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Influence of user density distribution on the pairing probability in GSM cell with implemented VAMOS technology

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ABSTRACT

In this paper, we present the influence of user density distribution in the base station cell on the (un)pairing probability and on the loss caused by the lack of idle traffic resources in GSM systems, which use VAMOS technology. The influence of user distribution is analysed together with the influence of environmental attenuation coefficient and allowed power difference in emission power between two signals, which are paired. It is pointed out that decreasing user density from the base station towards the cell edge is less favourable when considering total loss than it is for uniform and increasing user density. It is further presented to what extent the total loss in the system with the implementation of VAMOS technology is greater than the loss in the classic Erlang traffic model with the same traffic characteristics.

1. Introduction

Significant increase of classic GSM cell traffic capacity may be achieved by the VAMOS (*Voice service over Adaptive Multi-user channels on One Slot*) technique. When this technique is implemented in the classic GSM cell with frequency (FDM) and time (TDM) multiplexing, each time channel may be used for two full rate connections (over two *Orthogonal Sub-Channels* (OSC), subchannels). In the case of halfrate transmission, the number of connections quadruples. This capacity increase is made possible by implementation of Quadrature Phase-Shift Keying (QPSK) modulation and orthogonal training sequence codes (TSC) [1, 2]. QPSK modulation (i.e. its variant AQPSK or α - QPSK) is implemented in downlink connection realization direction when a signal is simultaneously transmitted to two users (mobile stations (MSs)) on the same timeslot. Implementation of α-QPSK modulation in the direction from base station (BS) to MS allows signals of different power to be sent to users who use the same channel having different values of signal attenuation. This property is intended to achieve that both MSs receive approximately the same signal level. Pairing is the process of placing two connections in one timeslot. Pairing can be realized if the power ratio of two connections (SCPIR – *SubChannel Power Imbalance Ratio*), using the same timeslot, is not greater than Δ_{max} (dB). The value Δ_{max} is determined by technological possibilities of VAMOS signal receiver to distinguish signals intended for each of MSs. In the case that this condition for SCPIR is fulfilled, pairing is considered to be successful. In this paper, it is determined how the distribution of surface user density affects the probability of successful pairing.

The main traffic assumptions and signal propagation characteristics, which are important for latter modelling of VAMOS systems, are highlighted in Section 2. Pairing technique, which is the basis of VAMOS, is presented in Section 3. Method for calculation of two connections pairing probability is explained in Section 4. After that, in Section 5 it is emphasized which factors have influence on the number of generated requests in some parts of base station cell. The user surface distributions, which are used in the paper, are listed in Section 6. In Section 6, it is also presented how the number of users in the subareas of BS cell is calculated. Section 7 is devoted to the calculation of user pairing probability, taking into account all factors having the influence on this probability. On the basis of this analysis, the expression for total unpairing loss is carried out and the expression for call traffic loss is mentioned in Section 8. Numerical examples are presented in Section 9. The description of simulated traffic process, which is used to estimate accuracy of unsuccessful pairing calculation, is given in Section 10.

2. Model, assumptions and designations

Let us suppose that we have a circular GSM cell with the radius R. The emission power control is implemented in BS in the direction BS $\rightarrow$ MS. Distance between MS and BS is designated by r, $0 \leq r \leq R$. Signal attenuation is designated by a. For the sake of simplicity, it is considered that the received signal attenuation depends

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on the distance between MS and BS, $a = k_a \cdot r^\gamma$, k_a is the coefficient of proportionality and γ is the attenuation coefficient, $2 \leq \gamma \leq 5$ [3]. The number of MSs is M and the number of traffic timeslots (TCH) is N. Traffic channels are mainly used to establish telephone calls. It means that a request for a new connection, which appears in random moment, must be satisfied in a short time interval [4, 5]. The total offered traffic (A) has constant intensity, independently of system state. Service time, i.e. connection duration, is a random variable with negative exponential distribution. Mean service time is $t_m = 1/\mu$ (where μ is mean call service intensity on one channel) and call intensity is λ, $A = \lambda/\mu = \lambda \cdot t_m$. It is supposed that the model is *pure VAMOS* [6], where all active users apply VAMOS technique, i.e. the maximum number of connections is $2N$.

As the majority telephone serving systems, this one also has loss. The only difference between this model and the Erlang model of full availability is in the case of pairing impossibility. Availability is limited in the case of pairing impossibility, i.e. each user is not able to seize each idle OSC. The number of connections j ($j = 0, 1, \ldots, 2N$) in the system is called system state and designated as $\{j\}$. The state probabilities in the considered VAMOS model are designated by $P\{j\}$, $j = 0$, $1, \ldots, 2N - 1, 2N$, and the probability of all busy channels is designated by $P\{2N\}$. Loss due to idle channel lack is designated by B. The difference in signal power, which is dedicated to the users with different attenuation, is designated by Δ. The signal power, transmitted from BS to MS, is designated by P, $P_{min} \leq P \leq P_{\max}$. Power control in BS is realized using 16 steps of 2 dB each.

3. Pairing

Two connection pairing in one timeslot is realized in such a way that connections of BS with users MSi and MSj (BS-MS) having an emission power imbalance not greater than Δ_l are joined, as illustrated in Figure 1. As an example, let us consider a group of six timeslots where four completely busy by paired connections and a simple GSM cell with only four attenuation levels. Timeslots TS3 and TS4 are half-busy, i.e. only one OSC is busy in each of them. A new call from a user MSn is generated at a random moment. Necessary power for user MSn is greater than allowed power for pairing with OSC1 in TS3 and OSC1 in TS4 for more than Δ_l, i.e. $|P_{MSn} - P_{MSk}| > \Delta_l$ and $|P_{MSn} - P_{MSm}| > \Delta_l$. New connection pairing in timeslots TS3 and TS4 is in this case unsuccessful. It is supposed in this paper that the new call, which may not be paired with any existing call when there are no timeslots with both idle OSCs, is lost due to unsuccessful pairing (unpairing). Pairing probability is P_p, and unpairing probability is B_p.

In principle, there are two pairing strategies, [7]: the first one is to pair all users who may be paired and the
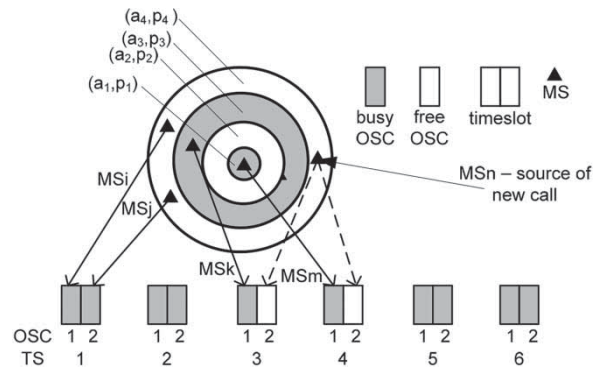

Figure 1. An example of timeslot pairing (illustration of the situation when pairing is unsuccessful).

second one to start pairing when a threshold of the total number of busy channels is reached. The first strategy gives priority to signal quality, while the second strategy gives priority to traffic conditions.

4. Principle properties of pairing

The principle rule for pairing is simple: connections, whose required emission power in the direction BS $\rightarrow$ MS is alike, may be paired. Let us consider one quite simplified example, for which Figure 1 is an illustration. In this example, the circle ($a1$) around BS and annuli ($a2$, $a3$, $a4$) in Figure 1 are areas from which requests may be mutually paired, i.e. a request from one area may be paired only with a request from the same area (one request from $a1$ with the other request from $a1$, one request from $a2$ with the other request from $a2$, etc.). The probability that a request originates from area ai is designated by p_i ($i = 1,2,3,4$). Let us, further, suppose that the relation between probabilities is designated by the equation $p_i = k^{i-1} \cdot p_1$, coefficient $k > 0$, $i = 1,2,3,4$, $p_1 + p_2 + p_3 + p_4 = 1$.

Now we consider timeslot 3 from Figure 1. The probability of successful pairing is equal to the product of probabilities that previously realized call in OSC1 originated from the same area ($i = 1,2,3,4$) from which a new call is initiated. Therefore, the probability of successful pairing in one half-busy timeslot is now $P_p = p_1 \cdot p_1 + p_2 \cdot p_2 + p_3 \cdot p_3 + p_4 \cdot p_4 = p_1 \cdot (1 + k^2 + k^4 + k^6)$ provided $p_1 + k \cdot p_1 + k^2 \cdot p_1 + k^3 \cdot p_1 = 1$. Let us suppose that probabilities alter in such a way that parameter k takes values ranging from 0.2 to 5. The probabilities of successful pairing P_p as a function of parameter k are presented in Figure 2 for the system from Figure 1.

The main conclusion from this simple example and calculation is: probabilities of successful paring as small as probabilities of request generation from certain areas are more uniform. It means that, as request generation probability in some area is greater, greater is the chance that both connections, which compete for the same timeslot, are from that area.
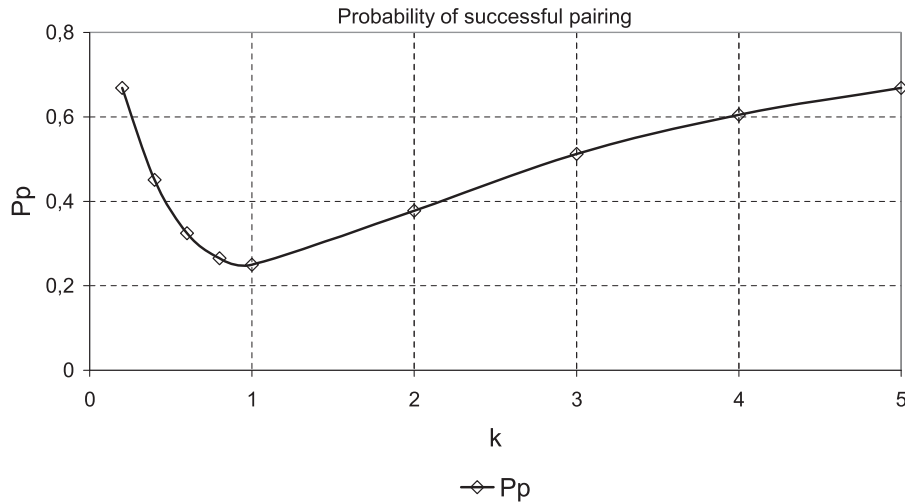
Figure 2. Probabilities of successful pairing (P_p) as a function of parameter k for the system from Figure 1.

5. Factors that affect call probability from one area

The call probability from one area depends on the ratio of the number of users that belong to this area and the total number of users. The number of users in the area depends on the size of the area and on the surface user density. Some examples of the distribution of user surface density in the GSM cell are presented in [8]. It is indicated in [8] that the ratio of the number of users in one area and the total number of users can be calculated as a ratio of the volume of the body bounded by the density distribution function of that area and the total volume of the body which is bounded by the considered cell and the density distribution in the whole cell.

The surface of an area depends on the attenuation coefficient. Namely, an area represents a space in which signal attenuation is changed for the same value, for example, 2 dB. It is clear that in the surrounding with greater attenuation an area has smaller surface.

6. Different densities of user distribution in a cell

In principle, three different density distributions of users in a cell, g, may be considered: a decreasing density from the centre of the cell towards the cell rim, uniform density and increasing density from the centre towards the cell periphery. Equation (1), which models distributions of the user density

$$g(x) = g_0 - (g_0 - g_R) \cdot \frac{x}{R} \qquad (1)$$

uses designations from Figure 3, where g_0 is the density in the centre of a cell, g_R is the density at the cell rim, R is the cell radius and g ($g = g(x)$) is the density at the distance x from the centre of the cell.

The decreasing user density from the centre of a cell towards the cell rim, i.e. the case $g_R < g_0$, is presented
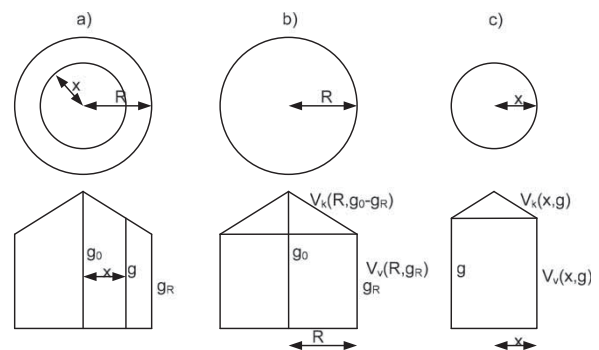

Figure 3. A cell with the decreasing user density from the centre of a cell to the cell rim (a), calculation of the number of users in the whole cell (b) and in the part of the cell (c).

in Figure 3. The same designations may be used in the case of uniform user density ($g_R = g_0$) or in the case of increasing user density ($g_R > g_0$). In this, the last, rare, but possible case, BS is a geometric centre of a cell, but the number of telephone users is as greater as they are further away from BS.

The number of MSs in the area bounded by circle with radius x may be expressed as the sum of the volume of cylinder $Vv(x,g)$ (radius x, height g) and cone $Vk(x, g_0 - g)$ (radius x, height $g_0 - g$) (Figure 3(c)). In accordance with this, the number of users in an area, i.e. in an annulus with the inner radius r_1 and the outer radius r_2 can be represented by the difference in volume of the cylinder and cone whose radius is r_2 and the cylinder and cone whose radius is r_1, in the case of decreasing user density (Figure 4):

$$V(r_2, r_1)_d = (Vv(r_2, g_2) + Vk(r_2, g_0 - g_2)) \\ - (Vv(r_1, g_1) + Vk(r_1, g_0 - g_1)) \qquad (2)$$

It will be in the case of increasing user density from the centre of a cell towards the cell rim:

$$V(r_2, r_1)_d = (Vv(r_2, g_2) + Vk(r_2, g_0 - g_2)) \\ - (Vv(r_1, g_1) - Vk(r_1, g_0 - g_1)) \qquad (3)$$
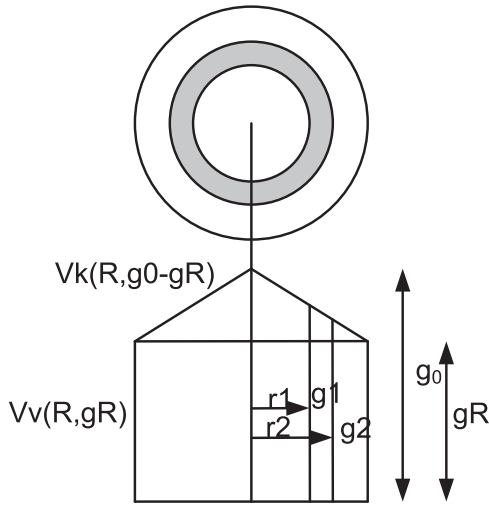
Figure 4. Determination of the number of users in a BS cell annulus (an example for decreasing user density).

It is clear that parts of equation related to the volume of cone are neglected in the case of uniform user density, i.e.:

$$V(r_2, r_1)_u = Vv(r_2, g_2) - Vv(r_1, g_1) \qquad (4)$$

Now the call probability from the area, i.e. annulus whose inner radius is r_1 and outer radius r_2 (area 2) can be calculated as

$$p_2 = \frac{V(r_2, r_1)}{V(R, 0)} \qquad (5)$$

or, generally

$$p_i = \frac{V(r_i, r_{i-1})}{V(R, 0)}, \quad i = 1, 2, \ldots, 16, \ r_0 = 0 \qquad (6)$$

In Equation (6), i takes values between 1 and 16, because, as it is already emphasized, power control in BS is realized 16 steps of 2 dB.

7. A detailed calculation of pairing probability

GSM cell with power control will be considered for detailed calculation of successful pairing probability. Emission power may obtain one of 16 values, depending on a position of MS to which signal is sent. On the base of emission power, users are divided on a circle and 15 annuli, i.e. areas $a1, a2, \ldots, a16$. Area ai is bounded by the annulus, whose radii are r_i and r_{i-1} (Figure 1). The same power is transmitted to all users, who belong to one area. Power P_i is transmitted to users situated in the area ai. Emission power that is sent to mutually neighbouring areas differ for $\sigma = 2$ dB, i.e. $P_{i+1} - P_i = 2$ dB, $i = 1, 2, \ldots, 15$. In one timeslot can be paired connections of users whose required power does not vary more than Δ_ldB, $|P_i - P_j| \leq \Delta_l$. It is common that Δ_l is integer multiple of σ, i.e. $\Delta_l = k_\Delta \cdot \sigma, k_\Delta = 2,3,4$ or 5 [9, 10]. A more detailed presentation of implemented Δ_l values may be found in [11].
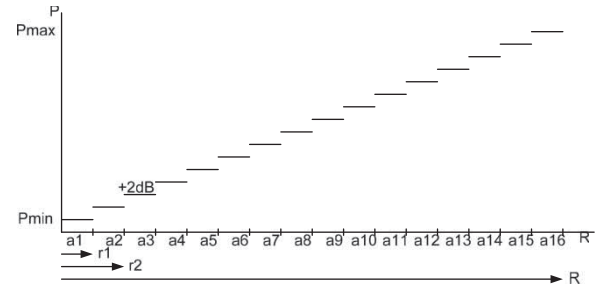

Figure 5. BS emission power as a function of distance between MS and BS.

Figure 6 presents areas in one cell where it is $k_\Delta = 2$. This means that in one timeslot can be paired connections for which the difference of emission power BS $\rightarrow$ MS does not exceed $k_\Delta \cdot \sigma = 4$dB. Connection of a user MS1 from the annulus $a4$ can be successfully paired with the connection of other user from the same annulus or from any of the areas $a2, a3, a5$ or $a6$ (Figure 6).

The probability of successful pairing in this case is equal to the product of probability that one call is from area $a4$ (p_4) and probability that the second call is from area $a2, a3, a4, a5$ and $a6$ ($p_2 + p_3 + p_4 + p_5 + p_6$), i.e.

$$P_{p(i=4)} = p_4 \cdot (p_2 + p_3 + p_4 + p_5 + p_6) \qquad (7)$$

Since the first user can be assigned to any area ($i = 1, 2, \ldots, 16$) and a second user, who is paired with the first one, to the same area or to its $+k_\Delta$ or $-k_\Delta$ neighbourhood, the general expression of the probability of a successful connection pairing in one timeslot of the cell, which uses the VAMOS technique is obtained as:

$$P_p = probability(\Delta_l \leq k_\Delta \cdot \sigma) = \sum_{i=1}^{i=i_{max}} p_i \sum_{j=i-k_\Delta}^{j=i+k_\Delta} p_j,$$

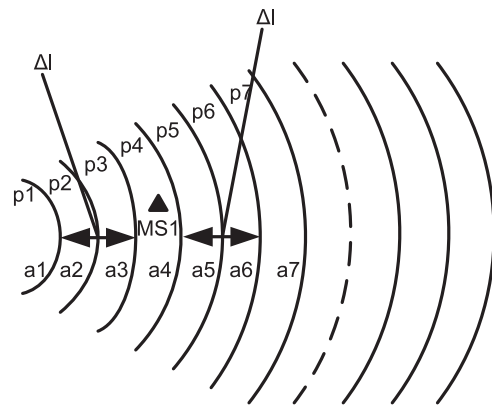$$\times 1 \leq j \leq i_{max} \qquad (8)$$

Figure 6. An illustration of areas from which a connection can be paired with a connection of user MS1 ($a4$) in the case that it is $k_\Delta = 2$.

In principle, successful pairing probability depends on the environmental attenuation coefficient γ, allowed power difference in emission power between two signals, which are paired (Δ_l i.e. k_Δ) and on probabilities of new calls p_i, $(i = 1, 2, \ldots, 16)$.

The greater attenuation coefficient causes surface decrease of area a_i, $(i = 1, 2, \ldots, 16)$. That's why the number of users in an area and successful pairing probability also decrease.

Increase of the difference between the allowed emission power of paired signal increases the successful pairing probability, which is self-explanatory.

In this paper, we are interested in the influence of user distribution density in the cell on the pairing probability. In order to estimate this influence, probability of pairing is calculated according to the expression (8) for the same values of γ and Δ_l. Probabilities p_i, $(i = 1, 2, \ldots, 16)$ are calculated using expression (6). Variation of surface user density g, i.e. parameters g_0 and g_R plays the main role in expression (6). Parameters g_0 and g_R together determine the slope of distribution of the user surface density.

Unsuccessful pairing probability in one timeslot, P_{np}, is obviously

$$P_{np} = 1 - P_p \qquad (9)$$

8. The total unpairing probability

Let us consider the group of N timeslots, i.e. $2N$ OSCs. In the state $\{j\}$, $j < N$ connection realization is always possible whether by pairing or by idle timeslot. In the states $\{j\}$, $j \geq N$ unsuccessful pairing is possible. Let us suppose that there are $j = N$ connections and of all possible distributions of these connections in OSCs probability that one OSC is busy in each timeslot is K_N. This probability may be also called probability that there are no idle timeslots in state $\{N\}$. Unsuccessful pairing probability in this state is

$$P_{np}(N) = K_N \cdot P\{N\} \cdot (P_{np})^N \qquad (10)$$

Unsuccessful pairing may occur in all states $\{j\}$, $j \geq N$, so total unsuccessful pairing probability is

$$B_p = P_{nptot} = \sum_{j=N}^{j=2 \cdot N-1} K_j \cdot P\{j\} \cdot (P_{np})^{2 \cdot N - j} \qquad (11)$$

In statistical equilibrium, state probabilities $P\{j\}$ are calculated from cut equations, as for other similar serving models. Model can be conditionally called one-dimensional model with limited (variable) availability, which depends on the voice signal power. In this birth-death model with $2N+1$ states, call arrival rate is $\lambda_i = \lambda = A/t_m$ for $i = 0, 1, \ldots, N-1$ and $\lambda_i = \lambda \cdot (1 - P_{np}(i))$ for $i = N, N+1, \ldots, 2N-1$. Call service rate μ_i in state $\{i\}$, $i = 1, 2, \ldots, 2N-1, 2N$ is $\mu_i = i \cdot \mu = i/t_m$.

Loss due to lack of idle channels B, (Call congestion [12]), is by definition equal to the proportion of call attempts which are lost. Only call attempts arriving at the system in state $2N$ are blocked.

$$B = \frac{\lambda_{2N} \cdot P\{2N\}}{\sum_{i=0}^{i=2N} \lambda_i \cdot P\{i\}} \qquad (12)$$

9. Numerical examples

Let us consider three cases of user density distribution in a cell: linearly decreasing density ($g_0 = 6$, $g_R = 1$), uniform density ($g_0 = g_R$) and linearly increasing density ($g_0 = 1, g_R = 6$).

Analysis of system is performed by calculation and simulation. In this analysis, state probabilities of a system (number of realized connections) are initial values. Unpairing loss, traffic loss and total loss are then determined on the basis of these state probabilities.

Probabilities of the number of busy OSCs $\{j\}$ for a system with increasing user density distribution are presented in Figure 7. This is a system with six timeslots (12 OSCs). State probabilities of a system are presented only for a case when the traffic is $A = 7$E (Erlangs), environmental attenuation coefficient is $\gamma = 3$ and allowed power difference between two channels, which may be paired, is $\Delta_l = 4$ dB. The simulation results are presented by mean values of three simulation trials, each with at least 100,000 realized connections.

The graph, presented in Figure 7 demonstrates good agreement between state probabilities determined by calculation and simulation. The simulation results are used in the further analysis.

Figure 8 presents unpairing loss (B_p) for these three distribution types. It can be concluded, as in Section 4, that unpairing loss is as greater as probability of new call arrival is less variably distributed in annuli. In our case, decreasing density has the least variable probability of call arrival, because decreasing user density reduces increase of the probability of a new call arrival when distance between BS and MS increases. (Further annuli have greater surface, that is why call arrival probability is greater in them than in annuli nearer to BS, when users are uniformly distributed). On the contrary, increasing user density enhances increasing character of new call probabilities (p).

Besides unpairing loss, there is also loss caused by the lack of idle resources, i.e. channels (traffic loss) (B). This loss is presented in Figure 9 for the same case as the one from Figure 8. It is obvious that traffic loss and unpairing loss are inversely dependent of the distribution type: traffic loss is the greatest for increasing distribution of user density from BS towards the cell rim.

Total loss (caused by unpairing and by the lack of idle channels $B_p + B$) is presented in Figure 10 for the considered parameters ($2N = 12, \gamma = 3, \Delta_l = 4$ dB). As

State probabilities (increasing density, A=7E, gama=3, delta=4dB, 12OSCs)
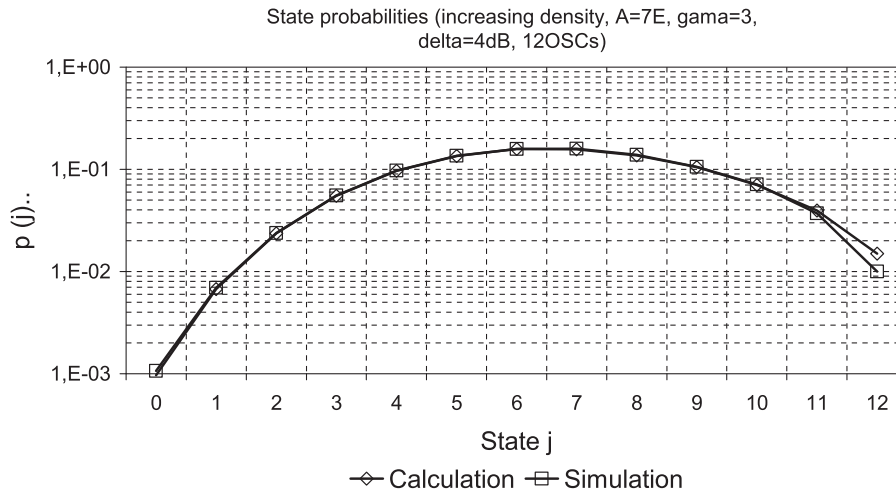

Figure 7. State probabilities of a system with six channels (12 OSCs) and increasing user density, obtained by calculation and simulation when it is $A = 7E$, $\gamma = 3$, $\Delta_l = 4$ dB.
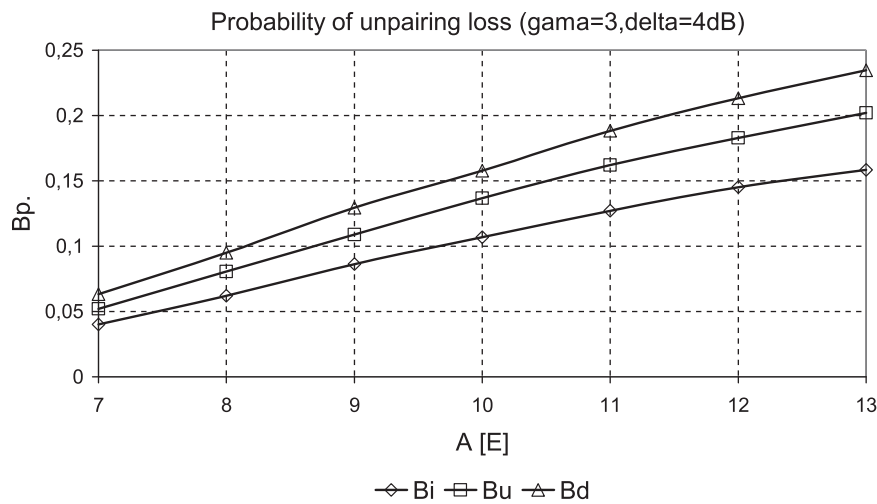
Probability of unpairing loss (gama=3,delta=4dB)

Figure 8. Unpairing loss for the cell with increasing (*Bi*), uniform (*Bu*) and decreasing (*Bd*) user density distribution when it is $N = 6$, $\gamma = 3$ and $\Delta_l = 4$ dB.
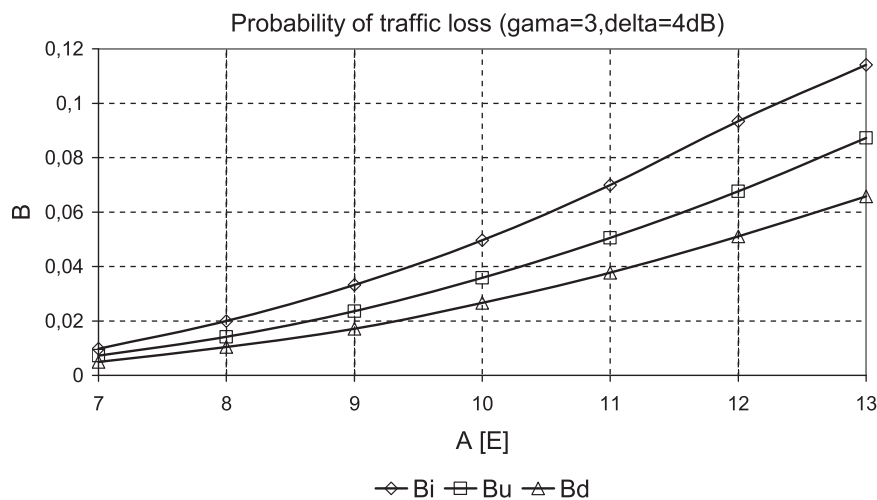
Probability of traffic loss (gama=3,delta=4dB)

Figure 9. Loss due to the lack of idle channels (traffic loss) for the cell with increasing (*Bi*), uniform (*Bu*) and decreasing (*Bd*) user density distribution when it is $N = 6$, $\gamma = 3$ and $\Delta_l = 4$ dB.

Probability of total loss (gama=3,delta=4dB)

Figure 10. Total loss (unpairing loss, B_p + traffic loss, B) for the cell with increasing (Bi), uniform (Bu) and decreasing (Bd) user density distribution when it is $N = 6$, $\gamma = 3$ and $\Delta_l = 4$ dB.
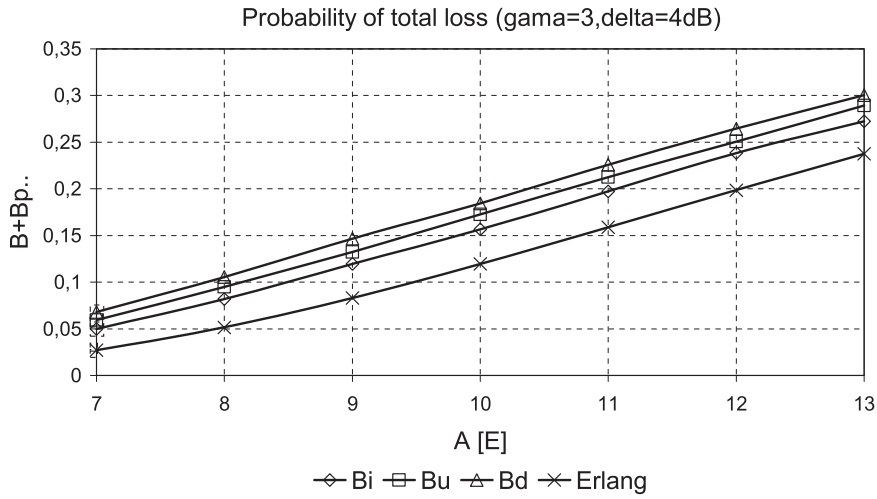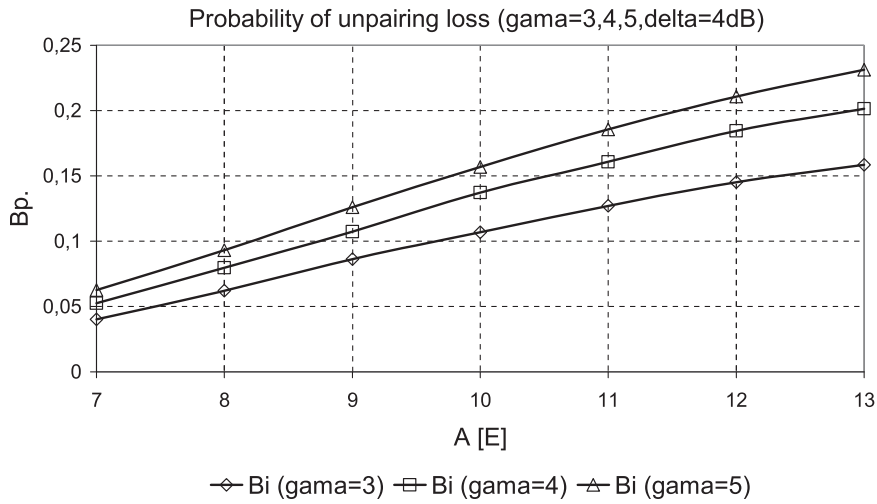
Probability of unpairing loss (gama=3,4,5,delta=4dB)

Figure 11. Unpairing loss for different values of γ in the case of increasing distribution of user density, $N = 6$.

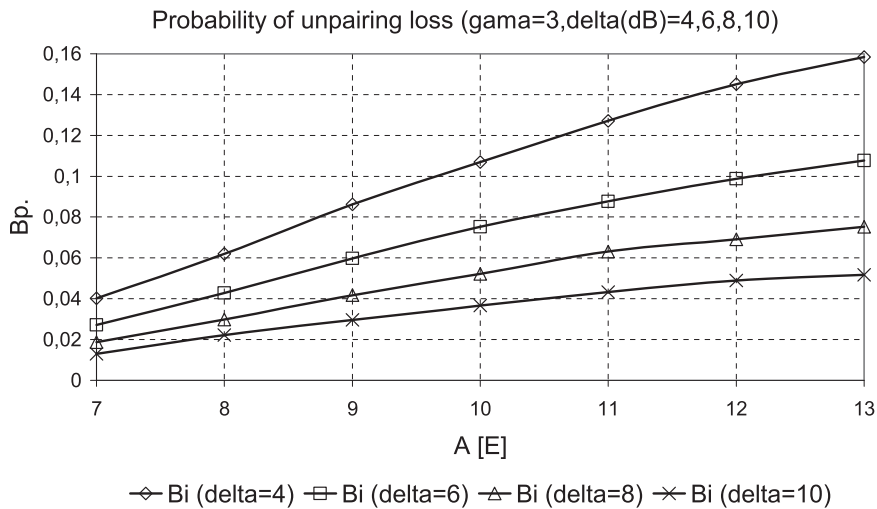## Probability of unpairing loss (gama=3,delta(dB)=4,6,8,10)

Figure 12. Unpairing loss for different values of Δ_l in the case of increasing distribution of user density, $N = 6$.

the loss caused by unpairing and the loss due to the lack of idle channels are inversely dependent on the distribution type, their sum has less dependence on the type of user density distribution.

Figure 10 also presents the loss line in the classical Erlang model. It can be concluded that the loss sum in VAMOS cell is greater than the loss in the corresponding classical Erlang model, but the dependence on traffic is similar.

Figure 11 presents dependence of unpairing probability on the environmental attenuation coefficient γ, while Figure 12 presents dependence of this probability on allowed power between two paired connections Δ_l. As it can be concluded from Figures 11 and 12, unpairing probability decreases when γ decreases and when Δ_l increases. In the theoretical case of further increasing the value Δ_l over 10dB, presented model would be more and more close to Erlang model and at the end will reach it. Graphs in Figures 11 and 12 are presented for increasing distribution of user density, but the same mutual relations are also valid for uniform and decreasing distribution of user density. It is emphasized in [13] that in urban areas with obstacles to electromagnetic wave propagation the value of γ may reach 5, while the measurement result for a specific γ, which is emphasized in [14], is 4.31. Since, therefore, greater values of γ are characteristic in urban environment where there are more mobile users, it is clear that it is of interest in these conditions to apply systems with the ability to pair users with a higher value Δ_l. In this way it is possible to compensate an increase in the unpairing probability resulting from the increase of the value γ.

10. Simulation

The simulation programme for the system with the implemented VAMOS technique is developed on the basis of earlier implemented simulation programmes for different mobile telephony systems [8, 15–17]. Among these references, contribution [8] is the most important for the simulation in this paper, because system with non-uniform user distribution is considered in [8], as in this paper.

The simulation programme in this development is based on the classic Monte Carlo method, which we adjusted for solving our specific problem. The Monte Carlo method is universal method of simulation, implemented in many scientific disciplines and for different problems solving, as may be illustrated according to examples from [18–20].

Loss, followed by the simulation programme in [8], represents traffic loss. The loss due to unpairing is analysed, in addition, in the simulation programme for VAMOS systems. The part, which has now been introduced into the analysis in addition to the programme from [8], is presented in Figure 13. These steps are adjusted to the analysis of VAMOS system. The first
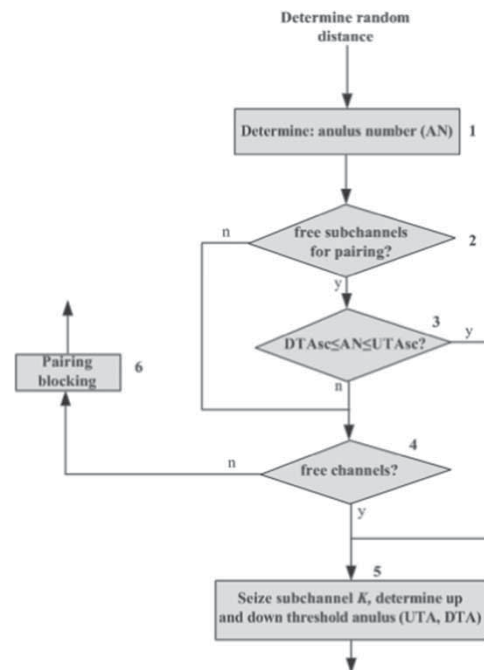

Figure 13. Supplement to the simulation programme presented in [8], adjusted to the analysis of VAMOS system.

step, when random distance between MS and BS is determined as in [8] is to find the annulus where the user, who generates the request, is situated (block 1). Then it is tested whether there are timeslots with only one busy OSC. These timeslots are candidates for pairing (block 2). In the case that there are timeslots – candidates for pairing, it is tested whether the newly generated request is located in an annulus, whose ordinal number (AN) is between the upper (UTAsc) and the lower threshold (DTAsc) of the annulus ordinal number, intended for pairing (block 3). If pairing can be performed in some channel, it is realized in block 5. The upper (UTA) and the lower threshold (DTA) of the annulus number are defined for a later eventual pairing with this newly generated request.

Testing whether there is a completely idle timeslot in order to seize one OSC is realized in block 4, if there are no available OSCs for pairing or if the distance between MS and BS is not such that pairing could be made with an existing requirement. In the case that there is a completely idle timeslot, OSC in this timeslot is seized using already explained procedure in block 5. Otherwise, the call is not established due to the pairing inability (block 6).

11. Conclusion

In the presented model with the VAMOS technique, pairing inability increases connection loss. The increase in this loss is caused by a small difference in the allowed power between paired connections and a high environmental attenuation coefficient. In addition, the loss due

to unpairing depends on the distribution of user density in the cell.

The largest loss due to unpairing occurs for the distribution of user density which decreases from the BS to the cell rim. This distribution is more common than the distribution when user density is increasing from BS to the cell rim. Loss due to unpairing is larger than the loss for uniform distribution about 20% even in the worst cases of a sharp density drop, small allowed power variation between two paired connections and high value of environmental attenuation coefficient.

However, if we consider the sum of loss due to unpairing and due to the lack of idle resources, the difference in loss is significantly reduced with a note that decreasing user density in the cell from the centre to the periphery remains the least favourable.

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