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TIME DISPERSION ESTIMATION FOR MOBILE RADIO NETWORK PLANNING

SUMMARY

In radio network planning, the goal is to specify optimal base station locations, service areas, antenna patterns and handover strategies for a given mobile radio system. The system performance is fixed and the radio channel is subject to optimisation. Network planning requires channel characteristics that provide information about the expected service quality, especially the outage probability. The channel description must only perform as a qualitative measure of an actual receiving area. Power delay profiles are a convenient and very common description of channel time dispersion, which can be easily physically understood as footprints of individual reflected or scattered paths, and provide a capability to a network planning engineer to discover areas of heavy time dispersion and important scattering regions on the terrain. This in turn enables better assessment of base station sites, antenna pattern selection, service region (cell) shaping (handover criteria) and solving network problems.

Time dispersion is mostly found to be the cause of poor coverage by excluding other possible causes. In cases where field strength coverage does not overlap and base station sites cannot be moved, shaping antenna directivity will be the only way to eliminate excessive time dispersion.

1. INTRODUCTION

The signal conditions at the vehicle antenna of a mobile cellular telephone receiver are among the worst that a radio circuit design engineer will ever encounter. Yet, cellular telephone customers demand conversation quality as good as if the telephone were connected by hardware lines. Compounding the radio design problem is the economic need and the customer demand to fit more telephone channels into the available frequency spectrum. To accomplish this, traditional analogue radio modulations are being replaced by digitally coded, compressed and heavily filtered systems. While these new digital modulation formats increase the information throughput, they are also more susceptible to the multipath distortions and interference experienced in an over-the-air, heavily reflective system environment.

1.1. Relevance of Time Dispersion for Network Planning

Today's time-division-multiple-access (TDMA) radio systems are at very high bit rates and thus very vulnerable to time dispersion. TDMA systems with an equaliser transmit a special fixed training bit sequence to enable measuring of the channel distortion within each transmitted block (burst) and subsequent training of the equaliser, before the actual data transfer begins. However, in case of time dispersion exceeding the capability of the equaliser, e.g. for GSM systems with echoes having excess delays longer than 16 us, bit-error-ratios (BER) may increase to unacceptable values [1].

Therefore, for mobile network planning, it is essential to consider the effects of time dispersion on the expected transmission systems performance.

1.2. Network Planning versus System Design

In system design the goal is to specify a mobile radio system that is able to cope with a given type of multipath channel. The type(s) of channel(s) is (are) fixed and the system components are subject to change and optimisation. The channel types are defined in "channel models" and are simulated by channel simulators for testing and certification of radio equipment.

In radio network planning, the goal is to specify optimal base station locations, service areas, antenna patterns and handover strategies for a given mobile radio system. The system performance is fixed and the radio channel is subject to optimisation. Only those links should actually be used in network operation that have acceptable radio channel properties.

The required channel models and measurements for network planning and system design differ significantly. In a certain environment one can expect a certain type of probability distribution channel parameter values (e.g. received field strength, path loss or rms delay spread), which has to be derived and proven by measurements. Radio network planning requires channel characteristics that provide information about the expected service quality, especially the outage probability. The channel description must only perform as a qualitative measure of an actual receiving area. This is fairly different with respect to system design requirements for knowing typical and worst case channels (independent of a specific environment or location) that are to be expected during system operation.

While with system design the channel is seen as a stochastic process, whose parameters are defined by measurement and assumed as typical, enabling models to provide realisations of the channel (e.g. channel simulators), with network planning, the parameters of the stochastic process are themselves subject to measurement, modelling and estimation for a certain location or, more precisely, for a prediction area that is not too large. Radio network planning is always performed for a real terrain, so that channel is not modelled just for typical cases.

Radio network planning is much more complex for digital radio than we were used to for analogue networks. The mobile radio system, the noise level, the desired signal-to-noise-ratio (S/N) and carrier-to-interference-ratio (C/I), and the environment causing time dispersion, are given constants. Consequently, the planning criteria for a digital FDMA/TDMA system include S/N (typically around 9 dB for GSM), C/I (co-channel and cross-channel with typical values from 9 to 12 dB applied at the cell borders where good reception is from another base station re-using the channel), time dispersion (with critical values discussed in what follows) and economics/logistics of location of base stations and antenna mounting.

2. PROPERTIES OF THE MOBILE RADIO CHANNEL

Multipath propagation

In mobile radio communication propagation of electromagnetic waves takes place mostly within the structures on the earth's surface (land cover) [2]. Antenna patterns have wide beams or omnidirection characteristics, both leading to the incidence of partial waves from several directions via different paths at the receiver antenna. The partial waves originate from reflections and scattering on both land cover and the geometry of the terrain.

Although multipath propagation causes difficulties in radio transmission, from the other side it is absolutely necessary to provide for sufficient mobile radio signal coverage for the area of interest.

Radio coverage

As the wave propagates within and through the land cover, a direct line of sight (LOS) between the transmitting and the receiving antennas is not available in most cases, but radio communication services can be provided via one or more reflected strong partial waves.

2.1. Channel Functions

The partial waves caused by multipath propagation arrive at different times, with different magnitudes and with different phases. If the receiver or the scatterers are moving, the frequencies of the received partial waves show a Doppler shift.

As a result of multipath propagation, the received signal spreads out both in time and frequency, which can be described by the Delay-Doppler-Spread function $S(\tau,\nu)$. Applying $S(\tau,\nu)$ to the input signal yields:

$$w(t)=\int_{-\alpha}^{\alpha} d\tau \left[z(t-\tau) \int_{-\alpha}^{\alpha} d\nu \cdot S(\tau,\nu) e^{j2\pi\nu t} \right] \quad (1)$$

where:

$z(t)$ is the complex envelope of the transmitted (input) signal

$w(t)$ is the complex envelope of the received (output) signal

τ is the delay variable

ν is the frequency shift variable

t is the time.

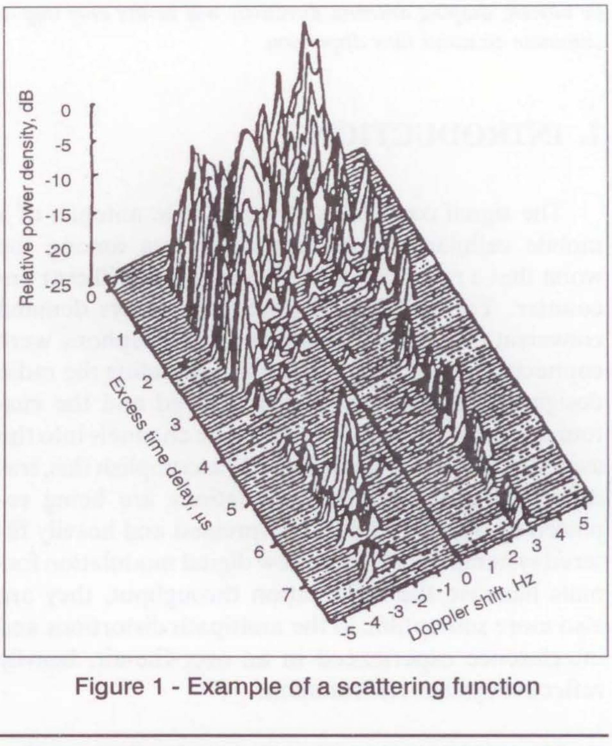

Figure 1 - Example of a scattering function

Signals corresponding to delays in the range $(\tau, \tau + d\tau)$ and Doppler shifts in the range $(\nu, \nu + d\nu)$, have differential scattering amplitude $S(\tau, \nu)\, d\tau\, d\nu$.

The definition of channel descriptions assuming deterministic behaviour is not appropriate for the discussion of real radio channels, which are randomly time-variant. The system functions then become stochastic processes.

The scattering function an example of which is shown in Fig.1, is defined as the squared magnitude of $S(\tau, \nu)$:

$$P_S(\tau, \nu) = E\left[S(\tau, \nu) S^*(\tau, \nu) \right] \tag{2}$$

and shows the received power versus excess time delay and frequency Doppler shift.

The use of the scattering function requires the assumption that the mobile channel is linear for each partial channel, wide-sense stationary (WSS) and that the contributions originate from uncorrelated scatterers (US).

Although the electrical properties and the geometric dimensions (roughness) of the materials involved with the radio path, change with frequency (wavelength), they can be assumed as frequency-independent over the bandwidths under consideration. Furthermore they are memory-less and isotropic, so that the linearity assumption holds.

On the other hand, a mobile radio channel is generally not stationary. However, in order not to make characterisation extremely difficult, stationarity can be assumed over a short period of time, or a geographical area, which is small in comparison to the period of the slow channel variations, so that the mean received signal strength is virtually constant. We also assume that significant scattering centres do not change, and the correlation functions are invariant under a translation of frequency, i.e. the fading statistics do not change over a short time [2].

Finally, the WSS and US assumptions are time-frequency duals. The channel can be described in terms of WSSUS statistics and so depicted as a continuum of uncorrelated scatterers in both time delays and frequency shifts. Since the autocorrelation functions of the channel functions are not depending on absolute time and absolute frequency, P_S is stationary and may be defined as by (2).

Power Delay Profile

The Fourier transform of the Delay-Doppler-Spread function $S(\tau, \nu)$ is the time-variant complex impulse response [2], i.e. equivalent baseband representation of the bandpass channel:

$$h(t, \tau) = \int_{-\alpha}^{\alpha} d\nu\, S(\tau, \nu) e^{j 2\pi \nu t} \tag{3}$$

The squared amplitude of $h(t, \tau)$ is the instantaneous power-delay profile $P_i(t, \tau)$, sometimes called impulse response [3]:

$$P_i(t, \tau) = h(t, \tau) h^*(t, \tau) \tag{4}$$

and it shows the received power versus time delay – hence the term instantaneous.

For radio network planning, power delay profiles are a convenient and very common description of channel time dispersion. Being a direct measurement output of various measurement systems, they can be easily physically understood as footprints of individual reflected or scattered paths:

$$P_i(t, \tau) = \left| \sum_k \alpha_k(t) \delta\left[\tau - \tau_K(t)\right] \right|^2 \tag{5}$$

where the coefficient α_K describes the gain (in fact attenuation) and the phase shift, while τ_K is the delay of the k-th partial wave [4].

Evidently – since it is real - power-delay profile does not contain phase information. However, in many practical engineering situations and techniques (measurements or predictions) phase information is not available.

From $P_i(t, \tau)$, we can calculate the average impulse response [4], commonly referred to as power-delay profile, as:

$$P(\tau) = E_i\left[P_i(t, \tau)\right] = E_i\left[h(t, \tau) h^*(t, \tau)\right] \tag{6}$$

$P(\tau)$ is independent of absolute time under the WSSUS assumption and can also be derived by averaging the scattering function over Doppler shifts.

2.2. Time Dispersion Parameters Relevant for Network Planning

For network planning the instantaneous channel characteristics are of very limited interest, although they are responsible for the actual bit-error or the "click" in the voice transmission. In addition, these are sometimes impossible to estimate, so that using mean values is the only approach available. In practice, time dispersion parameters are very often understood as derived from $P(\tau)$ if nothing else is explicitly mentioned.

Classical Parameters

The received power is distributed (dispersed) in delay from τ. From this distribution, the first and the second central moment, and the overall integral can be calculated; the Mean Delay $E(\tau)$, the Delay Spread S and the Carrier Power C, defined as:

$$E(\tau) = \frac{\int_{\tau_0}^{\tau_{max}} \tau \cdot P(\tau) d\tau}{C} \; ; \; ; \; S = \sqrt{\frac{\int_{\tau_0}^{\tau_{max}} \tau^2 \cdot P(\tau) d\tau}{C}} \; ; \tag{7}$$

where:

$$C = \int_{\tau_0}^{\tau_{max}} P(\tau)\,d\tau \qquad (8)$$

and τ_0 is the delay time of the first path and τ_{max} is the delay time of the last path in $P(\tau)$. The "last path" is the most delayed path that can be detected above a chosen "cut-off" level, which is determined by the noise level and dynamic range limits of the receiver. As shown in Fig.2, only peaks above the "cut-off" level, are considered valid, while the rest is suppressed as artefacts of the measurement system (sidelobes of the correlator and noise).

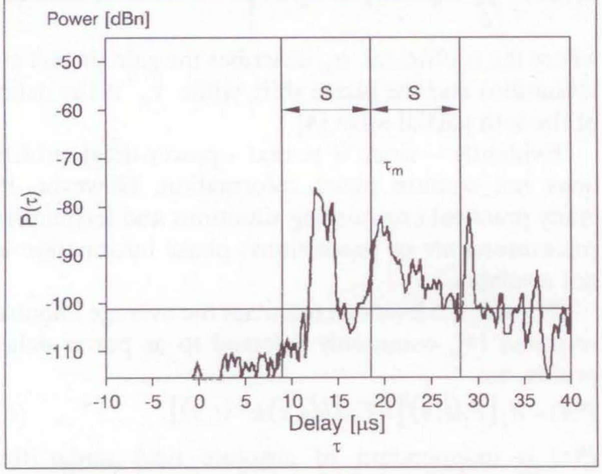

Figure 2 - Mean Delay, Delay Spread and Carrier Power

Window Parameters

The "window parameters' reflect the self-induced quasi co-channel interference caused by delayed echoes, which are harmful to TDMA system receivers.

The Interference Ratio Q_T can be defined as the maximum ratio of the power within a window of length T, to the power out of that window, Fig.3.

The Q_{16} parameter is the most popular one to assess the receiver performance of the GSM system, and

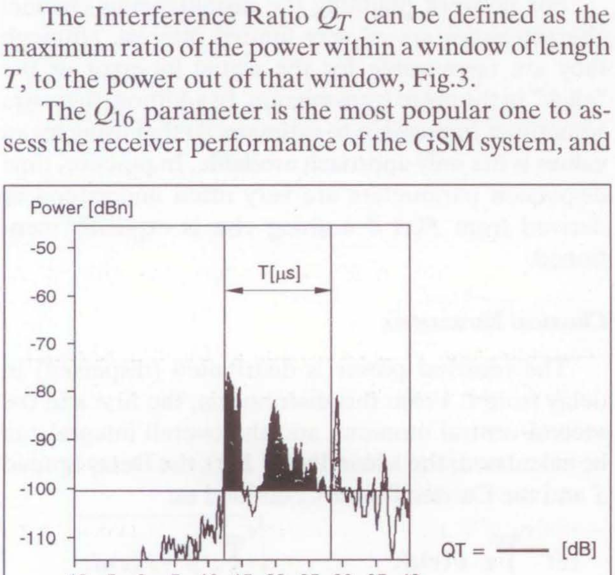

Figure 3 - Interference Ratio Q_T

for GSM, Q_{16} of 9 to 12 dB (for small interference-limited and large noise-limited cells, respectively) is a common threshold, which should be exceeded 90% of the time [5].

3. IMPACT OF TIME DISPERSION ESTIMATION ON NETWORK PLANNING

Types of scattering areas responsible for actual degradation of the channel are known in principle, and can be identified from measurements. It is not always easy to estimate the appearance of considerable time dispersion, since many factors must coincide for the dispersion to occur.

3.1. Critical Environments with respect to Time Dispersion

For the first approximation of the probability of the onset of time dispersion related problems, we can apply the following relation:

Time Dispersion Problem =
= Risk Factors Losing Quasi-Direct Path*

In other words, the more the terrain introduces risks and the more the quasi-direct path is attenuated, the worse time dispersion will be. Harmless terrain will compensate for losing quasi-direct paths and a strong quasi-direct path will compensate for risky terrain conditions.

Which kind of terrain is risky so that time dispersion related problems are to be expected?

Mostly prone to time-dispersion are: mountainous terrain, large basins or valleys surrounded by high mountains, hilly rural terrain, lakes or rivers surrounded by mountains, and large number of high-rise buildings or high-rise buildings of exceptional extension. In addition, to the terrain-related risk factors, long LOS distance and improper antenna patterns can also be included into consideration.

However, time dispersion measurements have shown that problematic terrain conditions do not necessarily lead to heavy time dispersion. This could most probably be due to two causes: strong quasi-direct path along the measurement route and poor reflection by the wooded hills.

On the other hand, heavy time dispersion sometimes shows up for relatively inconspicuous terrain, mainly due to the loss of dominant quasi-direct paths. The term quasi-direct path encompasses either LOS, (available only as an exception in mobile radio), or originates from reflections near (less than 300m, corresponding to 1μs) the receiver.

For planning purposes, significant time dispersion parameter together with a threshold, is selected. As already mentioned, for GSM it is the power ratio Q_{16} where at least $Q_{16}>9$dB is required.

3.2. Solving a Typical Coverage Problem

Let us consider an example of an existing specific network connection problem, encountered in a certain area approximately 2 km downhill from the Riedberg GSM test base station in Lower Austria, at the intersection of road B1 and road B213. Terrain elevation is presented in Fig.4, where it is subdivided into small quadratic prediction area elements (PAE) and the problematic area is denoted by "?".

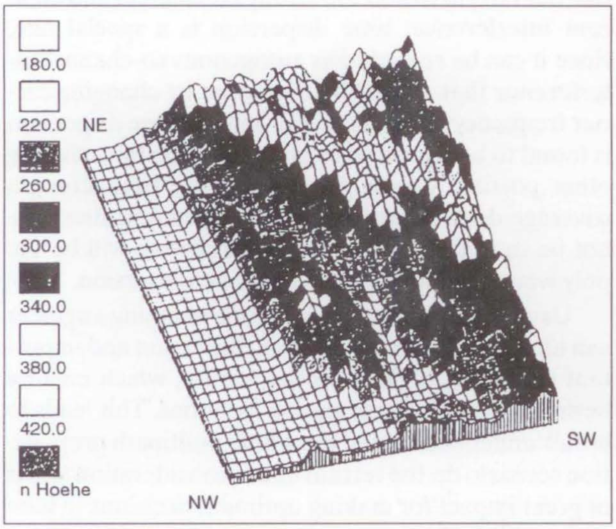

Figure 4 - Terrain elevation around BS Riedberg (area is 10 km x10 km)

The mobile test station reported good field strength conditions, but it was not possible to connect to the base station or the connection was interrupted.

Terrain Conditions

The route along which the measurement locations were set up is started near the base station, continued downhill to the coverage problematic zone and carried on to the north-east.

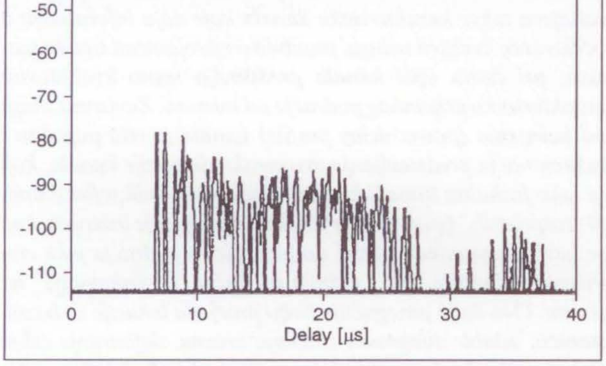

Figure 5 - Power delay profile for PAE#10

A typical delay power profile measured with the Realtime Channel Sounder RCS 900 [4], (in the frequency range of 760-1000 MHz, with sensitivity of −102 dBm, delay resolution of 0.1 µs, and burst of a BPSK modulated carrier as test signal), at one of the locations (PAE#10) within the problematic area, is shown in Fig.5.

As can be seen, significant excess delays exist (up to 20 µs). However, it seems that strong quasi-direct path shown in the plot does not exist in reality, since the LOS from PAE#10 to the base station is shadowed by trees of approx. 20-30 m height, as shown at the terrain profile from the base station to PAE#10, Fig.6. The LOS propagates entirely through the vegetation and thus suffers strong attenuation.

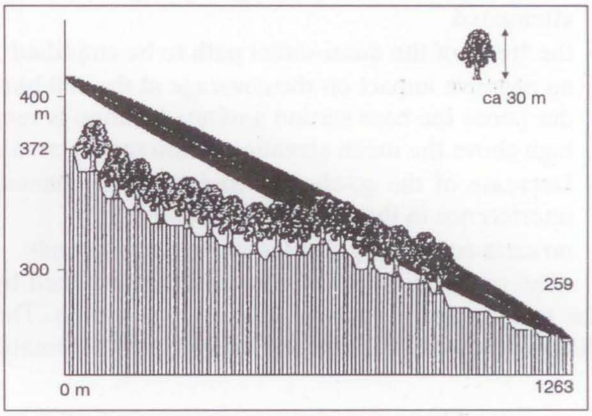

Figure 6 - Terrain profile from the base station to the problem area. The first Frenel zone is shown in dark grey

Since good field strength conditions are reported in the problem area, based on the terrain elevation from the base station to PAE#10, shown in Fig.4, we can assume with high probability that the hill at the other side of the problem area, opposite to the base station, is a strong reflection zone, providing for field strength coverage. However, significant distributed reflection zones are also likely to contribute to the excess delays.

In short, it is most probably the time dispersion which is the reason for connection problems in the considered area.

Improvement of Time Dispersion by Downtilt Antenna

The above considerations lead to the following conclusions:

- the direct path is obstructed, the quasi-direct path is strongly attenuated.
- in the critical zone, coverage is provided via a strong reflection zone opposite the base station
- multipath propagation being the source of unwanted time dispersion is caused by a number of distant reflectors

To improve the situation, we have two options:
- to select a better base station site with respect to time dispersion
- to modify the antenna pattern

The first option would involve a very expensive change in the network structure, especially since the existing base station is a fully equipped site of a prior network. Another less expensive but still hardly affordable solution might be sectorisation of antennas will require changes in antenna switching or even in network control and channel assignment. Thus, we focus on selecting a better antenna pattern.

The easiest to consider is a downtilt omnidirectional antenna pattern. From this solution, we expect several advantages:
- near reflections providing coverage to be amplified
- the distant reflections causing time dispersion to be attenuated
- the "rest" of the quasi-direct path to be amplified
- no negative impact on the coverage at the cell border (since the base station antenna location is very high above the mean elevation of the service area)
- Decrease of the co-channel and adjacent channel interference in the neighbouring cells
- no extra costs except for the change of antennas

The optimum angle of downtilt is determined by the terrain profile and the power delay profile. The distance between the base station and the problematic

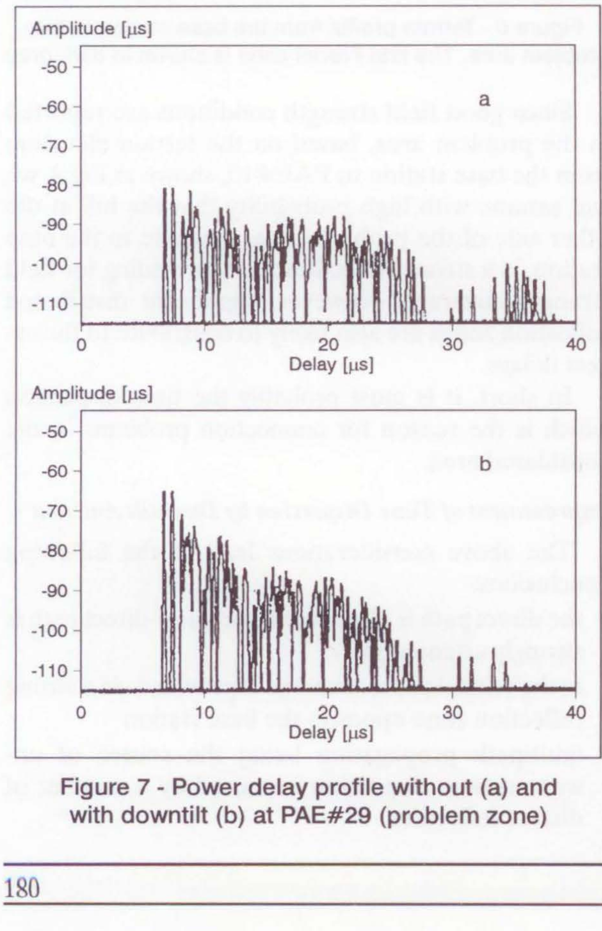

Figure 7 - Power delay profile without (a) and with downtilt (b) at PAE#29 (problem zone)

zone to be enhanced is approx. 200 m, which finally resulted with the antenna elevation of –5 degrees.

This was accomplished with an omnidirectional antenna with 5 degrees vertical 3 dB beam width.

The improvements are visible from the power delay profiles for PAE#29 without and with tilt, shown Fig.7a and 7b, respectively.

4. CONCLUSION

Among different causes of coverage problems in the existing networks or test setups, such as poor carrier field strength and too strong co-channel and adjacent interference, time dispersion is a special one, since it can be regarded as autogenous co-channel interference that cannot be overcome by changing carrier frequency or power levels. Mostly, time dispersion is found to be the cause of poor coverage by excluding other possible causes. In cases where field strength coverage does not overlap and base station sites cannot be moved, shaping antenna direction will be the only way to eliminate excessive time dispersion.

Using this approach, a network-planning engineer can identify areas of heavy time dispersion and important scattering regions on the terrain, which enables better selection of base station locations. This leads to better understanding of the whole multipath propagation scenario on the terrain under consideration and is of great impact for making optimum decisions in base stations site selection, assessment of base station sites, antenna pattern selection, service region (cell) shaping (handover criteria) and solving network problems.

SAŽETAK

PROCJENA VREMENSKE DISPERZIJE KOD PLANIRANJA MREŽE MOBILNOG RADIJA

Prilikom planiranja mobilnih radio mreža, cilj je da se specificiraju optimalne lokacije baznih stanica, područja pokrivenosti, zračenja antena i strategije preuzimanja poziva za dati mobilni radio sustav. Ovdje je performansa sustava konstanta, a radio kanal se treba optimizirati. Planiranje mreže zahtijeva takve karakteristike kanala koje daju informaciju o očekivanoj kvaliteti usluga, posebno o vjerojatnosti ispada sustava, pri čemu opis kanala predstavlja samo kvalitativnu karakteristiku prijemnog područja od interesa. Zavisnost snage od kašnjenja (power-delay profile) kanala je vrlo pogodan i raširen način predstavljanja vremenske disperzije kanala, koji se lako fizikalno tumači kao odraz individualnih reflektiranih ili "raspršenih" (engl. scatter) zraka, i omogućuje inženjeru koji se bavi planiranjem mreže, da identificira područja jake vremenske disperzije, kao i važnija područja "rasprskavanja" na terenu. Ovo dalje omogućuje bolju procjenu lokacije za baznu stanicu, odabir dijagrama zračenja antena, definiranje ćelija (kao i postupka preuzimanja poziva), kao i učinkovitije rješavanje problema.

Vrlo često se pretpostavlja da vremenska disperzija uzrokuje slabu pokrivenost terena signalom tek nakon što se isključe svi ostali mogući uzroci. U slučaju kada se ne preklapaju signali susjednih ćelija i kada se ne mogu pomjerati same bazne stanice, jedini način da se eliminira znatna vremenska disperzija je uobličivanje usmjerenosti antene.

LITERATURE

[1] **Steele**, **R**., *"Mobile Radio Communications"*, Pentech Press Publishers, London, 1992

[2] **Parsons**, **J.D**., *"The Mobile Radio Propagation Channel"*, John Wiley & Sons, New York, 1992

[3] **Bach Andersen**, **J**., *" A Note on Definitions of Terms for Impulse Responses"*, COST 231, TD(89)060, Oct. 1989.

[4] **Braun**, **W.R**., **Dersch**, **U**., *"A Physical Mobile Radio Channel Model"*, IEEE Trans. On Veh. Techn., vol. 40, no. 2, pp.472-482, 1991

[5] ETSI, Rec. GSM 03.30