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On the development of fully adaptive channel allocation strategies for usage in high-capacity cellular mobile radio systems

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SUMMARY

An alternative mathematical expression for the co-channel interference probability is used, in order to calculate the cellular mobile radio system capacity and to construct a set of compatibility constraints needed for the development of fully adaptive channel allocation (FACA) strategies. The development of such channel allocation techniques becomes a main thrust for the system engineers in order to design an efficient system to manage traffic demands over the service area of a third generation cellular system. Three proposed FACA strategies are analysed and a simulation model is developed, in order to examine the performance of these strategies. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: mobile communications; interference; channel allocation

1. INTRODUCTION

The future of mobile communications promises constant increase in subscriber numbers. To obtain this, more capacity is needed, in the cellular networks. This is especially true for GSM (900 & 1800) systems, which have been experiencing a tremendous growth during the last years and have become the leading cellular standard. As the markets are growing, operators are introducing new low-cost services. The telecommunication community is pressed for more efficient transmission techniques and more frequencies.

The International Telecommunications Union (ITU), is currently engaged in the development of global standards for wireless communications. International mobile telecommunications in the year 2000 (IMT-2000), formerly known as the future public land mobile telecommunications

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system (FPMLTS) and the universal mobile telecommunications system (UMTS), are intended to provide universal coverage and be capable of seamless roaming worldwide with a small, light-weight and convenient 'pocket' communicator. It will be also capable of offering a wide range of services, especially multimedia services, with the same quality as in the fixed network [1–4].

Smaller cells for a higher user capacity and larger cells for an extended coverage are two of the best-known principles, which have governed the deployment of conventional cellular mobile radio systems.

In the early days of cellular system deployment, good geographical coverage was of vital importance. The third-generation of mobile systems will concentrate on the service quality, system capacity and personal and terminal mobility issues. The service quality will be improved by decreasing the level of the co-channel interference especially during the handoff and roaming procedures (customized applications for mobile network-enhanced logic—CAMEL) and by increasing the data rates (multimedia applications). The system capacity will be improved by using smaller cells and the reuse of frequency channels in a geographically ordered mode.

As the user traffic attains saturation, especially within city centres, cell splitting and sectorization techniques have to be introduced to increase the user capacity. Hierarchical cell structures (HCS) are used to tailor the capacity and coverage of the system in order to support specific traffic and service needs. In particular, microcells with low transmission power will be widely deployed in urban areas, while other cell structures will be used according to the environment to provide sufficient coverage [2,3].

It is indeed of strategic importance, in order to meet the requirements for wireless communication, the maximization of the signal-to-noise ratio. To achieve this, it is necessary to investigate and calculate the system's interference environment and to select optimum techniques for channel allocation. The aim of these techniques is to reduce the blocking probability and to maximize the system's capacity.

Generally, there are two channel allocation schemes known as fixed channel allocation (FCA) and dynamic channel allocation (DCA). In a FCA scheme, a fixed subset of all the channels can be used in each cell according to the interference constraints. In a DCA strategy all the channels can be used in all the cells. In other words, channels are pooled together and allocations are made and modified in real time. The main target of a DCA strategy, is the minimization of the blocking probability and the high-level communication service to the subscribers, especially in heavy traffic conditions. Therefore, this strategy has the potential of achieving significantly improved bandwidth utilization when there are temporal or spatial traffic variations. It is also possible to have a hybrid of DCA and FCA in a cellular network, in which a fraction of channels are allocated permanently and the remainder are allocated based on a DCA technique. This strategy requires less system implementation complexity than a pure DCA one, but provides performance improvement depending on the DCA–FCA partitioning. Other channel allocation schemes are based on channel borrowing [5,6] or aggressive channel allocation.

This paper presents new fully adaptive channel allocation strategies and examines their performance and their features analytically. The aim of the optimum FACA strategies is to keep the system blocking probability in low level and simultaneously to provide an acceptable quality of service (QoS).

Section 2 presents the expression of the conditional co-channel interference probability q_c as developed in References [7–9]. Moreover, this expression is generalized in order to meet the requirements of a complex system design and environment. In addition, q_c is given in terms of the co-channel interference reduction factor. Examples of evaluation of q_c for several cases of cellular systems and calculation of co-channel interference reduction factor for given values of q_c, are also presented.

In Section 3, an alternative expression for the cellular radio capacity (CRC) is defined in relation with the conditional co-channel interference probability. Graphical representations are also given for several values of system's parameters as the modulation constant, the actual bit rate and several cellular environmental parameters.

Section 4 provides the formulation of the fully adaptive channel allocation problem and the co-channel interference compatibility constraints are determined, using the alternative direct formula for the calculation of the co-channel interference probability. This formula can be used for any suitable propagation model and environment (path loss and shadow fading parameters). In the same section, three FACA strategies are proposed, to achieve low-level blocking probability figures, optimum management of the offered radio-spectrum and simultaneous adaptation to the traffic demands.

Finally, in Section 5, a simulation model is developed for comparison of the performance of the FACA techniques, proposed in Section 4.

2. THE CONDITIONAL CO-CHANNEL INTERFERENCE PROBABILITY

The co-channel interference probability, is an important factor for the evaluation of the QoS, in cellular mobile radio systems.

Conditional co-channel interference probability (CCIP) denoted as q_c, is a measure to control the co-channel interference level, helping the designers to re-adjust the system's operating parameters.

CCIP is defined as the probability that the undesired signal local mean power (LMP) exceeds the desired LMP, by the protection ratio denoted as β, according to the average interference criterion. In References [7–9], an alternative direct method is proposed, for the evaluation of the CCIP. In order to derive this formula, the following assumptions were made (as in Reference [10]):

(i) The cellular system zoning is k-gonal and the mobile units are uniformly distributed over the communication service area studied.
(ii) The co-channel interference from the first tier is the dominant one and the interference from the adjacent channels can be ignored.
(iii) If the probability of interference for a given call is satisfactory at the base station, it is also satisfactory at the mobile unit.
(iv) There are k co-channel interfering cells (interferers) in the first tier in a fully k-gonal-shaped cellular system.
(v) Standard deviation σ has the same value in all the regions of the system.
(vi) The mean m of the LMP of all k interferers and the desired signal has the same value.

It can be shown in Reference [8] that the mathematical expression of the conditional co-channel interference probability (CCIP), is given by the following equation:

$$q_c = \frac{1}{(2\pi)^{k/2}} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \exp\left[-\sum_{i=1}^{k} \frac{r_i^2}{2} \right] F\left[\frac{\ln(\beta(3n_g)^{-\gamma/2}(e^{\sigma r_1} + e^{\sigma r_2} + \cdots))}{\sigma_s} \right] dr_1 \cdots dr_k \quad (1)$$

where β is the protection ratio in natural units, γ is the path loss propagation factor, n_g is the cluster size, σ is the standard deviation of the LMP of the interferers in natural units and σ_s is the standard deviation of the LMP of the desired signal in natural units.

The second part of Equation (1) can be calculated using the following Gauss–Hermite formula [11]:

$$\int_{-\infty}^{\infty} \exp[-x^2]\, g(x)\, dx = \sum_{i=0}^{v} \alpha_i g(x_i) \tag{2}$$

where α_i, x_i are constants given from special tables and v is a constant that denotes the accuracy at the vth decade digit.

With the Gauss–Hermite formula, we can control the error within the desired levels.

But, in a real cellular mobile radio environment, shadow-fading parameter σ has different value in different regions of the system area. In this case, the above formula for the CCIP, is modified to

$$q_c = \frac{1}{(2\pi)^{k/2}} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \exp\left[-\sum_{i=1}^{k} \frac{r_i^2}{2}\right] F\left[\frac{\ln(\beta(3n_g)^{-\gamma/2}(e^{\sigma_1 r_1} + e^{\sigma_2 r_2} + \cdots))}{\sigma_s}\right] dr_1 \cdots dr_k \tag{3}$$

where $\sigma_1, \sigma_2, \ldots, \sigma_k$ are the standard deviations of the logarithm of the LMPs of the k interferers.

From Reference [10]

$$\frac{D}{R} = (3n_g)^{1/2} \tag{4}$$

where R is the radius of the cell and D is the distance from the first tier.

Hence, q_c can be written as

$$q_c = \frac{1}{(2\pi)^{k/2}} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \exp\left[-\sum_{i=1}^{k} \frac{r_i^2}{2}\right] F\left[\frac{\ln(\beta(D/R)^{-\gamma}(e^{\sigma_1 r_1} + e^{\sigma_2 r_2} + \cdots))}{\sigma_s}\right] dr_1 \cdots dr_k \tag{5}$$

Equation (5) gives a general form for the CCIP in terms of the critical co-channel interference reduction factor D/R. This is very important for the system design because there is a direct connection between CCIP and the above factor. Hence, setting the desired value for q_c in (5) and solving this equation for D/R, the r factor can be calculated for several shadow and path-loss environments of the system.

Equation (5) is true as long as the cell size is fixed and consequently co-channel interference is independent from the transmitted power of each cell. But, in the case when the cell size is not fixed, the distances from the first tier are not the same for all the k interferers and (5) must be modified to

$$q_c = \frac{1}{(2\pi)^{k/2}} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \exp\left[-\sum_{i=1}^{k} \frac{r_i^2}{2}\right] F\left[\frac{\ln\beta - m_s + \ln(\sum_{i=1}^{k} e^{m_s (D_i/R_i)^{-\gamma} (\sigma_i r_i)}}{\sigma_s}\right] dr_1 \cdots dr_k \tag{6}$$

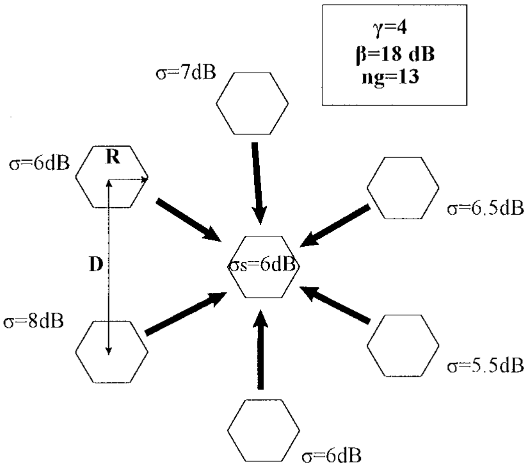

Figure 1. Six effective interferers with different shadowing parameters σ.

where m_s is the area mean power of the desired signal, R is the radius of the cell containing the desired transmission, R_i is the radius of the cell containing the ith interfere and D_i is the distance of the ith interferer from this cell.

Example 1

Let us assume the hexagonal cellular system of Figure 1 in which the shadowing parameter σ has different values in different regions of the system, due to the different synthesis of the geographic area, where the system operates. The parameters of the system are taken as

(a) protection ratio $\beta = 18$ dB,
(b) path-loss exponent $\gamma = 4$,
(c) cluster size $n_g = 13$.

Using Equation (3) with the above parameters, q_c is found to be 0.36233 or 36.233 per cent.

Example 2

Using the system design of Example 1 and considering a desired value of 0.15 or 15% for q_c, it is possible to calculate the co-channel reduction factor D/R of the system solving Equation (5). In this case, the value of D/R was found to be 5.85. It is noted here, that the determination of the frequency reuse ratio D/R in relation with the system's quality parameters q_c and β, helps the engineers upgrade the system's planning and reach the co-channel interference, in desired levels.

In Figure 2 the co-channel interference reduction factor is depicted, for several values of the desired CCIP. The system parameters σ, β, γ are the same as above.

3. KEY FEATURES OF THE CELLULAR SYSTEM'S RADIO CAPACITY

In this section, we try to connect the capacity of cellular systems with the probability of the co-channel interference. This connection is very useful in deciding which channel allocation technique to apply.

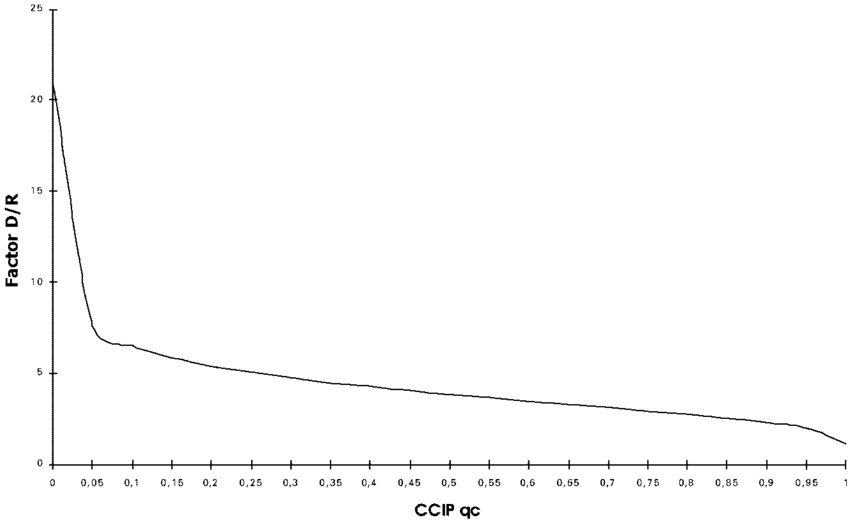

Figure 2. The co-channel reduction factor D/R versus CCIP with the parameters of the system of Figure 1.

In cellular systems, the conventional definition of spectrum efficiency does not hold true, because of the frequency reuse feature [13,14].

In the case of fixed channel allocation, the formula for the cellular radio capacity m is given in References [13,14]

$$m = \frac{(B_t/B_c)}{\sqrt{(2/3)(C/I)}} \tag{7}$$

where B_t is the total bandwidth in KHz, B_c is the channel bandwidth in KHz, R_b is the actual bit rate in Kb/s and C/I is the carrier-to-interference ratio used for system design in dB.

Channel capacity is given by the Shannon equation

$$C_c = B_c \log_2 \left\{1 + \left(\frac{C}{I}\right)\right\} b/s \tag{8}$$

and spectral efficiency is given by

$$C_c/B_c = \log_2 \left\{1 + \left(\frac{C}{I}\right)\right\} b/s \tag{9}$$

But in practice, it is very difficult to achieve the limiting spectral efficiency of Equation (9). The actual bit rate R_b is given by

$$R_b = \alpha C_c \tag{10}$$

where α depends on how closely the Shannon limit can be achieved by use of an improved modulation technique.

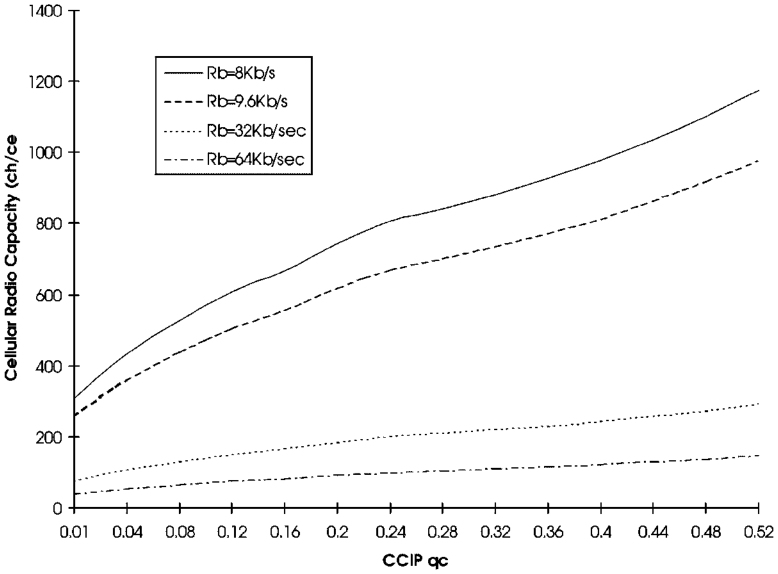

Figure 3. The cellular radio capacity (CRC) versus the CCIP for $\sigma = 6\,\text{dB}$, $\beta = 18\,\text{dB}$, $B_t = 15\,\text{MHz}$, $\alpha = 0.85$, $\gamma = 4$, and several values of the actual bit rate R_b.

From (7), (9) and (10) the final expression for m [15] is

$$m = 1.224\alpha\left(\frac{B_t}{R_b}\right)\frac{\log_2(1 + C/I)}{\sqrt{C/I}} \quad \text{(channels/cell)} \tag{11}$$

In a fully hexagonal-shaped cellular system [16]

$$\frac{C}{I} = \frac{(\sqrt{3}n_g)^{\gamma}}{6} \tag{12}$$

Using Equations (3), (11) and (12), the cellular radio capacity can be calculated numerically for desired values of CCIP, q_c, for any propagation environment, shadowing parameter σ and protection ratio β.

In Figures 3 and 4, the cellular capacity m is described versus the CCIP, for several values of α and R_b.

4. ANALYSIS OF THE FULLY ADAPTIVE CHANNEL ALLOCATION (FACA) STRATEGIES AND THE INVOLVED CO-CHANNEL INTERFERENCE CONSTRAINTS

In a fixed channel allocation (FCA) scheme, a fixed channel subset can be used in each cell. In a fully adaptive channel allocation (FACA) or dynamic channel allocation (DCA) strategy, all the

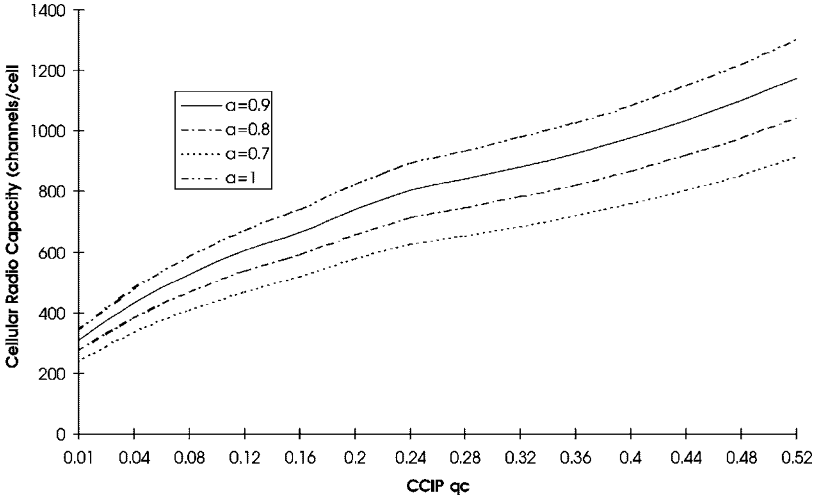

Figure 4. The cellular radio capacity (CRC) versus the CCIP for $\sigma = 6\,\mathrm{dB}$, $\beta = 18\,\mathrm{dB}$, $B_t = 15\,\mathrm{MHz}$, $R_b = 8\,\mathrm{Kbps}$, $\gamma = 4$, and several values of the parameter α.

channels can be used in all the cells. In other words, channels are pooled together and allocations are made and modified, in real time. Therefore, this strategy has the potential to achieve a significantly improved bandwidth utilization when there are temporal or spatial traffic variations [16–20]. It is possible to have a hybrid of FACA and FCA in a cellular network, in which a fraction of channels are statically allocated and the remainder are allocated based on a FACA technique. This strategy requires less system implementation complexity than a FACA one, but provides performance improvement depending on the FACA–FCA partitioning [21]. The main target of a FACA strategy, is the minimization of the blocking probability and the high-level communication service of the subscribers, especially in heavy traffic conditions [22].

A channel is considered to be 'free' for allocation in a specific cell, if this channel agrees with the appropriate compatibility constraints, which have been taken into account. For this reason, a FACA strategy is actually a technique for optimum channel selection, in order to serve a new call.

The basic principle during the cellular systems planning and operation, is the maximization of system capacity, by keeping the quality of service (QoS) in predetermined levels. Two of the most important parameters, that determine the QoS, are the blocking probability and the co-channel interference probability. It is noted, that the system successful operation depends on the determination of a set of constraints that are taken into account in order to define the system QoS.

To determine a set of constraints, that will satisfy the condition

$$q_C \leqslant q_{\mathrm{cmax}} \tag{13}$$

where q_{cmax} is the maximum desired CCIP for the system, it is needed to determine the smallest distance $L_{\min}$ in such a way that if k interferers (for a k-gonal system zoning) are located symmetrically at distance $L_{\min}$ from the centre of a given cell C, then Equation (13) is true.

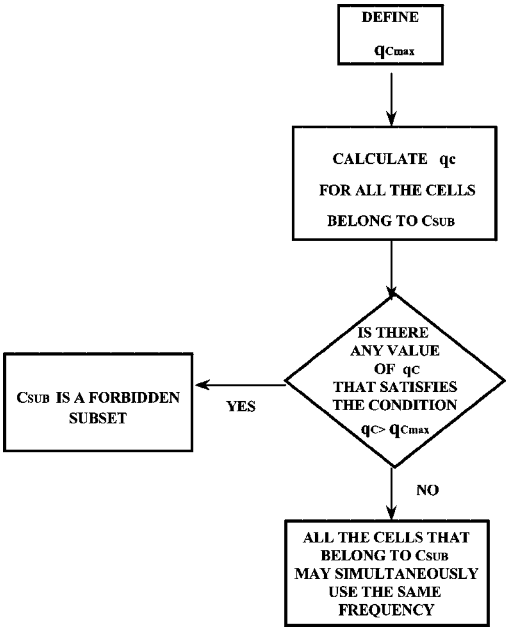

Figure 5. The fixed channel allocation (FCA) procedure.

In this case, all cells in distance L less than $L_{\min}$, are forbidden to use the same frequency (or set of frequencies) as the cell C. The procedure developed to decide whether all the cells of any given subset C_{sub} of the cells may simultaneously use the same frequency, with the constraints of Equation (13), is depicted in Figure 5. The determination of all forbidden subsets C_{sub} of the system is equivalent to solving the fixed channel allocation problem. In a FACA or DCA strategy, as denoted above, all the channels are available in all the cells. Calls are to be assigned frequencies in real time, with the compatibility constraints. The procedure shown in Figure 6 describes the way a particular frequency f can be allocated to a call in a cell C. It must be noted that in practice adjacent channel interference and intermodulation product constraints play a major role in the frequency allocation schemes. Generally, there are two kinds of proposed strategies for fully adaptive channel allocation schemes. The first does not permit reallocation of a call in progress whereas the second allows such a possibility. The following three FACA strategies are proposed [23]:

Strategy No. 1: A new call in a cell tunes on the first 'free' frequency, which satisfies the algorithm of Figure 6. If there is no free channel, the call is blocked. The algorithm of this strategy is presented in Figure 7.

Strategy No. 2: A new call is allocated to the frequency, which maximizes the total number of 'free' channels, in all the cells. The algorithm of this strategy is depicted in Figure 8.

Strategy No. 3: If no channel is 'free' with Strategy No. 2, another call in progress is reallocated to a different channel, in order that the new call be accommodated. The algorithm of this strategy is presented in Figure 9.

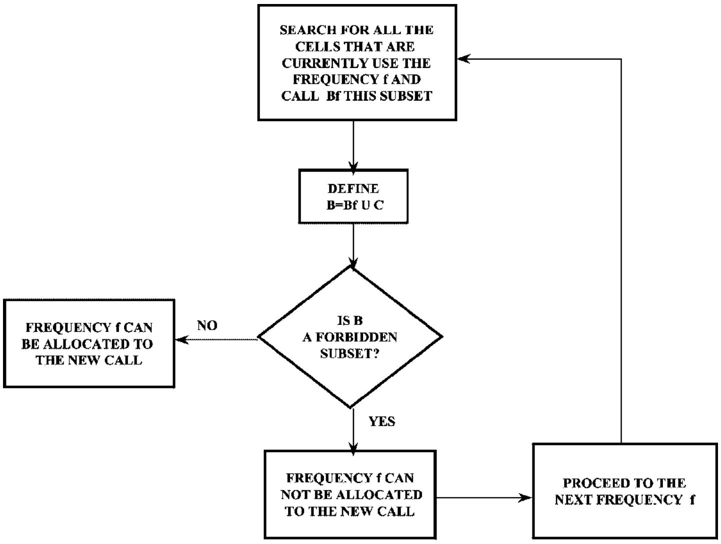

Figure 6. The fully adaptive channel allocation (FACA) procedures for the determination if a frequency f is free for allocation to a call in a cell C.

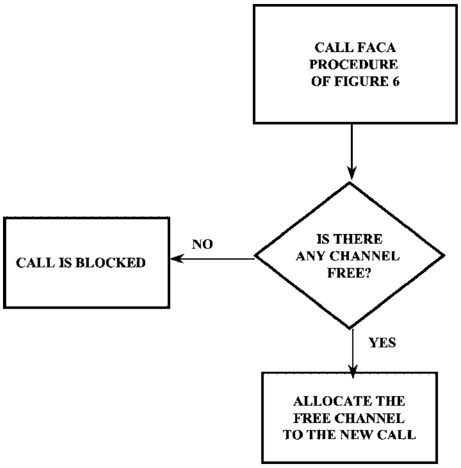

Figure 7. The FACA Strategy No. 1 procedure.

5. SIMULATION PROCEDURE AND COMMENTS ON THE OBTAINED RESULTS

In order to evaluate the performance of the proposed FACA algorithm a simulation model has been implemented using C programming language. This model belongs to the class of dynamic and stochastic models and satisfies the following assumptions:

1. A frequency is said to be ‘free’ in a cell, if it may be allocated to a new incoming call in that cell, according to the compatibility constraints described in the previous section.

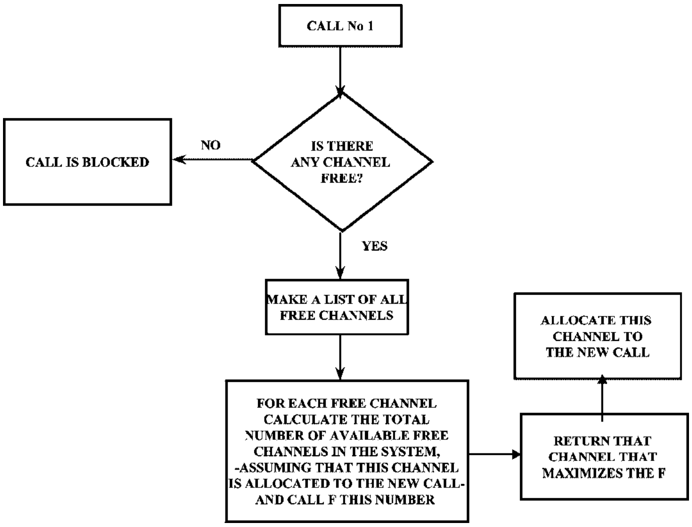

Figure 8. The FACA Strategy No. 2 procedure.

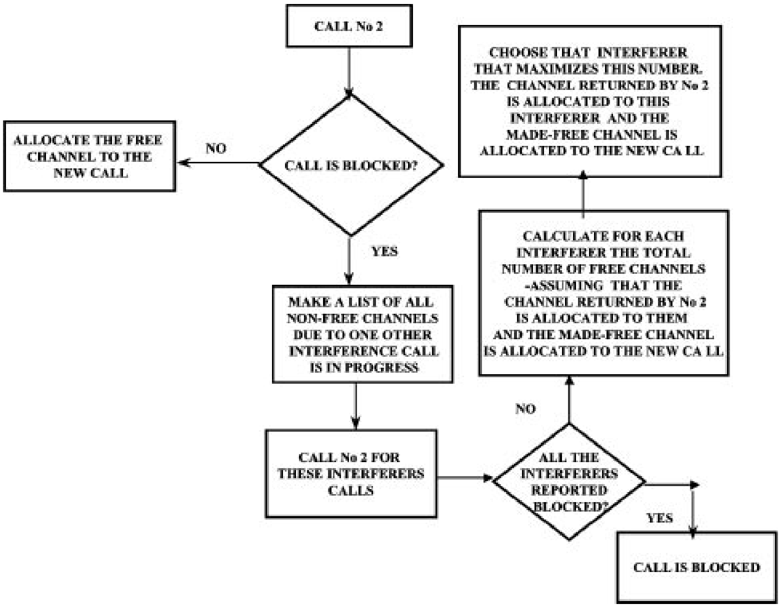

Figure 9. The FACA Strategy No. 3 procedure.

2. The call duration time follows an exponential distribution with a mean of 200 s.
3. Hand-offs are accepted by the system, as new incoming calls.
4. The traffic is uniformly distributed over the whole service area, i.e. the rate of the call arrivals is the same for all the cells.

5. The new call arrivals follow a Poisson distribution.
6. The cells are of equal size and hexagonal in shape.
7. All blocked calls are cleared (Erlang-B formula).
8. q_{cmax} is chosen to be 10.2%.
9. The values for σ and β are 6 and 12 dB, respectively.
10. It is assumed that the number of cells is 21 as in Reference [24], the cluster size is 12 and the total number of channels is 96.

With the above parameters for σ and β, the minimum permitted distance d_{min}, has been calculated by using Equation (1) and found to be 6.01. The characteristics of the simulation model used for implementation of the proposed FACA strategies are:

(1) The time steps are of 20 ms duration each. The call duration holds at least one step, and the minimum time between successive calls is one step.
(2) At the beginning the time is increased by one step and a check is made, about the existence of new arriving calls. The new arriving calls follow an exponential distribution with mean value of $200/T$, where T is the total traffic of the system in Erlangs and 200 s the mean call duration.
(3) The cell ξ is selected to accept the new call. New calls arrive with a Poisson distribution.
(4) The call duration follows an exponential distribution, with mean value of 200 s.
(5) When calls terminate the channels that serve that calls are released.

The calculated blocking probabilities for the above proposed three FACA strategies, are plotted in Figure 10. It can easily be seen that the three proposed strategies can be ranked in

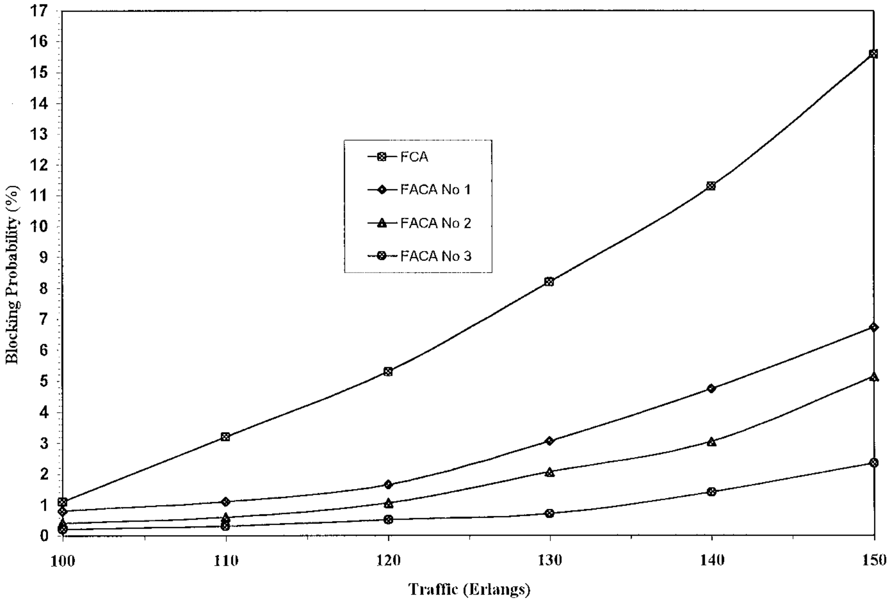

Figure 10. The estimated blocking probability performance of the proposed three FACA strategies for homogeneous traffic.

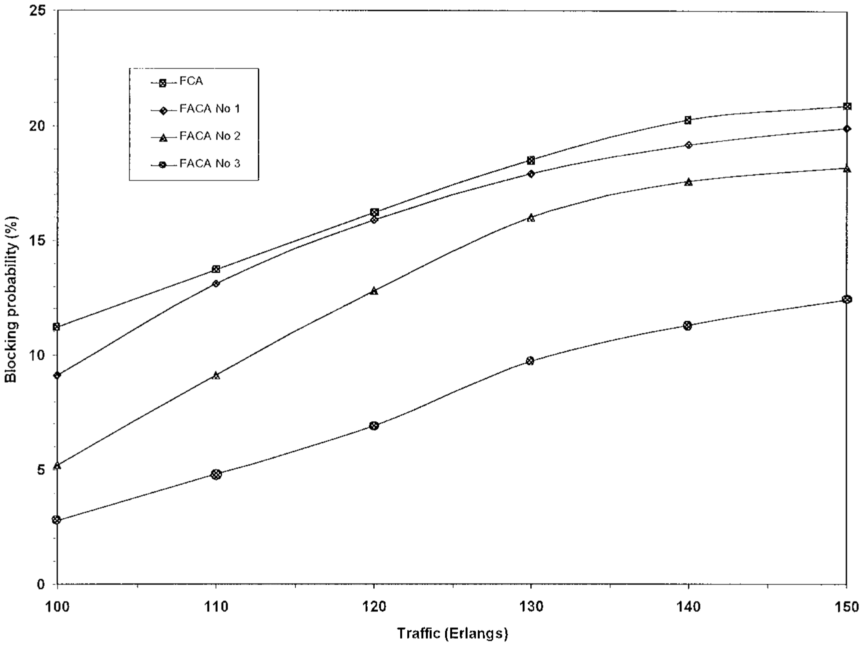

Figure 11. The estimated blocking probability performance of the proposed three FACA strategies for non-homogeneous traffic.

increasing order of performance as: No. 1, No. 2, No. 3. In this case, a question arises and needs an answer. The question is: 'why there is not any proposition of applying an 'ideal' FACA strategy that makes reallocation in a continuing mode for servicing a new arriving call and for providing zero blocking probability, even in heavy traffic load conditions?'. The answer is that such an ideal FACA technique, which needs a continuous updating of the system state, should demand optimum solution of the FCA problem, each time a new arriving call is going to be blocked. This means very high consumption in system computing power, possible communication interruption and consequently reduction of the QoS.

The case of the non-homogeneous traffic is of great importance. The non-homogeneous scenario is more realistic than the corresponding homogeneous one. The three proposed FACA strategies are also examined in a non-homogeneous environment and their behaviour is depicted in Figure 11. In this case, it is considered that the arriving call rate is not the same for all the cells.

Comparing Figures 10 and 11, it is obvious that the behaviour of the FACA strategies in a non-homogeneous traffic environment is worse than in the homogeneous case. Besides that, the three FACA strategies are very efficient and therefore represent realistic operation conditions.

Within the framework of the present work, simulation is made for heavy traffic (700 Erlangs) by considering homogeneous traffic condition. This case is of great importance, because it is known [25,26] that in such extreme situations the FCA techniques are more efficient than the FACA techniques. Such a scenario is also simulated for the FCA and the three proposed FACA strategies. The results for the blocking probability are: FCA: 0.692, No. 1: 0.715, No. 2: 0.708 and

No. 3: 0.697. According to these obtained results, it is obvious that the FACA strategy No. 3 is quite robust even in cases with blocking probability around 70 per cent.

The application of the examined FACA strategies in the futuristic cellular systems is possible. In this case, a number of new base transceiving stations (BTSs) will be added in the geographical area under service, with the ability of transmitting and receiving in all the offered available radio spectrum. Such capabilities are estimated to be available in the next few years.

The next problem that has to be solved is the demanded system computing power. The answer to this problem depends, on one hand, on the cost reduction rates of the computer systems—which will come up in the near future—and on the other hand, on the adoption of flexible and more efficient decentralized procedures for executing various complex calculations in the hardware of the Base Stations and the Mobile Units.

Finally, it is noted that when the number of the available channels is increased (real system situation) then the behavior of the proposed FACA strategies will improve. In this case the simulation results show that for 372 channels (DCS 1800) the corresponding blocking probabilities are: FCA: 0.128, No. 1: 0.119, No. 2: 0.091, No. 3: 0.056, considering homogeneous total communication traffic 700 Erlangs.

6. CONCLUSIONS

An alternative formula for direct calculation of the co-channel interference probability has been modified and generalized. The same formula is used for direct connection between CCIP and cellular radio capacity, in order to investigate the efficiencies in the design of the mobile cellular systems. Co-channel interference compatibility constraints are defined and three new fully adaptive channel allocation strategies are proposed. These strategies are simulated for several situations of cellular systems (homogeneous and non-homogeneous communication traffic, heavy traffic load conditions, etc.), and a study is made on their performance by checking the estimated blocking probability. The performance of each of these proposed strategies is proved to be acceptable and allows us to apply them to futuristic cellular systems. Moreover, there are some topics under research, such as the effects of hand-offs and the time-varying traffic. Finally, it is an open question the matter of how much the proposed strategies can be extended and also how much reduction of the blocking probability could be succeeded and still keeping QoS high.

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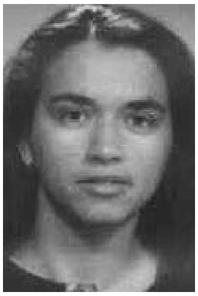

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