Calculation of Minimum Frequency Separation for Mobile Communication Systems

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Abstract —
This paper presents a new tool, named *SchutzAbstandsbestimmung für MObilfunksysteme (SAMO)*[1] which has been developed to determine the required minimum frequency separation (MFS) of coexisting mobile communication systems. The concept of the calculation of the MFS within SAMO, considering radio propagation, interferences, receiver and transmitter characteristics, and user densities, and results of simulation runs are presented in this paper.

I. Introduction

At the assignment of frequency bands for radio systems the simultaneous, undisturbed service of mobile radio systems which are operating in adjacent frequency bands has to be ensured. Thereby, in respect to frequency economic, the required minimum frequency separations (MFS, see section V) between coexisting systems have to be reduced to a limit that the quality of service guaranteed by the service provider is not jeopardized. Anyhow, the mutual interference of mobile communication systems separated by a given MFS calls for more FDMA/TDMA channels in those cells using the affected frequency channels than would normally be required by the traffic intensity (Erlang/km^2) to achieve the wanted quality of service. In respect to an efficient allocation of frequency spectrum to mobile communication providers the characteristics of the planned resp. existing mobile communication systems have to be considered. Especially this task will become important when planning future systems like Univarsal Mobile Communication Systems (UMTS) that are based on different mobile system standards that have to reside in an appropriately chosen frequency band.

Particularly, the interferences due to simultaneous operation of the systems as a function the transmitted power, attenuation and carrier frequency, have to be taken into account. The effects of the interferences largely depend on the interfering frequency, the receive frequency of the victim system, and on the receiver, especially the receiver's filter characteristic. In the evaluation of the impact of the interferences on the receiver the modulation methods used by the interfering and the victim system have to be taken into account. Intermodulation products and interfering signals generated by the signal edges within the system and in adjacent systems, which are attenuated by propagation loss and fall into the receive band of the system under consideration, have to be identified and their effects assessed.

To describe the general situation that has to be investigated an example interference scenario is considered where a mobile station (V, victim receiver) with link to its base station is interfered by mobile stations of a system in an adjacent frequency band, Fig. 1.

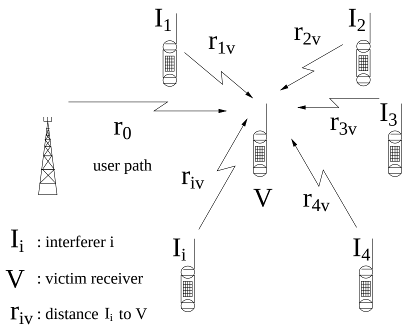

Fig. 1: Example interference scenario

The unwanted emissions of the interfering stations (I_i) and their impacts at the victim receiver (V) have to be assessed (*sec.* II). As the distance on the user path between the base station and the victim receiver as well as the distances on the interference paths have an impact on the resulting carrier-to-interference (C/I) ratio the distances have to be determined (*sec.* III). Depending on the distances appropriate propagation models have to be chosen to assess the attenuation on the respective paths (*sec.* IV).

To come to a conclusion regarding the required MFS (*sec.* V), the probability of the carrier-to-interference ratio exceeding the maximum permissible level (C/I ratio) is determined considering all relevant parameters mentioned before by means of Monte-Carlo (MC) technique (*sec.* VI). For the systems TETRA (Trans European Trunked RAdio), GSM (Global System for Mobile Communications) and the GSM system of the UIC (Union Internationale des Chemins de Fer) the results are depicted exemplarily in section VII.

[1] SAMO is a product of the study which was commissioned by the *"Bundesamt für Post und Telekommunikation"* (BAPT — Federal Office for Posts and Telecommunications)

II. MODELING TRANSMITTER AND RECEIVER CHARACTERISTICS

For the efficient use of the radio spectrum it is essential to know the spectrum emitted by interfering stations. The impact of the emissions at the receiver depend on the interfering frequency, receive band, interference power and on the receiver characteristics. The modulation method used has to be considered, too.

Therefore, the transmitter and receiver characteristics of the different systems have to be taken into account. For this purpose the permissible interference power and acceptable received signal levels of each system as defined in the relevant standard specifications [1], [2] are used to define masks.

The mask for the interfering transmitter represents the maximum permissible unwanted emission levels as a function of the frequency. To define a mask for the emissions, the different sources of interferences, as there are

- effects of modulation process,
- rise and fall times of the transmitted signals (switching transients),
- intermodulation products,
- wideband noise,

are combined in one mask. Therefore, the maximum permissible transmitted power $I(f_i)$ at the respective frequency f_i referred to a predefined bandwidth Δf and power class is taken from the standard. The equivalent analytical expression for the permissible emission is given by

$$I(f_i) = \int_{f_i-\Delta f/2}^{f_i+\Delta f/2} P(f) H_{tx}(f) df, \qquad (1)$$

where $P(f)$ denotes the power spectral density that is defined by the power class and $H_{tx}(f)$ denotes the transfer function of the transmitter characteristic.

In Figure 2 a mask for unwanted emissions of a TETRA transmitter is depicted, that defines the permissable interferences over the frequency difference to the carrier frequency referred to a bandwidth of 25 kHz.

The emissions that are received at the victim station in an adjacent frequency band in its user bandwidth are observed as co-channel interferences. Unwanted signals outside the receiver band cannot be suppressed completely owning to the response of the filter and are observed as adjacent channel interferences. In order to assess the receiver characteristic appropriate masks have been developed (see Fig. 3) which model the effects of adjacent and co-channel interferences taking into account

- intermodulation,
- blocking characteristic, and
- the required carrier-to-interference ratio.

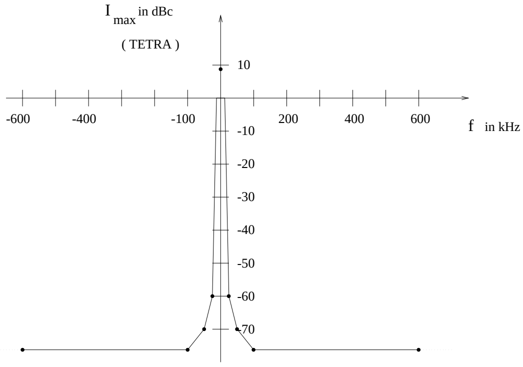

Fig. 2: Mask for permissible unwanted emission (TETRA transmitter)

This mask can be described by the receiver transfer function $H_{rx}(f)$ the same way it has been done for the transmitter mask.

To create one mask for the receiver, the interference rejection mechanisms defined in the standards are transfered to an equivalent carrier-to-interference (C/I) ratio, e.g. a blocking value of -40 dBm is referred to the sensitivity level of -100 dBm that results into an equivalent C/I ratio of -60 dB.

A mask for a GSM victim receiver that shows the required C/I ratio over the frequency and thus for a particular received carrier power the maximum permissible interference power level, is depicted in Figure 3.

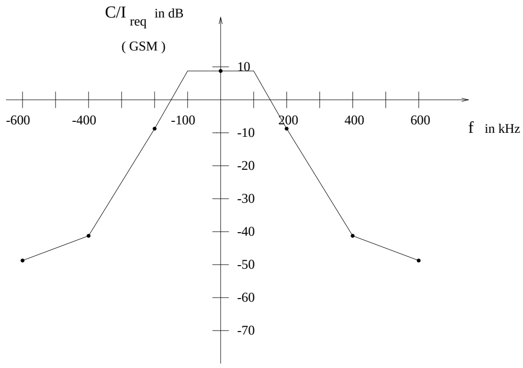

Fig. 3: Mask for required C/I (GSM receiver)

Because, the masks are represented in the simulation as data files they easily can be modified if different specific filter characteristics have to be assumed or if a different system with another modulation scheme will be used. Thus, the definition of masks to consider the transmitter and receiver characteristic enable the simulation tool to adapt its calculation to different systems and transmitter and receiver structures.

III. DISTANCE DISTRIBUTION

To estimate the distance between the transmitter and receiver on the user link (see Fig. 1) as well as between the interfering stations and the victim receiver the density of active users are an important parameter.

A. Modeling of the traffic load

In the various scenarios the mobile user densities given in Table I were assumed.

TABLE I
User densities of different systems

Area	GSM user/km^2	TETRA user/km^2
Urban	190	10
Suburban	45	3
Rural	7	0.3
Highway	75	20

These data, which were taken from [3] and [4], were used as a guideline for the simulations.

Because the interfering station with the minimum distance to the victim receiver is in the mean the dominant interferer only the nearest interferer is considered, though under special circumstances interfering stations with greater distances will contribute to noticeable interferences. The eight basic types of interference situation, where the transmitter, victim receiver and interferer can be a mobile station as well as base station, respectively, are described in Table II.

TABLE II
General interference situations

	Transmitter	Victim receiver	Interferer
A	Base station	Mobile station	Base station
B	Base station	Mobile station	Mobile station
C	Mobile station	Base station	Base station
D	Mobile station	Base station	Mobile station
E	Mobile station	Mobile station	Base station
F	Mobile station	Mobile station	Mobile station
G	Base station	Base station	Base station
H	Base station	Base station	Mobile station

The interference situation A to D in Table II are the typical interference situations for cellular mobile communication systems. The interference situation E and F take into account the possible communication between two mobile stations as it is foreseen e.g. in the TETRA standard with the “Direct Mode“. The situations G and H also are presented for generality and consider possible situation where point-to-point radio connection exists. The presented simulation results only cover the situations A to D.

B. Distribution of the user path length

Assuming that there is exactly one receiver within the coverage radius R of the base station for the user path under consideration the following distribution function is obtained. The probability that there is a receiver within the transmit radius R is

$$P(R) = 1. \tag{2}$$

Assuming that the receiver in the cell follows the law of uniform distribution this yields a density of mobile station of

$$d_E = \frac{1}{\pi R^2} \tag{3}$$

hence the distribution function as a function of the distance r from the base station is:

$$P(r) = \int_0^r \frac{2\pi r}{\pi R^2} dr = \frac{r^2}{R^2}. \tag{4}$$

The equation 4 constitute the distribution function for the length of the user link.

C. Distribution of the interference path length

As the closest user of the co-existing disturbing system is substance of the main interference power, only this active user is considered as interfering station. The following applies for the interfering mobile station. The density of interferers d_s is taken as parameter. If the interferers are observed from a fixed point (without considering the physical characteristics of the victim receiver), the number of interferes within a circle with radius r around a fixed point follows the Poisson distribution

$$p(i) = \frac{\left(d_S \pi r^2\right)^i}{i!} e^{-d_S \pi r^2}. \tag{5}$$

The probability that there is no interferer is described by p(0) and hence the distribution function for at least one interferer (the closest) is described by

$$F(r) = 1 - p(0). \tag{6}$$

The probability density function for the radius r can be derived after differentiation from

$$p(r) \quad = \quad 2 d_S \pi r e^{-d_S \pi r^2}. \tag{7}$$

In case the interferer is a base station and it is assumed by approximation that the base stations of a single system operator are equally distributed, the distribution function for the distance to the next interferer is:

$$P(r) = \frac{r^2}{R^2}, \tag{8}$$

where R denotes the coverage radius of the interfering base station,

$$R = \sqrt{\frac{d_S}{\pi}}, \tag{9}$$

and d_s the density of base stations.

IV. Transmission models

In order to assess the influence of the interference power and the wanted power at the receiver and thus the carrier-to-interference ratio C/I the propagation loss on the interference path and the user path have to be calculated.

Methods have been developed to determine the properties of radio channels which take the main physical effects into account in the form of models. They simulate various characteristics of a channel, i. e. the propagation coefficients and fading behaviour. Especially, the fading has to be considered in mobile communication scenarios. In view of permissible level of unwanted emissions, some of which are defined in the standards for long measurement periods in relation of transmission time of up to 500 bits, it suffices to take the fading due to shadowing into account and to calculate the median multipath fading value. This slowly varying signal strength can be described by a log–normal distribution [5]. Respective values for the variance of the distribution are known from measurements and are dependent on topology and morphology, e.g. for the user path in urban areas 6.3 dB and on the interference path 4 dB standard deviation is used.

The mean path loss can be obtained by averaging the fading values over different locations at respective distances. The mean path loss values which are used in SAMO are based on the models of Hata–Okumura [8] for distances above 2 km and COST–231–Walfisch–Ikegami [9] for distances between 20 m and 1 km. Over a distance of 200 m LOS and non-LOS is chosen randomly for the COST model. Above 200 m non-LOS is assumed. For distances between 1 km and 2 km linear interpolation of the COST and Hata models is used. For very small distances less than 20 m and LOS between transmitter and receiver free–space attenuation is assumed.

V. Definition of Minimum Frequency Separation (MFS)

The unused frequency band between two different radio systems intended to decrease the possibility of mutual interference is referred to as MFS.

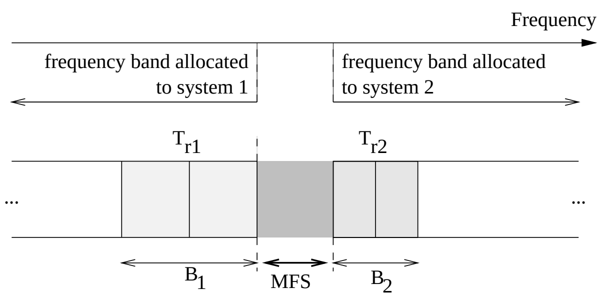

Fig. 4: Definition of minimum frequency separation, MFS

Thus, the MFS can be derived from the following equation:

$$MFS = (Tr_2 - \frac{B_2}{2}) - (Tr_1 + \frac{B_1}{2}) \qquad (10)$$

where T_{rx} stands for the carrier frequency of system x and B_x for the bandwidth requirement of a carrier in system x.

For the simulation results in section VII , where the systems GSM, UIC, and TETRA are contemplated, the scenarios regarding to the MFS‘s are explained in the following Table III.

TABLE III
System specific interference situation

	Interferer	Victim receiver
1.1	GSM mobile station (890-915 MHz)	TETRA hand-held (915-921 MHz)
1.2	UIC base station (921-925 MHz)	TETRA hand-held (915-921 MHz)
1.3	UIC mobile station (876-880 MHz)	TETRA base station (870-876 MHz)
2.1	TETRA base station (915-921 MHz)	GSM base station (890-915 MHz)
2.2	TETRA base station (915-921 MHz)	UIC mobile station (921-925 MHz)
2.3	TETRA mobile station (870-876 MHz)	UIC base station (876-880 MHz)

VI. Algorithm for MFS calculation

In the study of the *BAPT*[2] a tool was developed allowing the C/I ratios to be determined in the presence of an interfering system in an adjacent frequency band as function of various parameters such as MFS, output power, antenna heights, user densities, etc. The general algorithm which has been used to determine the probability of link failure and thus the required MFS is depicted in Figure 5.

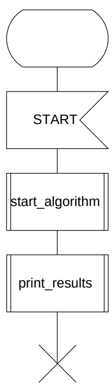

Fig. 5: Main algorithm for MFS determination

The evaluation cycle starts with the positioning of the receiver station by means of the distribution function for the

[2]Bundesamt für Post und Telekommunikation, Federal Office for Posts and Telecommunications

user path (see section III). This receiver becomes the victim receiver due to interferences of the interferer station (Fig. 6).

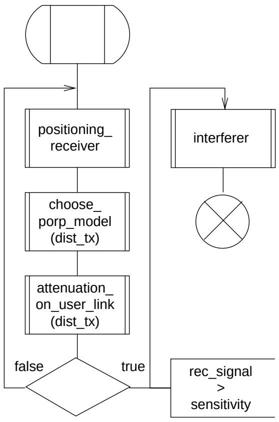

Fig. 6: Distribution of receiver

Depending on the distance between transmitter and victim receiver the appropriate propagation model is chosen, considering the relevant parameters, e.g. topology and morphology, carrier frequency, antenna heights, etc. (see section IV).

If the signal strength at the victim receiver meets the required sensitivity level, the interferer with the minimum distance to the victim receiver will be positioned (see section III), otherwise the algorithm starts at the beginning (see Fig. 7).

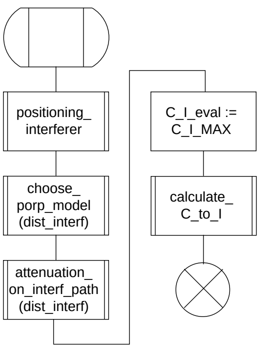

Fig. 7: Distribution of interferer

After all participating stations are located the attenuation between the victim receiver and the interferer will be calculated, using the appropriate propagation model depending on the distance (see section IV).

To determine the interference power at the victim receiver, the unwanted emissions of the interferer $I(f_i)$ are calculated with the help of the mask (see section II) and the loss on the interference path L_I will be substracted from it.

With the information of the signal strength $C(f_i)$ on the user link and the interference power, the present C/I(f_i) at the victim receiver can be calculated

$$\frac{C}{I}(f_i) = C(f_i) - (I(f_i) - L_I(f_i)), \qquad (11)$$

which is depicted in Figure 8.

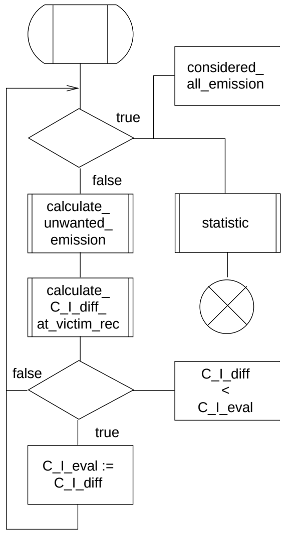

Fig. 8: Calculation of C/I

All present C/I values, whether they are measured in the receiver band or outside the receiver band, are compared with the respective required carrier-to-interference ratios C/I_{req} and the minimum difference between the present and required C/I ratio

$$\min_{f_i} \left\{ \frac{C}{I}(f_i) - \frac{C}{I}_{req}(f_i) \right\} \qquad (12)$$

is chosen as the value for statistical evaluation algorithm (LRE, see section VI.A). As soon as this value amongst an adequate number of observed values falls below a specified relative error limit the simulation can be discontinued and the desired statistical precision of the results has been achieved (Fig. 9).

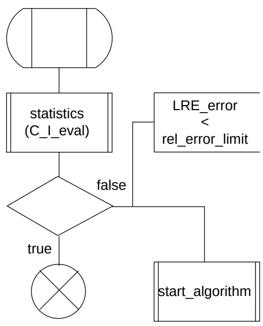

Fig. 9: Statistical evaluation

Otherwise, a further iteration is initiated.

A. Statistic evaluation of the simulation results

For statistical evaluation in SAMO the ***L**imited **R**elative **E**rror* (LRE) algorithm is used which allows the analysis of correlated random sequences in order to gain the stationary distribution function $F(x)$ [11], [12]. The LRE algorithm provides not only the distribution function of the variable but also the local correlation coefficient as a measure of the dependence of successive values. This algorithm can be used to control systematically the required number of trials of a simulation run by a formula which depends on the desired minimum value F_{min} of $F(x)$, on the prescribed upper limit d_{max} of relative error per $F(x)$ interval, and also on the measured mean value of the correlation coefficient $\bar{\varrho}(x)$. Correlated random sequences are typical for simulation runs of communications systems. Therefore, this algorithm is more appropriate for the analysis of MFS than conventional evaluation methods such as batch means.

VII. Results

In this section some of the simulation results for the different scenarios are presented and discussed. The following graphics depict the distribution function of the difference between the required and the generated C/I ratio for a fixed cell size of the victim system. The C/I difference = 0 on the x-axis applies exactly at that moment at which the required C/I ratio is still achieved. The probability of an inadequate coverage corresponds to the probability value along the curve at C/I difference = 0.

The parameter "density of interferers" describes the active mobile users causing interferences. If an activity of 20 mE per mobile user is assumed and a density of 1 user/km^2 applies, this yield a density for all mobile terminal stations of 50/km^2.

It is further assumed that the outer system frequency will be used. The power emitted at the antenna (EIRP) is taken as the transmitter power. If not stated explicitly a transmitter power of the base station of 45 dBm and that of the mobile station of 33 dBm is assumed. These typical transmission power values are chosen whithout the loss of generality. Antenna gains for the base station of 4 dB and for the mobile stations of -2 dB are used, that include cable losses. The morphological structure is assumed to an urban area.

A. GSM mobile station causes interference to the TETRA hand-held

Figure 10 shows the susceptibility of interference as a function of the coverage radius R of the serving TETRA base station. The simulation was based on a density of 20 interferes/km^2. In all cases the MFS was 600 kHz.

Base stations with large transmitter radius serve many mobile users in reception areas with a low signal level. For this reason mobile users in such areas are much more susceptible to interference from other systems. From this follows that hot spots should not be located in poorly served areas of a cell to ensure that a satisfactory receiving level is available to the victim receiver.

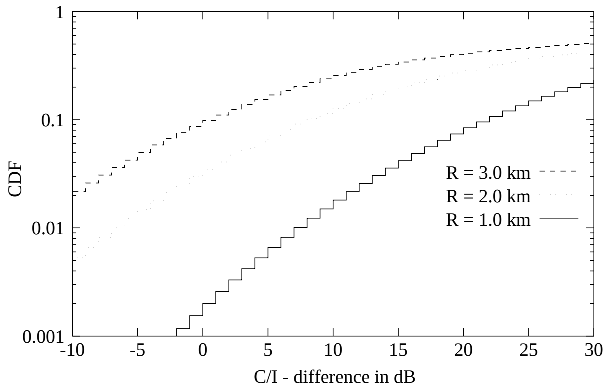

Fig. 10: Distribution of C/I difference (GSM MS interferes with TETRA hand-held with the coverage radius of TETRA BS as parameter)

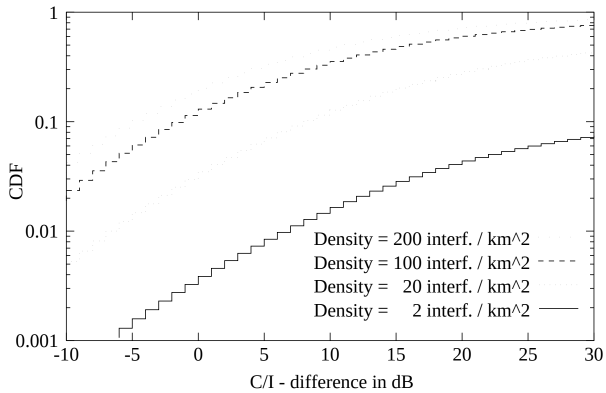

Fig. 11: Distribution of C/I difference (GSM MS interferes with TETRA hand-held with the density of interferers as parameter)

The variation in the density of interfering GSM mobile stations in Fig. 11 shows that for densities of 2 interferes/km^2 and a coverage radius of 2 km a MFS of 600 kHz is quite sufficient, as the probability of a link failure is less than 1%. At higher densities of interfering GSM mobile stations the values remain below an acceptable probability of failure at the C/I difference = 0. At much higher densities (e.g. 200 interferer/km^2) the interferences are unbearable for the victim receiver (only approx. 20 % availability). Nevertheless, it should be noted that high interferer densities only occur at hot-spots. Presumably TETRA system operators will expect higher traffic loads to occur at such spots and will ensure that such areas are served by satisfactory signal levels resulting from a shorter distance to the serving base station.

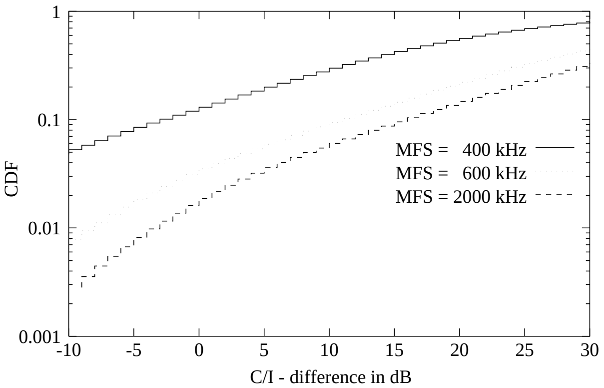

Fig. 12: Distribution of C/I difference (UIC MS interferes with TETRA base station with the MFS as parameter)

B. UIC mobile station causes interference to the TETRA base station

For this simulation run a coverage radius of 2 km and density of 2/km^2 were assumed. In Fig. 12 the impact of the MFS on the C/I difference is depicted.

Because the height of the base station is considered in the path loss, a larger separation distance can be assumed on average compared to those of the scenario presented in sec. VII.A (GSM MS interferes with TETRA hand-held). But due to the different propagation conditions on the interference path with a higher probability for line-of-sight and the antenna gain of the base station, that increases the received interference power the scenario becomes a critical interference situation. This leads to an availability of approx. 90 % at a low density of interferers for a MFS of 400 kHz. A larger MFS of 600 kHz can reduce the outage probability to approx. 3 %. An additional increase of the MFS to 2 MHz can not improve the availability significant.

C. TETRA mobile station causes interference to the UIC base station

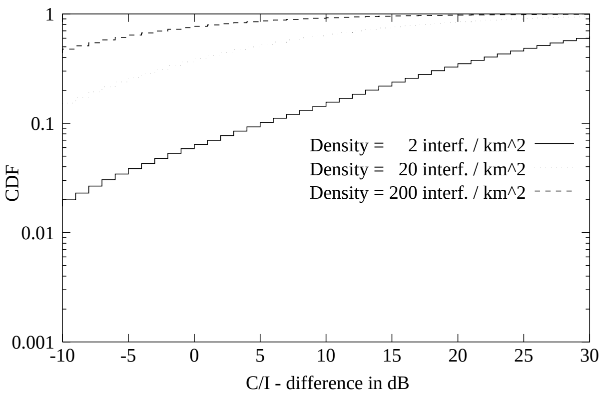

Fig. 13: Distribution of C/I difference (TETRA MS interferes with UIC base station with the density of interferers as parameter)

In Figure 13 the results for a MFS of 600 kHz and coverage radius of 2 km with the density of interferers as parameter are shown. The interference situation is comparable to that in section VII.B where the UIC mobile station interferes with the TETRA base station.

Even for a density of 2 interferers per km^2 approximately 3% of the links suffer from interference. In comparison to the scenarios listed above in this case the interferences outside the receiver bandwidth have an impact on the outage probability. As the filter characteristic of the TETRA interferer is more strict in its definition of permissible emission far away from the carrier, the definition of the acceptable adjacent channel interferences at the UIC receiver account for the critical situation.

VIII. Conclusions

In this paper a new tool for the calculation of MFS called SAMO has been presented. Due to its modular concept this tool can be adapted to analyse the required MFS for arbitrary coexisting mobile communication systems. The MFS calculation is based on the modeling of receiver and transmitter characteristic with the help of masks and takes into account all major parameters (geometric distances, coverage radius, propagation conditions, etc.). Geometric distance ratios between victim receiver and interferer and between transmitter and receiver are calculated on the basis of probability values. Appropriate propagation models are used individually on the user link and the interference path.

As example the MFS for the coexisting systems GSM/UIC and TETRA in the 900 MHz frequency band have been derived. The probability of the interference exceeding the maximum permissible level (C/I ratio) was determined by simulation and results have been presented.

This simulations suggest that a MFS of 600 kHz may be suitable. Even substantially larger MFS (2 MHz) do not preclude the possibility of a victim system failure under adverse conditions because of wideband noise. A more stringent definition of the masks would improve the interference situations.

The mutual interference of mobile communication systems separated by a given MFS calls for more FDMA/TDMA channels in those cells using the affected frequency channels than would normally be required by the traffic intensity (Erlang/km^2) to achieve the wanted quality of service.

Intra-cell handover allows critical interference situations to be bypassed. Thus, a lower MFS could possibly be achieved by frequency handover whilst virtually retaining system capacity.

Future work concentrates on the integration of protocols for the channel allocations and handover control to determine the sum of loss of capacity caused by other systems separated by a given MFS by simulation.

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