also challenging. Indeed, even if the original design was good, it took a lot of time to get a really thorough understanding of the kinds of experiments that this type of simulator allows, and to make the required changes whilst maintaining and existing working code base. From a technical point of view, the implementation of the new version of the GPRS traffic proved extremely complicated, in particular the integration of all the limit conditions.

Finally, the selection of the CAC schemes to implement and the choice of the most interesting experiments to run were very time-consuming.

## 7.3 Future Work

For this project, a second GPRS traffic model has been proposed. However, even if it is much more realistic than the previous one, it still has some limitations as mentioned in chapter 5. To make the results more accurate, it would be necessary to remove these limitations, but this can not be done with the current type of simulator. Therefore, a new simulator, enabling real time signalling, would need to be implemented.

Some of the experiments presented in chapter 6 suffered from using a network that was too small. It would be illuminating to run those experiments again on a larger scale in order to draw more definitive conclusions.

Another interesting direction for future research would be to run the same types of experiments on a network where the incoming traffic is not equally shared among the different cells, and to include the relationship between the price and users' mobility as done it [4]. This could simulate a real traffic condition where one point in space is far more loaded than others, as happens sometimes in stadiums for example. Some CAC schemes efficiency, such as borrowing schemes for example, would reach their maximum in these conditions and it would be very interesting to see how well they can perform when faced with such challenges.

The experiments carried out for GPRS traffic highlighted the need for a different, higher price to that of GSM calls. To try to design a new pricing scheme, or to use some of the schemes presented in section 2 and put them into the simulator could be another possible research direction.

Finally, after all the research about dynamic pricing has shown that it is a very powerful tool that achieves a better utilization of the available resources, and that it often leads to better revenue as well, the next step before its application would be to test it in real life conditions, and to measure its actual benefits.

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