Problems by Simulation and Analysis of the Mobile Satellite Systems

Vladimir Obradovic
Communication Networks, Aachen University of Technology

ABSTRACT

In this work the comparison between analytical and simulative approaches for investigation of mobile satellite systems (MSS) has been presented. Main parameters for calculation of the capacity i.e. new call and handover blocking probabilities of MSSs have been identified. These parameters have been determined analytically and by simulation, where it was possible. The differences by results obtained by analysis and simulation have been identified and their cause was clarified. For that purpose it was necessary to use different simulators. Some of them reflected the real system and the other have neglected some effects in the same way like it was necessary in analytical work. The main results show that the most differences are due to neglecting of real geometrical shape of the cells and because of edge effect. Less impact had, for analysis necessary, approximation of the channel holding time (CHT) and handover arrivals distributions.

INTRODUCTION

The common approach to estimate the performances of some system or scheme is to use analytical methods. This methods should usually be validated and compared with simulations. However, if the analytical modelling and estimation is not possible only the simulation tools have to be used. This case occurs if some of the needed parameters for analysis are not known or if it is not possible to calculate them because of too complicated relations. The most often case is that systems could be analytically modelled if some simplifications are used. The question is how the simplifications affect the results and how far is allowed to go with simplifications.

This work deals with comparison of the analytical and simulation methods for traffic modelling, capacity calculations and resource management in the Low Earth Orbit (LEO) MSSs. In the following chapters, firstly the capacity calculations by LEO MSSs and necessary parameters will be described. In that part the short overview of the analytical process will be given. It follows simulators description. The results will be presented and compared. Finally, the reasons for differences between analytical and simulative results will be pointed out.

CAPACITY CALCULATIONS BY LEO MSSs

The distinguishing features of cellular mobile networks which set them apart from conventional circuit-switched networks are channel re-use and handover facility. These factors influence the capacity of the considered system. The aim towards it is tended is to have more capacity. However, a lot of limiting factors makes the disposed resource amount usually insufficient. Because of all this reasons the calculation of the capacity is of very big importance. For system analysis and capacity calculation a teletraffic model is proposed. The model takes into account the users mobility and allows evaluation in terms of parameters such as new call blocking probability, handover blocking and grade of service.

Each mobile satellite system can be seen as an open queuing network. For each cell (queue) there are new call arrivals and arrivals from neighboring cells. Handovers are modeled as transitions between queues: after spending a certain amount of time in a cell, a customer may either terminate the call or attempt a handover to another cell, with a certain probability. The time spent in a cell before either call termination or handover is assumed to have a negative exponential distribution. This assumption is necessary in order to be able to perform analytical calculations. This open queuing network can be described as follows:

- Total number of available channels is N
- New call requests arrive to the queue as a Poisson process
- A user moves from cell j to the surrounded cell with a rate m_h
- A user leaves the network with a rate m_n

and is depicted in figure 1.

A user will require service from the channel j for a time which is assumed to be negative exponentially distributed with the mean value m^{-1}. This is the channel holding time. After receiving this service the user will move to the surrounded cell with probability m_h/m. The call duration time, distinct from the CHT, has a negative exponential distribution with rate m_M.

With the traffic model described above, the performance of the mobile satellite systems can be evaluated. When there is no blocking in the system, analytic expression can often be found for the equilibrium probabilities.

When the blocking in the network is considered, the analytic expression becomes more complicated and several assumptions need to be made.

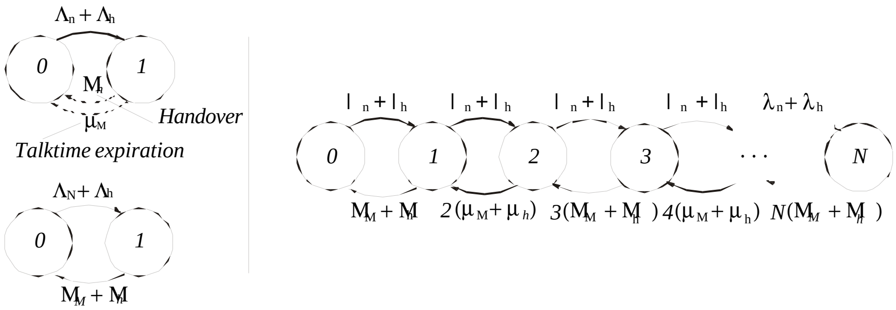

Figure 1. Markov chain state-transition diagram

However, this assumptions introduce an additional error source by MSSs. Especially, the nature of the inter arrival processes consisting of the both, the new call attempts and the handover call attempts, as well as the characteristic of the channel holding time distribution have to be investigated.

Evaluation Parameters

In this analysis the fixed channel allocation (FCA) has been considered. For the purpose of performance evaluation of the developed traffic model, several parameters need to be defined. The input parameters required by the analysis are:

- the geometry of the examined mobile satellite system
- the mean new origination call rate $l_n \rightarrow$ Poisson process
- the mean call completion rate $m_M \rightarrow$ Negative-exponential distribution
- the number of the channels available in the single spot cell N

The call duration can be represented by a negative exponentially distributed random variable T_M, with probability distribution function (pdf) given by,

$$f_{T_M}(t) = \begin{cases} 0, & t < 0 \\ m_M e^{-m_M t}, & t \geq 0 \end{cases} \tag{1}$$

The following performance indicators have been used and have to be calculated:

- *Blocking probability P_B*: The probability that a new call attempt is rejected,
- *Handover failure probability P_{fh}*: The probability that a handover attempt is unsuccessful resulting in the call being dropped.

From the users point of view, lost connections due to the rejecting of the handover call attempts while the call is in progress, are much less desirable, then the rejecting of the new call attempts. Therefore the grade of service (GoS) criteria is introduced. It takes both the new call and the handover blocking probabilities into account, weighted with appropriate factors in order to satisfy the above statement. This is in fact the most important parameter for evaluating of system performances, and is defined as follows [Walke]:

$$GoS = \frac{rejected\_connections + 10 * rejected\_handovers}{requested\_connections - rejected\_connections} \quad (2)$$

These three parameters offer good basis for a system performance analysis in terms of the capacity.

As stated above under certain conditions described traffic model can be presented by a Markov chain, which gives the possibility for convenient determination of the state blocking probabilities. Assuming that handover arrival is a Poisson process, and the channel holding time (T_H) probability distribution is negative exponential, P_B can be obtained using the Erlang B formula. It is obvious that in case that both, new and handover calls are sharing the same amount of available channels the probabilities that the new call or handover attempt will be blocked are equal. Therefore, for the non prioritized strategy:

$$P_B = P_{fh} = P_N = \frac{\frac{r^N}{N!}}{\sum_{k=0}^{N} \frac{r^k}{k!}} \quad (3)$$

where $r=(l_h+l_n)T_H$.

The further objective is to model and calculate all parameters that influence new call and handover blocking probability: channel holding time and handover inter-arrival rate l_h.

Modeling of Channel Holding Time

Mobile users located within a certain cell and wishing to initiate a call will be allocated a frequency channel by the cell site from among its free ones. It can be realized at this point that a channel occupancy time will in general not be equal to the call duration. Regarding the low satellite visibility times it is clear that the mobile will often change cells while involved in a single call. In this case, the occupancy time of a given frequency channel only corresponds to the fraction of the total call duration. Therefore, even if the call duration itself is still taken to be exponentially distributed, the channel occupancy time need not.

Basic Assumptions

The basic system model assumes that the new call origination rate is uniformly distributed over the whole service area. The average number of new call attempts is denoted as l_n. It is assumed that the number of the mobile users is large enough, thus the new call origination process can be modeled as the Poisson process. Further, it has been assumed that, in equilibrium, all the satellite cells have a similar traffic behavior. This means that performance values obtained for one cell are applicable to the whole system. It has been taken that the channel occupancy time ends when a call is terminated due to the talk time expiration, when the mobile involved in a call moves into another cell or if the new call or handover request has been blocked.

The circle cell shape has been considered in order to be able to perform analytical calculations. The variable cell intersection factor as well as the variable point where the mobile enters the neighboring cell can be used.
Because of the very high speed of the satellite cells, in order of kilometers per second, the speed of the mobile stations has been neglected in the analysis.

Channel Holding Time distribution

Channel holding time is defined as the amount of time that a call occupies a channel in a particular cell. When a call is originated in a cell and gets a channel, the call holds the channel until either the call is completed in the cell, or the mobile user moves out of the cell. If the handover was successful, the channel is held until the call is completed in the cell, or the mobile user again moves out of the cell before call completion.

After extensive calculations, provided in [2] and [3], the pdf of the CHT is given with:

$$f_{T_H}(t) = K_1 f_{T_{H_o}}(t) + K_2 f_{T_{H_t}}(t) \tag{4}$$

and the mean value is

$$T_H = K_1 \int_0^t t f_{T_{H_o}} dt + K_2 \int_0^{(1-\frac{a}{2})t} t f_{T_{H_t}} dt \tag{5}$$

where

$$K_1 = \frac{l_n(1-P_B)}{l_n(1-P_B) + l_h(1-P_{fh})} \tag{6}$$

$$K_2 = \frac{l_h(1-P_{fh})}{l_n(1-P_B) + l_h(1-P_{fh})} \tag{7}$$

$$f_{T_{H_o}}(t) = \begin{cases} e^{-m_M t}[m_M + \frac{4}{pt}\sqrt{1-(\frac{t}{t})^2} - m_M \frac{2}{p}(\frac{t}{t}\sqrt{1-(\frac{t}{t})^2} + \arcsin\frac{t}{t})], & 0 \le t \le t \\ 0, & \textbf{\textit{elsewhere}} \end{cases} \tag{8}$$

$$f_{T_{H_t}}(t) = \begin{cases} m_M e^{-m_M t}\sqrt{1-(\frac{t}{t})^2} + \frac{(t/t)e^{-m_M t}}{t\sqrt{1-(\frac{t}{t})^2}}, & 0 \le t \le (1-\frac{a}{2})t \\ e^{-m_M t(1-\frac{a}{2})t}\sqrt{a(1-\frac{a}{4})} & t = (1-\frac{a}{2})t \\ 0, & \textbf{\textit{elsewhere}} \end{cases} \tag{9}$$

Approximation of the CHT

It can be seen that CHT is not negative exponentially distributed. However, for the analysis of the given traffic model it has been presumed that the service mechanism follows a negative exponential distribution. The distribution of CHT can be approximated with a negative exponential one, with mean $\overline{T}_H (\equiv 1/m_H)$ in the way that from the family of negative exponential functions, one function which fits best to the distribution of CHT by comparing the obtained cdf and $e^{-m_H t}$ should be chosen. Thereby,

$$F^C_{T_H}(t) = 1 - F_{T_H}(t) \tag{10}$$

represents the complementary distribution function (cdf). Chosen $\overline{T}_H (\equiv 1/m_H)$ must satisfy the following condition:

$$\int_0^\infty (F^C_{T_H}(t) - e^{-m_H t})dt = 0 \tag{11}$$

In order to prove the fairness, the goodness of fit for this approximation is measured by:

$$G = \frac{\int_0^\infty \left| F_{T_H}^C(t) - e^{-m_H t} \right| dt}{2\int_0^\infty F_{T_H}^C(t)dt} \qquad (12)$$

where G indicates the normalized difference between two functions [4]. Values of G are in range *(0,1)*. The value of $G=0$ represents an exact fit, and the value of $G=1$ indicates that there is no correlation at all.

It has been verified that the fitted exponential distribution attain acceptable fitting with the expected values of negative exponential function, since the obtained value of $G=0.13$ is close to the optimum. Nevertheless, it should not be neglected that slight discrepancies are to be expected. However, exponential distribution functions given by f_{TH} have been used in this work for the further analysis.

Handover Arrival Process

The second parameter that should be derived for capacity calculations is the handover arrival rate l_h. Arrival process in the MSS consists of the arrival of the new call attempts, and the handover requests. While the new call arrival is a Poisson process, the handover arrival process must be derived first. The mobile cellular satellite system can be in fact considered as a cascade queuing model. Thus, although the first level input is a Poisson process, the output traffic from this process is not Poisson, but it is smooth [5]. A smooth traffic gives a lower blocking probability than the Poisson process. In a LEO MSS this characteristic of the handover traffic is very important due to the high frequency of handover requests. In the later part of this work the smoothness of the handover process and its discrepancy in comparison with exponential distribution will be analyzed.

Assuming that the handover arrival process is negative exponentially distributed it has been found that the handover arrival rate is [2], [3]:

$$l_h = \frac{P_n(1-P_{fh})}{1-P_h(1-P_{fh})}\frac{1-P_B}{1-P_{fh}}\, l_n \qquad (13)$$

SIMULATORS DESCRIPTION

In order to validate the performed teletraffic analysis, two event driven Mobile Satellite Simulators have been used (MoSSS+ and MoSSS++) [6].

MoSSS+ has been used to simulate the real system characteristic and to obtain results that would appear in real system exploitation. In particular it means that the satellite constellation and the cell geometry have been implemented without any approximation. As consequence the cells have not regular shapes and sizes. Further, the interference situation has been taken into account and as well as propagation aspects. The Earth curvature has been considered too. The simulation cycle starts with definition of a rectangular user area where the users are uniformly distributed. The area is limited with given longitude and latitude. Different satellite constellations could be parameterized. Apart of the satellite, user and propagation channel modules, which overtake all tasks related to the mentioned objects, MoSSS+ includes also the modules for the allocation of traffic channels, for handover protocols and for statistical evaluations.

The simulator MoSSS++ mainly has the same structure as MoSSS+. However, it has been adapted to be closer to the analytical model. Its main purposes are verification of the analytical models, focused and faster analysis of system parameters and estimation of the differences between analytical results and those obtained by simulation of a real system. The adaptations implied approximation of the system geometry and satellite constellation. The cells in MoSSS++ have regular circular shape which has always the same size. The satellite constellation has been simplified. Smaller number of satellites is usually used and they form just one track of cells (no cells over and under the track). Further, the whole cell surface is always in the observed area .This means that when one cell starts to leave the area, in the same time it enters the area from the other side. In this way the edge effect has been eliminated. No propagation and interference aspects have been taken into account. This fact is in line with analytical model which is based on traffic theory and can not consider mentioned aspects. All these simplifications lead to further advantages of MoSSS++: efficiency and quickness.

REFERENCE SYSTEM

The reference system simulated by MoSSS+ is based on IRIDIUM. It consists of 66 satellites in low Earth polar orbits of *780 km* altitude. There are six orbital planes with an orbit inclination of 86°. Eleven satellites are placed on each orbit at an equal distance of $Dl = 32.7^{\circ}$. The geographical area served by each mobile satellite is divided into *48* beams. This configuration guarantees the overall Earth coverage. The distance between the orbits has a maximum at Equator and decreases to the poles.

The reference satellite stands always above the middle point of its footprint. This is also the intersection point of the three inner cells denoted with the numbers *1-3*. The other cells of the footprint have lower elevation angles as the inner three cells. Because of that fact their shape distinct from the cells in the center of the satellite coverage zone. While the inner cells could be considered as circles, the form of the outer cell is more like a ellipse. In order to achieve a power level of the received signal on the downlink channel for each mobile terminal in the *48* cells to be equal to the power level of the mobile terminal within the three inner cells, the passive power control scheme has been implemented. The transmit power of the satellite and of the mobile station have been corrected in order to equalize the path loss, which occurs due to the different distance between the sub satellite point and the middle point of the considered cell.

Considered reference system uses for radio access the Frequency Division Multiple Access (FDMA) combined with Time Division Multiple Access (TDMA). The whole frequency band is divided into sub-bands and every one of them is assigned to one carrier frequency. Furthermore, each carrier sub-band consists of eight time slots: four for the up-link and four for the down-link connection (Time Division Duplex - TDD).

For the simulations performed using MoSSS++ it was not necessary to include whole satellite constellation, power control and radio access schemes

In both simulators the following assumptions related to the traffic model have been made:

- the disposed frequency band is divided in *24* reusable carriers,
- call duration is negative-exponentially distributed (mean $m_M = 180s$),
- the guaranteed elevation angle is 8°,
- the relative speed of the satellites to the Earth is *26900 km/h*,
- there are *96* transceivers per satellite,
- max. satellite power = *96* (power units per slot).

COMPARISON BETWEEN ANALYTICAL AND SIMULATIVE RESULTS

The simulations have been used to verify the obtained analytical results. It has been noticed that the simulation and analytical results show some difference. Further investigations proved that the analytical assumptions have been made with some simplifications compered to reality, what had impact on final results.

Lets consider the blocking probability of the new calls by capacity limited LEO MSSs. Capacity limited means that the system constraint is power and not the bandwidth. Considering this systems we don't have to pay attention to the interference because interference problems in such MSSs are negligible. The figure 2 shows the new call blocking probability obtained by different means: analysis, MoSSS++ simulation, MoSSS+ simulation with minimisation of the edge effect and "normal" MoSSS+ simulation. It could be noticed that the biggest difference is between analytical result and the one calculated by MoSSS+ simulator that includes all real facts.

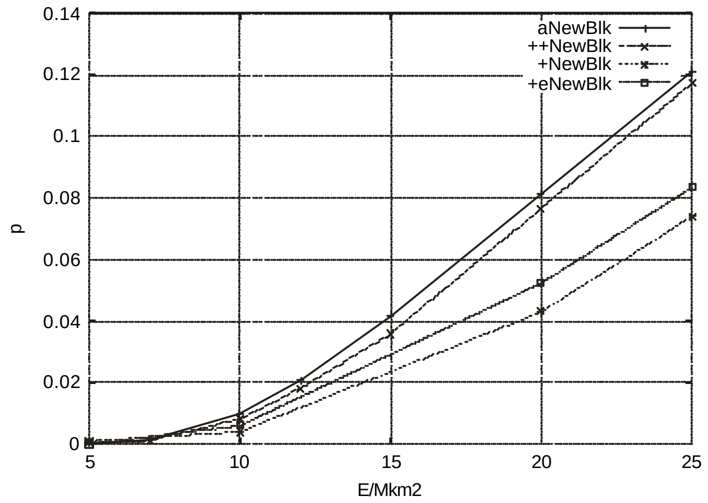

Figure 2: Comparison of the new call blocking probability

The following parameters could influence the differences:

- distribution of the CHT,
- distribution of the handover arrivals,
- cell geometry and
- edge effect

Influence of the CHT distribution

In one of the previous sections it has been derived that channel holding time does not have a negative exponential distribution. However, in some earlier works [7] it has been shown, that the solutions for M/M/n loss model are also valid for M/G/n models, where G indicates a departure process with general distribution. In those situations Markov chains of higher dimensionality can also be used to model more-dimensional systems with a general departure process, as long as the final result leads to product form of solutions, such as in Erlang-B formula. Thus, if such solutions can be found, the nature of the departure process is of secondary importance and only the knowledge of the mean value of the CHT is necessary. These means that the distribution function of CHT has no impact on the presented results differences. Dealing with mean value it should be stated that it has been obtained very similar result by analysis and simulation. This means it also could not remarkably influence the difference in results.

Influence of the Handover Arrival Process

Theoretically the handover arrival process is smooth process. Nevertheless a smooth process could be more or less near to the exponential one. In the diagrams (figure 3) the handover arrival probability distribution function obtained from the simulation results has been compared with the negative exponential functions. It can be seen that in cases with lower traffic, depicted in the first part of figure 3, the approximation for pdf holds better then for the heavy traffic load. According to this it could be expected that the discrepancy between results rises with traffic. However, it could be concluded that both curves seam to be very close to the ideal negative exponential function. As the system load is usually in the limits where the approximation for the handover arrival distribution function causes only very small and acceptable discrepancies. It could be concluded that the approximation of the nature of the handover attempt rate with Poisson process could influence the results, but, the obtained difference is usually in acceptable range.

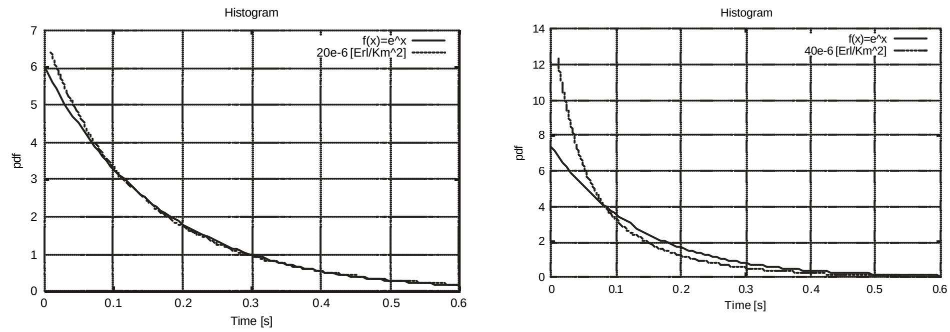

Figure 3: Handover arrival probability distribution functions for different traffic intensities

Edge Effect

Edge effect is consequence of the limitation of the simulated user area. Because the whole satellite constellation was simulated one satellite footprint is often only partially in user area (figure 4). The part out of the user area could not be burdened because of user absence. This implies that cells on the edge of the simulation area have a lower traffic load than those cells which are completely within the simulation area. The result is lower blocking rate in edge cells and in average in the whole area. This kind of simulation is not far from reality, where urban areas border with e.g. water bodies and similar areas which are not populated, but on the other side the edge effect has not been taken into account for analytical calculations.

The set of simulations have been performed whereby the edge effect has been minimised. Simply the area of 10° beside each border has been excluded from statistical evaluation, so only the inner cells have influenced the new call blocking probability. The influence of the edge effect is reflected through the difference between the two bottom curves in figure 2. The Edge effect is much stronger when the dynamic channel allocation strategy is applied where all channels could be allocated in a whole foot print.

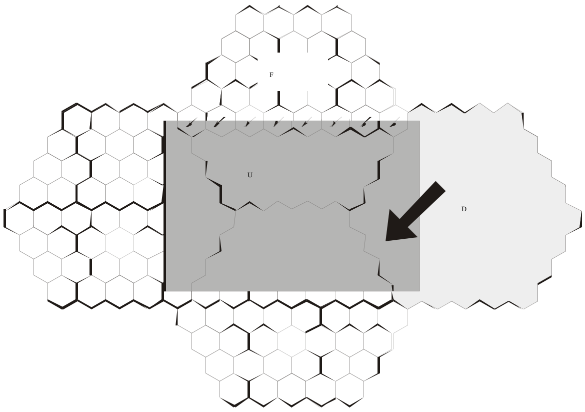

Figure 4: Edge effect

Influence of the System Geometry

While the cell geometry inside the analytical model is fixed, since the cells are assumed to be circles, inside the simulation model the cells shape and area vary a lot due to the radio propagation properties in the model where the cell form is determined on the measurement basis, and where the Earth curvature has been taken into account. In fact, the simulation model is very close to the reality circumstances, which can not be modelled with teletraffic analysis tools. The cells geometry of the simulation model has been shown on the figure 5. It can be seen that the marked beams 30, 33, 35, 37 and 40 are much larger than the rest beams and especially larger than inner beams. As a consequence the new call and handover blocking vary a lot for each single beam. The analysis of that phenomena has been presented in the figure 6. The normalized traffic for each single beam has been calculated by dividing the total number of new/handover attempts in the system, with the number of the attempts within the certain beam. The number of attempts has been obtained using MoSSS+ simulator. It can be seen that in only five cells placed on the footprint border occurs almost *40%* of the overall blocking.

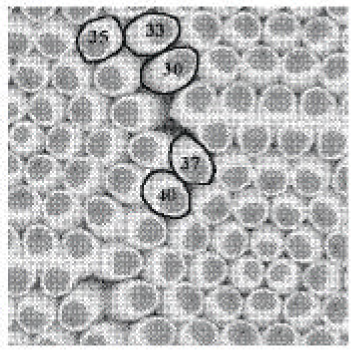

Figure 5: Real (simulated) cell geometry

In order to give statements regarding the geometry constellation it must be stressed again, that the new offered traffic is uniformly distributed over the simulation area and the fixed channel allocation strategy is considered.

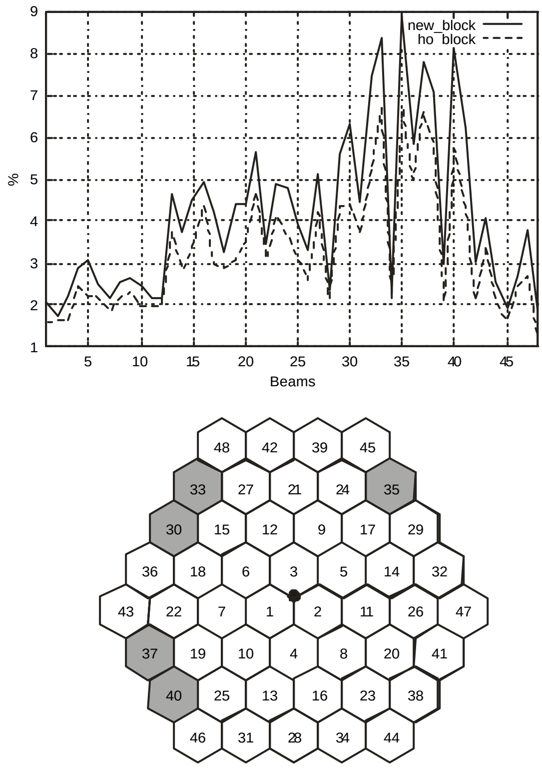

Figure 6: Influence of the geometry cell constellation

The new call traffic is directly proportional to the cells surface, but the handover traffic depends mostly upon the cells circumference. This fact implies a high sensitivity regarding chosen cell radius within the analytical model. With the cell size increase the new call traffic load increases proportionally. However, the number of disposed resources is always the same. This means that the cell blocking rate is directly proportional to the cell surface. The overall blocking rate is consequently a complicated mixture of the cell blocking rates. Finally, on the figure 2, it could be seen that the difference between analytical results and results obtained using MoSSS++ simulator, which neglects differences in cell geometry, are very small.

CONCLUSION

In this work it has been shown where are the differences between analytical and simulated calculations of blocking probability by LEO MSSs. Simulation results have been used to reflect the real situation.

Firstly the parameters that influence the blocking probability have been described and some of them analytically derived. Further, every parameter has been analysed and his impact on the mentioned difference has been clarified. For the clarifications the additional simulator has been used. It has been obtained that the main influence on difference between analysis and "reality" causes the geometry of the system. The influence of the, so called, Edge effect is also not remarkable. Much less impact has the distribution of the handover arrival process and only minor contribution to difference gives the approximation of the distribution function of the channel holding time.

It could be concluded that described analytical models of the LEO MSSs provide satisfactory results. However, for more precise results one has to keep in mind that for analysis necessary approximations could cause up to *50%* difference compared to reality.

REFERENCES

[1] B. Walke, "Mobile radio networks – networking and protocols", John Wiley & Sons, April 1999.

[2] S. Cigoj, "Analysis and Performance Evaluation of the Resource Management Strategies for Different Quality of Service Classes in Mobile Satellite Systems", Diploma Thesis, Communication Networks, Aachen University of Technology, December 1999.

[3] G. Ruiz, T. L. Doumi and J. G. Gardiner, "Teletraffic Analysis and Simulation for Nongeostationary Mobile Satellite Systems", IEEE Transactions on Vehicular Technology, vol. 47, no.1, February 1998.

[4] S.S. Rappaport, D. Hong, "Traffic Model and Performance Analysis for Cellular Mobile Radio Telephone Systems with Prioritized and Nonprioritized Handoff Procedures", IEEE Transactions on Vehicular Technology, Vol. VT-35, No. 3, August 1986.

[5] A.A. Frederics, “Congestion in blocking systems – A simple approximation technique”, Bell Systems Technical Journal, Vol. 59, No. 6, July-August 1980.

[6] B. Bjelajac, “Modeling and evaluation of the mobile satellite systems with dynamic channel allocation”, (in german), Ph.D. Thesis, Communication Networks, Aachen University of Technology, July 1998.

[7] D. Everitt, “Traffic Engineering of the Radio Interface for Cellular Mobile Networks”, Proceedings of the IEEE, volume 82, September 1994.

[8] V. Obradovic, S. Cigoj, “Improvement of the Performances of the Mobile Satellite Systems by Sophisticated Handover Management”, Proceedings European Wireless (EW‘99), Munich, Germany, October 1999.

[9] V. Obradovic, S. Cigoj, “Performance Evaluation of Prioritized Handover Management for LEO Mobile Satellite Systems with Dynamic Channel Assignment”, Proceedings Globecom 99, Rio de Janeiro, Brazil, December 1999.