Performance Analysis of Dynamic and Fixed Channel Allocation Techniques in a LEO constellation with an "Earth-Fixed Cell" System

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Abstract— **This paper deals with the performance evaluation of different channel resource management techniques in Low-Earth Orbit (LEO) satellite systems based on an earth-fixed cell concept. Both fixed and mobile users have been considered resulting in several classes of users. Each class requires a given Quality of Service (QoS) and thus a fixed part of the shared resource. Two channel allocation techniques have been investigated : fixed channel allocation (FCA) and dynamic channel allocation (DCA). An analytical model has been derived to analyse the performance of the FCA scheme supporting different kinds of users. A performance comparison of FCA and DCA strategies has also been carried out by simulations as regards the blocking probabilities of each type of users.**

Keywords — **LEO, earth-fixed cells, handover, FCA, DCA.**

I. Introduction

The future third generation of mobile systems is referred to as IMT 2000 (International Mobile Telecommunications for the year 2000). A member of this familly is provided by the Universal Mobile Telecommunication System (UMTS). The aim of this new mobile communication technology is to offer new worldwide personalized services. Mobile Satellite Systems (MSSs) constitute an important component of UMTS. They will extend and complement the existing terrestrial cellular networks and provide global mobile telephony and data transmissions for both mobile and fixed users especially those located in rural, sparsely populated and remote areas. Several satellite constellation systems have been proposed, including Geostationary (GEO), low-earth orbit (LEO) and medium-earth orbit (MEO) satellite systems. The term LEO is used to identify satellites with orbiting altitudes between 500 and 2000 km above the earth's surface. LEO systems constitute an interesting solution since they offer small end-to-end delays and allow low-power requirements for both satellites and handheld terminals [1]. Another important advantage of LEO systems is their frequency reusability. Due to its closeness from the earth's surface, a LEO satellite involves additional areas in which the same frequency can be used by another satellite. This allows a high degree of channel reusability and increases the overall system capacity [2]-[4].

Depending on a coverage concept, two kinds of LEO systems are defined: *satellite-fixed cell* (SFC) and *earth-fixed cell* (EFC) systems. As in terrestrial cellular networks, the footprint of a satellite can be divided into cells, each one corresponds to a beam of the satellite antenna. When beams remain constant relative to the spacecraft, the corresponding cells on the ground move along with the satellite. This is what defines the satellite-fixed cell concept.

In SFC systems, cells move along with the satellites, so it is the satellite motion which introduces the handover process and not the mobile users motion. Therefore, users will experience two kinds of handover: from beam to beam (beam handover) and from satellite to satellite (satellite handover). It is important to notice that, unlike terrestrial systems, all users either fixed or mobile experience the handover procedure.

In a system that emploies earth-fixed cells, the earth surface is divided into predetermined cells that have fixed boundaries, just like in terrestrial cellular networks. Each satellite beam is assigned to a given cell for a fixed time period (as the satellite moves overhead). At the end of this period, all beams are reassigned to new adjacent cells. This paper only deals with earth-fixed cell systems.

EFC systems are intended to provide several services for both fixed and mobile users. The aim of this paper is to present, in the FCA case, a suitable mathematical model of such a system considering different user classes and to compare the performance of fixed and dynamic channel allocation techniques (FCA and DCA) under non-uniform traffic conditions.

The paper is organized as follows: Section II presents the concept of the EFC coverage and introduces the handover procedure in such systems. Section III deals with some preliminary assumptions. A mathematical description of the model is presented in Section IV. Fixed and dynamic channel allocation schemes are described in Section V. Finally, section VI presents and discusses simulation results obtained for both schemes.

II. EFC Systems

Implementing the EFC coverage means that the satellite is able to perform two main functions : beam steering and cell switching.

A. Beam steering

As satellite beams are assigned to the earth-fixed cells during a given time period and since the satellite is moving relative to these cells, each beam antenna has to adapt its direction to maintain the illumination of the corresponding cell. Thus, during the considered time interval, the beam steering is achieved and the beam-to-cell allocation remains fixed (see Fig. 1(a)).

Due to physical limitations, the steering angle of the antenna is bounded. This limitation fixes the time interval during which the beam steering is achieved. When this interval duration has elapsed, a new beam-to-cell allocation is performed.

Two steering techniques can be carried out: mechanical and electronic steering [5]. When the satellite motion relative to the earth surface is quite slow, such as in MEO satellite systems, the mechanical steering is more suitable. The electronic technique is chosen when the satellite velocity with respect to earth cells is high, as in LEO sytems.

B. Cell switching

When the beam steering time interval expires, the maximum steering angle is reached. This introduces the "cell switching" phase, which corresponds to a modification of the beam-to-cell allocation. The switching procedure is illustrated in Fig. 1(b). When the beam *Sat1-b1* covering cell $c1$ reaches its maximum steering angle, it frees cell $c1$ and takes over the entering cell $c2$. The other beams also move forward a row to take over the adjacent cell.

Most of the under-developing non-GEO projects providing multimedia services have adopted the EFC concept as Teledesic, Skybridge, and M-star LEO systems. They plan to use electronic steering and cell switching. Odyssey, which is a MEO system, also uses the EFC technique, but has adopted the mechanical steering rather than the electronic one.

C. Handover in EFC systems

The great advantage of using earth-fixed cells is achieved when a mobile user experiments a beam or a satellite handover. With satellite-fixed cells, this handover means that a new channel has to be allocated to the mobile user within the new beam. The call can be interrupted and dropped if no channel is available in the next serving beam. Moreover, the allocation process involves time and processing requirements at both terminal and satellite sides.

In EFC systems, the relatively small fixed cells provide a means to contour service areas to country boundaries. A database onboard each satellite defines the type of services allowed within each cell, and also ensures that interference to or from specific areas is avoided [6]. Communication channels (frequencies and time slots) are associated with each fixed cell, and are managed by the current serving satellite. As long as the user terminal remains within the cell, it keeps the same channel during the call duration, whatever is the serving beam or satellite. Channel reassignments will thus become the exception rather than the rule. Therefore, the EFC coverage offers significant advantages in terms of no handover failure probability for fixed users, and a low value for mobile ones.

Consequently, the handover failure probability, in EFC systems, depends on the number of mobile users which leave their cell during their communication's lifetime. Thus, this probability is a function of both users mobility and earth-fixed cell size. In under-developing EFC systems, cells sizes are quite small (53.3 km for Teledesic). Furthermore, systems designers are studying, for the future generation of LEO satellite systems, a new generation of efficient satellites which use extremely narrow beam antennas able to cover very small areas on the earth's surface. With such small earth-fixed cells, the frequency reuse factor is maximized, leading to an extremely efficient use of the spectrum and thus a large number of simultaneously active users. In such a context, the handover probability increases since the considered cell size is reduced. For our investigations, we consider small size cells systems.

III. Basic assumptions

The paper uses a Teledesic-like system data [6] as an example for numerical evaluations, but the obtained results are generally valid for all LEO systems based on EFC coverage. In Teledesic system, the earth surface is mapped into a fixed grid of approximately 20000 supercells, which are again divided into 9 cells. The supercell is a square of 160 km on each side. A satellite footprint encompasses a maximum of 64 supercells, i.e. 576 cells. Channel resources (frequencies and timeslots) are associated to each cell, and managed by the serving satellite.

In this paper, the system is assumed to be composed of a set of adjacent square cells supporting a non-uniform traffic. Moreover, we consider that the model supports different kinds of users. Fixed and mobile users are considered, and both of them can also be divided into different kinds according to a given criterion. In our simulations, we considered three types of users: M denotes mobile users and $F1$ corresponds to fixed users with a relatively low channel rate such those requiring services as data, facsimile, and other similar facilities. The third type $F2$ corresponds to higher channel rates supporting a wide range of fixed broadband services.

IV. Mathematical model

In this section, an analytical method to access the blocking probability for each class of users is presented. We assume that the system supports k customer types and contains M cells, each one has a finite capacity of C channels.

The model requires the following assumptions:

- New call arrivals for a type i user in cell j are assumed to be Poisson processes with a parameter $\lambda_{i,j,nc}$.

- A user with type i requires b_i units of channel resources; the user is blocked and cleared if fewer that b_i units of the total channel resource is available (Complete Sharing).

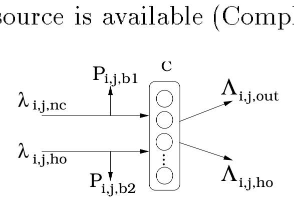

Fig. 2. Cell model.

- The channel holding time in a cell by a type i user is exponentially distributed with a parameter $\mu_{i,h}$.

- The communication's lifetime of a type i user is exponentially distributed with a parameter $\mu_{i,c}$.

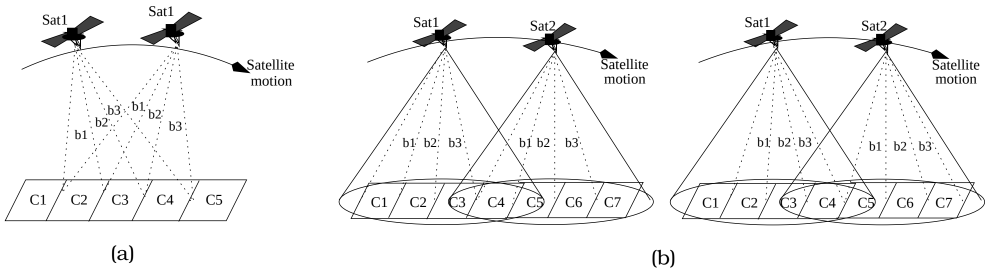

Fig. 1. Beam steering (a) and cell switching (b).

- $T_{jj'}$ denotes the probability for a given mobile user to go from cell j to cell j', and $N(j)$ is the set of neighbor cells of cell j.

Let us denote by $P_{i,j,b1}$ the blocking probability of new call attempts of type i users in cell j, and $P_{i,j,b2}$ the handover failure probability.

A. Traffic contributions in a given cell

Fig. 2 shows the various traffic components that ask for a channel in a given cell j. We can remark that the cell receives new call attempts of different type i users and also the handover traffic coming from the adjacent cells. Let $\lambda_{i,j,ho}$ denotes the handover arrival rate in cell j for users with type i.

The mean output rate can be expressed as follows:

$$\Lambda_{i,j} = \Lambda_{i,j,out} + \Lambda_{i,j,ho} \tag{1}$$

$$\Lambda_{i,j} = \lambda_{i,j,nc}(1 - P_{i,j,b1}) + \lambda_{i,j,ho}(1 - P_{i,j,b2}). \tag{2}$$

The output handover traffic rate of cell j is given by:

$$\Lambda_{i,j,ho} = \frac{\mu_{i,h}}{\mu_{i,h} + \mu_{i,c}}(\lambda_{i,j,nc}(1 - P_{i,j,b1}) + \lambda_{i,j,ho}(1 - P_{i,j,b2})). \tag{3}$$

However, approximating the handover call arrival process by a Poisson process and seeing that handover and new call traffics are treated within the server (cell) in the same manner (no priority of one traffic over the other), we can group together the two probabilities $P_{i,j,b1}$ and $P_{i,j,b2}$ into a global blocking probability $P_{i,j}$.

Then the equation (3) becomes:

$$\Lambda_{i,j,ho} = \frac{\mu_{i,h}}{\mu_{i,h} + \mu_{i,c}}(\lambda_{i,j,nc} + \lambda_{i,j,ho})(1 - P_{i,j}). \tag{4}$$

We face here a fixed-point problem since the input handover traffic depends on the output one:

$$\lambda_{i,j,ho} = \sum_{j' \in N(j)} T_{j'j}\Lambda_{i,j',ho}. \tag{5}$$

The problem can be solved using an iterative method through the following linear system [7]:

$$\begin{cases} \lambda^0_{i,j,ho} = \sum_{j' \in N(j)} \Lambda^0_{i,j',ho} T_{j'j} \\ \Lambda^0_{i,j,ho} = \frac{\mu_{i,h}}{\mu_{i,h}+\mu_{i,c}}(\lambda_{i,j,nc} + \lambda^0_{i,j,ho}) \end{cases} \tag{6}$$

In each step n of the iterative method, the value of $\lambda^n_{i,j,ho}$ is computed and compared to the one found in the previous step. The procedure is repeated until a convergence criterion ϵ is reached: $\| \lambda^{n+1}_{i,j,ho} - \lambda^n_{i,j,ho} \| < \epsilon$. The first value $\lambda^0_{i,j,ho}$ is computed disregarding the blocking probabilities as shown in the system (6).

Once the handover arrival rate $\lambda^0_{i,j,ho}$ is derived, the blocking probability of each user class can be determined. All C channels of a given cell j are shared by new calls and handover traffics. Therefore, the analytical structure of this problem is essentially the same as in a system where several types of customers share a finite group of servers. The sharing policy considered in this paper is known as the Complete Sharing (CS) [8].

Let us consider the state description n:

$$n = (n_1, n_2, ..., n_k)$$

where n_i = number of type i customers using the cell channels. The remaining notations needed are as follows:

$$n_i^+ = (n_1, ..., n_{i-1}, n_i + 1, n_{i+1}, ..., n_k)$$
$$n_i^- = (n_1, ..., n_{i-1}, n_i - 1, n_{i+1}, ..., n_k).$$

The set of allowable states is referred to as Ω (determined by the CS policy). It has been shown that the state probabilities can be expressed in a product form [8]:

$$P_j(n) = \prod_{i=1}^{k} \frac{\rho_{i,j}^{n_i}}{n_i!}.G^{-1}(\Omega) \qquad \forall n \in \Omega \tag{7}$$

where the normalization constant $G(\Omega)$ is defined by the formula:

$$G(\Omega) = G(C,k) = \sum_{n \in \Omega} \left(\prod_{i=1}^{k} \frac{\rho_{i,j}^{n_i}}{n_i!} \right) \tag{8}$$

and $\rho_{i,j} = \lambda_{i,j}/\mu_{i,c}$ given that $\lambda_{i,j} = \lambda_{i,j,nc} + \lambda_{i,j,ho}$.

The probability $P_{i,j}$ that a type i arrival is blocked in cell j is given by:

$$P_{i,j} = \sum_{n \in B_i^+} P_j(n) \tag{9}$$

where $B_i^+ = \{n \in \Omega : n_i^+ \notin \Omega\}$. B_i^+ denotes the set of blocking states for type i users.

The probability $P_{i,j}$ can be written as:

$$P_{i,j} = \sum_{n \in B_i^+} P_j(n) = 1 - \sum_{n \in \Omega - B_i^+} P_j(n) \tag{10}$$

$$P_{i,j} = 1 - G^{-1}(\Omega) \sum_{n \in \Omega - B_i^+} \prod_{i=1}^{k} \frac{\rho_{i,j}^{n_i}}{n_i!} = 1 - \frac{G(\Omega - B_i^+)}{G(\Omega)} \quad (11)$$

thus,

$$P_{i,j} = 1 - \frac{G(C - b_i, k)}{G(C, k)}. \quad (12)$$

Computing the normalization constant $G(\Omega)$ involves significant computation problems especially for large size systems. Therefore, to bypass this problem, a Buzen-type recursion expression was found by Kaufman [8], considering the distribution of the number of allocated resource units. Let $q(m)$ be this quantity:

$$q(m) = \sum_{\{n: n \bullet b = m\}} \prod_{i=1}^{k} \frac{\rho_{i,j}^{n_i}}{n_i!} \cdot G^{-1}(C, k) \quad (13)$$

where $m = n \bullet b =$ total number of occupied resource units. The recursion expression is as follows:

$$q(m) = \begin{cases} \frac{1}{m} \sum_{i=1}^{k} \rho_{i,j} b_i q(m - b_i) & m > 0 \\ 0 & m < 0 \\ G^{-1}(C, k) & m = 0 \end{cases} \quad (14)$$

At this step, the probability $P_{i,j}$ is determined using $\lambda_{i,j,ho}^{0}$. With these two values, $\Lambda_{i,j,ho}^{1}$ can be computed using system (6). The iterative procedure is repeated until the convergence criterion ϵ is reached.

V. Channel allocation techniques

Two different cells may reuse the same communication channel only if they are at a suitable distance, called reuse distance D, which allows tolerable levels for co-channel interference. We will describe below two channel allocation techniques we used for our simulations : FCA and DCA schemes.

A. Fixed channel allocation (FCA)

With fixed channel allocation, the full set of A available channels of the system is divided into S equal groups each composed of A/S channels. Regular groups of S cells (clusters) are formed such that the frequency reuse distance is maximized. Decreasing S (the cluster size) increases the frequency reuse. However, S must be large enough to provide sufficient frequency reuse distance and guarantee the required carrier to interference ratio (CIR).

A set of A/S channels is permanently assigned to each cell. A new call can be served only if a free channel is available in the set of the cell. If all channels are used, the new call will be blocked and lost even if other channels are available within the frequency reuse area (cluster).

For high network loads, fixed channel allocation is efficient if the traffic is equally distributed among the cells. For a non-uniform traffic, a complex planning is required to allocate more channels in the cells where a higher traffic is expected. Therefore, for varying traffic loads and non-uniform traffic, more flexible allocation strategies are necessary [9], [10].

B. Dynamic channel allocation (DCA)

With dynamic channel allocation, all channels are kept in a common pool. Any channel can be temporarily allocated to any cell, provided that the constraint on the reuse distance is fulfilled (a given signal quality can be maintained). All DCA schemes evaluate the cost of using each available channel and choose the one which introduces the minimum cost.

In satellite systems, a dynamic channel allocation means that all channels of the satellite are variably shared by all beams. The satellite can be a centralized controller which holds the pool and assigns the minimum cost channel to an initiated call.

Several DCA schemes were proposed. For our implementation we have chosen the algorithm described in [11]. The scheme uses a bookkeeping procedure that keeps track of the status and availability of channels in each cell. Let A_{kc} be the number of cells which currently interfere with channel k in cell c including cell c itself. Therefore, if $A_{kc} = 0$, channel k is available in cell c. It means that none of the calls in progress in the system interferes with channel k in cell c. Thus, only when $A_{kc} = 0$, channel k may be allocated to a new call in cell c. The proposed algorithm applies several channel allocation policies in the case where several channels are available. For our investigations, we have chosen the policy that allocates the first available channel. Further details on this algorithm are given in [11].

VI. Simulation results

In this section, the performance of channel allocation techniques FCA and DCA have been derived by simulations. The used parameter values are:

- two tiers of interfering cells (for FCA);

- the average call duration is 3 minutes for mobile users and 4 minutes for fixed ones;

- the simulated cellular network is a grid of square shaped cells folded onto itself with six cells per side;

- the system has 180 channels, thus 20 channels/cell are available with FCA;

- the proportions of users groups are assumed to be 20% for users with a type M (requiring one channel), 50% for type F1 (requiring one channel) and 30% for type F2 (requiring two channels);

- the system supports a non-uniform traffic distribution.

Fig. 3 plots the handover blocking probability P_{b2} for the FCA scheme. The figure indicates that the analytical analysis is consistent with the simulation study.

Fig. 4 shows different blocking probabilities as a function of the traffic load for the FCA scheme. A global call blocking probability P_{b1} and a class call blocking probability (M, $F1$, and $F2$) relative to each type of users are represented. Moreover, the handover dropping probability P_{b2} resulting from the mobile traffic has also been derived.

As stated in the analytical model (section IV), we can note that the behavior of P_{b2} is basically the same as P_M since handovers are not queued and have the same service priority as new call arrivals. Furthermore, as users of type

F1 require the same number of channels as type M users, blocking probabilities $F1$ and M are quite equal. However, $F2$ shows a higher blocking probability since the users of this class require more channels than the other kinds of users.

Performance of FCA and DCA schemes are shown in Fig. 5 and Fig. 6 in terms of P_{b1}, P_{b2} and all call blocking probabilities of different classes. We can notice, in both figures, that the DCA scheme outperforms FCA for medium and low traffic loads, but in the presence of congestion there is a trend inversion. We expect that the performance of DCA can be enhanced by implementing a rearrangement technique at call termination times. Furthermore, queueing of handover requests and handover prioritization schemes permit to achieve a better service quality for both FCA and DCA. The impact of these considerations will be investigated in our future works.

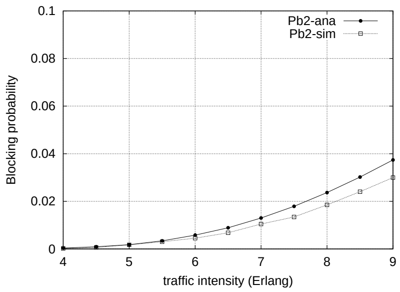

Fig. 3. Performance of FCA - simulation and analytical results

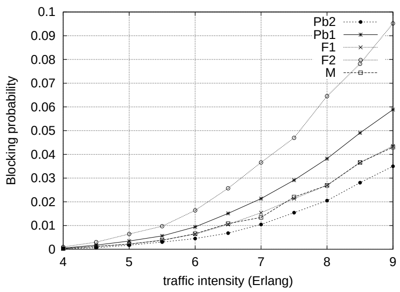

Fig. 4. Blocking probabilities of each type of users for FCA

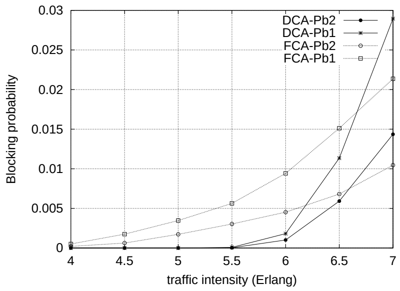

Fig. 5. FCA versus DCA, P_{b1} and P_{b2} performance

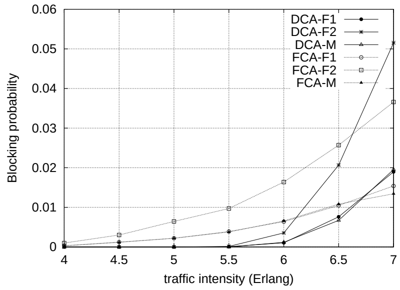

Fig. 6. FCA versus DCA, call blocking probabilities of each type of users

VII. Conclusion

This paper has presented a performance comparison of fixed and dynamic channel allocation techniques in a LEO satellite system. The case of earth-fixed cell systems was studied and different kinds of fixed and mobile users were considered. We developped a mathematical model in the FCA case by taking into account the various types of users. The model was based on the results presented in [8], and the complete resource sharing strategy was used to serve the different users. Performance evaluations and comparisons have been carried out in terms of blocking probabilities of the various users classes. In particular, we have proved by simulations that the DCA technique outperforms the FCA scheme for medium-low traffic loads.

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