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USING RF REPEATERS TO IMPROVE WCDMA HSDPA COVERAGE AND CAPACITY INSIDE BUILDINGS

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ABSTRACT

The role of indoor coverage will be very important in WCDMA networks, both due to customer expectations and the introduction of high speed packet data services. General outdoor-to-indoor coverage is and will be the most common solution, but macro cells may not always be able to deliver adequate indoor coverage and capacity, suggesting the need for dedicated indoor solutions, such as RF repeaters. RF repeaters are typically deployed to extend the coverage of existing (macro) cells. They are characterized by low cost, ease of installation and low power consumption. The simulation results shown in this paper clearly indicate how the repeater deployment improves the HSDPA coverage throughout the building. The results also demonstrate how the repeater deployment off-loads the donor cell, resulting in increased cell capacity. However, this paper also discusses the trade-off between the repeater gain and the reduced uplink coverage and capacity within the donor cell, which eventually can limit the maximum achievable HSDPA performance.

I. INTRODUCTION

Good indoor coverage will in general be more important in WCDMA networks than in 2G. This is due to the fact that customers nowadays expect their phones to work wherever they go, whether outside or inside buildings; and with the advent of High Speed Packet Access, i.e. High Speed Downlink Packet Access [1] and High Speed Uplink Packet Access [2] targeted initially for business users, indoor coverage is gradually moving from “nice to have” to a “necessity”. Furthermore, the newest building materials, such as coated glass designed to save energy by keeping the heat out of the building, are effective at keeping the RF signals out as well. This can make it difficult for macro cells to provide adequate indoor coverage and capacity, suggesting the need for dedicated indoor solutions for high traffic facilities.

RF repeaters, which are connected to their donor cell via a directional radio link, are typically used in cellular networks for providing coverage in areas shaded from normal macro cell coverage. RF repeaters are characterized by their low cost as compared to an equivalent base station solution, their ease of installation, low power consumption and the fact that they need no transmission to the RNC. However, additional uplink interference generated by the RF repeaters will desensitize the donor cell, and result in reduced uplink capacity. Furthermore, it will also negatively affect the uplink coverage in the areas not covered by the repeater.

The scope of this paper is to study the performance of a repeater-based in-building solution in a scenario with background speech traffic outside and HSDPA traffic inside the modelled building. Both the coverage and capacity inside the building and the capacity of the overlaying macro cell are evaluated. The performance evaluation is based on the dynamic system simulator introduced in [3]. This paper is a continuation of the work presented in [3] and [4].

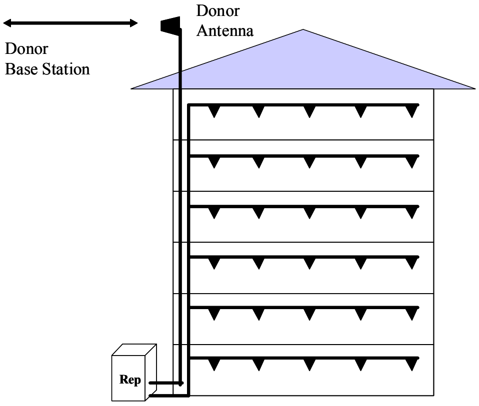

Figure 1. Assumed repeater deployment.

The rest of this paper is organized as follows. First, in Chapter II some technical aspects of RF repeaters are discussed, and the assumed repeater equations are presented. Then, in Chapter III, some simulation assumptions are introduced. The system simulation results are presented and analysed in Chapter IV. Finally, some conclusions are drawn in Chapter V.

II. RF REPEATERS

A. Technical Aspects

This paper assumes an in-building solution based on an RF repeater, see Fig. 1. For a given WCDMA connection, uplink or downlink, the repeater input and output frequencies are assumed to be the same. In downlink, the repeater taps the donor base station signal through a directional donor antenna. Then the signal is filtered, amplified and re-radiated in the repeater service area through the passive coaxial distributed antenna system. For uplink, the repeater works in a similar way.

In general, passing the WCDMA signal through a repeater degrades the signal quality. First of all, since the repeater includes an amplifier, it adds noise into the system, reducing the maximum cell capacity. Furthermore, the majority of WCDMA base stations offer a dual-branch receive diversity whereas many repeaters do not have this functionality. This results in an increased fast fading margin and a greater uplink E_b/N_0 requirement, which further have an impact on the

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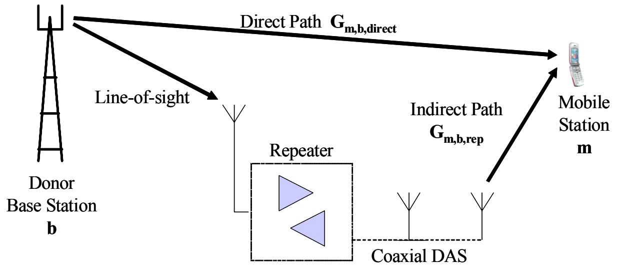

Figure 2. Description of the repeater scenario.

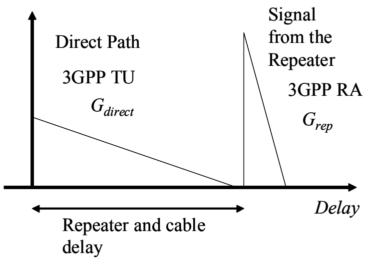

Figure 3. Combined delay spread.

repeater uplink coverage area as well as on the uplink capacity of the donor cell. According to [5], field tests have shown an average increase in required uplink E_b/N_0 of 2 dB for mobiles in the repeater coverage area.

Soft handover is not applicable between the donor cell and the repeater. This is because both belong to the same logical cell and transmit the same downlink signal with the same scrambling code. Mobile stations located within the border area between the donor cell and the repeater may experience high levels of multipath propagation generated by the two sources of downlink power, and the corresponding loss of downlink orthogonality [6].

B. Repeater Equations

Before the uplink and downlink equations can be derived, let us assume the scenario depicted in Fig. 2, where mobile station m is connected to base station b. Furthermore, a repeater has been deployed between the mobile and the base station. Thus, the communication link consists of both the direct path and the indirect path coming from the repeater.

When it comes to the multipath propagation scenario for a mobile station inside a building, the mobile will experience a radio channel, which is a combination of the direct path signals and the delayed signals coming from the repeater, as shown in Fig. 3. The total delay difference between these two clusters of signals is caused by both the delay introduced by the repeater, typically a few microseconds, and the propagation delay introduced by the distributed antenna system inside the building, when applicable. The relative strengths of the clusters are defined by the average path gains of the direct path ($G_{direct,m,b}$) and the repeater path ($G_{rep,m,b}$). Thus, the effective width of the combined delay spread depends both on the repeater gain and the location of the user within the building.

In the downlink direction, the Carrier-to-Interference Ratio (CIR) can be calculated as

$$\rho_{m,b} = \frac{P_{m,b} \cdot G_{m,b}}{I_{tot,m} - \left(1 - \alpha_{m,b}\right) \cdot P_{tot,b} \cdot G_{m,b}} \tag{1}$$

In (1),

$$I_{tot,m} = \sum_{k=1}^{B} P_{tot,k} \cdot G_{m,k} + N_m + N_r \tag{2}$$

$$G_{m,b} = \left(G_{direct,m,b} + G_{R,b} \cdot G_{R,DL} \cdot G_{m,R}\right) \cdot G_{ff,m,b} \tag{3}$$

$$N_r = N_{R,DL} \cdot G_{R,DL} \cdot G_{m,R} \cdot G_{ff,m,R} \tag{4}$$

In (1)-(4),

$P_{m,b}$	is the transmission power from base station b towards mobile station m,
$G_{m,b}$	is the total path gain between base station b and mobile m, taking both the direct and the repeater path into account, and including the normalized multipath fading gain $G_{ff,m,b}$ for the combined multipath channel,
$I_{tot,m}$	is the total received downlink power at the mobile station receiver,
$\alpha_{m,b}$	is the non-orthogonality factor for the connection between base station b and mobile m,
$P_{tot,b}$	is the total output power for base station b,
B	is the total number of macro base stations in the system,
N_m	is the thermal noise power of mobile m,
$N_{R,DL}$	is the thermal noise power of the repeater,
$G_{R,DL}$	is the repeater gain in the downlink direction,
$G_{m,R}$	is the path gain between mobile m and the repeater,
$G_{ff,m,R}$	is the normalized multipath fading gain for a connection between the repeater and mobile m,
$G_{R,b}$	is the path gain between base station b and the repeater.

In the uplink direction, assuming that the donor cell contains only one repeater solution, the CIR can be calculated as

$$\rho_{m,b} = \frac{P_m \cdot G_{m,b}}{I_{tot,b} - P_m \cdot G_{m,b}} \tag{5}$$

$$I_{tot,b} = \sum_{s=1}^{M} P_s \cdot G_{s,b} + N_b + N_r \tag{6}$$

$$G_{m,b} = \left(G_{direct,m,b} + G_{R,b} \cdot G_{R,UL} \cdot G_{m,R}\right) \cdot G_{ff,m,b} \tag{7}$$

$$N_r = N_{R,UL} \cdot G_{R,UL} \cdot G_{R,b} \tag{8}$$

Now, in (5)-(8)

P_m	is the transmission power of mobile station m,
$I_{tot,b}$	is the total received uplink power at base station b,
M	is the total number of mobiles in the system,
N_b	is the thermal noise power of base station b,

$N_{R,UL}$ is the thermal noise power of the repeater,
$G_{R,UL}$ is the repeater gain in the uplink direction.

III. SIMULATION ASSUMPTIONS

The dynamic system simulations are performed using the tool described in [3]. All the main simulation assumptions, including the general network layout, traffic scenario, and the structure of the passive coaxial distributed antenna system are assumed to be the same. The only difference compared to [3] is that the dedicated in-building base station has been replaced by a RF repeater.

The donor antenna is placed on the roof of the building and is assumed to have a line-of-sight propagation condition towards the donor macro site. The antenna gain is assumed to be equal to 20 dBi towards the donor base station, -17 dBi with 90° angle and -13 dBi with 180° angle. Together with the assumed cable losses and the vertical antenna mismatch, the path gain $G_{R,b,dB}$ becomes equal to -59.5 dB towards the donor base station.

As explained, the multipath propagation scenario depends on the strengths of the direct and repeater paths as well as the delay difference between the two multipath clusters. It is assumed in the simulator that the clusters representing the direct and repeater paths correspond to 3GPP Typical Urban and 3GPP Rural Area channel [7], respectively. Furthermore, it is assumed that the time difference between the direct and repeater paths is large enough so that the clusters are not overlapping with each other. Finally, if the strengths of the paths differ more than 19.5 dB, the combined channel is assumed to be equal to the dominating channel. For smaller differences, a number of combined channel profiles have been calculated prior to the simulations. Finally, the repeater noise figure is assumed to be equal to 5 dB, resulting in thermal noise power equal to -103.2 dBm.

IV. SIMULATION RESULTS

A. *Definitions*

The simulation results for the background speech traffic are normalized using the "pure background scenario" as a reference. There, all simulated speech users are located outside the modelled building. Furthermore, the building is assumed not to contain any traffic or a dedicated in-building solution. The *maximum background speech traffic capacity* within the overlaying macro cell is defined as the maximum average level of offered traffic, when the speech user blocking probability is below 10%, and the average uplink noise rise does not exceed 3 dB in that particular cell. According to the simulation models, the speech users can be blocked either due to the lack of downlink power or channelisation codes. No quality-of-service -based user dropping functionality has been implemented.

An estimate of the HSDPA quality-of-service is based on the packet bit rate distribution. Packet bit rate is defined as the size of the downloaded packet in bits ($1.6 \cdot 10^6$) divided by the packet delay. HSDPA capacity is measured by the HSDPA throughput, which is defined as the total number of delivered bits (packet traffic) during the simulation divided by the simulation time. The *maximum HSDPA capacity* is defined as the maximum HSDPA throughput so that a) the packet bit rate is not smaller than 50 kbps for the worst 10th percentile of HSDPA users, and b) the speech user blocking probability does not exceed 10% within the donor cell. Simulation results for the indoor HSDPA traffic are normalized using the "pure outdoor-to-indoor HSDPA coverage" as a reference. There, the simulated HSDPA users are located inside the modelled building, and are served by the appropriate macro base stations. The base stations, which are not connected to any of the users, are transmitting only the common control channels.

B. *Coverage*

Due to the link adaptation functionality, the HSDPA bit rate for a certain user m served by base station b is an increasing function of the downlink CIR, see (1). With an increasing repeater gain the path gain $G_{m,b}$ increases, reducing the impact of mobile station thermal noise power on CIR. Furthermore, due to the directional donor antenna, the level of intercell interference is reduced with respect to the intracell interference. In addition to that, the downlink orthogonality is improved, resulting in smaller $\alpha_{m,b}$ and hence, level of intracell interference. Finally, due to the reduced interference, the end-user bit rates are improved throughout the building, resulting in shorter scheduling queues and slightly reduced total non-HS transmission power, which both improve the packet bit rates further.

The improved HSDPA coverage is verified by simulating the system with a constant offered load, normalized background speech traffic equal to 24% together with a medium level of offered HSDPA traffic inside the building, but with different repeater gain values. In Fig. 4 the average packet bit rates per specific floors are depicted. Furthermore, the corresponding average packet bit rates for outdoor-to-indoor coverage with the same level of offered traffic are shown as a reference. The packet bit rates have been normalized with respect to the average packet bit rate calculated over the whole building in the reference scenario. As expected, the simulated HSDPA packet bit rates are increasing as a function of the increased repeater gain. However, once the repeater gain has become high enough to make the repeater path clearly dominating, and the inter-user interference considerably larger than the thermal noise power, the downlink CIR, as well as the end-user bit rate can no longer be improved. This happens on the ground floor when the repeater gain is larger than 55 dB. On the top floor, the direct path is considerably stronger, and the users can benefit from even larger repeater gains. This difference in the strength on the direct path with respect to the repeater path explains also why the end-user performance becomes better on the ground floor compared to the top floor. Namely, on the ground floor, the users can benefit from the various advantages offered by the repeater path, such as smaller path loss, reduced intercell interference and better downlink orthogonality, with considerably smaller repeater gain values compared to the users on the top floor.

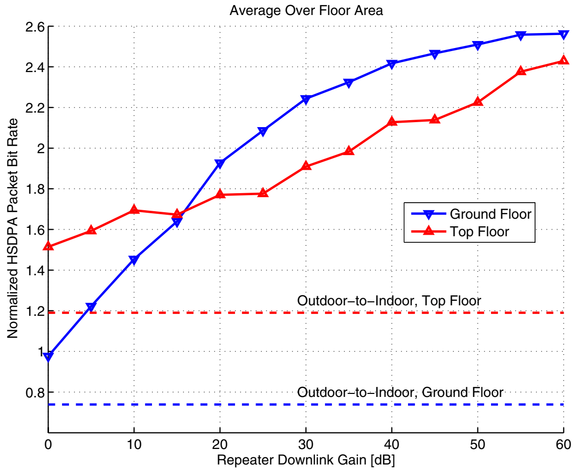

Figure 4. Normalized HSDPA packet bit rate as a function of the repeater gain.

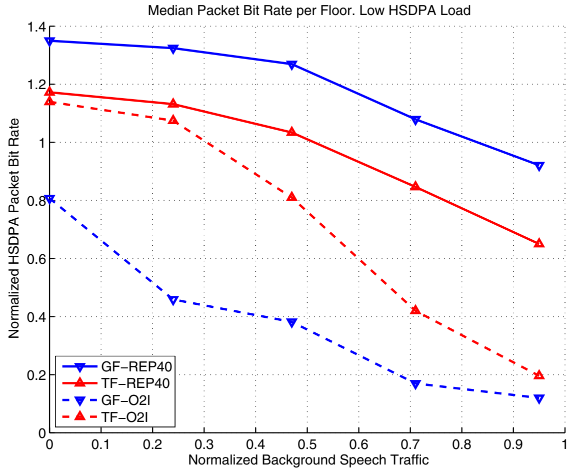

Figure 5. Normalized HSDPA packet bit rate as a function of the normalized background speech traffic.

Fig. 5 presents the median level of the normalized packet bit rate as a function of the normalized background speech traffic for a low level of HSDPA load. The results are shown both for the users on the ground floor (GF) and on the top floor (TF), as well as for the outdoor-to-indoor coverage (O2I) and the repeater deployment with the repeater gain equal to 40 dB (REP40). The packet bit rates have been normalized with respect to the median bit rate over the entire building in the reference scenario. As can be noticed, the dependency of the HSDPA coverage on the background load becomes weaker in the repeater scenario. Again, the reason for this is that even though the available $P_{m,b}$ decreases with an increasing background load in a similar way as in case of outdoor-to-indoor coverage, the received CIR is improved due to increased $G_{m,b}$ and reduced interference.

C. Capacity

By deploying the repeater with a directional donor antenna the indoor HSDPA users are moved closer to the serving base station both from the link loss and inter-to-intracell interference point of view, resulting in improved CIR and end-user performance throughout the building. From the donor macro cell point of view, the repeater deployment will off-load the downlink, as demonstrated by the simulation results in Fig. 6, where the outdoor-to-indoor coverage with the same level of offered traffic, including also background speech users, has been used as a reference. The general conclusion from the downlink curves is that a larger repeater gain will result in lower average base station power, leaving more room for additional background speech or indoor HSDPA users.

Studying the curves a bit closer, one can notice that only a small part of the total base station power reduction is due to reduced non-HS power. There are a couple of reasons for this: Firstly, the number of A-DCHs is fairly low as is also the total A-DCH power. Secondly, the background speech users contributing the most to the total base station are located close to the cell border, and cannot benefit as much from the reduced intracell interference as the users located closer to the base station.

Hence, the main reason for the reduced total base station power is the reduced average HS-DSCH power. Although the scheduled HSDPA users can still occupy all the remaining base station power, the maximum achievable CIR may exceed the UE capabilities, resulting in lower total transmission power. What is more, due to the improved end-user performance, the number of idle HSDPA TTIs increases, resulting in a lower average transmission power over the whole simulation time.

While the increased repeater gain is shown to be beneficial both for the end-user performance and the cell capacity in the downlink direction, it will harm the uplink coverage and capacity within the donor cell. This can be understood by studying the uplink CIR equation a bit closer. First of all, as a result of a larger $G_{R,UL}$, the value of N_r increases, effectively desensitizing the donor base station and increasing the level of uplink interference over the thermal noise power. Secondly, due to the considerably reduced receive diversity gain the average required uplink E_b/N_0 is increased at the donor base station for the mobiles communicating via the repeater. The increased E_b/N_0 results in higher received carrier power, term $P_s \cdot G_{s,b}$ in (6), and hence, higher total uplink interference. With an increasing repeater gain, the number of indoor users having the repeater path as dominating increases, and so does also the level of uplink interference. Finally, since each repeater solution will degrade the donor cell, the number of deployed repeater solutions, as well as the repeater gain values should be carefully planned. In general, assuming a certain level of desensitization, the maximum allowed number of repeater solutions within a donor cell becomes smaller with high gain repeaters compared to repeaters with lower gain.

The level of desensitization D as a function of $G_{R,UL,dB}$ is depicted in Fig. 6, assuming only one repeater solution. In the figure,

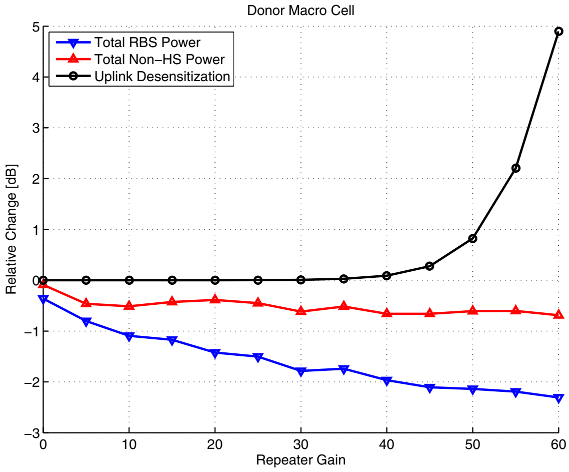

Figure 6. Uplink desensitization, and the relative change in the donor base station output power.

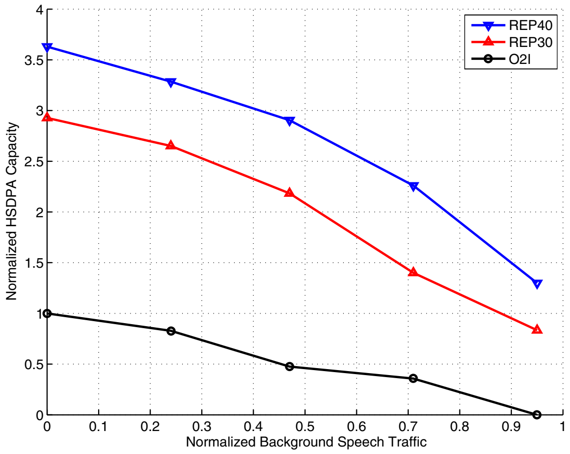

Figure 7. Normalized HSDPA capacity as a function of the normalized background speech traffic.

$$D = \frac{N_b + N_r}{N_b} = 1 + \frac{N_{R,UL} \cdot G_{R,UL} \cdot G_{R,b}}{N_b} \tag{9}$$

Furthermore, $(N_{R,UL}/N_b)_{dB}$ is assumed to be equal to 2.7 dB and $G_{R,b,dB}$ equal to -59.5 dB.

The curves in Fig. 6 suggest that in order to obtain the best possible HSDPA coverage and capacity, the $G_{R,UL}$ and $G_{R,DL}$ should be set individually so that $G_{R,DL}$ is larger than $G_{R,UL}$. However, large imbalance between the uplink and downlink can result in errors in open-loop power control, resulting in access problems and large swings in closed-loop power control. This is due to the fact that the WCDMA open-loop power control builds on the general assumption that there exists a significant correlation between the uplink and the downlink average path loss. Therefore, $G_{R,UL}$ and $G_{R,DL}$ should in practise have fairly similar values.

Hence, the actual HSDPA capacity gain will be a compromise between the applied repeater gain and the uplink capacity and coverage degradation within the donor cell. Based on the curves in Fig. 4 to Fig. 6, HSDPA capacity is in this paper chosen to be evaluated with two repeater gain values: 30 dB (REP30) and 40 dB (REP40).

The results are shown in Fig. 7, where the capacities of the different deployment options are compared with each other assuming different levels of background speech traffic. As can be noticed, the HSDPA capacity is tightly coupled with the background speech load when the indoor traffic is served by the overlaying macro cell. However, the curves demonstrate how the HSDPA capacity can be considerably increased by deploying a RF repeater inside the building. For example, with a repeater gain equal to 30 dB the HSDPA capacity becomes roughly three-fold compared to the outdoor-to-indoor coverage, and with a larger repeater gain the difference increases further.

V. CONCLUSIONS

In this paper the performance of a repeater-based in-building solution has been evaluated with speech traffic outside and HSDPA traffic inside the modelled building. Simulation results show that the repeater deployment improves HSDPA coverage throughout the building. In addition, also the cell capacity is considerably increased compared to the scenario with general outdoor-to-indoor coverage.

Furthermore, it has been explained how a repeater degrades the uplink coverage and capacity in the donor cell, limiting the maximum achievable HSDPA performance. This is in particular the case when the applied repeater gain is large enough to compensate for the coupling loss between the repeater and the donor base station, and/or when the donor cell includes multiple repeater deployments. Therefore, the usage of repeaters, in particular repeaters with high gain values, i.e. typically repeaters with high maximum output power, should be carefully planned in order to avoid any major performance losses within the donor cell. In all, repeaters are found to be useful mostly in areas where the general outdoor-to-indoor coverage is rather poor, and the overlaying donor cell can survive the increased uplink interference.

REFERENCES

[1] S. Parkvall, E. Dahlman, P. Frenger, P. Beming, M. Persson, “The evolution of WCDMA towards higher speed downlink packet data access”, in proceedings of VTC 2001 spring.

[2] S. Parkvall, E. Englund, K. W. Helmersson, M. Samuelsson, ”WCDMA uplink enhancements for high-speed data access” in proceedings of VTC 2005 spring.

[3] K. Hiltunen, B. Olin, M. Lundevall, ”Using dedicated in-building systems to improve HSDPA indoor coverage and capacity”, in proceedings of VTC 2005 spring.

[4] K. Hiltunen, “Using RF repeaters to improve WCDMA speech coverage and capacity inside buildings”, to be presented at VTC 2006 Fall.

[5] Qualcomm Inc., “Repeaters for indoor coverage in CDMA networks”, white paper.

[6] J. Laiho, A. Wacker, T. Novosad (ed.), “Radio network planning and optimization for UMTS”, John Wiley & Sons, 2002.

[7] 3GPP TSG-RAN 25.943 V5.1.0, “Deployment aspects (Release 5)”, June 2002.