An Efficient Technique for Dynamically Allocating Channels in Satellite Cellular Networks

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ABSTRACT - *This paper proposes an improved technique for dynamically allocating channels in mobile satellite cellular networks. Channel assignment on demand is performed on the basis of the evaluation of a cost-function. When the cell of a new call arrival has not available channels, a single channel reconfiguration in an interfering cell is attempted in order to accept a new call. Handover requests that do not receive immediate service can be queued for a maximum time. The scenario envisaged is Low Earth Orbit - Mobile Satellite Systems (LEO-MSSs). A performance comparison with other dynamic channel allocations has been carried out in order to highlight the higher efficiency of the dynamic technique proposed.*

I. INTRODUCTION

The steady growth in the cellular telephony market requires an ever increasing capacity in order to meet the range of services and the foreseen wide population of users of the future "Personal Communication Services" (PCS) [1],[2]. PCS will encompass, in a unique standard, the different technologies of cordless, terrestrial and satellite mobile cellular networks. At present, R&D efforts are addressed towards the definition of Mobile Satellite Systems (MSSs) that use a constellation of Non-GeoStationary Orbit (NGSO) satellites. In particular, Low Earth Orbit satellites (LEO-MSSs) are considered since they permit to relax the constraints on the budget link and allow the use of low-power hand-held mobile terminals. Several LEO-MSSs have been proposed, e.g., IRIDIUM (by Motorola), ARIES (by Constellation Communications Inc.), GLOBALSTAR (by Loral Qualcomm Satellite Services Inc.), TELEDESIC (the former CALLING, by Microsoft et al.). The working example assumed in this paper is given by the IRIDIUM system [3], which is formed by 66 satellites over 6 polar circular orbits at about 780 km of altitude. Each satellite covers a 48-cell-network with a multi-spot-beam antenna. However, the techniques described here can be directly applied also to other satellite orbital configurations. The inter-beam handover request procedure is assumed based on the signal quality received by the mobile user. Accordingly to a de-centralized implementation, the handover procedure is "*mobile controlled*": each active Mobile Station (MS) continuously checks the power level, p, received from the spot-beam managing it and compares this level with that relative to other "visible" spot-beams, p_i. A handover request is issued

by the MS to the satellite (currently managing it) whenever $p < p_i$ -h (h=hysteresis level) and p falls below a given threshold, s [4]. If a handover procedure cannot be completed in the destination cell of the mobile user the communication is dropped and lost. In this paper, an efficient Dynamic Channel Allocation (DCA) technique is proposed which achieves a performance improvement by allowing a channel rearrangement at the call arrival instant. Channel allocation performance has been derived in terms of probability that a call is not completely served, P_{ns}, owing to the initial blocking or the failure of a subsequent handover procedure (=call dropping). It will be shown that the DCA technique proposed attains the lowest P_{ns} values with respect to other approaches previously proposed in the literature.

II. A MOBILITY MODEL

The coverage area has been assumed divided into cells and each cell is illuminated by an antenna spot-beam from a satellite. All the cells are disposed according to a hexagonal regular layout and have a circular shape obtained by means of beam-forming in order to compensate the footprint distortion due to the spherical nature of the earth surface. It has been shown [5] that a convenient representation of the LEO mobility scenario is that of considering any MS moving relatively to the footprints of the antenna beams on the earth with a speed equal to the ground-track speed of satellites, V_{trk}. The user mobility will be characterized in what follows by the parameter α, defined as:

$$\alpha \triangleq \frac{2R}{V_{trk}T_m} \qquad (1)$$

where T_m represents the average call duration. Parameters R and V_{trk} depend on the satellite constellation altitude; moreover, R is also dependent on the Half Power Beam Width of the spot-beams from the satellite antenna. By considering a fixed value for T_m, the MS mobility increases if V_{trk} increases and/or R decreases (i.e., α decreases). In the IRIDIUM case, it has been considered $R = 212.5$ km and $V_{trk} \approx 26,600$ km/h. Further details about this mobility model are given in [5].

III. A DYNAMIC CHANNEL ALLOCATION TECHNIQUE FOR LEO-MSSs

In this section, a DCA technique is proposed to allocate resources efficiently. Propagation and interference

considerations were simply represented by the constraint that, if a channel is used in a given cell x, it cannot be re-used in two tiers of cells around that cell. These cells form the belt of interfering cells of x, $I(x)$. Accordingly, the minimum distance for two co-channel cells, D, (i.e., the *"reuse distance"*) has been set. Let us denote with $\Lambda(x)$, the set of the channels not used in x and in $I(x)$.

A) *Management of new call attempts*

Let us assume that a new call arrival must be served in cell x:

1) if it results $\Lambda(x) \neq \varnothing$, the best channel i^* to be allocated is selected according to the following rule:

$$C_x(i^*) = \min_{i \in \Lambda(x)} \{ C_x(i) \} \qquad (2)$$

Terms $C_x(i)$ in (2) denote the cost-function per channel i. This function will be defined later in this Section.

If more channels verify (2), a random choice is performed.

The channel allocation technique previously proposed in [5],[6] blocks the new call arrival if $\Lambda(x) = \varnothing$; conversely, the DCA technique under consideration permits to serve new call arrivals by means of the "Persistent Polite Aggressive" (PPA) approach [7] even if $\Lambda(x) = \varnothing$, as outlined below.

2) If it results $\Lambda(x) = \varnothing$, the PPA mechanism defines the elements (if any) of the set of couples, $\Omega(x) = \{(\beta, \delta)\}$, where the generic couple (β, δ) represents a channel β that results locked in cell x only by its use in cell $\delta \in I(x)$. Then, within $\Omega(x)$, we must exclude the couples (β, δ), where cell δ has no available channel:

$$\Gamma(x) = \{ (\beta, \delta) \in \Omega(x) : \Lambda(\delta) \neq \varnothing \} \qquad (3)$$

- If $\Gamma(x) \neq \varnothing$, each couple $(\beta, \delta) \in \Gamma(x)$ represents a possible channel rearrangement solution in an interfering cell of x to serve the new call arrival in x. Then, the most convenient channel rearrangement, characterized by the couple (β^*, δ^*), is performed:

$$\delta^* : Z\{\Lambda(\delta^*)\} = \max_{\Gamma(x)} \{ Z\{\Lambda(\delta)\} \} \qquad (4)$$

where $Z\{\theta\}$ gives the number of elements belonging to the discrete set θ.

In cell δ^*, channel β^* is de-allocated and the call in progress on β^* is passed on another channel according to the assignment criterion outlined in the first step of this algorithm. Then, channel β^* becomes available in cell x and it is used to serve new call arrivals.

- If $\Gamma(x) = \varnothing$, the call attempt in x is blocked and lost.

This algorithm is *"polite-aggressive"* since it tries to serve a new call arrival (otherwise blocked) by allowing a channel rearrangement in an interfering cell. Moreover, this technique is also *"persistent"* because it tries to obtain this result by considering each possibility given by the set $\Omega(x)$, without

limiting itself to only one or two attempts. In the following, it will be proven that the complexity introduced in the allocation algorithm by the second step is negligible and can be supported by the system.

The cost-function $C_x(i)$ used in (2) is described below. We start by considering the channels allocated according to a Fixed Channel Allocation (FCA) [5], assuming a reuse distance equal to D. Let $F_D(x)$ be the set of channels assigned to cell x according to FCA. A fixed allocation assures a distribution of channels among the cells of the network, with the minimum possible reuse distance, D. With the proposed technique, we select channels belonging to $F_D(x)$, whenever possible, in allocating channels to cell x. The allocation cost contribution for channel $i \in \Lambda(x)$, due to the interfering cell $k \in I(x)$, $C_x(k,i)$, can be expressed as:

$$C_x(k,i) = u_k(i) + 2(1 - q_k(i)) \quad , \quad \forall k \in I(x) \qquad (5)$$

Where $u_k(i)$ and $q_k(i)$ are given by:

$$u_k(i) = \begin{cases} 1, & \text{if } i \in \Lambda(k) \\ 0, & \text{otherwise} \end{cases} \qquad (6)$$

$$q_k(i) = \begin{cases} 0, & \text{if } i \in F_D(k) \\ 1, & \text{otherwise} \end{cases} \qquad (7)$$

In defining the cost-function contribution $C_x(k,i)$, relative to the status of channel i in cell $k \in I(x)$, the first term takes into account the availability of channel i in cell k, while the second term takes into account if channel i belongs to the optimal set for cell k (i.e., $F_D(k)$). This second term is weighted by a factor 2 to follow as much as possible the FCA channel distribution. Therefore, the overall cost function can be obtained as:

$$C_x(i) \triangleq q_x(i) + \sum_{k \in I(x)} \{ C_x(k,i) \} \quad , \quad \forall i \in \Lambda(x) \qquad (8)$$

where the term $q_x(i)$ is introduced in (8) because it is preferable to allocate in x a channel $i \in F_D(x)$.

B) *Management of inter-beam handover requests*

Let us assume that an active MS is approaching the borders of its cell x (=beam footprint) and is going into an adjacent cell y. In this new cell, the MS must be provided with a new channel to carry on the communication; subsequently, the channel used in the source cell must be released by the MS.

As a matter of fact, we assume that there is a certain degree of overlap among the footprints on the earth of adjacent beams. Within an overlap area an MS can receive the signal from two beams. This is a prerequisite to allow the Queuing of Handover requests (QH). Let us assume that an MS sends a handover request as soon as it enters the overlap area between cell x and cell y. The maximum waiting time for any handover request,

t_{wmax}, can be derived as the time spent by an MS to cross the overlap area with a speed V_{trk}. According to the proposed mobility model, we have assumed that the overlap area extension crossed by an MS is fixed and equal to $R/5$. This is a conservative choice that considers a purely geometric overlap of circular coverage areas disposed according to a hexagonal layout, as explained in [5]. Therefore, t_{wmax} results in:

$$t_{wmax} = \frac{\alpha\, T_m}{10} \qquad (9)$$

Of course, we must admit that the overlap area extension and then t_{wmax} are random variable, that depend on several parameters, such as the direction of MS (relative to the spot-beam footprint) motion, the satellite antenna characteristics and the propagation conditions, but this aspect will not be addressed here where the deterministic value of t_{wmax} given by (9) is used. An inter-beam handover request sent by an MS is served according to the following steps:

1) if it results $\Lambda(y) \neq \varnothing$, an arrival due to handover is served in cell y and a call termination (see point C of this Section) is performed in cell x,

2) if it results $\Lambda(y) = \varnothing$, the handover request is queued waiting for an available channel in cell y. In the meantime, the communication is served by the source cell. The queue service discipline is FIFO. A handover request leaves the queue owing to one of the three following reasons:

- *the handover procedure is successful*: the handover request is served, before the call is ended and the maximum queuing time has expired.

- *The handover procedure has been useless*: the associated call ends before the corresponding handover request is served and the maximum queuing time has expired.

- *The handover procedure fails and the associated call is dropped*: the handover has not been performed within t_{wmax} and the call is not ended before the maximum queuing time has expired.

C) *Management of call terminations*

In order to improve the performance of a DCA technique, we propose that whenever a call termination occurs in a cell x (due either to the end of the call or to handover), the channel assignments in x must be defined again to de-allocate in x the channel at maximum cost. The cost-function to be used in this case is complementary to that defined at point A to allocate new call arrivals. Then, if the most convenient channel to be de-allocated is different from the channel released due to the call termination, a channel rearrangement (i.e., intra-beam handover) is required.

In the following, we will denote with DCA the technique previously described in [5], with DCA-QH the same allocation technique with queued handover requests [5] and with PPA-DCA-QH a further refinement of the DCA-QH algorithm with the PPA policy is used to manage new call attempts.

IV. A FOLDED NETWORK OF CELLS

The simulated network is parallelogram shaped; this is a common choice in the literature to study terrestrial cellular systems. However, in order to adapt this topology to the different characteristics of global MSSs, where the cellular network is three-dimensional, we define a folded network of cells to obtain that each cell has a complete belt of interfering cells. We denote with N the number of cells per side in the cellular network. Each cell of the network has an identification number: $n = 1, 2, 3, \ldots, N^2$ (see Fig. 1, where $N = 7$). Let us denote with Π the set of cells belonging to the simulated network: $\Pi = \{1, 2, 3, \ldots, N^2\}$. Moreover, an oblique reference with the origin in the center of the cell No. 1 is used, as shown in Fig. 1. If we normalize the distance among two adjacent cell centers, each cell center is denoted in this reference by a couple of integer numbers (ξ, η). We assume that the belt of interfering cells of cell x, (i.e., $I(x)$) is formed by two tiers of adjacent cells. Then, the two orders of more external cells in the parallelogram shaped network have an incomplete belt of interfering cells and form the set of "*border*" cells, B. Consequently, we name "*central*" cells those cells belonging to the set $\Pi - B$. Let us consider a generical cell $z \equiv (\xi_z, \eta_z)$ on the border of the network; a generical cell $k \in I(z)$ has the following coordinates: $k \equiv (\xi_z + a, \eta_z + b)$, where $a, b \in \{0, 1, 2, -1, -2\}$ and $|a| + |b| \neq 0$.

- If $k \in \Pi$, the interfering cell really exists;

- Otherwise, if $k \notin \Pi$, the interfering cell does not exist; then, k becomes a dummy interfering cell of z according to the following rule: the coordinates of the interfering cell $k \equiv (\xi_z + a, \eta_z + b)$ are transformed into $k \equiv (\xi_k, \eta_k)$, where $\xi_k = (\xi_z + a) \bmod (N)$ and $\eta_k = (\eta_z + b) \bmod (N)$. Therefore, a cell on a border of the simulated network interferes with border cells on the other side of the network. In Fig. 1, the dummy interfering cells for border cell No. 48 are shown.
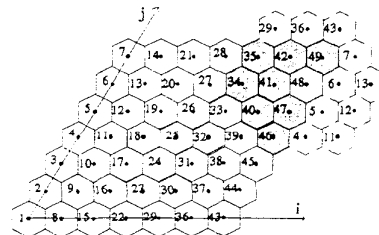

Fig. 1: An example of dummy interfering cells for the parallelogram shaped cellular network.

When a folded network is used an MS with a call in progress, which goes out of a side of the network, re-enters the network from the other side, thus ideally reproducing the behavior of an infinite network. This is a significant advantage when the performance of a channel allocation technique is evaluated jointly with a mobility model for the users. Owing to the chosen topology of the simulated network (i.e., parallelogram shaped) and the size of the belt of interfering cells, if we use the cost-function defined in (8), the previous folded network is valid only for values of N which are integer multiple of 7. Only for these special values of N the dummy interfering cells around a border cell have the nominal channel allocation that follows the same regular FCA pattern, $F_D(x)$, used for the network.

V. SIMULATION RESULTS

All the simulation results shown in this Section have been derived by assuming that:

- the call arrival process is Poisson independent from cell to cell with average call arrival rate per cell equal to λ,

- the call duration is exponentially distributed with average value equal to $T_m = 3$ min,

- the belt of interfering cells is formed by two tiers of cells,

- the simulated cellular network is parallelogram shaped with 7 cells per side (i.e., $N = 7$),

- a number of 70 channels is available to the system,

- the IRIDIUM mobility case is considered ($\alpha \approx 0.32$),

- the maximum queuing time is $t_{wmax} \approx 0.1$ min,

- an infinite queue capacity is assumed.

Let us denote with P_{b1} the blocking probability for new call arrival and with P_{b2} the inter-beam handover failure probability. In our simulations, we verified that the values of P_{b1} and P_{b2} as well as of P_{ns} are uniform for all the cells of the simulated network. This is due to the folded network where all the cells have a complete belt of interfering cells. Another interesting result was the insensitivity of the blocking results to the network dimensions (i.e., to the value of N which was assumed as an integer multiple of 7): e.g., the performance of the channel allocation techniques presented in this paper for $N = 7$, was also evaluated in the case of $N = 14$ and no significant difference was found. Therefore, the simulations carried out on a network of reduced dimensions give results that are also valid for networks of greater dimensions. This permits to speed-up the simulation runs.

In this paper, we have assumed that acceptable values of P_{b1} are of the order of 1-3%, while the acceptable values of P_{b2} are equal to 10^{-4} (ITU-T recommendations). The comparison among DCA, DCA-QH and PPA-DCA-QH techniques in the IRIDIUM mobility case is shown in Figs. 2, 3 and 4 for P_{b1}, P_{b2} and P_{ns}, respectively. We can see that the P_{b1} and P_{b2} performance of the DCA technique is unsatisfying, because of the high values of P_{b2}

all over the traffic range under consideration (i.e., $P_{b2} > 10^{-4}$). A possible solution to decrease these values of P_{b2} is achieved by queuing handover requests. Then, we consider the DCA-QH technique that privileges the handover service at the expenses of an increased blocking for the new call arrivals. Finally, if we use the PPA-DCA-QH technique, it is possible to reduce this increase in P_{b1} by accepting a negligible increase in P_{b2}.
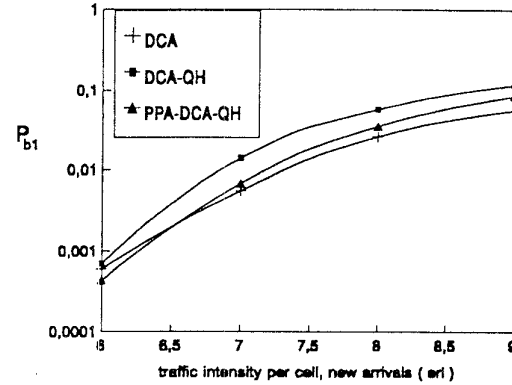

Fig. 2: P_{b1} performance of DCA, DCA-QH and PPA-DCA-QH (IRIDIUM mobility case).
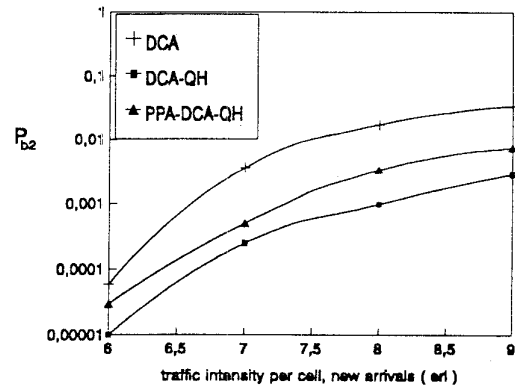

Fig. 3: P_{b2} performance of DCA, DCA-QH and PPA-DCA-QH (IRIDIUM mobility case).

The P_{ns} performance for DCA, DCA-QH and PPA-DCA-QH techniques is presented in the curves of Fig. 4. Moreover, for the sake of completeness, the results for FCA and FCA-QH derived from [5] are also shown in this graph. We can conclude that the PPA-DCA-QH strategy achieves the best performance.
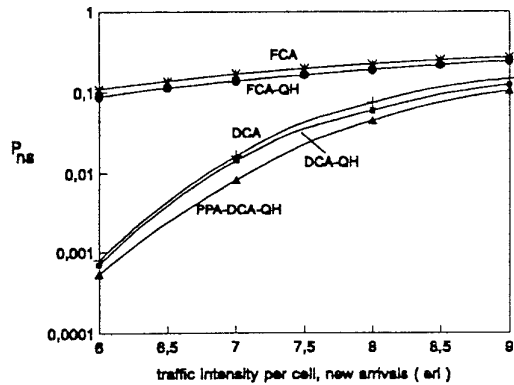
Fig. 4: P_{ns} performance of DCA, DCA-QH and PPA-DCA-QH (IRIDIUM mobility case).
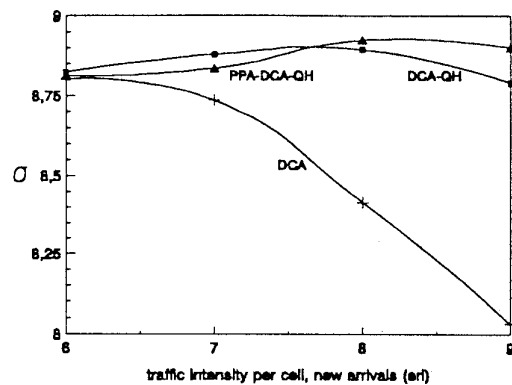

Fig. 5: Average signalling load per served call, σ, in the IRIDIUM case.

Another parameter to be evaluated in order to study the practical feasibility of the proposed channel allocation techniques is the signalling load carried out by the network. In particular, we consider only the signalling load supported by the network per served call to manage intra-beam (= "*channel rearrangement*") and inter-beam handover procedures, σ. The events during the call lifetime that contribute to σ and the relative contributions evaluated in terms of "*number of signalling operations*" are summarized in Table 1, taking into account the definition of the following parameter ϕ :

$$\phi \triangleq \begin{cases} 1, \ \textit{if a channel rearrangement is required} & (10) \\ 0, \ \textit{otherwise} \end{cases}$$

EVENTS	CONTRIBUTIONS TO σ
new call arrival	ϕ
handover	$2 + \phi$
physical end	ϕ

Table 1: Contributions to σ in correspondence with each event during call lifetime.

The question to be investigated here is whether the introduction of the PPA technique causes a significant increase in signalling load due to the channel rearrangements required to serve the new call arrivals which are otherwise blocked. To this end, we compare in Fig. 5 the σ performance for DCA, DCA-QH and PPA-DCA-QH techniques. This figure highlights that with DCA σ decreases when the traffic increases, because the handover failure probability, P_{b2}, increases and, then, the average number of handover procedures per call decreases. Whereas different behaviors are obtained in the cases of DCA-QH and PPA-DCA-QH techniques where the P_{b2} values are smaller than in the DCA case. The most interesting result is that PPA-DCA-QH technique does not increase σ with respect to DCA-QH technique from low to medium traffic intensity per cell.

VI. CONCLUSIONS

In this paper, an efficient DCA technique for applications in MSSs was proposed in order to cope with the increasing need of mobile satellite communications. The scenario envisaged was LEO-MSSs. A particular dynamic channel allocation technique based on the evaluation of a cost-function, namely DCA, was proposed. The queuing of handover requests was used to manage the user mobility. A performance improvement has been obtained in the case of the PPA-DCA-QH technique, where a new call arrival is accepted by the network even if there is not available channels by allowing a channel rearrangement in an interfering cell. Finally, it has been proven that the introduction of the PPA strategy does not increase the signalling load of the DCA-QH technique from low to medium traffic intensity per cell.

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