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DESIGN PRINCIPLES OF MOBILE RAILWAY NETWORKS

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The basic principles of GSM railway network planning are examined. The method of the frequency channels distribution between cells is described. The development of frequency channel reuse scheme is performed. The procedure of an operational planning is proposed. The principles of even radio coverage are considered for cells with mainly free radio propagation and for urban areas.

Introduction

The main criteria during development of GSM-Railway cellular communication network is high efficiency and minimal price. It is obvious that high efficiency and minimal price are contradictory conceptions. In case of big number of cells or small cell size the connection reliability is better. More network users can be served simultaneously and mobile station output power is being decreased. That means the decrease of electromagnetic radiation which affects mobile station user. But the price of development, deployment and maintenance of such network is more expensive. In case of small number of cells the price of network development, deployment and maintenance is less expensive, but dead spaces in radio coverage may occur and mobile station output power level is being increased. Therefore, less number of network users can be serviced simultaneously.

Cellular network parameters and deployment technology considerably depend on area relief, foliage and building density. Thus, during network development it is needed to have the area topographical cards with description of all these parameters. Besides, it is necessary to have the numerically calculated maps of serviced area radio coverage, which are taking into account technical parameters of network equipment being used, as well as the frequency reuse plan for developed network; numerically calculated traffic throughput and capacity values for certain cells and the entire network.

In case if any of the numerically obtained results on the network planning stage don't fulfill the set requirements, recurring correction has to be done. Thus, the cellular network planning process is iterative.

Spectrum considerations

One of the most important constraints on GSM-R (Global System for Mobile Communication — Railway) network planning is the availability of spectrum. The core UIC (Union Internationale des Chemins de fer, International Union of Railways) GSM-R spectrum allocation is 876—880 MHz for mobile station transmit paired with 921—925 MHz for base station transmit.

This equates up to nineteen pairs of useable frequency channels. The carrier frequency is designated by the absolute radio frequency channel number. For GSM-R carriers the following convention is used $f_l = 890 + 0.2(m - 1024)$, MHz; $f_u = f_l + 45$, MHz. Here m is an integer varying in the range $955 \le m \le 973$; f_l denotes the carrier frequency value in the lower band, and f_u is the corresponding frequency value in the upper band.

Each pair will henceforth be referred to as a frequency channel. Aside from the nineteen channels, this allocation also includes a 200 kHz guard band to protect against interference between the GSM-R band and the adjacent E-GSM (Extended-GSM) band at the upper end. In addition, a 400—600 kHz guard band is recommended to prevent interference with PMR/PAMR (Private Mobile Radio/Public Access Mobile Radio) services below the GSM-R spectrum allocation, 100 kHz of which is taken from the UIC band. It should be noted that this frequency range has also been reserved for UIC direct mode. Table 1 provides an overview of the spectrum allocation.

Table 1. Overview of spectrum allocation

	Mobile transmit, MHz	Base station transmit, MHz
PMR/PAMR band	870 — 876	915 — 921
UIC Direct mode	876 — 876.1	921 — 921.1
GSM-R band	876.1 — 880	921.1 — 925
E-GSM band	880 — 890	925 — 935
P-GSM band	890 — 915	935 — 960

Additional available spectrum for railway use may be sought on a national basis. For example, the E-GSM band is suitable for this purpose because all GSM-R equipment will be capable of functioning at these frequencies.

Overview of cell and frequency planning for GSM-R

Let us consider the cellular network concept which is founded upon the principle of breaking up a large desired coverage area or served region into a series of much smaller coverage areas. The application of this principle increases the available capacity and spectral efficiency of the system as a whole.

Envisage a service area, represented by the external hexagon in Fig. 1, is limited to the use of just two radio channels. In this case, base transceiver station (BTS) would quickly become congested and overloaded by the number of subscribers.

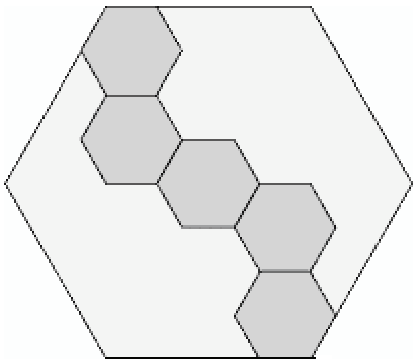

Fig. 1. The basic cellular concept

The cellular concept allows smaller service areas to be deployed, each using a limited part of the available radio spectrum to provide localized service. Just one channel is considered in this example. This scenario is represented by the internal hexagons in Fig. 1, which could for example be used to provide service to a railway line. Such an approach allows multiple re-use of the same radio channels in the global service area, providing more efficient service to every subscriber.

The cellular solution is typically more expensive, but a network design process is employed to find an optimal position with respect to all system constraints. Such optimal solution allows to maximize the number of subscribers and to increase the commercial revenue that can be generated from the available spectrum.

For further investigation it is advisable to overview the radio planning. A key challenge for the radio engineer is to design the network with the reuse of the available frequencies so that the entire mobile communication system would be able to provide the radio capacity that is required in each area, whilst ensuring that the levels of service quality remain within acceptable limits for the applications it must support.

Many aspects are important inputs to the cell and frequency planning process. Some of these will need to be visualized geographically. The radio capacity is to be provided in each location by the network. The required quality of service for all of the applications must be supported. This encompasses coverage requirements, handover breaks, dropped calls, error rates, and latencies. Cell site planning consists of determination of available sites for base station construction, permitted mast heights, provision of power and communications to cell sites, permitted broadcast power. Operational considerations may dictate where cell boundaries need to be located. These are, for example, areas of emergency call, shunting and controller. Terrain types and geographical features should be taken into account during radio planning. These include hills, woods, urban areas, large buildings, cuttings and tunnels. An identification of the available frequencies is one of the important stages of radio planning. It is required to evaluate whether there are any limitations on the use of the UIC GSM-R spectrum allocation in the area and whether additional frequencies, for example, in the E-GSM band are available.

The cell and frequency planning process results in the generation of the initial data for the design of each GSM-R base station. These data include: geographic location of each site; mast height; antenna type and its position; required cabling, feeders and fixed links; frequencies and transmission powers to be used.

It should be noted that the use of computer based radio planning tools is central to undertaking successful cell and frequency planning. Let us consider a simple illustration of GSM-R frequency reuse.

Each frequency channel is divided into eight timeslots. One timeslot is required per base station to serve as a control channel. The other seven timeslots left are available to be used as traffic channels to support voice or circuit switched data calls. The composition of larger number of frequency channels by the addition of more transceivers to each base station will add up to a further eight traffic channels.

If coverage is required over a wide area, for example to support communications across a city with many railway lines and stations, a seven cell repeat pattern could be used. In this case available spectrum is distributed between seven cells.

One of the most important considerations in the development of a viable cell and frequency plan is to maximize the distance between base stations transmitting/receiving at the same frequencies otherwise co-channel interference will arise, thus degrading service quality. Interference will also arise from adjacent channel assignments between neighboring cells and this must be minimized too. If this distance is too small, it will have a detrimental effect on the co-channel interference in the network (and hence the carrier to interference ratio *C*/*I* and the bit error rate).

In a real situation, it is highly likely that some areas will need more capacity than others (for example, large stations). This and other factors such as geographical features, the need to optimize group call areas, and considerations related to location dependent addressing will also have an effect on the optimal cell and frequency plan. This is likely to result in a much less regular distribution of cells and channels than the one shown in this simplified example. In practice, a radio planning tool would be used to simulate the coverage and traffic capacity requirements.

The example of providing coverage over a wide area can be contrasted with that of providing coverage along a linear corridor, for example along a reasonably straight section of railway line, as it is shown in Fig. 2.

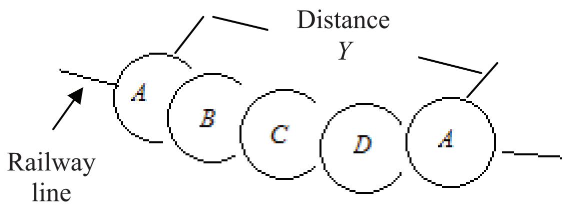

Fig. 2. Illustration of a linear repeat pattern

Since there are fewer cells in the repeated pattern, a larger number of channels can be allocated to each cell and hence greater radio capacity is achievable. The following features are to be specially considered when planning the GSM-R network coverage: tunnels and cuttings; regions shadowed by structures, such as bridges; obstructed sections of track that fall on a bend; railway stations; terrain height profiles; shunting areas; emergency call areas.

Operational planning

Operational planning is vital part of the successful GSM-R network planning process. It is important to consider which type and number of applications are to be supported by the network and which are supported application requirements for quality of service.

The capacity has to be estimated for each GSM-R cell separately, based on the following factors: the peak number of active trains that will occupy that cell; the volume of voice and data traffic expected from these trains; the volume of network traffic arising from handhelds and other devices such as possession management terminals, customer information systems, diagnostic systems, etc that are expected in that cell; scope for future expansion. Mobile station controller and base station controller boundaries, and border areas between national networks are to be defined.

The operational needs of European train control system (ETCS) including appropriate coverage, capacity, quality of service, support of handovers, etc are to be planned. All of these operational planning aspects need to be considered when developing an appropriate cell and frequency plan for the area under analysis [2].

Frequency planning methodology

The fundamental problem during the assignment of radio channels to planned cells is to ensure the allocation and reuse of any given channel that maximizes usable radio signal and minimizes the interference.

Every plan will have an associated signal to noise ratio: represented in the radio environment as the carrier to interference ratio, or *C*/*I*, and is expressed in decibels (dB). The fundamental quality of a frequency plan is reflected in the *C*/*I* for a given area.

Let us introduce frequency channel assignment methodology. It is assumed that there exists a proposed cell site distribution with an associated channel requirements profile (driven from the projected capacity demand in each area). It is also assumed that the software tools required for the processing and production of appropriate data sets are available.

To distribute frequency channels between cells, the following information is required: available radio spectrum, absolute radio frequency channel numbers that may be used; forbidden channels, test channels, guard bands; any other specific requirements. A schedule of cells to be frequency planned uses channel and transceiver requirements, driven by the demand for capacity.

An appropriate radio coverage model for the cluster of cells under consideration specifies the expected radio signal levels from all detectable cells in the immediate area at discrete geographical locations. An appropriate ‘Interference Table’ represents the ability of each cell to interfere with any other. Interference table is not a carrier to interferer assessment, but simply an indication of potential inter-cell interaction. Inter cell handover data are the datasets showing the actual passage of mobile terminals from cell to cell, used to validate theoretically defined neighbor cells.

Methodology

A classic algorithm is to define a set of rules for channel assignment with associated penalties (or costs) in case if any rule is broken. Initially channels are assigned in a quasi random fashion and the obtained channel plan is evaluated in terms of its cost. Using simple differential methods, the minimum cost may be found by selective reassignment of individual radio channels. Due to the nature of the problem and the fact that the associated cost is calculated on radio channels assigned, the determination of the minimum cost is cyclical.

A useful parallel may be drawn with the Newton-Rhapson approach for the solution of polynomial equations, where each successful iteration brings the solution closer to the ideal. The quality of the final plan is therefore highly dependant on the number of performed iterations and the quality of the costs assigned.

Let us consider an example of rule set for frequency channel distribution between cells. There must be at least 2 channel separation for the following cases: between transceivers in the same cell, otherwise assign a cost of 100000; between control channels for first order neighbor cells, otherwise assign a cost of 10000; between control channels for second order neighbor cells, otherwise assign a cost of 5000; between traffic channels for first order neighbor cells, otherwise assign a cost of 1000. If the same traffic channel is used for second order neighbor cells, assign a cost of 100. For specific forbidden channel allocations assign cost as required.

Whilst the cost values are arbitrary, an appropriate level may be found to apply the desired scaling of preference given to allowed or preferred route of rule breakage. It is important that assigned cost values do not exceed variable provision within the computer program code, the individual values do not physically affect the functionality of the mathematics [2].

Assessment and key performance indicators

Once radio channels have been assigned to the appropriate cellular transceivers it is necessary to create a carrier to interference ratio matrix. With respect to cellular network engineering tools, this is produced in a similar way to coverage matrix, and evaluating the carrier to interference ratio across defined areas of given resolution, typically 50m squares. Normally, this would be presented on a map and plotted in defined bands: 0, 3, 6, 12 and 15 dB. Typically, radio engineers would plan for at least 9 dB for voice and at least 2—15 dB for data applications. It should be noted that adjacent channel allocation is typically modeled under *C*/*I*, assigning a *C*/*A* (carrier to adjacent ratio) equivalent. In practice co-channel interference dominates but adjacent channel interference must still be considered. If two equal power GSM carriers are adjacent to one another, the power leaking from one into the other bandwidth is approximately 18 dB below the wanted carrier level by virtue of the GSM signal sideband characteristics. The value 18 dB may therefore be used as an equivalent figure for *C*/*A* to *C*/*I* mapping.

When frequency plans have actually been uploaded onto a given network, the base station system is capable of detecting real time interference. This is captured as bit error rate and is then quantized as received signal quality. There are 8 indices of received signal quality ranging from 0 to 7. The digit 0 reflects the lowest bit error rate, and digit 7 indicates the highest one.

Outputs and documentation

Whilst formal documentation may vary from network to network and between operators, the inputs, method, and outputs above would typically give rise to the following documents, schedules or other deliverables: spectrum specification; schedule of planned cells; interference table; *C*/*I* and *C*/*A* matrices; inter-cell handover profile; appropriate cost schedule; frequency plan; exception report; per carrier analysis; co-channel assignment schedule; adjacent channel assignment schedule; pre and post implementation received signal quality data set.

Link budget and coverage design levels

The link budget is a calculation encompassing all of the technical factors associated with the uplink, transceiver, and downlink to determine, amongst other things, the maximum permissible air interface path loss. The link budget can be separated into two calculations, one for the downlink and one for the uplink.

In order to calculate the link budget for the downlink, the first step is to calculate the base transceiver station effective isotropic radiated power (EIRP) this is the effective power that is radiated from the base station antenna.

Let us consider EIRP calculation examples for the following network parameters: base station transmitter power 45 dBm; duplexer loss –1 dB; internal jumper loss –1 dB; transmitter filter loss –1 dB; transmitter power splitter loss –3 dB; antenna feeder loss –3 dB; base transceiver station antenna gain 15 dBi. The calculated EIRP is the sum of all of the above figures and in this example is equal to 51 dBm.

The next step is to calculate the mobile station minimum permissible received signal. Let us consider calculation example for the following network parameters: mobile receiver sensitivity –104 dBm; mobile antenna feeder loss –2 dB; mobile antenna gain 0 dBi; antenna position/mounting loss 0 dBi; body loss for handhelds 0 dB; interference margin loss 0 dB; fast fading margin loss –3 dB; degradation due to Doppler shift loss 0 dB.

Body loss is the attenuation of the received signal due to the mobile station being close to a human body. Interference margin accounts for the increased radio noise level due to mobile users located in other cells. This is not normally a significant factor unless the network employs frequency hopping. Antenna position/mounting accounts for attenuation due to non-optimal positioning of the antenna because of the presence of other equipment on the train roof and/or the shape of the roof itself. Losses due to the fast fading margin principally affect slow-moving mobiles. Receiver sensitivity degradation due to Doppler shift principally affects fast-moving mobiles.

The minimum permissible received signal is the mobile receiver sensitivity minus the sum of the gains and the losses. In the above case, this equates to –99 dBm. The minimum permissible received signal should be lower than the minimum coverage levels specified in the EIRENE SRS (European Integrated Railway Radio Enhanced Network System Requirements Specification), otherwise the mobile station may not be suitable for operation on GSM-R networks. The extract from the EIRENE SRS for the required values is provided below.

For network planning, the coverage level is defined as the field strength at the antenna on the roof of a train, nominally at a height of 4 m above the track. An isotropic antenna with a gain of 0 dBi is assumed. This criterion will be met with a certain probability in the coverage area. The target coverage power level is dependent on the statistical fluctuations caused by the actual propagation conditions.

For voice and non-safety critical data, the signal level of 38.5 dBµV/m (–98 dBm) has to be secured in the point of reception with the probability of 95%. On lines with ETCS levels 2 and 3 and for train speeds lower than or equal to 220 km/h the signal level of 41.5 dBµV/m (–95 dBm) has to be secured in the point of reception with the probability of 95%.

It should be noted that the specified coverage probability means that with a probability value of at least 95% in each location interval (length 100 m) the measured coverage level shall be greater than or equal to the figures stated above. The coverage levels specified above consider a maximum loss of 3 dB between antenna and receiver and an additional margin of 3 dB for other factors such as ageing.

The values for ETCS levels 2 and 3 concerning coverage and speed limitations are to be validated and, if necessary, reviewed after the first operational implementation of ETCS. The maximum path loss is calculated from the difference between the EIRP and the minimum received signal. In this example, the maximum path loss is equal to 150 dB.

Let us investigate the link budget for the uplink. In order to evaluate the link budget for the uplink, the first step is to calculate the EIRP for the mobile. Let us assume that mobile EIRP is equal to 37 dBm, based on following network parameters: mobile transmitter power (max 8 W) 39 dBm; mobile antenna feeder loss –2 dB; mobile antenna gain 0 dBi; antenna position/mounting loss 0 dBi; body loss 0 dB.

The next step is to calculate the base station minimum permissible received signal. Let us consider the base transceiver station parameters, which obtain the characteristics of the mobile telecommunication network.

As follows from [1], the receiver sensitivity of the base transceiver station must be not less than –110 dBm in order to avoid a deterioration of the signal reception on the border of service zone. For increasing of radio communication efficiency the base transceiver station antenna can be performed as an array with gain not less than 17 dBi.

While the mobile system planning it is necessary to take into account losses of both antenna feeder and Rx power splitter, which may reach –3 dB. An inherent part of the system is a diplexer which parameters must be optimized in order to decrease its insertion loss to –1.5 dB. Internal jumper loss (–1.5 dB), degradation due to Doppler effect (0 dB) and fast fading margin (–3 dB) are also taken into account.

The minimum permissible received signal is the BTS receiver sensitivity minus the sum of the gains and the losses. In the above case, this equates to –115 dBm. As before, the maximum permissible path loss is the difference between the mobile EIRP and the minimum Rx signal at the base transceiver station. In the above case, this equates to 152 dB.

In this example, the maximum permissible path loss in the uplink and the downlink are reasonably similar. This helps to ensure that there is good balance between the qualities of reception at either end of the call. The link budget is slightly “downlink limited”. This means that it is likely that the downlink of the call will break up before the uplink in areas of poor coverage.

50% confidence design threshold

In general, mobile radio planning tools work with high uncertainty level. Thus, to secure required signal level in the point of reception for the real situation, it is assumed that software return results with the 50% uncertainty. In order to convert the 95% confidence levels quoted in the EIRENE specifications to 50%, a conversion margin must be used.

Let us consider an example of such conversion. It is assumed that the probability function follows a normal distribution. The standard deviation of this distribution is assumed to be equivalent to the one of slow fading (the long term variation in the mean signal level principally caused by shadowing) and is equal to 8.5 dB. However, this value will vary depending on the type of terrain, the type and density of vegetation/tree foliage present, the number of buildings, etc.

It is assumed that the signal level of 41.5 dBμV/m (–95 dBm) has to be secured in the point of reception with the probability of 95%. We can calculate the number of standard deviations between the 95% confidence level and the 50% confidence level using the function of Microsoft Excel: $g(x)$=NORMSINV(x).

This function returns the inverse of the standard normal cumulative distribution. The distribution has a mean value of zero (i.e. is centered on the y-axis) and has a standard deviation of one. The required calculation is therefore as follows: g(0.95)–g(0.5). The (0.95) in the function relates to the probability (i.e. is equal to 95%) and $g(0.5)$ is equal to zero. This case can therefore be simplified as follows: $g(0.95)$.

Using this value and taking into account the standard deviation which in this case equals to 8.5 dB, the margin required to convert between 95% and 50% confidence levels is being obtained. For the illustration, in the example considered above, the corresponding 50% confidence level for the specified requirement is equal to –81 dBm [3].

Direct mode considerations

The operational requirement for direct mode is to: provide short range fall-back communications between train drivers and trackside personnel in the event of failure of all railway and public GSM services normally available; provide short range communications for railway personnel operating in remote areas where no GSM facilities are available.

In order to minimize the effect of direct mode interference on the neighboring GSM-R and PMR/PAMR bands, the EIRENE specifications mandate that direct mode equipment shall have a maximum transmit power of 1 Watt and a sensitivity of at least –107 dBm.

Not withstanding these requirements, practical direct mode system solutions may need to employ other frequency ranges. The following spectrum parts could be used to support direct mode systems: parts of the E-GSM band (frequency will not be available in all countries); parts of the GSM-R band if the railway operator is able to spare the bandwidth; other parts of the spectrum depending on national availability and licensing considerations.

Direct mode implementation is optional, however if implemented, the EIRENE SRS states that the equipment shall be capable of operation in the following channels: $f = 876 + 0.0125n$; $1 \le n \le 5$, where n is frequency channel number [3].

Conclusions

In this paper the basic principles of GSM-R network planning were developed. To build a cost effective and technically efficient cellular communication network it is necessary to take into account many different parameters (such as area parameters, equipment technical parameters, potential number of users, etc.) even on the very first planning stage. Parameters of the area include relief, foliage and building density. To increase design efficiency it is necessary to have the numerically calculated maps of serviced area radio coverage, which are taking into account technical parameters of network equipment being used, as well as the frequency reuse plan for developed network; numerically calculated traffic throughput and capacity values for certain cells and the entire network. In the case, if any of the numerically obtained results on the network planning stage don't fulfill the set requirements, recurring correction has to be done. Thus, the cellular network planning process is iterative.

All the stages of high efficient GSM-R cellular communication network planning were consistently considered. The main planning steps are: spectrum allocation; development of frequency reuse scheme; operational planning; designing of even serviced area radio coverage; numerical calculation of network traffic throughput; capacity and reliability.

It is shown that operational planning is vital part of the successful GSM-R network planning process. Frequency planning methodology was proposed for solving the problem which occurs during the assignment of radio channels to planned cells so that to ensure the allocation and reuse of any given channel to maximize usable radio signal and minimize the interference.

The link budget was calculated encompassing all of the technical factors associated with the uplink, transceiver, and downlink to determine the maximum permissible air interface path loss. Examples of numerical link budget estimation for downlink and uplink are considered.

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