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A Unified Framework for Handover Prediction and Resource Allocation in Non-Geostationary Mobile Satellite Networks

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A Unified Framework for Handover Prediction and Resource Allocation in Non-geostationary Mobile Satellite Networks

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Abstract— **Efficient satellite resource management and allocation techniques aim at providing reliable real-time service, taking into consideration the scarcity of resources and the large number of handovers. This paper presents algorithms and modules for accurate satellite and beam handover prediction at the SBS. The call is assigned to that path which provides the highest preference factor. Several alternative solutions for path selection are proposed and evaluated in terms of time consumption and computational intensity.**

Keywords— **Mobile satellite systems, handover, resource allocation, path selection**

I. INTRODUCTION

Existing terrestrial radio networks provide mobile communications services within limited regions. In order to extend the availability of these services and finally provide global coverage, several satellite systems have been proposed as a supplement to these networks. To provide service to small mobile or hand-held terminals with large enough elevation angle, MEO and LEO non-geostationary satellites are an appealing solution. Subject to such orbits, the satellite moves continuously relative to the earth and permanent global coverage entails the use of several satellites per orbit plane and several orbit planes per constellation. The traffic generated by a User Terminal (UT) is supported by satellites successively passing over the service zone and must be handed over from one satellite to the next. Moreover, diversity attribute is provided as a means of mitigating unpredictable call blockage [2].

Several scenarios for efficient handover and resource allocation have prevailed in literature. In the context of satellite handover, two strategies have been proposed [3]: Maximizing the instantaneous elevation angle or minimizing the handover rate for a user. In the former case, that satellite providing the highest elevation angle is selected, whereas in the latter case a satellite is chosen provided for as long as it remains visible.

The standard procedure of beam signal level monitoring, applied in cell reselection schemes in GSM terrestrial cellular networks is analyzed in [4] in the context of a satellite system. The proposed scheme may be integrated or optimized with a positioning system (e.g GPS), but it can also work without that. In [5] a combined handover algorithm is proposed, where transition decisions are dependent upon UT position and signal strength measurements.

One of the major problems in wireless networks is the large amount of exchanged signalling information. Due to reduction of the beams' size in non-GEO satellite systems, the number of handovers tends to increase. In order to save valuable satellite resources, signalling information must be kept to a minimum. In that aspect, *seamless handover* is a smart approach for TDMA-based systems, since it does not interrupt the call and requires minimum signalling exchanges [6]. A Satellite Base Station (SBS) which is served by a satellite cell α initiates a handover procedure towards a new satellite cell b when it perceives that the received power level for cell α is below a certain threshold. Thus, it switches its transmitter to the new carrier (while still receiving from the old cell α, until the network becomes aware of the handover) and provides resources for routing the forward traffic via the new cell b. Efficient handover is also directly related to Dynamic Channel Allocation techniques [7].

We investigate the problem of seamless handover from a "macroscopic" point of view. In section II we build the basic setup and mention preliminaries of a mobile satellite system and in section III we analyze the Path Selection algorithm. Section IV provides an insight into satellite and beam handover and turns attention in the maximum beam residence criterion, while section V focuses on evaluation of the beam monitoring procedure. In section VI numerical results are illustrated and conclusions follow.

II. PRELIMINARY STRUCTURES AND PRINCIPLES

The satellite component of a mobile satellite system essentially consists of r SBSs, n satellites with m beams per satellite footprint and a traffic distribution assignment according to a population of mobiles.

A. Geographical coordinate systems

To record the position of a satellite, SBS or UT, the following coordinate systems are considered:
1. ECI (Earth Centered Inertial) System : This system is based at the earth center. The x-axis is fixed towards vernal equinox and the z-axis is the polar axis.
2. ECEF (Earth Centered Earth Fixed) system : This system is based at the earth center and rotates with it. The positive x-axis points towards the intersection of the prime meridian and the equator (0^o longitude and latitude) and the

z-axis is the polar axis [1].
3. OF (Orbit Frame): Our innovation comprises this satellite-based system. Its x-axis points in the direction of the satellite, the positive z-axis points towards earth center and y-axis completes a right-handed triplet. This system provides a simple pictorial representation of the beam pattern, overcoming complicated patterns on the curved earth surface and is used in beam handover prediction. A point on the earth surface is mapped onto a two dimensional system (the z-dimension gets eliminated), so that residence within a satellite footprint s_i and a specific beam b_j can be easily detected. The transformation matrix from ECEF to OF system is provided in Appendix A.

B. Channel configuration

Broadcast Common Channels (BCCH) are shared between a number of users in a cell, whereas Traffic Channels (TCH) are Dedicated Channels and carry information for one user. A TCH frame comprises $N_s = 6$ timeslots and a BCCH frame consists of $N_b = 25$ timeslots, all of duration $6.66msec$ each.

III. BASIC ALGORITHMS EXECUTED AT THE SBS

A. Algorithm A: Beam selection for power measurements

In order to ensure the most appropriate cell selection at a transition, each UT continuously monitors the received BCCH signal of a proper set of adjacent satellite cells. The SBS periodically commands the UT to measure the BCCH signal strength of all visible serving and non-serving satellites and creates a list of the beams that will provide measurements and will serve as a confirmation to handover decisions. The list comprises a set $\mathcal{C}$ of beams currently covering the UT position and belonging to visible satellites from both the UT and the SBS, and a set $\mathcal{A}$ of approaching beams of serving satellites. The above sets of beams are candidates for a satellite and a beam handover respectively. Upon reception of this list via an uplink Common Control Channel (CCH), the UT performs measurements for each of these beams and sends the enhanced list back to the SBS on the downlink CCH. This procedure takes place both during signalling and traffic phase of a call and is depicted in firure 1.

B. Algorithm B: Path Selection

Path Selection algorithm provides input to Resource Allocation and takes place after Algorithm A and before a handover of any type or a non-diversity to diversity transition attempt. Each entry e_i of the list is initially a pair of satellite and beam indices (s_i, b_i). The list is modified as follows:
1. All possible combinations (e_i, e_j) of single elements are created and appended to the list.
2. Entries with a power measurement below a given threshold are eliminated, as indicating unreliable connection.
3. Double entries including an overloaded satellite are eliminated, as not eligible for diversity.
4. The list is ranked according to a predefined preference factor. Finally the first node of the list will have the highest preference factor.

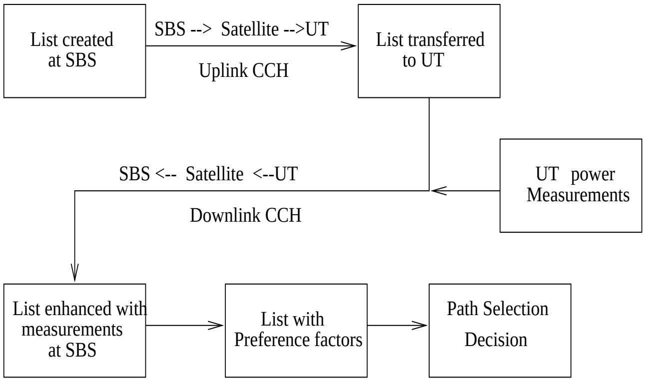

Fig. 1. Schematic representation of Path Selection procedure.

Each entry of the list represents a single or a diversity path, eligible for resource allocation. For each entry k the Preference Factor P_k is a function of the satellite elevation angle θ, the signal level I and the azimuth separation angle ϕ, in case the node denotes a diversity path. Thus

$$P_k = A \times \left(\frac{\theta_{k,1}}{\pi} + \frac{\theta_{k,2}}{\pi} + \frac{\phi_{k,12}}{2\pi} \right) + B \times (I_{k,1} + I_{k,2}) \quad (1)$$

In the above equation, I_k is a parameter illustrating the difference of the received signal level from the threshold value. The received signal strength is computed with a simplistic channel propagation model that takes into consideration UT position in a beam, multipath fading loss, shadowing loss and free space loss. A big azimuth angle provides a preferable path, since there are fewer chances that both paths will be corrupted due to an unpredictable blockage.

IV. CRITERIA FOR SATELLITE AND BEAM HANDOVER

A. Beam Handover

UT position is mapped to OF through a matrix, whose elements depend on current satellite position and velocity. This ephemeris data is used to determine future satellite locations, so that future positions of the UT in the OF are known. A binary search method of successive mappings of UT position to the OF determines the time to handover to virtually any desired accuracy (other errors notwithstanding).

When a UT enters a beam, it is mapped to the OF several times until a time interval of acceptable length (e.g. 1 minute) is found, where the UT resides in the current beam at the beginning of the interval and lies in a different beam at the end of the interval (Figure 2). Handover must occur sometime during this interval and predicted handover time is the midpoint of the interval. If the acceptable time inaccuracy is 1 minute, the handover prediction algorithm is accurate within 30 seconds. Equivalently, the contribution to the error in handover prediction is at most 30 seconds in this case. In reality several other factors contribute to prediction error, such as ephemeris data and UT position inaccuracy and UT mobility.

Assuming an initial horizon window length of W_0 minutes and an acceptable time prediction error of δ seconds, the

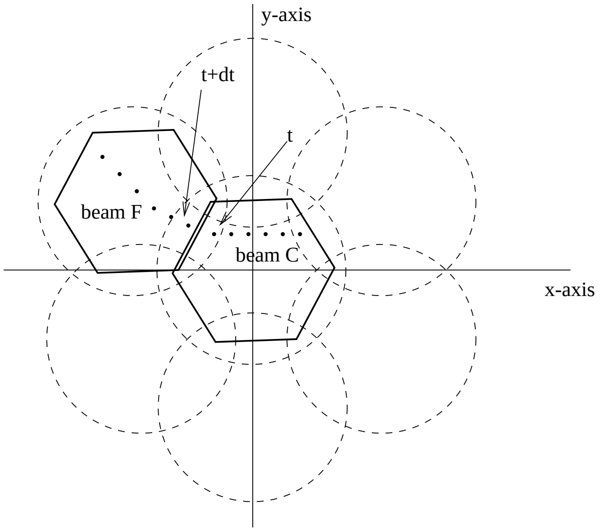

Fig. 2. Demonstration of beam handover from the beam located in the satellite nadir (C) to a neighboring beam (F).

number of OF mappings before convergence is at most:

$$N = \left\lceil \log_2 \frac{60W_0}{\delta} \right\rceil \tag{2}$$

B. Satellite Handover

For the satellite handover we have the procedure:

- Obtain the serving satellite(s) at current time t_c.
- Update those to a future time t_f, using the satellite ephemeris data.
- If $\theta_{UT}(t_f) \leq 10^o$ or $\theta_{SAN}(t_f) \leq 10^o$, then conclude that a satellite handover has occurred at some time $t^* \epsilon (t_c, t_f)$.
- Apply bisection idea on that interval.
- Stop after n^* iterations when $t_{f,n^*} - t_{c,n^*} < W$.
- The predicted satellite handover time is thus

$$t_s = \frac{t_{f,n^*} + t_{c,n^*}}{2} \tag{3}$$

C. Maximum beam duration criterion for beam handover

Motivated by the fact that additional handover occurances contribute to excess signalling load and significant transmission delays in the system, we propose a new criterion for handover event triggering. The basic characteristic is the minimization of satellite and beam handover rates, since the residence time in a cell is forced to be the maximum possible. Upon creation of the list with the candidate paths for transition, no preference factor computation is required. Simply the node containing the beam in which the mobile is predicted to stay the longest is selected as the transition beam. This beam may belong to the current serving satellite or not, providing thus the definition of beam handover or satellite handover after adopting this criterion.

This criterion is computationally less intensive than Path Selection. UT residence time for each beam in the list is computed by standard mappings in the OF satellite coordinate system and no elevation angle computation is required. More importantly, no power measurement information exchange between the UT and the SBS is necessary in order to confirm handover decisions.

V. ESTIMATION OF BCCH MEASUREMENT RECEPTION TIME

Given the UT and satellite positions, the required time for the execution of Path Selection and essentially the Resource Allocation algorithm, depends on the size of the created list at the SBS. A worst case scenario would be a UT with diversity connection in view of four satellites, where the maximum number of measured beams is 10. During signalling mode, it is highly recommended to minimize this time, so that transition to traffic mode occurs fast. The alternative method of measuring only one beam for each visible satellite has the obvious advantage of requiring less time to accomplish. The SBS receives the list and proceeds in allocating resources to the call, so that it enters traffic mode. In traffic mode however, this alternative method may result in a suboptimal path. Therefore, this method can be applied during signalling mode, where a fast switch to an initial path is required.

A. Assumptions

In a realistic environment, a dynamic BCCH Frequency Allocation Plan is employed for each beam, where the assigned BCCH frequency and timeslot is subject to changes. A relatively simplistic fixed allocation has been applied here, in which the BCCH timeslot for a beam is $BCCH = b_i \; modN_b$, where b_i is the beam index.

Without loss of generality, we assume a Random TCH timeslot allocation. A UT which is assigned to traffic slot x receives and transmits traffic during timeslots $x, x+1$ and $x+2$, which form the reference window x. For a non-diversity situation, the windows where the UT receives and transmits traffic are

$$W_m = x + mN_s, \; m = 1, 2, \ldots \tag{4}$$

The list is tranferred to the UT via the CCH channel in one message, which is equivalent to $p = 12$ bursts of $40msec$ each and its transmission time is considered to be practically independent of the list size. A BCCH burst is considered to be eligible for measurement if and only if it is received by the UT for one timeslot duration in a *free* reference window.

B. BCCH measurement procedure and list recovery

Suppose the list leaves the SBS at time $t = 0$. The time when the UT receives the complete list depends on the relative positions of the SBS, the satellite and the UT and can be approximated as

$$T_{r,UT} = d_{ss} + d_{c-s} + T_p + 12 \times 0.04 \;\; (sec) \tag{5}$$

where d_{ss} is the delay from the SBS to the satellite, d_{c-s} is the C-band to S-band frequency conversion delay, and T_p is the propagation delay from the satellite to the UT.

The UT intends to perform measurements of the BCCH bursts for beams in the list. BCCH bursts leave the satellite in series at the beginning of a reference interval with a period of N_b timeslots. The beginning of the n-th BCCH burst arrives at the UT at times

$$t_n = [N_b(n-1) + BCCH - 1] \times T + T_p \tag{6}$$

and is subject to measurement *only after* the measurement of the previous burst has been accomplished.

If t_n^k is the time instant when the beginning of the n-th series burst of the k-th element in the list is received by the UT then the above condition can be expressed as

$$t_n^k > T_{r,UT} + \sum_{\ell=0}^{k-1} X_\ell \tag{7}$$

where X_ℓ is the required time to measure the burst of the ℓ-th element in the list. Assume that $n = n_k^*$ is the minimum integer for which condition (7) holds. From that point, BCCH bursts will arrive sequentially, until the existence of an open reference window (three empty consecutive slots) is detected. The r-th order BCCH of the n_k^* BCCH series arrives at the UT at times

$$\tau^k_{n^*,r} = t^k_{n^*_k} + (r-1)N_b \tag{8}$$

and last for one timeslot. Assume $r = r_k^*$ is the minimum burst order until an unoccupied reference window is found, i.e

$$\tau^k_{n^*_k,r^*_k} \neq x + \rho N_s, \;\; \rho = m,\, m+1,\, m+2 \tag{9}$$

Measurements are performed instantaneously. The transfer time of the list with the measurements back to the SBS is

$$T_{s,UT} = T_p + d_{s-c} + d_{ss} + 12 \times 0.04 \; (sec) \tag{10}$$

As a consequence, the *total time* needed for the SBS to recover the list of measurements, will be

$$T_{total} = T_{r,UT} + T_{s,UT} + \sum_{k \,\epsilon\, list} X_k \tag{11}$$

where X_k is essentially $\tau^k_{n^*_k,r^*_k}$

VI. Simulation and results

A realistic satellite system environment has been built and a representative traffic distribution has been adopted. Specific terrestrial areas expose greater traffic density, whereas others (e.g. the poles, or areas covered by sea) are characterized by negligible traffic. The earth surface is projected onto a two dimensional plane and is divided into 288 $15^o \times 15^o$ squares, covering a surface from -180^o to 180^o longitude and 90^o to -90^o latitude. Calls are assumed to arrive in independent Poisson streams while call hold times follow the exponential distribution with mean $150sec$.

Depending on geographical location, the average elevation angle varies between 30^o and 48^o and the azimuth separation angle varies between 65^o and 135^o. In the simulation the contribution of those parameters and power measurements is taken into consideration, i.e $A = B = 1$ in equation 1.

Regarding diversity path allocations, it was observed that a transition for one of the two paths occurs for at least 88% of the cases. The transition of both diversity paths depended on the the proximity of the diversity monitoring time point and the handover time instant and occurred for $2 - 12\%$ of the cases.

In figures 3 and 4 we present comparative results about satellite and beam handover rates under the UT Position and the Maximum Beam Residence criteria in a region with moderate load (0.92 calls per second). By using the latter criterion, a reduction to beam handover rate up to $85 - 90\%$ was observed in steady state, while for heavier traffic load this reduction reached $35\% - 40\%$. A small drawback is the increased satellite handover rate for some time periods. Taking into consideration the low satellite handover rate ($3-4$ handovers per minute in steady state), this fact should not receive further attention. At any rate, under heavy traffic, the satellite handover rate is reduced by more than 50% as well.

Finally, results about the estimated time for Path Selection Algorithm execution were obtained by performing the experiment for an SBS. We notice that the involved average elapsed times are virtually independent of the location of the SBS. For each of the squares s_{ij} of the geographic configuration, we define an average time T_{ij}, a minimum time m_{ij}, a maximum time M_{ij} and a time variance $Var_{t,ij}$. Over the entire earth, we define the average T, average minimum m, average maximum M, the average variance Var_t and the absolute minimum and maximum measurement recovery times. We also define the absolute minimum m_α and absolute maximum M_α times. Results are summarized in table I. The measurement method using only one beam per satellite reduces the measurement recovery time by 60% on the average. Average minimum and maximum times and the variance of the elapsed time reduce accordingly. Taking into account the specifications about the maximum waiting time tolerance during call set up, the percentage of cases when only one beam per satellite is used can be derived.

VII. Conclusion

A unified simulation framework for a high-level study of handover and resource allocation has been presented and some alternatives of transition path selection have been proposed and evaluated in terms of handover rate and time consumption. Further study should focus on viewing the system from the aspect of channel allocation.

VIII. Appendix A

Transformation matrix between ECEF and OF coordinate systems

The transformation matrix is a 3×3 matrix that relates the ECEF an d OF coordinate systems and is obtained as follows:

1. Get the satellite position and velocity vectors in the ECEF coordinate system, $\vec{P}(t)$ and $\vec{V}(t)$ and the corresponding magnitudes $|\vec{P}(t)| = R_E + h$ and $|\vec{V}(t)| = 2\pi(R_E + h)/T$.
2. Evaluate the vector $\vec{\gamma}(t) = -\vec{P}(t) \times \vec{V}(t)$.

3. Get the third row of the transformation matrix as:

$$\vec{r}_3 = -\frac{\vec{P}(t)}{|\vec{P}(t)|} \tag{12}$$

4. Get the second row of the transformation matrix as

$$\vec{r}_2 - \frac{\vec{\gamma}(t)}{|\vec{\gamma}(t)|} \tag{13}$$

5. Get the first row of the transformation matrix as

$$\vec{r}_1 = \vec{r}_2 \times \vec{r}_3 \tag{14}$$

IX. APPENDIX B

COMPUTATION OF AZIMUTH SEPARATION ANGLE

The azimuth separation angle is the angle on the earth surface between arc L_1 connecting UT position and subsatellite point S_1 of first satellite and arc L_2 connecting UT position and subsatellite point S_2 of second satellite.

The function $D(\cdot,\cdot)$ computes the distance of two points P_1, P_2 with given longitudes and latitudes $P_1(\phi_1, \theta_1)$ and $P_2(\phi_2, \theta_2)$ on the earth as

$$D(P_1, P_2) = 2\tan^{-1}\left(\frac{\sin\alpha_x}{\sin\alpha_y}\,\tan\frac{a_1 - a_2}{2}\right) \tag{15}$$

where

$$\alpha_x = arctan\left(\frac{\cos((a_1 - a_2)/2)}{\cos((a_1 + a_2)/2)} \times \frac{1}{\tan(a_{12}/2)}\right) \tag{16}$$

$$\alpha_y = arctan\left(\frac{\sin((a_1 - a_2)/2)}{\sin((a_1 + a_2)/2)} \times \frac{1}{\tan(a_{12}/2)}\right) \tag{17}$$

and $a_1 = \pi/2 - \theta_1$, $a_2 = \pi/2 - \theta_2$,

$$a_{12} = \begin{cases} \phi_1 - \phi_2 & \text{if } \phi_1 - \phi_2 < \pi \\ 2\pi - (\phi_1 - \phi_2) & \text{otherwise} \end{cases} \tag{18}$$

The azimuth angle is calculated using spherical trigonometry as

$$\phi_{azim} = \frac{\cos(D(S_1, S_2)) - \cos(D(S_1, UT))\cos(D(S_2, UT))}{\sin(D(S_1, UT))\sin(D(S_2, UT))} \tag{19}$$

TABLE I

STATISTICAL RESULTS OVER THE ENTIRE EARTH FOR THE MEASUREMENT RECOVERY TIME FOR AN SBS.

Quantity	Entire list	One beam per sat
T	3.405 sec	2.063 sec
m	1.741 sec	1.258 sec
M	5.506 sec	3.167 sec
Var_t	0.597 sec	0.159 sec
m_α	1.432 sec	1.135 sec
M_α	7.283 sec	4.221 sec

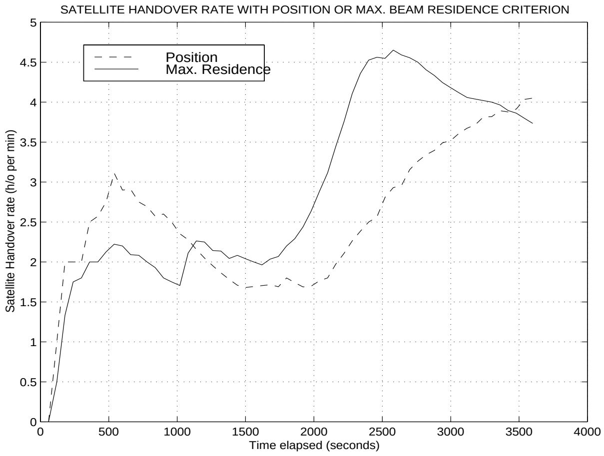

Fig. 3. Comparison of satellite handover rate under UT position or maximum beam residence time triggered handover event at a region with 0.92 calls/sec.

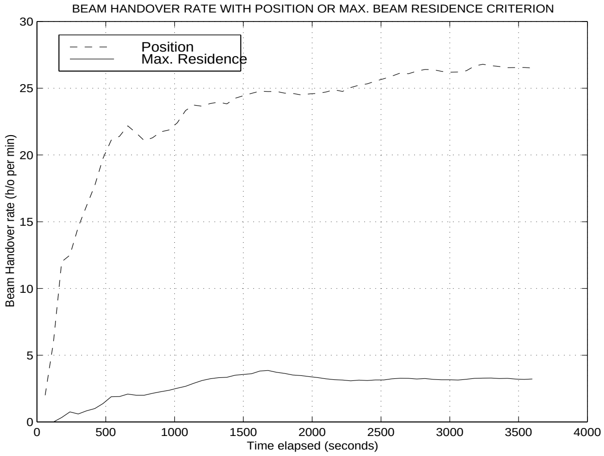

Fig. 4. Comparison of beam handover rate under UT position or maximum beam residence time triggered handover event at a region with 0.92 calls/sec.

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