

Performance Between Circuit Allocation Schemes for Half- and Full-Rate Connections in GSM

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Abstract—This paper considers three circuit allocation schemes for half- and full-rate connections in the global system for mobile communications (GSM): best fit, repacking, and fair repacking. Analytic numerical methods are used to investigate each scheme's blocking probability behavior. The analysis is based on a reduction of the state space to a manageable size. Fair repacking is found to be the fairest and most efficient. However, the best-fit scheme, while being somewhat less efficient and fair, is simpler to implement. The effect on quality of service (QoS) of voice dropouts related to intracell handover (repacking) was found to be negligible.

Index Terms—Cellular mobile radio system, GSM.

I. INTRODUCTION

GLOBAL SYSTEM for mobile communications (GSM) uses a time-division multiple-access (TDMA) structure with eight slots-per-frame to support speech and data transmission. Full-rate speech calls use one time slot in every frame, while half-rate calls will use a single TDMA slot every second frame on average. It is expected that future mobile terminals will have the capability to operate at both rates. However, it is reasonable to assume that if a cell is equipped with half-rate capability, the terminal will operate in the half-rate mode in that cell. The exact time organization for slots for full- and half-rate transmission is summarized in [11, Section 4.2.1.1] and is in accordance with GSM standards development [4].

Thus, mixing full- and half-rate traffic in a frame can result in eight full-rate calls, 16 half-rate calls, or any feasible combination. This is illustrated in Fig. 1. At first glance, it might appear that introducing half-rate calls will double the capacity of a GSM network. However, this optimistic view fails to consider two important factors: 1) when first introduced, the portion of existing GSM customers that will change over to the new half-rate system is unknown and 2) although a half-rate call uses on average half a time slot, its *effective usage* is higher because when a slot is occupied by a half-rate call, no full-rate call can use that slot. With this notion of mixed traffic, the issue is how best to allocate slots. Although some schemes perform far better than others, the goal of all of the allocation policies should be to attempt to allocate resources in such a way that the blocking probabilities of half- and full-rate calls are equalized as far as possible and at the same time kept to a minimum.

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In this paper, we focus on three schemes: best fit, repacking, and fair repacking. Section II describes the model. Section III gives a description of each of the three schemes and briefly mentions several others. Section IV focuses on details of the method used to find an analytic solution. Section V gives insight into the optimization problem which was solved in order to objectively calculate scheme efficiencies. Numerical results are presented in Section VI, and the conclusions are in Section VII.

II. THE MODEL

For the purposes of evaluating the traffic performance of a mixed full- and half-rate network, the arrangement in Fig. 1 can be represented as slots being capable of supporting one full-rate call or two half-rate calls (refer to Fig. 2). Note that the boundaries between the eight slots are considered "stone walls," and in that sense, a full-rate call may never be placed across one of these walls. In a simplified model as depicted in Fig. 2, each frequency (frame) could support exactly eight full-rate users, with the *broadcast channel* ignored. This assumption was the basis for our initial "one carrier, no broadcast functionality" model. In a real situation, however, on average one channel within each cell must be reserved for the broadcast function, meaning that only $8n - 1$ time slots are available for user traffic in an n carrier cell. We will also consider a cell with $n = 2$ and $n = 3$ carriers and, hence, 15 and 23 available user-traffic time slots, respectively.

As usual, we assume Poisson arrivals and exponential holding times with λ_1 and λ_2 being the arrival rates for full- and half-rate calls, respectively, and $1/\mu_1$ and $1/\mu_2$ the holding times for the full- and half-rate calls, respectively. We use standard Markov chain techniques (e.g., [2], [15]–[17]) to obtain numerical solutions for the loss probabilities for each of the schemes. We also classify the schemes according to the most efficient numerical method required to obtain the loss probabilities.

In this model, we have not distinguished between new and handoff call categories. Note that if we are to consider the two traffic categories each with half- or full-rate types, the dimensionality of the problem will increase significantly, and numerical solutions for realistic problems, e.g., two or three carriers, will not be obtainable. Although it is straightforward to obtain by means of simulation [solutions for blocking probabilities (of new calls) and dropping probabilities (of handoff calls)], we feel that the introduction of the distinction between the two traffic categories will not affect the conclusions about the fairness and efficiency of the schemes under consideration.

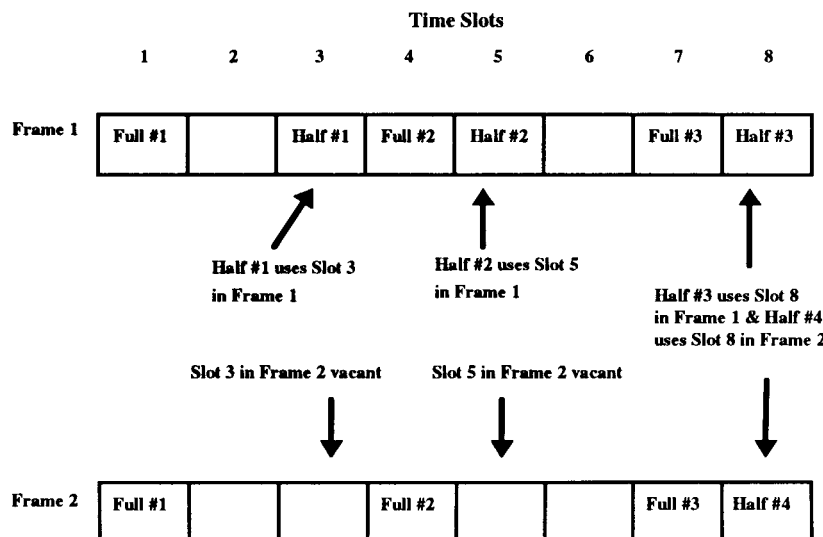


Fig. 1. A typical half- and full-rate traffic mix.

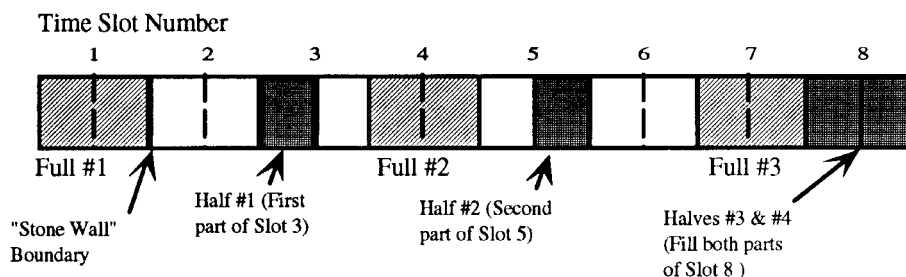


Fig. 2. A model for analyzing the traffic mix in Fig. 1.

III. CHANNEL ALLOCATION SCHEMES

A. Best Fit [10]

This scheme targets the lone half slots that are present in the frame and assigns to them any new incoming half-rate calls. The eight slots in the frame are permanently allocated ID numbers (say, zero–seven). In the case of our system, each full slot may contain: 1) no calls {0}; 2) a half-rate call {1}; 3) two half-rate calls {2}; or 4) a full-rate call {3}. To each of these possibilities, the value in the braces is attached, as has been done in the braces above. The allocation algorithm then functions as follows.

- 1) Each incoming full-rate call is allocated to the smallest ID-number full slot that is totally empty.
- 2) An incoming half-rate call is allocated to a lone half slot. If more than one is available, the one with the smallest ID number is filled. If none are available, we place it in the smallest ID-numbered empty slot.

No action is taken upon call departure, and a *hole* (an empty half slot in a slot with a lone half slot) may remain.

B. Repacking [16], [17]

This method is similar to best fit with one major difference: the action taken upon call departure.

- 1) When a full-rate call departs leaving a full slot hole, no action is taken.
- 2) When a half-rate call departs, either a full or half hole will remain. In the former case, no action is taken. In the latter case, if an isolated half is available, it will be moved into the half hole. If not, no action is taken.

Implementation of the repacking strategy makes use of intracell handover [1], including repacking across different radio frequency carriers within the same cell. In the numerical examples of this research work, we have considered both repacking within a single radio frequency carrier as well as between multiple carriers. A large number of intracell handovers during a call may have a negative effect on the quality of service (QoS). It is therefore important to have this number as small as possible. To reduce the number of intracell handovers in practice, Step 2) above will not be performed upon a half-rate **departure**. Instead, intracell handovers will only be performed upon an **arrival** of a full-rate call when there are no completely empty slots and there are at least two isolated halves. Although this results in a slightly different scheme, it does not in any way change the complexity or size of the state space, and it does not affect loss probability. When all of the traffic is half rate, repacking is simply the best-fit scheme since intracell handover is never required.

The result of the repacking scheme is that a full-rate call arrival will not find a situation where there is more than

one isolated half slot. Therefore, we expect an increase in **utilization** (where utilization is defined as the average number of occupied slots divided by the total number of slots). The only essential difference between admittance criteria for full- and half-rate calls is that when there are seven and a half slots full, a half rate will be admitted whereas a full rate will not.

Repacking in a broader sense has also been used in [3], [9], and [12], which consider channel allocation *between* cells in the context of dynamic channel assignment. In our work, we consider channel allocation *within* a cell in the context of fixed channel assignment, with two types of calls with different capacity requirements.

C. Fair Repacking [14]

This scheme is a variant of ordinary repacking. We reserve half a time slot, thus introducing a small amount of resource wastage and basically “forbidding” the halves to enter the system when only one half slot is available. In this way, the blocking probability of half- and full-rate traffic is equal for every traffic mix at the expense of lowering the half-rate call utilization somewhat. A scheme based on reserving an entire time slot solely for use by full-rate callers, repacking with perpetual reservation (RPR), is discussed in [5].

It is worth mentioning that the repacking with random reservation (RRR) scheme [5]–[7] is a more general variation of the repacking scheme. Under this scheme, if only one full slot is empty and a half-rate call arrives, then the call is accepted with probability p_1 and rejected with probability $(1-p_1)$. If only a half slot is available, then the call is accepted with probability p_2 and rejected with probability $(1-p_2)$. Note that the special case of $p_1 = 1.0$ and $p_2 = 1.0$ is ordinary repacking while the case of $p_1 = 1.0$ and $p_2 = 0$ is fair repacking, which equalizes blocking probability. The case of $p_1 = 0$ is the RPR scheme.

There are also other schemes which may be implemented (see [5] for detailed descriptions) such as the following.

- 1) *Random*: All calls are assigned to any free channels without any control.
- 2) *First Fit*: Same as best fit, but arriving half-rate calls are not specifically inserted into holes for efficiency.
- 3) *Fixed Boundary*: Fixed numbers of channels are permanently allocated to full- and half-rate calls, respectively. Very inefficient.
- 4) *Sliding Boundary*: Like fixed boundary, but the number of channels allocated to calls of either type can vary dynamically with traffic load.

IV. ANALYSIS

In this section, we provide analytic solutions for loss probabilities for the methods mentioned above. An analytic solution for RRR by means of Gauss–Seidel iterations is available in [5].

One way of solving this problem is to consider a set of as many state variables as there are time slots, each of which could take four values. This would result in a state space, which described *every possible permutation* of half- and full-rate caller occupancies in the available time slot. As

a result, any such state space would be enormous, especially for realistic numbers of time slots. However, it is possible to reduce the state space to a manageable size by using some ideas from [2], [16], and [17]. Using the model defined in Section II as a framework, all of the allocation schemes may be described by such a reduced state space where each state is described by the parameters: 1) i : the number of full-rate calls currently in the frame; 2) j : the total number of half-rate calls; and for the best-fit scheme, we require an additional parameter which is 3) k : the number of isolated half-rate calls in the frame. The last parameter is only needed for the best-fit allocation scheme (and the random scheme [5]) because unlike the repacking and fair repacking, this scheme can have more than one isolated half-rate call. The numerical **analytic** method was based on generating the state transition rate matrix and solving it using a Gauss–Seidel iteration technique with relative error $< 10^{-5}$. The matrix generation process eliminated invalid states reducing size significantly.

Because the repacking family of schemes including the fair repacking has two state parameters, the resulting state spaces will be two dimensional (2-D), and it is therefore possible to construct 2-D Markov chains for any such scheme [5]–[7].

As discussed, the best-fit scheme requires a three-dimensional (3-D) structure of its state transition matrix. If the reader considers the state space in terms of a transition diagram [5], [6], a typical state will have five possible transition types. Of particular interest are the transitions weighted by probabilities related to half-rate departures which create holes and those which eliminate them. For example, when we are in the state (2, 3, 3), there are six completely empty half slots as well as three holes. Hence, upon a half-rate call departure, the probability of the hole-elimination transition taking place is 3/9 while that of the hole-creation transition 6/9.

In the case of the repacking scheme only, we can use the exact recursive solution due to Kaufman–Roberts [8], [13]. According to this method, the probability of having m -basic bandwidth units (under repacking, one basic bandwidth unit is equal to half a channel) occupied is

$$\tilde{p}(m) = \begin{cases} 1, & m = 0 \\ 0, & m < 0 \\ \frac{1}{m} \sum_{i=1}^2 \tilde{p}(m - m_i) m_i \frac{\lambda_i}{\mu_i}, & 0 < m \leq M \end{cases} \quad (1)$$

where m is the state number and m_i is the number of required basic bandwidth units for users of class i . We are using here the index $i = 1$ for full-rate calls and $i = 2$ for half-rate calls. Accordingly, $m_1 = 2$ and $m_2 = 1$ for full- and half-rate calls, respectively. The maximal number of basic bandwidth units is M (which is two times the number of available channels). Note that there are only M states in one dimension since the users’ requirements are mapped from two dimensions to one by use of the m_i variable. The state probabilities are after normalization

$$p(m) = \tilde{p}(m) \cdot \left(\sum_{m=0}^M \tilde{p}(m) \right)^{-1} \quad (2)$$

TABLE I

Circuit Allocation Scheme	Numerical Analytical Method
Repacking	Kaufman-Roberts
Fair Repacking, RRR, RPR	Gauss-Seidel: 2-D State Transition Matrix
Best Fit, Random	Gauss-Seidel: 3-D State Transition Matrix

and, finally, the blocking probability B_i for class- i calls ($i = 1, 2$) can be calculated as

$$B_i = \sum_{m=M-m_i+1}^M p(m). \quad (3)$$

In Table I, we summarize the above by classifying the circuit allocation schemes according to their most suitable analytical method.

V. FINDING SCHEME EFFICIENCY

The speed of the analytic solution also allows us to find the *efficiency* of each scheme, defined as the maximal call capacity of the system (comprising n carriers), subject to a specified call blocking probability. Call capacity is defined as the maximum number of customers of either type supportable simultaneously by the system. In particular, an optimization problem was solved separately for each allocation scheme. A simple linear search method was used. The blocking probabilities $P(\text{Blocking})_{\text{fulls}}$ and $P(\text{Blocking})_{\text{halves}}$ are functions of θ (the proportion of full-rate arrivals) and Λ (the total number of arrivals to the system). The following relationships are apparent:

$$\begin{aligned} \theta &= \frac{\lambda_1}{\Lambda} \\ \Lambda &= \lambda_1 + \lambda_2 \\ C &= \Lambda/\alpha \end{aligned} \quad (4)$$

where C = system call capacity (total number of customers of either type the system can support simultaneously) and α = number of call attempts per unit time per customer:

1) constraints:

$$\begin{pmatrix} (1)P(\text{Blocking})_{\text{fulls}} \leq 0.02 \\ (2)P(\text{Blocking})_{\text{halves}} \leq 0.02 \end{pmatrix}$$

2) optimization problem: maximize C , subject to both constraints for any given θ .

Because C and Λ are related by the positive constant α which is taken to be identical for all customers, the optimization problem can now be restated as follows. **Maximize Λ , subject to both constraints, for any given θ .**

VI. RESULTS

A. Scheme Fairness

It is important to precisely define what is meant by the concept of scheme *fairness*. Let

$$f = \log_{10} \frac{P(\text{Blocking})_{\text{fulls}}}{P(\text{Blocking})_{\text{halves}}}. \quad (5)$$

Equation (5) shows that fairness is the measure of numerical proximity (i.e., the f value) of the blocking probabilities for the two types of calls, namely, full and half rate. Complete fairness is only achieved when $f = 0$. To compare the relative fairness of the schemes, we plot in Fig. 3 the f value versus θ and consider a case of $n = 1$, where the broadcast/control channel is ignored so that a single frame with eight time slots is entirely for use by customers. As mentioned in Section II, λ_x and μ_x are the average arrival and departure rates, with $x = 1$ for full-rate calls and $x = 2$ for half-rate calls. Note that the departure rates are both set equal to $(3 \text{ min})^{-1}$ and that the time period between successive arrivals (departures) is exponentially distributed. The *offered traffic per channel* (in this case, one eighth of total offered traffic) is given by $\rho = (\lambda_1 + \frac{1}{2}\lambda_2)/8\mu$. The offered traffic per channel is the control parameter in Fig. 3 and is set to $\rho = 0.4$. The analytic results presented in Fig. 3 were confirmed by simulation. Notice the *convergence toward a mix-insensitive f value of zero* as we approach fair repacking—the fairest scheme. Another observation to be made about Fig. 3 is that it exemplifies the general principle of connection admission control (CAC) [14] in that schemes with progressively less access control were progressively more unfair. The random scheme [5]–[7] has *no access control* with full- and half-rate calls able to take any time slot or hole that is available to them. Such a scheme, as its f -value range illustrates, is much more unfair than a scheme with *stringent access control* such as fair repacking, where a range of conditions (i.e., control) is imposed on the access of arriving calls.

If the reader is also interested in the absolute values of blocking probability for these three schemes, under the same load conditions, they are referred to [5].

B. Scheme Efficiency

Figs. 4 and 5 show for each of the three schemes (and random as a reference case) the maximal call capacity of the system subject to the previously mentioned constraint that the blocking probability [referred to as grade of service (GOS)] for both call types cannot exceed 2%, regardless of traffic mix (i.e., the θ value). System sizes of $n = 1$ and $n = 3$ carriers

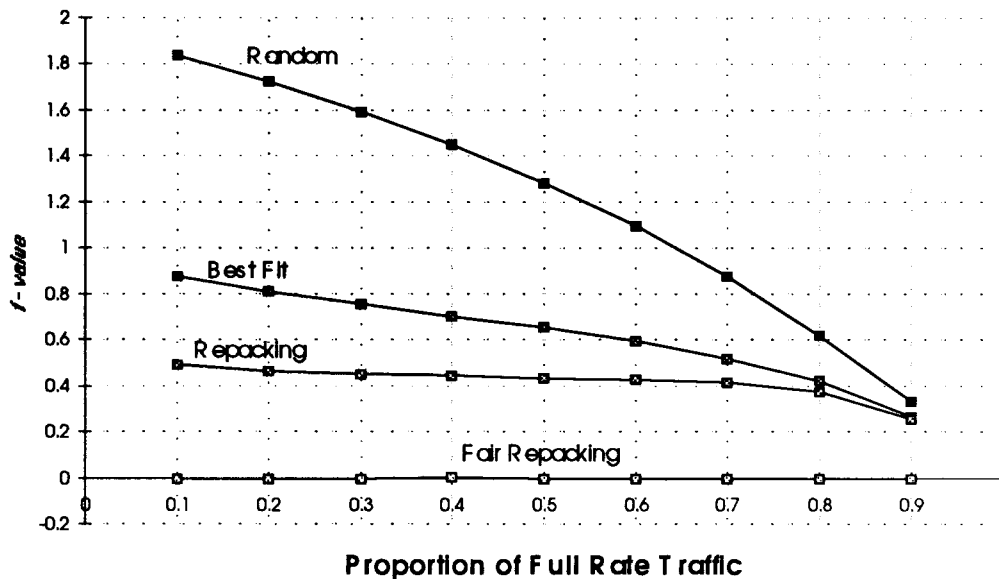


Fig. 3. f versus θ (at $\rho = 0.4$).

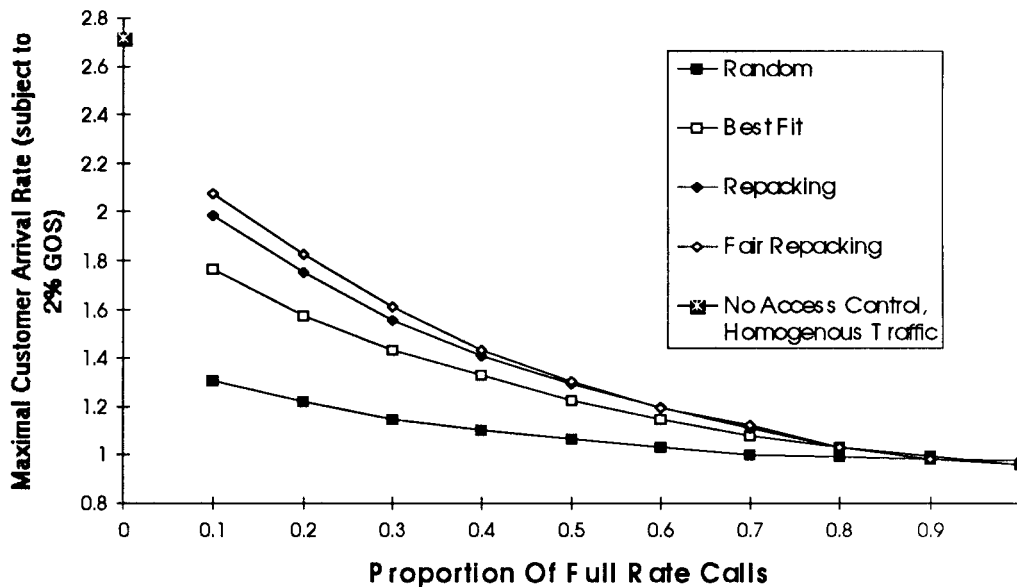


Fig. 4. One carrier frequency system—comparison of maximal customer arrival rates subject to a 2% GOS.

have been investigated (Figs. 4 and 5, respectively). In each case, the optimization problem described in Section V was solved separately for each allocation scheme.

Looking at Figs. 4 and 5, where the maximal value of Λ (the equivalent measure of capacity) is plotted versus θ for systems with one carrier frequency (seven slots) and three carrier frequencies (23 slots), it is noticeable that the data point, where all the arrivals are half-rate calls (i.e., 0% fulls or $\theta = 0$), is clearly discontinuous from the others. Although Figs. 4 and 5 do not show any points for $\theta < 0.1$, it has been observed that as θ approaches zero, we have the following.

- 1) The maximal capacity of the random, best fit, and repacking schemes asymptotically approaches an intermediate value before making a *discontinuous jump* to the value shown on the graph at $\theta = 0$ (*ideal peak capacity*).

This is due to the fact that at very small values of θ , it is those few present full-rate calls which suffer extreme blocking probabilities because of their inability to “get in.” In order to keep below the predefined GOS of 2%, the overall user capacity must be constrained. When there are absolutely no full-rate calls arriving, this constraint disappears.

- 2) On the other hand, the maximal capacity of the fair repacking scheme *continuously* approaches a value which is just below the ideal peak capacity shown on the graph. Because this scheme imposes a certain degree of blocking probability balancing, even when there are very few full-rate calls, they are treated approximately equally in terms of access to resources.

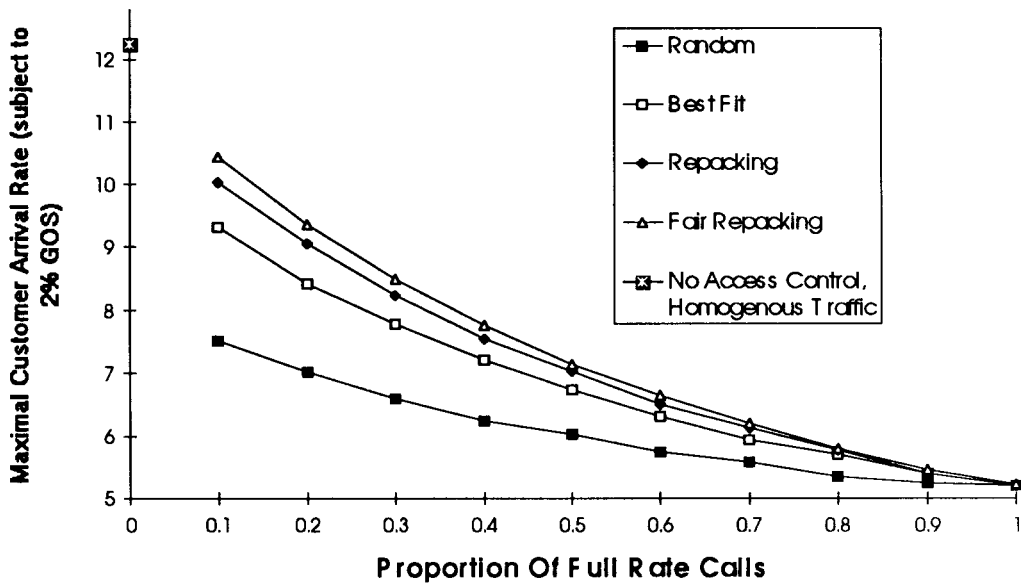


Fig. 5. Three carrier frequency system—comparison of maximal customer arrival rates subject to a 2% GOS.

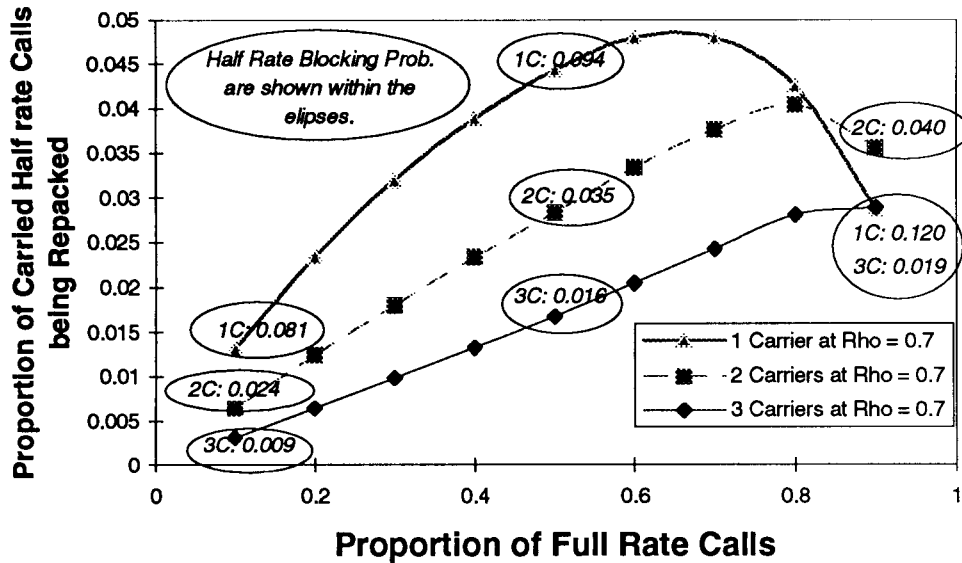


Fig. 6. Proportion of repackings per carried half-rate call with fixed offered traffic per channel ($\rho = 0.7$).

The point $\theta = 0$ represents the situation where we are left with **homogeneous half-rate traffic**. In this case, there is no need to impose any form of access control. The above graphs were produced with the *assumption* that when this point is reached, none of the schemes is used, the system becomes an M/M/N/N queue, and blocking is calculated by the Erlang loss formula using $N = 2 * N_{Channels}$. In this case, the maximum capacity is equal to the ideal peak capacity as shown. This assumption is particularly well justified in the case of the nonreservation schemes by observing that when $\theta = 0$, the random, best fit, and repacking schemes all yield identical blocking probabilities to those obtained by use of the Erlang B formula with $N = 2 * N_{Channels}$. This holds since none of these schemes prevents access by half-rate calls to any part of the frame. On the other hand, the fair repacking scheme prevents part of the frame resources from being utilized by

half-rate calls. It was found that with homogeneous half-rate traffic, this “prevention of access” causes the fair repacking scheme to give a slightly higher value of blocking probability than that for the random, best fit, and repacking schemes. This happens because at $\theta = 0$, $N < 2 * N_{Channels}$. This explains observation 2) from above, where it is noted that for $\theta = 0$ the fair repacking scheme actually yields a maximal capacity slightly lower than the ideal peak capacity shown on the graph.

However, the real indicator of scheme performance is the other part of the curves—the region ($0.1 \leq \theta \leq 1.0$). The best scheme must have the largest maximal capacity in this region, and with this in mind, it is clear that the optimal performance is given by the fair repacking scheme. It was also found that for a half-rate-dominated traffic mix ($\theta < 0.5$), the schemes converge in terms of capacity as system size increases. For example, when $\theta = 0.1$, the capacity increase

benefit gained by using fair repacking over the best-fit scheme reduced from 17.5% for a one-carrier system to only 11.9% for a three-carrier system. Also, the capacity increase benefit (i.e., how many more call arrivals can be handled for a given blocking probability) of using more complex schemes such as fair repacking over relatively simple ones such as best fit was *only notable (e.g., more than about 5%) when the traffic was dominated by half-rate customers ($\theta < 0.5$)*. This observation holds for all system sizes. It is particularly important when deciding which scheme to use for larger systems. This is because the capacity increase benefit for large systems is much smaller.

C. Intracell Handover

So far, we have demonstrated the benefit in efficiency obtained by repacking. However, use of repacking has certain QoS implications, which should be considered. In particular, periods of voice dropout of up to 450 ms in duration may occur each time a user is repacked from one time slot to another, and so it is desirable to know how often this key intracell handover operation is performed. For the systems of one-, two-, and three-carrier frequencies, the proportion of repacked half-rate calls is illustrated in Fig. 6 as a function of the traffic mix for the repacking scheme.

In particular, in Fig. 6 we compare the frequency of repacking, under fixed offered traffic per channel, for the systems of different sizes. Of course, this comparison results in all points on the curves having differing probabilities of loss. As expected, the less full-rate callers we have in the traffic mix, the smaller the probability of full-rate arrivals. Since only full-rate calls may prompt the repacking of half-rate customers, this directly leads to a smaller proportion of repacking. On the other hand, the proportion of repackings per carried half-rate call after an initial period of monotonic increase with increasing θ begins to again decline as θ approaches 1.0. This can be accounted for by the fact that for θ close to 1.0, there is a smaller number of half-rate calls in the system, and, hence, the probability that full-rate calls will arrive at an instant when the frame has enough holes embedded in it to prompt a repacking is significantly decreased. The observations made from Fig. 6 for repacking are consistent with numerical results presented in [7] for the RRR scheme.

It is interesting to note that for a fixed offered traffic per channel, the smaller the system is, the greater the chance that carried half-rate calls experienced a repacking. The reason for this phenomenon is that when there is a smaller number of user channels available to a constant amount of offered traffic:

- 1) the probability that upon a full-rate call arrival the call may freely enter the system and not necessitate a repacking is greatly reduced;
- 2) the probability that upon a full-rate call arrival the call may only enter the system if a repacking is possible is increased;
- 3) the probability that upon a full-rate call arrival the call cannot fit into the system at all is also increased.

The above effects are clearly visible both from the ordinate axis of Fig. 6 and half-rate call blocking probability values

which have been inserted at a few important points in the graphs. In any case, we must make it clear that from the actual numbers obtained for the intracell handover proportions (at most, 5 per 100 calls), we can draw the conclusion that the repacking family of schemes, which are the most efficient, are almost *negligibly affected by intracell handover-related voice-quality degradation*.

VII. CONCLUSION

This paper has described several schemes for allocating time slots to full- and half-rate users in a GSM network serving mixed traffic. It has presented a simple Markov chain model and used it to analytically obtain the blocking probability of the two classes of users. The analytic solution was based on a reduction of the state space to a manageable size of a 2-D or 3-D state space. For traffic **with** full-rate users, fair repacking is found to incur the lowest blocking probability and achieve best fairness, but when the traffic mix has **no** full-rate users, best fit and repacking (even random) are better than fair repacking. Therefore, vendors making equipment based on fair repacking should include a scheme (e.g., repacking or best fit) to be used if all the traffic is half rate. The practical effect of intracell handover due to repacking is negligible.

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