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Radio Planning Algorithms for Interference Reduction in Cellular Networks

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Abstract: *The influence of different propagation models and frequency assignment methods on the interference in a cellular network is investigated. The algorithms are applied to a part of the E-Plus GSM1800 network. The considered sub-network consists of 1856 cells. Both homogeneous and inhomogeneous traffic distributions derived from realistic measurements are used. Furthermore, different traffic loads are simulated. It is shown how elaborate propagation models and frequency planning can lead to (substantial) interference reduction, when the corresponding frequency plans are implemented in a live network.*

1 Motivation

In GSM systems, an increasing demand for voice traffic has to be covered with a limited amount of spectrum. The situation will become even worse with the introduction of the new circuit- and packet-switched high bit-rate data services. In such a planning environment manual frequency assignment and network optimisation is time consuming and inappropriate from an economic point of view. In order to apply automatic planning tools, reliable radio planning algorithms are required. Radio planning algorithms include mainly propagation modelling, cell calculation, interference analysis, and frequency assignment. Much research is done especially in the areas of radio propagation prediction and frequency assignment algorithms. Up to now, these algorithms have been treated separately in the literature. Although the influence of propagation modelling on the network quality is more important, when automatic frequency planning is used, radio propagation tools are predominantly seen as a tool for coverage planning,. However, when an automatically created frequency plan is evaluated in a real-world scenario only the combined impact of all used components can be measured. In this paper, different propagation models and frequency assignment methods are studied on the basis of a GSM1800 network using five different channel demand profiles. These profiles are derived from realistic traffic distributions.

2 Radio Planning

Propagation prediction models. Three different types of propagation models are used. In the so-called simple model (SM), the path loss L is given by $L = 20n\log(4\pi d/\lambda)$, where λ is the wave length in m, d is the distance from the base station in m, and n is the propagation decay factor (n = 1, 1.5, and 2 is used in the article). This model does not take any terrain information into account. In principal, SM corresponds to the models that are used to derive regular frequency plans based on a hexagonal cell layout [1]. The second model is a modified Okumura-Hata model (OHM) [2]. Terrain irregularities are included by knife-edges [3], whereas the influence of land-use is modelled by an additional clutter loss [4]. Such OHM approaches are often implemented in commercial planning tools. Finally, the E-Plus model (EM) [5] is the most complex of the models applied here. The model is a combination of several sub-models which are selected automatically after the terrain profile between base station and mobile station has been analysed. This model is used to plan and optimise the E-Plus network.

A Frequency Assignment Problem (FAP). The following problem is considered: given are a list of elementary transceivers (TRXs), a set of available channels for each TRX (this accounts for potential channel blockings within the allocated frequency spectrum), and three symmetrical matrices with rows and columns indexed by the TRXs. The *separation matrix* tells what the minimum allowed distance between channels assigned to pairs of TRXs is. The *co-channel* and *adjacent-channel interference matrices* list, for every pair of TRXs, how much co- or adjacent-channel interference is incurred in case the TRXs use the same or adjacent channels, respectively. The task is to find an assignment of channels to the TRXs (i) such that each TRX receives one of its available channels and (ii) such that all separation requirements are met. An assignment is called *feasible* if conditions (i) and (ii) are fulfilled. There are several reasonable objectives when computing frequency assignments. The *objective* pursued here is to find a feasible assignment such that the *sum over all interference occurring between pairs of TRXs is minimal*. Given this objective, an assignment is optimal if it is feasible and incurs the least interference among all feasible assignments. See [6] for a mathematical model of this problem. The frequency assignment problem as stated above is NP-hard. That is, according to the state-of-the-art, we cannot expect to find an interference-optimal (feasible) assignment or even simply any feasible assignment in "polynomial time".

Frequency Assignment Methods. Several heuristics are used to compute frequency assignments in this article. A heuristic is an algorithmic procedure that is not guaranteed to give optimal or even feasible solutions. In general, the best one may hope for are good approximate solutions. Due to space limitations, only a brief sketch of the heuristics employed is given.

GT: The GAMST-algorithm [7] tries to compute a frequency assignment where channels from an as narrow range as possible are used (minimum-span). The co- and adjacent channel interference information is only indirectly taken into account: All interference relations exceeding some fixed threshold value are transformed into separation requirements. All other relations are dropped. Hence, all information on interference not exceeding the threshold value is completely lost. In order to retain as much interference information as possible, the threshold value is fixed by some search procedure in such a way that a feasible assignment can still be found and the threshold is as small as possible. The algorithm iterates the following core part until a provably (span-)optimal assignment is found or a given number of iterations is completed. For the core part, the TRXs are arranged into an order that is determined by the previous runs. Then, starting from the lowest channel, each channel is assigned to as many TRXs as possible, proceeding according to the fixed order, until all TRXs have received a channel.

DC5-IM: DSATUR with Costs (DC) is a construction heuristic whose basic idea is to recursively assign the TRX "hardest" to assign first. Simply speaking, while there are unassigned TRXs, the TRX which has the least number of channels left available is picked. If there is more than one such TRX, an interference-based tie-breaking rule is applied. The TRX chosen is assigned a channel that (locally) incurs the least interference. The choice of the TRX to start with has considerable impact on the quality of the assignment obtained. Since no generally good rule is known as to which TRX to start with, 5% of the TRXs are picked at random and each of those is used as a starting point once. The best assignment obtained is picked. Finally, the two heuristics Iterated 1-Opt and MCF try to improve on this assignment. Iterated 1-Opt is a local search procedure. MCF is a min-cost flow based procedure that is motivated by studying the dual of an general integer linear program modelling the frequency assignment problem. These two improvement heuristics try to change assignments in different ways that are in some sense "independent" to each other. They are applied in turns until no more improvement is obtained (IM). See [6] for details.

SA: Simulated Annealing is a randomised local search procedure that has been applied to frequency assignment problems of various forms, see [8,9,10,11] for applications with similar objectives. The implementation employed here uses a neighbourhood where two assignments are neighbours if and only if they differ by the assignment of one TRX only. Moreover, a simple standard cooling schedule [12] and successions of homogenous Markov chains are used. The temperature is decreased by a constant factor (0.9873) from level to level. There is a fixed upper bound (spectrum size * number of TRXs) on the length of the Markov chain at every level.

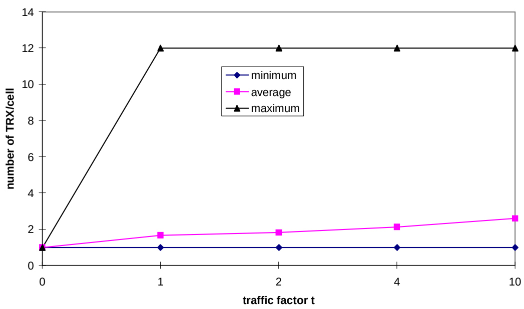
3 Test Scenario

The test scenario contains 1856 cells in the Rhine-Ruhr area. A spectrum of 75 channels within the GSM1800 spectrum can be used. The area comprises a mixture of different terrain including flat, hilly, urban, and rural areas. The performance of the propagation models is analysed by a comparison with measurements from 5 randomly selected base stations (15 cells) of this area. Table 1 shows the corresponding standard deviations, mean, and RMS errors.

Table 1: Statistical parameters of the prediction models. The mean error is calculated by taking predicted power levels minus measured power levels.

Propagation model	mean error/dB	Std. /dB	RMS error /dB
Simple model (SM_1); n=1	+26,4	8,9	27,9
Simple model ($SM_{1.5}$); n=1.5	-8,1	8,9	12,0
Simple model (SM_2); n=2	-42,0	10,3	43,2
Mod. Okumura-Hata-model (OHM)	-4,9	8,6	9,9
E-Plus-model (EM)	+1,2	8,8	8,9

The calculation of co-channel and adjacent-channel interference for frequency planning is based on predictions. These are computed in a resolution of 200m x 200m using any of the above propagation prediction models. Interference probabilities are calculated in a simplified way based on a best server cell model [15]. In this case, the interference probability corresponds to the percentage of affected best server area of the victim for each of the potential interferers. A pixel (200m x 200m) is considered as interfered if C/I is below 18 dB for co-channel interference and below 3 dB for adjacent-channel interference. Figure 1 (left) shows the overall amount of predicted interference using the different propagation models.



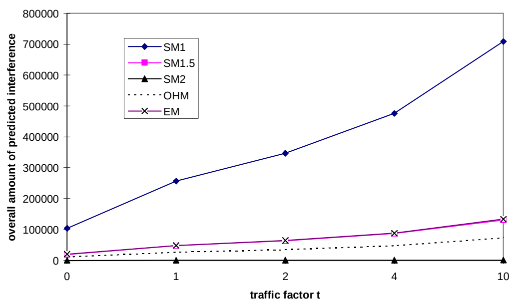


Figure 1: Cell demand statistics (left) and overall amount of predicted interference for the different propagation models (right) depicted versus traffic factor t. Note that in the right diagram the curve for SM1.5 is very close to that of EM.

The generated channel demand profiles are based on the traffic of each cell and an assumed maximal blocking rate of 2% using the Erlang-B-formula [1]. For simulating inhomogeneous spatial traffic distributions with different loads in a realistic scenario, traffic figures are created by a random number generator. The spatial statistics of cellular traffic is assumed to be adequately described by a lognormal distribution [13]. The parameters of the distribution are derived from measurements in the E-Plus network (mean value -3.5 dB Erlang and standard deviation 4 dB Erlang). In order to simulate different loads, the (linear) traffic values are multiplied by a factor of t. The case with a homogeneous traffic demand of one elementary transceiver (TRX) per cell is represented by t = 0. Other traffic factors are t = 1, 2, 4, and 10. Figure 1 (right) displays statistical information about the resulting demand profiles.

Some light on the complexity of the resulting frequency assignment problems (FAP) can be shed by examining (i) the average number of TRXs that a TRX shares a separation- or an interference-relation with (average degree) and (ii) the maximal size of a subset of TRXs that are all mutually related to each other (clique number) [14]. If the clique number exceeds the spectrum size of 75, provably no assignment without interference exists.

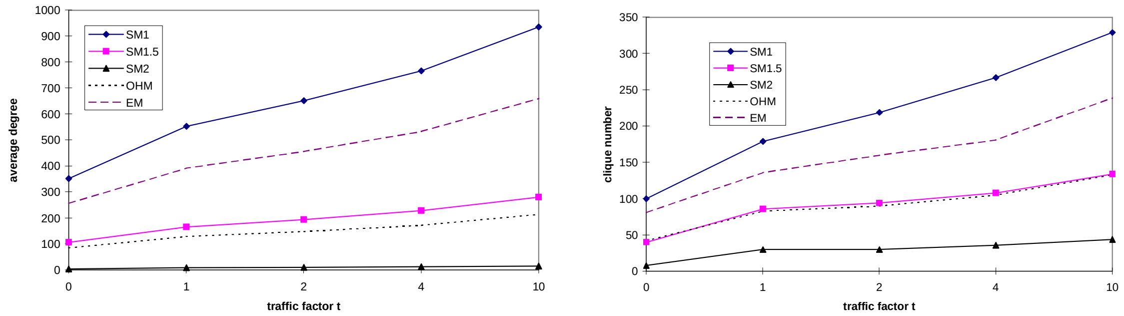


Figure 2: Average degree (left) and clique number (right) of the FAP as a function of the traffic load factor m for the three different propagation models (SM with parameters n=1, 1.5, and 2).

Figure 2 shows the average degree and clique number for the FAP as a function of the traffic load factor t for different propagation models. The higher these figures are, the harder the assignment problem is. The highest complexity can be observed for SM_1 (free space propagation only), whereas SM_2 yields the lowest complexity. In both models such extreme propagation conditions are assumed that the complexities derived from these situations can be assumed to be upper and lower bounds for this specific FAP. In the following investigations only $SM_{1.5}$, OHM, and EM are considered.

4 Combined Propagation Predication and Frequency Assignment Results

In this section, an analysis of the results from DC5-IM for the three different propagation models is given as well as an analysis of the quality of the three different frequency planning algorithms based on the propagation prediction model EM. A configuration consisting of EM and DC5-IM is used as a reference. Note that a combination of EM and DC5-IM proved its capacity in a field trial in a region consisting of 2118 cells in the E-Plus network in the northern part of Germany, where the cell demand ranged from 1 to 3 TRXs. A frequency plan automatically created by EM and DC5-IM was implemented. After the implementation, the total quality improved. For example, OMC measurements show that the number of quality handover requests has reduced by 19,2%.

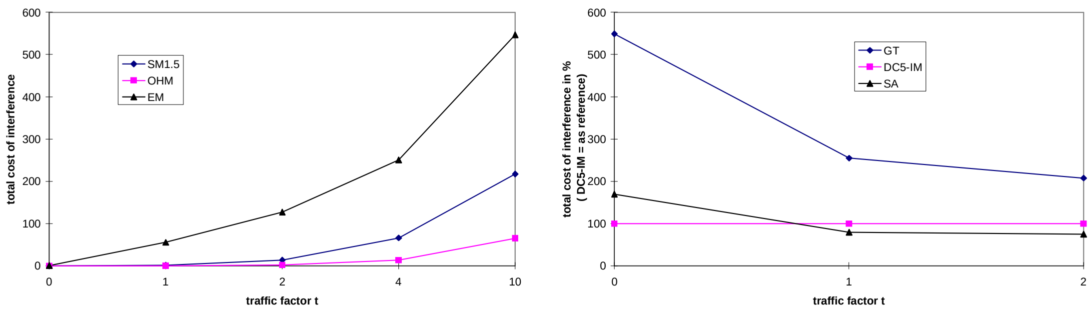


Figure 3: Overall predicted interference for the assignment computed for the different propagation models using DC5-IM (left) and different assignment algorithms based on EM (right) depicted versus traffic factor t. In the right figure all interference refers to the interference achieved by DC5-IM.

Analysis of different propagation models. Figure 3 shows the interference incurred by the assignments produced by DC5-IM for all three propagation models. The lowest value of interference is achieved by OHM whereas the highest is observed using EM. In the light of the mean errors of the different models (Table 1), it is not surprising that the model with the most optimistic values (EM) produces the highest interference values. However, OHM has a prediction error between those of EM and $SM_{1.5}$, but produces the least interference.

Table 3: Ratio r of total interference (assignment algorithm DC5-IM).

$r_a(b)$	r(t=1); analysis done with			r(t=2); analysis done with			r(t=4); analysis done with		
Assmt. based on	$SM_{1.5}$	OHM	EM	$SM_{1.5}$	OHM	EM	$SM_{1.5}$	OHM	EM
$SM_{1.5}$	1.0	116	64	1.0	18.7	14.3	1.0	5.5	5.2
OHM	277	1.0	110	47.9	1.0	27.3	11.2	1.0	8.1
EM	5.1	6.5	1.0	3.1	3.7	1.0	2.3	2.5	1.0

When comparing the impact of different propagation models on frequency assignment, the most adequate method would be to install all the corresponding frequency plans in the real network and perform measurements. However, it is obviously not feasible to do such an experiment in a live network. A different approach for comparing the prediction models has to be chosen. For a fixed traffic factor t the following is done: For each model a frequency assignment is computed using a fixed assignment method, DC5-IM in this case. The resulting assignments are then evaluated according to the different predictions. Technically speaking, let $r_a(b)$ be the ratio of the interference incurred by the assignment computed using model M_a over the interference incurred by the assignment computed using model M_b both evaluated according to model M_b. For the traffic factors t = 1, 2, and 4, Table 3 contains the corresponding values of r for all possible combinations of propagation models. Assuming that interference predictions by a more accurate model are closer to reality than those of a less accurate model and assuming that, for a fixed traffic factor t, the quality of the frequency assignments produced by DC5-IM is roughly the same for each model, r is an indicator for the additional interference introduced by using a less accurate propagation model. With this understanding, EM comes out as the clear favourite. All entries in the last row of Table 3 are comparatively small. Hence, most of the interference predicted using the other models is also predicted using EM. (This is in accordance with Figure 1.) On the other hand, inspecting the corresponding columns shows that the converse is false. The potential objection that EM is heavily overestimating interference (as SM_1 does) is ruled out by measurement results as shown in Table 1.

Analysis of different frequency assignment algorithms. Other than in case of the prediction models, there is no clear favourite among the frequency assignment heuristics tested here. DC5-IM is by far the fastest algorithm, GT is second, and SA last. To give an impression of the relations: SA takes, on averages, 85 times the running time of DC5-IM. In terms of the quality of the produced assignments, GT cannot compete with DC5-IM or SA. Moreover, GT is incapable to produce feasible assignments for traffic factors t = 4 and 10. The reason might be that GT is designed for computing frequency assignments with a minimum spectrum use and not for low-interference assignments using a given spectrum. Much information is lost when transforming the original problem into a problem that is handled by GT. Looking at the remaining two heuristics DC5-IM outperforms SA in case of t = 0, but falls slightly behind in cases t = 1 and 2, see Figure 3. (Due to the very high running times of SA, no assignments for t = 4 and 10 are computed.) This is readily explained by the fact that DC5-IM is tuned for networks with a homogenous channel demand profile where the numbers of TRXs per cell range from 1 to 3. The case t = 0 falls into this category. For t = 1 and higher, the maximal demand per cell is 12 (see Figure 1). This leads to significantly different problem characteristics for which the deterministic selections-rules of DC5-IM are not well-suited. Although, the cases t = 1 and 2 are in favour of SA, the case t = 0 and other experiments show that SA results are often far from optimal even after considerable running times.

5 Conclusion

The influence of different propagation models and frequency assignment methods on the interference in a cellular network is investigated. These algorithms are examined in a scenario consisting of 1856 cells, where both homogeneous and inhomogeneous traffic loads are simulated. A method to compare frequency plans derived by means of different propagation prediction models is presented. Among the models used in this article, the E-Plus-model (EM) turns out to be the most accurate one. EM produces the highest interference values, however the interference situation of the so-derived frequency plans proves stable even if analysed with other prediction models. This is supported by a field trial in a region consisting of 2118 cells in the E-Plus network, where the combination of EM and the DC5-IM frequency planning heuristic has proved its potential. A frequency plan, which was automatically created using EM and DC5-IM, was implemented. The overall quality has improved substantially. This is indicated by a 19.2% reduction of downlink quality handover requests. The frequency planning algorithms DC5-IM and Simulated Annealing (SA) are close competitors with respect to the quality of the produced assignments. The GAMST-algorithm (GT) produces more interference compared to DC5-IM and SA. In terms of run-time, however, DC5-IM outperforms SA by far. A factor of 85 is observed on average in the experiments. Although SA can be sped up by using a more sophisticated cooling schedule, this is not likely to change the relation dramatically. Moreover, there is evidence (DC5-IM for t = 0) that SA can be outperformed in terms of quality and run-time by heuristics especially designed for the frequency assignment problem studied here. Those heuristics may require different versions for different channel demand profiles, but promise to produce very good assignments in a couple of minutes as opposed to several hours. Finally, further research should include frequency assignments based on improved interference and cell models. One way to describe cells more realistically is to use cell assignment probabilities [15].

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