

PERFORMANCE EVALUATION OF AN INTEGRATED SATELLITE/TERRESTRIAL MOBILE COMMUNICATION SYSTEM BASED ON LEO SATELLITES

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***ABSTRACT** - Future mobile communication systems will be characterized by the coexistence and interworking of several cellular layers. In this paper the integration of satellite and terrestrial mobile communication systems is investigated from the channel allocation standpoint. The performance of the integrated system is evaluated in terms of the overall probability of not completely served call. A simulation model has been built to estimate the performance improvement of the integrated system with respect to a stand-alone terrestrial cellular system.*

1 - INTRODUCTION

Radio-resources of the future Universal Mobile Telecommunication System (UMTS) have to be efficiently used, in order to face the expected mass diffusion of tetherless services. The basic approaches that can ensure high channel utilization are: the reuse of the same channel as much as possible within the cellular network and efficient channel allocation strategies [Raym91].

At present, the solution adopted in order to increase the capacity of a cellular network is the subdivision of the territory into smaller cells so allowing the decrease of the transmitted power and the use of small-size low-power hand-held terminals with longer stand-by periods. However, some difficulties arise in locating Base Stations (BSs), in assuring connectivity to fast moving users and in managing a greater number of handovers per call (i.e., a greater signaling load and a greater risk of call dropping).

These problems can be overcome by the development of a hierarchic cellular architecture [Rapp95]: areas with different traffic densities will be covered by overlaying cellular networks. Of course, a real improvement in system performance will not be achieved by the coexistence of different cellular layers alone, but by their interworking. A future mobile system is expected to be composed of nano- and pico-cells in buildings, micro-cells in urban areas, macro-cells in suburban areas and satellite cells for the global coverage of the earth. Where the terrestrial and the satellite coverage areas will overlap, satellite cells will act as "umbrella" cells that will serve many cells of a terrestrial system; moreover, where the implementation of a terrestrial system would be unfeasible or too expensive (e.g., the sea or scarcely populated areas), mobile services will be provided by satellites. Three types of handovers should be considered in a multi-layer cellular architecture:

- *intra-cell handover*, between channels of the same BS, in order to pack the use of resources in the network, with a Dynamic Channel Allocation (DCA) technique (see the next Sect.);
- *inter-cell handover*, between channels of adjacent BSs, when the "active" mobile unit crosses the borders between them;
- *inter-layer handovers*, between different layers of the cellular coverage. This handover may happen when a call is re-routed from a congested layer towards an upper layer (overlying coverages), or when a call (due to the motion of the related user) gets out the coverage of a cellular network and must be switched to an upper layer (complementary coverage).

The satellite network can serve wide regions with a low traffic density and in a short time, whereas terrestrial systems may manage higher traffic densities concentrated in relatively small areas.

The expected integration of both systems and the introduction of dual-mode terminals promises a substantial increase in service quality: high-speed services will be provided by the terrestrial network in densely populated areas, while the satellite segment will be able to provide a global access at least for low-speed services. We have considered that the satellite segment of UMTS will be based on Low Earth Orbit (LEO) satellites [Mara91].

The aim of this paper is to study the effect of different channel allocation techniques in the terrestrial part of the system together with the study of selection policies for the satellite resources that are suitable for future UMTS services. These strategies will be compared in terms of quality of service parameters that have been specified in ITU-T Recommendations [ITUT95]: in particular, the blocking probability for new call attempts (P_{ba}) should be in the order of few percent, while the probability of call dropping due to an unsuccessful handover (P_{drop}) should not exceed 5×10^{-4} . Another significant blocking parameter is represented by the probability that a call is not completely served because of the blocking of its initial attempt or the failure of a subsequent handover request (P_{ns}).

2 - CHANNEL ALLOCATION TECHNIQUES AND PRIORITIZATION STRATEGIES

In the terrestrial network, either Fixed Channel Allocation (FCA) or Dynamic Channel Allocation (DCA) have been considered.

With FCA, cells at a distance D (*reuse distance*) have permanently allocated the same set of resources: D is obtained according to the minimum acceptable C/I ratio. Cells with different subsets of channels form a cluster of N cells. Each cell can use only the channels from its subset. A channel request in a congested cell is blocked even if there are free channels in adjacent cells. Such an approach leads to an inefficient use of system resources, especially in the presence of non-uniform traffic loads in the network.

Whereas, the DCA technique temporarily allocates channels to cells provided that the constraint on the reuse distance is respected. Since many channels in a cell may fulfill this constraint, different algorithms have been proposed in the literature to choose among them [Rapp95]. Moreover, DCA techniques may include an additional algorithm that performs intra-cell handovers in order to pack the use of channels in the network; intra-cell handovers may take place at the origin and/or termination instant of a call in a cell. For example, algorithms without intra-cell handovers are the *First Available* (FA), the *Nearest Neighbour* (NN) and the *Mean Square* (MS) [Kand94], whereas more efficient algorithms with intra-cell handover are the *Cost Function* (CF) [DelR95] and the *Markov Allocation* (MA) [Raym91]. In this paper, we have used only the simple FA DCA algorithm, without intra-cell handovers: a new call attempt or a handover request in a cell is served by the first channel that is not used in the cells at a distance less than the reuse distance.

Satellite communications are known to be power and bandwidth limited. Then, the use of satellite channels entails higher costs because they are more scarcely available per unit area than terrestrial ones. In this paper, the following satellite resource selection policies have been considered:

- *Satellite channels have the same priority level with respect to terrestrial ones*: the satellite network is considered as an extension of the terrestrial network, the choice between satellite and terrestrial channels is only based on link quality measurements. With such an approach, satellite resources are not efficiently utilized, because they are more costly and scarcely available than terrestrial ones.
- *Satellite channels have a lower priority with respect to terrestrial ones*: satellite channels are allocated only when users' calls can not be served by the terrestrial network due to the unavailability of terrestrial channels. This solution permits a more efficient use of satellite resources, as it will be proved in this work.

3 - THE SIMULATION MODEL

A simulation model has been built to estimate the performance improvement of the integrated system in comparison with a stand-alone terrestrial cellular system; it consists of a terrestrial and a satellite part and enables the study of different assumptions regarding the users' mobility, the traffic load, terrestrial channel allocation techniques, the priority level of the satellite resource, inter-layer handovers and the queuing of handover requests.

For the study of a stand-alone terrestrial system, the FCA technique has been used (as in presently implemented cellular systems) and compared with FA DCA; moreover, the FA DCA strategy has been adopted to manage the terrestrial resources of the integrated mobile network.

We have taken into consideration only voice traffic and Blocked Calls are Cleared (BCC service). Call attempts arrive in a generic terrestrial cell k according to a Poisson process with average rate λ_k ; in case of integrated network, the traffic overflow from terrestrial cells is re-routed to satellite cells. Call duration is exponentially distributed with an average value $T_m=100$ s. Mobile-to-mobile calls have been assumed to be 5% of the overall traffic.

Let us focus on suburban and rural area cells of the terrestrial network, because they represent the layer from which overflow calls are re-routed to the satellite system. The simulated terrestrial cellular network, hereafter called *area*, consists of 36 (6×6) circular cells disposed according to a hexagonal regular layout. The traffic load in an *area* can be uniform or non-uniform. In case of non-uniform traffic, the pattern shown in Fig. 1 has been used: the numbers in the cells denote the normalized traffic loads. The statistical parameters of the non-uniform pattern are listed in Table 1. In the terrestrial network, a reuse distance $D=3a$ has been assumed (i.e., $N=3$), where a denotes the cell radius. Moreover, we have considered $a = 4.3$ km for the suburban/rural environment.

Call demands are served by $M=36$ terrestrial channels in the integrated mobile system. Whereas, for a fair comparison, the number of channels M in the stand-alone terrestrial mobile system is increased with the average number of satellite channels available per *area*, L , (i.e., $M= 36 + L$, see (2) for a suitable estimate of L).

A terrestrial mobility model has been developed for the special case of suburban/rural area cells: the starting position of the mobile unit can be anywhere in the origination cell and it can move in any directions. The motion direction is chosen from a uniform distribution, and it is maintained by the mobile user for all its call duration (i.e., the mobile is moving according to a straight line, for instance along a road of the suburban/rural area, for all the duration of its call). The mobile speed V is fixed for all the call duration; we have assumed $V = 60$ km/h.

According to this model, the average mobile residence time in a cell, T_s , has been estimated as follows:

$$T_s = \psi \frac{a}{V} \quad (1)$$

where ψ is a dimensionless parameter that only depends on the mobility assumptions, the cellular layout and the cells shape. According to previous assumptions, $\psi \approx 1.2$. Then, $T_s \approx 300$ s.

In order to take into account both mobility and propagation aspects, the mobile residence time in a cell, t_s , has been considered spread according to a Gaussian truncated distribution (i.e., only with positive values), with mean value $T_s = 300$ s and a standard deviation of 15 s.

A request of inter-cell handover occurs whenever the mobile residence time in a cell is shorter than its call duration. A handover is successful if a new free channel is assigned to the mobile unit in the destination cell within a maximum time.

The average number of inter-cell handovers during a call duration for the terrestrial suburban/rural cellular coverage is given by $T_m/T_s \approx 0.34$ (i.e., a low mobility scenario is considered). The handover probability from a cell is almost equal to 25%.

The satellite part of the model is based on the IRIDIUM system: this is a LEO satellite constellation whose main parameters have been shown in Table 2 [DelR95]. Each satellite spot-beam

covers n areas, and the probability that a satellite channel is used in an area is, on average, the same for all the areas covered. We have considered that the number of channels available per spot-beam, C , equals 200. The area of a terrestrial cell is πa^2 , where a is the cell radius; the circular footprint of a spot-beam on the earth is assumed to have a radius $R_s=212$ km [DelR95] and covers an area that is equal to πR_s^2 . Now we can express the average number of satellite channels available in the simulated area (i.e., 36 cells), L , as follows:

$$L = \left\lfloor \frac{36 \cdot C}{n} \right\rfloor, \quad \text{where} \quad n = \left\lceil \left(\frac{R_s}{a} \right)^2 \right\rceil \quad (2)$$

In the simulation model, we have considered $a=4.3$ km, then, $n=2431$ and $L \approx 3$ from (2).

Since many areas (in the case under examination more than two thousand) are served by the same spot-beam, a lot of random factors influences the actual availability of satellite channels in a given area. According to the Central Limit Theorem, this situation has been modeled by assuming that the number of satellite channels available in an area, s , is a random variable with a truncated and discretized Gaussian distribution between 0 and $2L$, with mean value L and standard deviation $L/4$. Then, $s \in \{0, 1, 2, \dots, 2L\}$. According to the truncated and discretized Gaussian distribution, a probability $p(s)$ is associated with each value of s . If R satellite channels are already assigned to the terrestrial area and another call overflows from that cellular network, the probability that at least one satellite channel is available to serve the call, $P_{serv} | R$, is given by the complementary distribution function for variable s evaluated in $s=R+1$: that is,

$$P_{serv} | R = \sum_{s=R+1}^{2L} p(s), \quad P_{serv} | 2L = 0 \quad (3)$$

This channel request will be immediately served by the network with probability $P_{serv} | R$; otherwise, if the request is a new call arrival, it is blocked or if the request is due to a handover, it is queued for a maximum time T_q , waiting for an available satellite channel. We have assumed that T_q is proportional to T_s by means of a multiplying factor ε , which represents the degree of overlap between adjacent cells. We may consider that the greater ε is, the lower the risk of call dropping is. The maximum possible overlap between adjacent cells is characterized by $\varepsilon=0.5$. We have used a conservative estimate for ε in the suburban/rural area: $\varepsilon=0.05$. Therefore, if $T_s=300$ s, $T_q=15$ s.

Finally, it has been considered that a call re-routed from a congested terrestrial cell to the satellite system can be switched back to the terrestrial network (i.e., *satellite-to-terrestrial handover*) as soon as G terrestrial channels become available in the cell or it is managed by the satellite system for all its duration ($G=\infty$). The use of $G>1$ avoids continuous handovers between the terrestrial network and the satellite network and a heavy signaling load to be managed by the system. We have studied the two extreme situations: that is, $G=1$ and $G=\infty$.

Table 1: Statistics of the non-uniform traffic pattern

mean value	1
stand. deviation	0.647
maximum	2.0
minimum	0.1
max/min ratio	20.0

Table 2: Parameters of the IRIDIUM system

Number of satellites	66
Number of orbital planes	6
Orbital altitude	780 km
Approx. orbital satellite velocity	26 600 km/h
Number of spot-beams per satellite	48

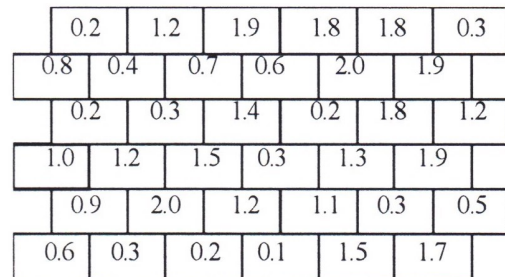


Fig. 1: Non-uniform traffic pattern.

4 - SIMULATION RESULTS

In this Section the simulation results are presented and compared in terms of blocking probabilities: P_{ba} , P_{drop} , P_{ns} . Curves denoted by “*terr.*” are related to the stand-alone terrestrial system; whereas, curves labeled by “*int.*” are related to the integrated mobile communication system. The priority level of the satellite channels with respect to the terrestrial ones is denoted by “*eq*” for equal and “*lo*” for lower priority. Finally, the FA DCA technique will be simply denoted by DCA in the graphs.

The comparison of the integrated mobile system and the stand-alone terrestrial cellular system in terms of P_{ns} is shown in Figs. 2 and 3 for uniform and non-uniform traffic loads, respectively.

In both graphs, as expected, the FA DCA assures a better resource utilization than FCA in the stand-alone terrestrial system. The performance of channel allocation techniques worsens when we pass from uniform traffic loads to non-uniform traffic patterns. However, the use of non-uniform traffics leads to the study of more realistic scenarios, where the advantages of DCA techniques (due to their intrinsic adaptability to spatially varying traffic demands) with respect to FCA are more evident (Fig. 3).

Among the resource management policies for the integrated system, the lowest P_{ns} is obtained by the “*lo*” strategy with the possibility of performing a satellite-to-terrestrial handover as soon as a terrestrial channel is available (i.e. the strategy denoted by “*int.*, $G=1$, *lo*, DCA”).

Moreover, the integrated mobile system with the strategy “*int.*, $G=1$, *lo*, DCA” performs better than the stand-alone terrestrial cellular system for low and moderate traffic loads approximately up to 5 Erl/cell, in the case of uniform traffic loads (Fig. 2). This advantage is more evident in case of non-uniform traffic, because the integrated system attains a better performance up to 7 Erl/cell (Fig. 3).

Referring to the strategy “*int.*, $G=1$, *lo*, DCA”, Figs. 2 and 3 show that P_{drop} is higher than P_{ba} and this entails that the more critical requirement is for P_{drop} ; then, in high mobility systems, it can be only fulfilled by a suitable prioritization strategy of handover requests over new call arrivals.

The model with satellite-to-terrestrial handovers ($G=1$) provides a higher quality of service with respect to the case with $G=\infty$ from low to medium traffic loads per cell, because there is an increased percentage of call blocked by the terrestrial system successfully handed over to the satellite network; for instance, this percentage is equal to 10% for $G=1$ and 6% for $G=\infty$ in case of non-uniform traffic and an average load of 6 Erl/cell. The difference between these cases disappears in the presence of high traffic loads, because terrestrial channels are congested and satellite-to-terrestrial handovers cannot take place.

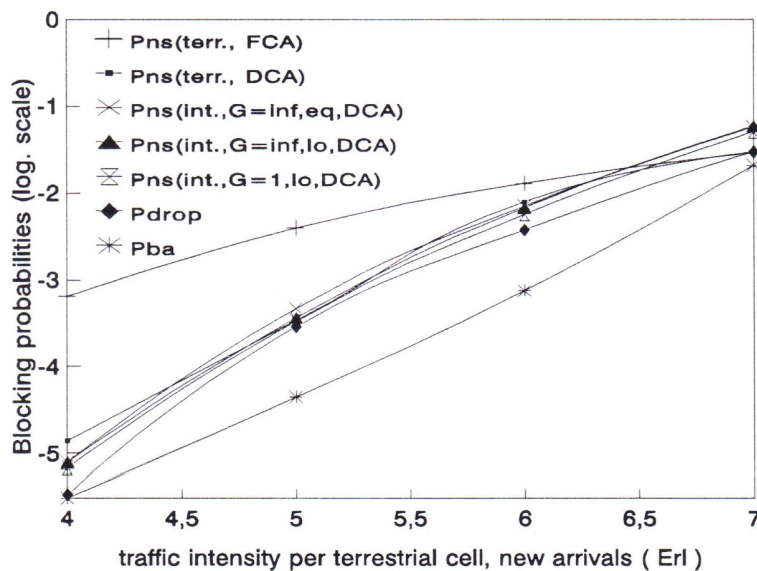


Fig. 2: Blocking probabilities for uniform traffic.

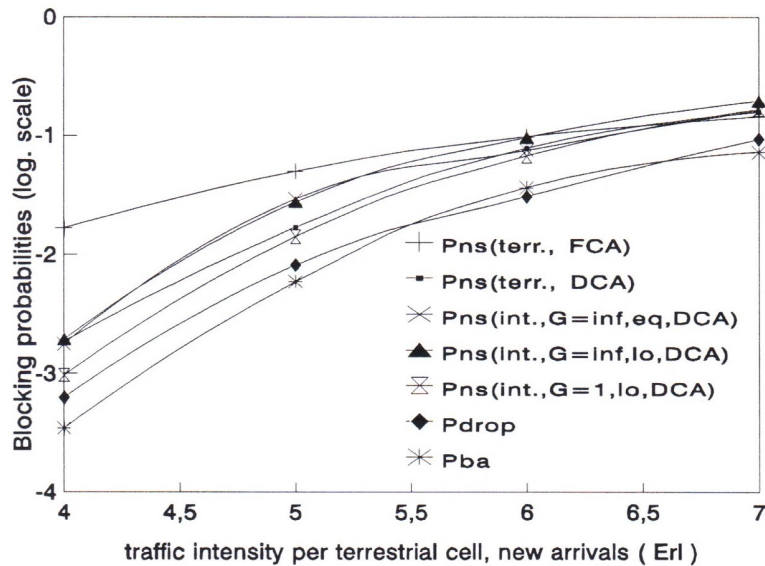


Fig. 3: Blocking probabilities for non-uniform traffic.

Finally, we have considered prioritization strategies with and without the queuing of handover requests to the satellite: FA DCA is used in the terrestrial network with non-uniform traffic load, lower priority is assigned to satellite channels and satellite-to-terrestrial handovers are permitted if at least one terrestrial channel is available (i.e., the strategy “*int., G=1, lo, DCA*”). In Fig. 4, the simulation results for models with $T_q=0$ s (i.e., no queuing for handover requests) and $T_q=15$ s are compared in terms of P_{ns} , P_{drop} and P_{ba} : no apparent advantage is achieved by the use of the queuing strategy in terms of P_{ns} ; of course, the queuing strategy allows a reduction of P_{drop} with respect to the technique without queuing, but this advantage is evident only for low traffic loads per cell. Such results are not very surprising; the number of satellite channels available per *area* is small, so they are most of the time occupied and the queue is full.

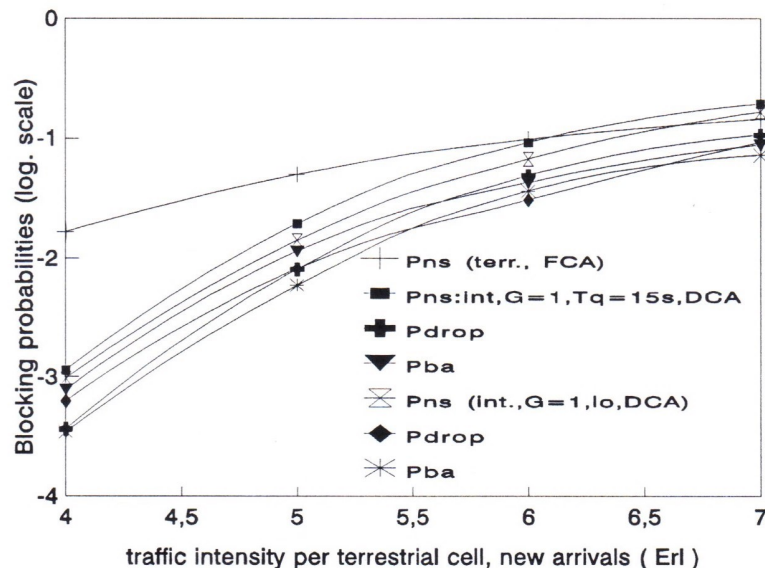


Fig. 4: Blocking probabilities for non-uniform traffic with or without queuing of handover requests.

5 - CONCLUSIONS

In this paper, several resource management strategies have been proposed for the future integrated satellite/terrestrial mobile communication system (UMTS). A simulation tool has been developed that allow us the comparison of different channel allocation techniques in terms of

blocking probabilities. The integrated system has outperformed the stand-alone terrestrial cellular system, regardless of the allocation techniques used and the traffic characteristics. Finally, the use of satellite-to-terrestrial handovers has permitted a better utilization of satellite resources because they allow an increase of the portion of calls refused by the terrestrial system that are handled by the satellite network.

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