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Research Article

Improving HSDPA Indoor Coverage and Throughput by Repeater and Dedicated Indoor System

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The target of the paper is to provide guidelines for indoor planning and optimization using an outdoor-to-indoor repeater or a dedicated indoor system. The paper provides practical information for enhancing the performance of high-speed downlink packet access (HSDPA) in an indoor environment. The capabilities of an outdoor-to-indoor analog WCDMA repeater are set against a dedicated indoor system and, furthermore, compared to indoor coverage of a nearby macrocellular base station. An extensive measurement campaign with varying system configurations was arranged in different indoor environments. The results show that compared to dedicated indoor systems, similar HSDPA performance can be provided by extending macrocellular coverage inside buildings using an outdoor-to-indoor repeater. According to the measurements, the pilot coverage planning threshold of about −80 dBm ensures a 2500 kbps throughput for shared HSDPA connections. Improving the coverage above −80 dBm seems to provide only small advantage in HSDPA throughput. Of course, the pilot planning thresholds may change if different channel power allocations are used. In addition, network performance can be further improved by increasing the antenna density in the serving distributed antenna system. Finally, good performance of repeater implementation needs careful repeater gain setting and donor antenna siting.

1. INTRODUCTION

Evolution of mobile communication systems started to roll on in the 1980s when the first analog 1st generation (1G) frequency division multiple access (FDMA) mobile networks were launched. In the early 1990s, the first 2nd generation (2G) global system for mobile (GSM) communications networks were launched in Europe, as well as corresponding time division multiple access (TDMA) systems in the US. Until the early 2000s, the networks were mainly used for speech communication. Data connections, limited to tens of kilobits per second (kbps), played only a minor part in the system. In the early 2000s, when 1G networks started to disappear, the first 3rd generation (3G) networks were launched: universal mobile telecommunications system (UMTS) in Europe/Japan, and CDMA2000 in the US were introduced, both using code division multiple access (CDMA) technology, and providing significantly higher data rates compared to earlier systems.

The first specification of UMTS, Release 99 (R99), was published by 3rd generation partnership project (3GPP) in 1999, and commercial networks were launched between 2001 and 2003. The basic UMTS system provided user level throughput of 384 kbps for the downlink (DL) and 64 kbps for the uplink (UL), which was later updated to 384 kbps as well. Together with the conquest of the internet, requirements for mobile broadband access grew and higher data rates were needed to fulfill the requirements. Release 5 (R5) specifications included improvements for R99, and most importantly, introduced high-speed downlink packet access (HSDPA) for UMTS, which enables above 10 Mbps data rates for downlink, thus providing high-quality broadband access for mobile users.

HSDPA is an add-on for R99, thus all functionalities of R99 remained, and new properties have been added to enable the high data rates in downlink. Channel bandwidth remained the same, and the main sources for high data rates are fast adaptation for radio channel changes, higher-order modulation, and shared channel, which enable scheduling of all cell resources for one user when necessary.

Both the modulation and the channel coding rate can be changed to adapt to the fast changes in radio channel quality, the target being to always provide the best achievable throughput. In addition to quadrature phase-shift keying (QPSK), 16-quadrature amplitude modulation (16QAM) was introduced for HSDPA, doubling the available throughput in good radio channel conditions. Regardless of power control, due to the small dynamic range in the downlink direction, R99 Node B (UMTS base station) often sends with higher downlink power than needed for the used 50% channel coding and QPSK modulation, and higher data rates can be achieved without any drawbacks. Efficient utilization of adaptive modulation and coding (AMC) requires real-time knowledge of channel quality, which is provided by the channel quality indicator (CQI) messages. CQI messages are sent by the mobile every 2 milliseconds, thus Node B can change the modulation and coding scheme (MCS) every 2 milliseconds (transmission time interval (TTI)) [1, 2].

In addition to AMC, hybrid automatic repeat request (HARQ) and fast scheduling were introduced to accelerate network performance. In R99, retransmissions were made in radio link control (RLC) layer by radio network controller (RNC). The procedure was fastened by bringing retransmissions from the RNC to Node B, and down to the physical layer. Also soft combining was implemented for efficient utilization of all received data. In HSDPA, all users share the radio resources. HSDPA uses 1–15 channelization codes, with fixed spreading factor of 16. Thus, all available radio channel resources can be utilized for HSDPA use. One user can have all the available resources if needed, and multiple access principle is fulfilled by scheduling the resources consecutively for each user. To ensure fast scheduling, the scheduling functionality is located in Node B on MAC layer [1, 2].

R5 also introduces new channels to the system on the physical layer and transport layer. The most important is the transport layer high-speed downlink shared channel (HS-DSCH) which carries the user data of the downlink physical high-speed physical downlink shared channels (HS-PDSCHs) separated by channelization codes. High-speed shared control channel (HS-SCCH) on the physical layer carries information for demodulating HS-DSCH correctly. Uplink feedback information, such as CQI and acknowledgment/nonacknowledgment messages are sent on physical high-speed dedicated physical control channel (HS-DPCCH). HSDPA also utilizes R99 channels, and it is good to note that the user data in the uplink is sent similarly as in the R99 [1, 2].

WCDMA downlink physical layer maximum total user data rate can be approximately calculated as

$$R_{\text{phy}} = \frac{W \cdot N \cdot c \cdot m}{\text{SF}}, \tag{1}$$

where W is the system chip rate (3.84 Mcps), N is the number of allocated channelization codes, c is the channel coding rate, m is the number of bits per symbol for used modulation, and SF is the spreading factor for the physical channel. Where R99 data connection provides maximum 480 kbps in physical layer ($N = 1$, $c = 0.5$, $m = 2$, $\text{SF} = 8$), R5 HSDPA can reach up to 14.4 Mbps in optimal radio channel and system conditions ($N = 15$, $c = 1$, $m = 4$, $\text{SF} = 16$). Practical data rates, however, are significantly lower due to the changes in radio interface (lower MCS), parameterization of Node Bs, limited transmission capabilities between Node B and RNC, and hardware limitations at Node B and user equipment (UE).

The target of the paper is to discover the coverage requirements for different average and momentary HSDPA data rates, in the dedicated indoor system and outdoor-to-indoor repeater implementation. In addition, performances of indoor and repeater systems are compared.

The paper is organized as follows. First, the used radio system is shortly described and Section 2 introduces the indoor environment and principles of repeaters and distributed antenna systems. The measurement setup and the measurement environment are described in Section 3 and the measurement results are shown in Section 4. The results are concluded in Section 5.

2. INDOOR COVERAGE PROVIDERS

In the era of line telephones, wireless communication networks were mainly used for speech connections and out of office, thus requirements for indoor coverage and capacity were modest, and low service probabilities were accepted indoors. However, cellular 3G networks are planned to compete equally with fixed broadband services, and high coverage quality is also presumed in all indoor locations.

2.1. Macrocellular indoor coverage

Moderate indoor coverage can be provided as a side product of macro-/microcellular planning, as outdoor signal propagates inside buildings despite higher attenuation. However, building penetration loss can be as much as 20 dB, and propagation loss indoors are often tens of dBs [3, 4], which limits the coverage in larger buildings and buildings in cell edges. Indoor users also require higher downlink power, which increases the total interference level in the network. Indoor coverage from outdoor base stations at the cell edge could be improved by higher cell overlapping, but this may deteriorate the outdoor network performance due to pilot pollution and higher soft handover overhead. Therefore, it is often impossible to achieve good indoor coverage throughout the building provided by the outdoor network.

2.2. Dedicated indoor systems

Dedicated indoor systems (Figure 1) can be implemented using pico- or femtocells, distributed antenna system (DAS), radiating cables, or optical solutions [5–7]. In a distributed antenna system, one base station is used to provide service for large areas via multiple antennas. The base station is connected to the antennas via splitters, tappers, and coaxial cables [8]. Since the coverage areas are rather scattered, and difficult to estimate accurately in indoors, typically omnidirectional or lightly directional antennas are used with DAS. Picocell is a base station equipped with an antenna, typically mounted on the equipment itself, and femtocells are similar to picocells with smaller transmission power enabling

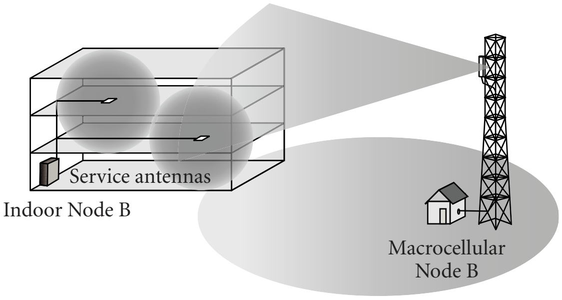


FIGURE 1: Dedicated indoor system using a dedicated indoor base station.

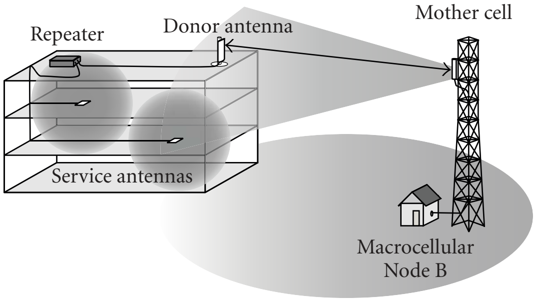


FIGURE 2: Outdoor-to-indoor repeating.

a very small coverage area for, for example, home/office use. Radiating cables can be used to provide smooth coverage for limited areas [9]. Optical solution is an antenna system where antenna/amplifier units are connected to base station by optical cables, providing a very flexible system with minimal cable loss [7].

The benefits of the pico base station are easy installation and high capacity per antenna unit, whereas DAS requires antenna cable installation, providing a wide range of coverage from one base station. Earlier studies for DAS with R99 UMTS indicate that the ensuring coverage is the primary rule for planning, and the enhancement of increasing the antenna density is rather small [10]. However, similar measurements for HSDPA indicate that increasing the antenna density could improve the HSDPA capacity in poor coverage [11]. System simulations for HSDPA DAS systems emphasize the importance of dedicated indoor systems for ensuring indoor coverage [12], but verifying measurement results are lacking.

2.3. Repeaters

Repeaters can be considered as an alternative solution to the dedicated indoor systems. Outdoor-to-indoor (Figure 2) repeating can be used to improve coverage in an indoor environment by exploiting the existing outdoor macrocellular network. The signal from the outdoor network can be captured using a rooftop antenna and forwarded inside the building using cables. Furthermore, the received signal can be amplified before retransmission and the building penetration loss can be avoided. Single antenna or DAS can be used indoors to provide the extension in signal coverage offered by the repeater. Repeaters in this paper stand for simple bidirectional linear amplifiers that can be installed in the cell area to provide an amplified replica of the received UMTS frequency bands. As the whole band is amplified without signal regeneration, interference from other UMTS mobiles is included in the amplification process. Therefore, only out-of-band interference is filtered out. Repeater amplification ratio (repeater gain) can be adjusted to tune the effective isotropic radiated power (EIRP) level at the serving antennas in the downlink.

The impact of a repeater on the noise experienced by the base station receiver can be represented by using effective noise figure of the base station (EF_B) as presented in [13]. The definition of EF_B is based on the thermal noise including the noise originating from the equipment (repeater and Node B). The thermal noise density of a single component can be generally expressed in the form

$$N_{TH} = kT, \tag{2}$$

where k is the Boltzmann constant and T is the noise temperature of a component. The noisy components are illustrated in Figure 3 in a case with and without repeater. By using (2) and Figure 3, the combined noise contribution at Node B becomes

$$N_0 = k(T_a + T_R)G_T + k(T_a + T_B), \tag{3}$$

where T_a is the ambient temperature, and T_R and T_B are the noise temperatures of the repeater and base station equipment. The gain and loss components on the link between the repeater and the base station are combined into a parameter

$$G_T = G_R \cdot G_D \cdot L_P \cdot G_A. \tag{4}$$

In (4), G_R is the repeater gain, G_D and G_A are the antenna gains of the repeater donor and the Node B, and L_P is the repeater donor link loss. EF_B for the total noise contribution in an unloaded network scenario can now be defined as the relation of the signal-to-noise ratios between the input and the output (Figure 3):

$$\mathrm{EF}_B = \frac{S_{\text{in}}/N_{\text{in}}W}{S_{\text{out}}/N_{\text{out}}W} = \frac{S_{\text{in}}/kT_a}{S_{\text{out}}/\left(k(T_a + T_R)G_T + k(T_a + T_B)\right)} \tag{5}$$

if $S_{\text{in}} = S_{\text{out}}$ and W is the signal bandwidth. Equation (5) can be then further simplified to form

$$\mathrm{EF}_B = \frac{(T_a + T_B) + (T_a + T_R)G_T}{T_a}, \tag{6}$$

which can be reproduced to form

$$\mathrm{EF}_B = F_B + G_T \cdot F_R \tag{7}$$

by using the definition for the noise figure [13].

As visualized in (2)–(7), the amount of total noise at the Node B receiver depends on the noise properties of the repeater equipment and on the loss and gain components in

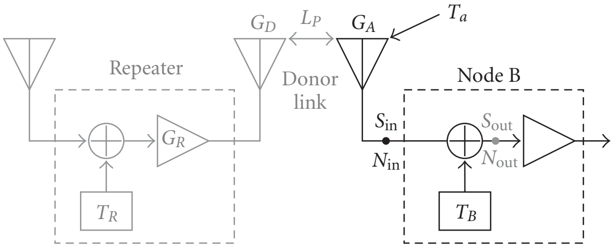


Figure 3: The effective noise figure of the base station can be calculated taking the ratio of the SNR at the Node B antenna connector (repeater not installed) and the SNR at the Node B receiver output.

the donor link. Thus, the repeater configuration (including the location, gain, and donor antenna properties) affects the performance of the donor macro cell as well. Thereby, it is important to consider the effects to the donor macrocell together with the repeater service area performance. Increased noise level is visible in the uplink noise plus interference value measured by the base station.

In order to achieve successful repeater operation, the donor and serving antennas must be placed in a way that the isolation requirement between the two antennas is fulfilled. Referring to [14], the isolation between the repeater donor and serving antenna should be at least 15 dB higher than the repeater gain. If the isolation is insufficient, self-oscillation (reamplification of the repeater own signal) of the repeater totally blocks the mother cell. To prevent self-oscillation, automatic gain control (AGC) is implemented in the repeater to automatically keep the repeater gain at a safe level.

Some studies have been made considering repeaters as a method of improving HSDPA performance in indoor environment. In [15], the performance of outdoor-to-indoor repeating was measured in WCDMA Release 99 macrocellular network. The measurements in [15] were done in a building measuring the signal-to-interference ratio (SIR) from the primary common pilot channel (P-CPICH). The results indicated that the average indoor SIR level was remarkably improved due to an amplified signal through repeater. The improved pilot channel SIR can be seen as improved HSDPA coverage and capacity, since higher modulation and coding schemes can be utilized. Furthermore, the indoor HSDPA coverage and capacity have been studied together with repeaters [16] by system level simulations. The HSDPA bitrate experienced by the indoor mobile users was seen to clearly increase together with the increased repeater gain [16, 17].

3. MEASUREMENT SETUP

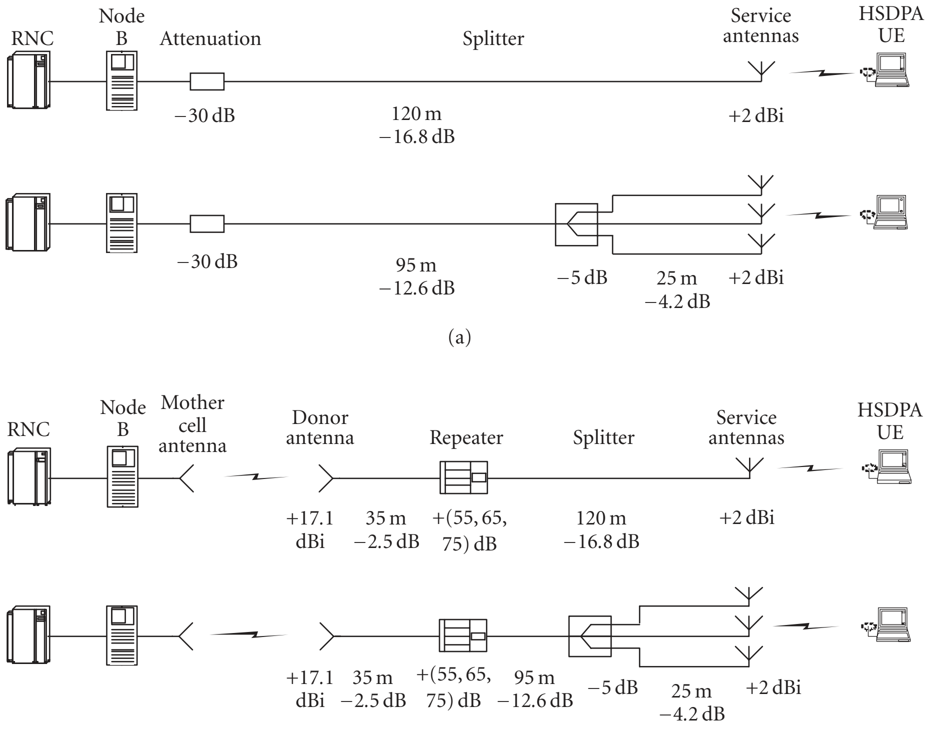
Measurements were performed in a UMTS system, based on 3GPP Release 5 specification [18]. The network included a fully functional RNC connected to a core network. The measurements were performed with two different indoor systems: a dedicated indoor system (Figure 4(a)), and an outdoor-to-indoor repeater (Figure 4(b)). Both used HSDPA capable UMTS Node Bs, connected to a distributed antenna system either directly or via a donor antenna and an analog WCDMA repeater. DAS consisted of 1/2 inch feeder cables connected to omnidirectional antennas with a 2 dBi gain, and in addition 7/8 inch feeder cables were used with the repeater. Depending on the serving antenna configuration, the signal from Node B or repeater was transmitted either directly to the antenna or split into 3 equal parts. For the dedicated indoor system, the signal was additionally attenuated by 30 dB to be able to study HSDPA performance in a coverage limited network. The relevant parameters of an indoor system are listed in Table 1.

Measurement equipment consisted of a category 5/6 HSDPA data card [19] with maximum bitrate of 3.6 Mbps ($N = 5$, $c = 0.75$, $m = 4$, $\mathrm{SF} = 16$ in (1)), connected to a laptop computer, equipped with a WCDMA field measurement software [20]. The used data card was calibrated only for commercial use, thus absolute values of radio channel measurements may include some error. Therefore, the analysis of the results is mainly based on relative comparison of the measured scenarios.

In the repeater configuration, the mother cell was a macro-/microcellular base station equipped with a directional antenna at the height of rooftops. The donor antenna was a typical macrocellular antenna with a horizontal beamwidth of 65° and a gain of 17.1 dBi [21], installed on the roof of a building (Figure 5(d)). The donor antenna was pointed toward the mother cell antenna, located 10° off from the mother cell antenna main beam direction. At the reference repeater configuration, the pilot signal level difference to the neighboring macrocell measured at the repeater serving antenna was about 10 dB ($\Delta P = \mathrm{RSCP}_{\mathrm{BestCell}} - \mathrm{RSCP}_{\mathrm{2ndBestCell}} = 10\,\mathrm{dB}$). Additionally, the impact of poor repeater location or installation was studied by misorienting the repeater donor antenna from the mother cell direction toward a neighboring sector. Then the received signal code power (RSCP) difference between the serving and neighboring cell was reduced to about 0 dB ($\Delta P = 0\,\mathrm{dB}$). This illustrates the case when repeater is installed on soft or softer handover region in the network.

The distance between the mother cell antenna and the repeater donor antenna was about 450 meters. The radio path between the mother cell and donor antenna was optically in line of sight, but Fresnel zone of the radio path was not clear because some trees and rooftops were in the way. An analog WCDMA repeater [22] with varying gains (55, 65, and 75 dB) was used to amplify the signal of the wanted WCDMA frequency band from the donor antenna in the downlink and from the serving DAS in the uplink (Figure 4(b)). Relevant parameters of the repeater are listed in Table 1.

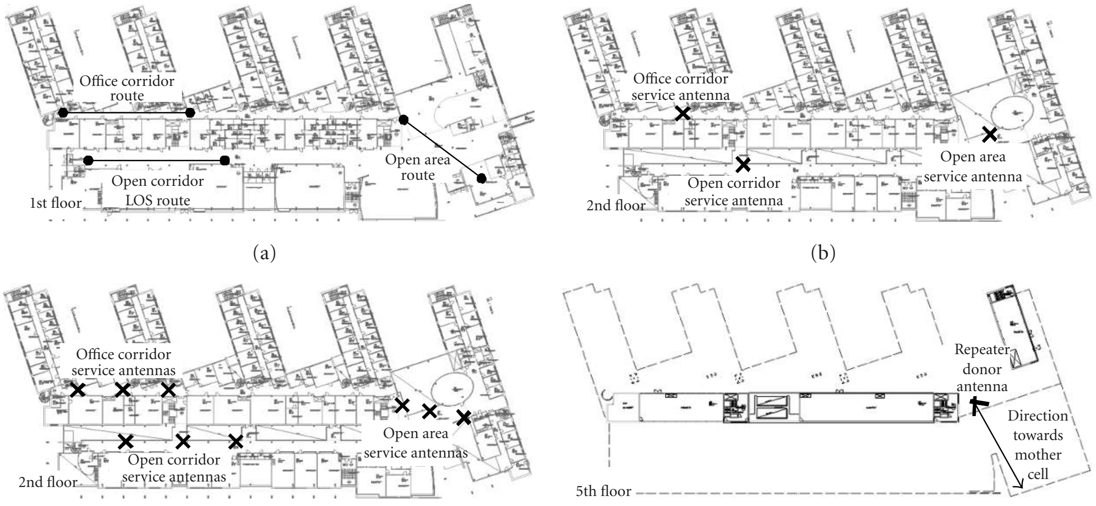
The measurements were carried out in a university building, representing different environments; a dense *office corridor*, a long wide *open corridor*, and a large *open area* in the entrance hall, where approximate room heights were 2.5 m, 6 m, and 6 m, respectively. 1 antenna and 3 antennas with constant antenna spacing were placed at the height of 2 m, 4.5 m, and 4.5 m, respectively (Figures 5(b)-5(c)). The measurements were carried out on different



(a)

(b)

Figure 4: System block diagrams and antenna configurations for (a) dedicated indoor system measurements and (b) outdoor-to-indoor repeater measurements, both with 1 and 3 antenna DASs.



(a)

(b)

(c)

(d)

Figure 5: (a) Measurement routes for all indoor and repeater measurements, (b) antenna locations for 1 antenna, (c) 3 antennas, (d) and repeater donor antenna.

routes, consisting of line-of-sight (LOS) and nonline-of-sight (NLOS) signal paths in open corridor and open area, and only NLOS in the office corridor (Figure 5(a)). The measurements were carried out by establishing one HSDPA data connection and repeating each measurement route several times. The measurements were done at walking speed, and the measuring UE was placed on a trolley at height of one meter. During the measurements, the network was empty, thus, no other traffic was present. Hypertext transfer protocol (HTTP) download was used to create traffic on the downlink, and the measuring UE requested full downlink throughput (TP).

To indicate coverage and quality of the received radio signal, typical WCDMA network performance indicators

Table 1: System parameters.

	Value	Unit
Indoor system parameters		
Max. total DL power	38	dBm
Common pilot channel power	30	dBm
Power allocated for HSDPA	5	W
Repeater parameters		
Maximum repeater DL power	35	dBm
Maximum repeater UL power	20	dBm
Repeater noise figure	3	dB
Repeater donor antenna gain	17.1	dBi
Donor antenna beamwidth	65	deg

as RSCP and received signal strength indicator (RSSI) were used. RSCP is the received power of P-CPICH after despreading. RSSI is the total received power over the whole wideband channel. RSCP indicates purely the coverage of the cell and

$$\frac{E_C}{I_0} = \frac{\text{RSCP}}{\text{RSSI}} \tag{8}$$

can be used as a coverage quality indicator, since it takes into account the noise-and-interference level. With the used configuration, in empty network and close to Node B antenna, maximum value of E_C/I_0 is -3 dB, and after a user establishes a shared HSDPA connection, E_C/I_0 is reduced to -7 dB. Measurement of the HSDPA throughput on the medium access control layer (MAC) indicates the available system capacity. MAC throughput corresponds to physical layer throughput, with constant, approximately 5% overhead. All the measured throughput values are with one user and for HSDPA with 5 code transmissions; throughput per code is one fifth of the presented values. The results can be converted for 10 codes with rather small error. If the same power per code is allocated, the available throughput at the air interface with 10 codes should be theoretically doubled, but in practice, for example, nonorthogonality between the codes may cause some error. CQI is not a direct radio interface measurement, but a vendor-specific value generated at the mobile, based on, for example, RSCP and E_C/I_0 measurements. However, CQI is a useful indicator, since Node B decides the used modulation and coding scheme based on mobile CQI reports. Uplink noise plus interference power level (P_{NI}) is measured at Node B, which sends the value to the UE in system information block 7 at the beginning of each connection. The resolution for the P_{NI} value reporting is one dBm. Too high P_{NI} is one limiting factor when maximizing repeater gain. In an empty- or low-loaded network, the impact of the repeater to the uplink load and system uplink performance is visible in the P_{NI}.

4. MEASUREMENT RESULTS

The measurement results are presented focusing on the essential observations from the measurement data. First, averaged results of all measurements (Table 2) are covered, discussing separately different issues risen from macrocellular, outdoor-to-indoor repeater, and dedicated indoor configurations. Next, the results of the selected scenarios are studied focusing on the coverage requirements for certain HSDPA capacities. Lastly, selected examples of raw measurement data are shown to illustrate the system behavior.

4.1. *Indoor coverage from macrocellular network*

Since macrocellular networks are a common way for providing indoor coverage, indoor performance of a nearby outdoor Node B was measured for the reference of comparison. Coverage varied in different indoor locations. In an office corridor, coverage was poor (mean RSCP -119.1 dBm) and HSDPA connection could not be established. For open corridor and open area environment, macrocellular coverage was better (mean RSCP -104.3 dBm and -101.4 dBm), providing acceptable or good HSDPA throughput (mean TP 1373 kbps and 1892 kbps), respectively.

4.2. *Outdoor-to-indoor repeater*

Based on the measurement results, implementation of an outdoor-to-indoor repeater enhances significantly indoor coverage and HSDPA performance. In all environments and scenarios with a repeater, HSDPA performance is clearly improved compared to macrocellular. Depending on the environment, repeater gain G_R, and antenna configuration, pilot coverage was improved by between 13.9 and 41.2 dB, and HSDPA throughput by between 247 and 1628 kbps (Table 2).

Increasing the G_R has a positive impact on the coverage, but the challenge in planning is to find out the optimal value of G_R from a system performance point of view. The minimum required G_R for improving the coverage depends at least on the outdoor and indoor environments, and the system configuration. The limits for the maximum repeater gain are set by the repeater equipment, donor and serving antenna isolation, and uplink received noise plus interference power (P_{NI}). The measurements were done with three different G_Rs, in 10 dB steps. In the measurements, the repeater antenna isolation requirement was fulfilled in all measured configurations. This was resolved by observing the functionality of the automatic gain control function of the repeater. Since the increase in the measured average RSCP values equal approximately to the repeater gain steps (10 dB), the automatic gain control has not been activated and the isolation has remained sufficient.

Already the lowest measured G_R (55 dB) clearly provides improved performance in all environments. G_R 65 dB provides good performance, and the best HSDPA performance was always achieved with the highest G_R (75 dB). Optimal G_R can be found, when the coverage and capacity requirements can be met without deteriorating mother cell operation.

P_{NI} in empty network was measured as -105 dBm (Table 2). Impact of the repeater with G_R 55 dB is not yet visible in the P_{NI} and G_R 65 dB increases P_{NI} by one dB, thus the impact on the mother cell is rather small. With G_R 75 dB, P_{NI} has risen by 5 dB to -100 dBm, which already had

Table 2: Numerical averaged measurement results.

	Gain, G_R	RSCP [dBm]		E_C/I_0 [dB]		TP [kbps]		Mean CQI		P_{NI} [dBm]	
Number of service antennas		1	3	1	3	1	3	1	3	1	3
Office corridor											
Macrocellular	—	−119.1		−17.6		n/a		n/a		−105	
Repeater	55	−98.7	−97.5	−11.8	−11.4	2012	2212	15.2	15.9	−105	−105
Repeater	65	−90.3	−88.5	−11.0	−10.5	2563	2948	17.1	18.1	−104	−104
Repeater	75	−80.7	−77.9	−10.1	−9.8	2926	2974	18.2	18.5	−100	−100
Indoor	—	−104.5	−101.9	−11.1	−9.2	1174	1562	12.5	14.7	−105	−105
Open corridor											
Macrocellular	—	−104.3		−10.7		1373		10.9		−105	
Repeater	55	−86.3	−83.9	−8.1	−10.5	1818	2566	15.9	17.0	−105	−105
Repeater	65	−77.1	−74.4	−7.6	−10.3	2231	2871	16.2	17.4	−104	−104
Repeater	75	−67.3	−64.5	−7.7	−9.6	2173	3001	15.5	17.6	−100	−100
Repeater $\Delta P = 0dB$	55	−92.9	−89.9	−12.3	−12.3	1497	1553	14.6	14.2	−105	−105
Repeater $\Delta P = 0dB$	65	−83.9	−80.2	−11.6	−11.4	1579	1633	15.2	15.2	−104	−104
Repeater $\Delta P = 0dB$	75	−73.2	−70.3	−11.6	−12.1	1450	1516	14.6	13.9	−99	−99
Indoor	—	−91.1	−95.7	−8.9	−8.7	2315	2043	17.1	16.4	−105	−105
Open area											
Macrocellular	—	−101.4		−13.3		1892		15.5		−105	
Repeater	55	−87.5	−82.9	−11.0	−10.6	2139	2416	16.1	16.7	−105	−105
Repeater	65	−79.5	−73.6	−10.5	−10.6	2640	2895	17.2	17.5	−104	−104
Repeater	75	−69.7	−63.5	−10.3	−10.2	2879	3007	17.7	18.4	−100	−100
Indoor	—	−95.4	−94.7	−8.0	−7.9	2260	2313	16.7	17.0	−105	−105

a significant impact on the available uplink capacity. System configuration in the uplink from repeater toward the mother cell has not changed, so the P_{NI} results are the same for each environment and antenna configuration. From the set of measured repeater gains, 65 dB is the optimum value, since the average HSDPA capacity is at a good level (from 2231 to 2948 kbps), but uplink interference has increased by only one dB. With one outdoor-to-indoor repeater per cell, good indoor coverage and capacity can be provided without any deterioration in the mother cell, but limitations may occur if multiple repeaters are installed under one WCDMA cell.

Antenna misorientation was studied to illustrate the situation where a repeater is installed in a soft/softer handover area, or good radio path toward the mother cell is not available. According to the results, misorientation of the repeater donor antenna reduces HSDPA indoor performance significantly. Comparing $\Delta P = 10\,\text{dB}$ to $\Delta P = 0\,\text{dB}$, RSCP drops by between 5.9 and 6.8 dB and additional interference from neighboring cell causes E_C/I_0 to drop by between 1.2 and 4.0 dB, resulting in 321 kbps to 1485 kbps smaller HSDPA throughput values (Table 2) than optimal donor antenna orientation. This indicates that in repeater implementation, special attention should be paid to finding the optimal location and orientation for the repeater donor antenna.

4.3. Dedicated indoor system

Compared to the repeater serving antenna line, the signal from indoor Node B was attenuated by 30 dB (Figure 4). Thus, the coverage measurements of the repeater and indoor system are not directly comparable. Attenuation was used in order to achieve lower average RSCP to emphasize HSDPA behavior in weaker coverage areas.

Even with a heavily attenuated signal, a dedicated indoor system is able to provide satisfactory HSDPA performance. Measured mean RSCP values (between −104.5 and −91.1 dBm) are relatively low, but can provide average HSDPA throughput between 1174 and 2315 kbps. Removing the 30 dB attenuation would either boost the indoor coverage by 30 dB or alternatively enable the implementation of a larger and denser DAS, which indicates very good HSDPA performance expectations.

Dividing the signal in several antennas, thus increasing the antenna density, has a clear positive impact on system coverage and HSDPA capacity. Depending on the environment and scenario, improvement in RSCP was 1–5 dB, and improvement in HSDPA throughput was 5–30%.

4.4. HSDPA performance analysis

Based on the measurement results, coverage requirements for good quality HSDPA performance can be given. The analysis is based on coverage-capacity mapping of the measurement results. For all the measurements, corresponding measured RSCP for each measured throughput sample is collected. Next, average throughput for each collected RSCP sample (1 dB accuracy) is calculated. The results of the analysis are shown in Figures 6–8. Each figure presents separate environment, where the results for macrocellular, indoor, and

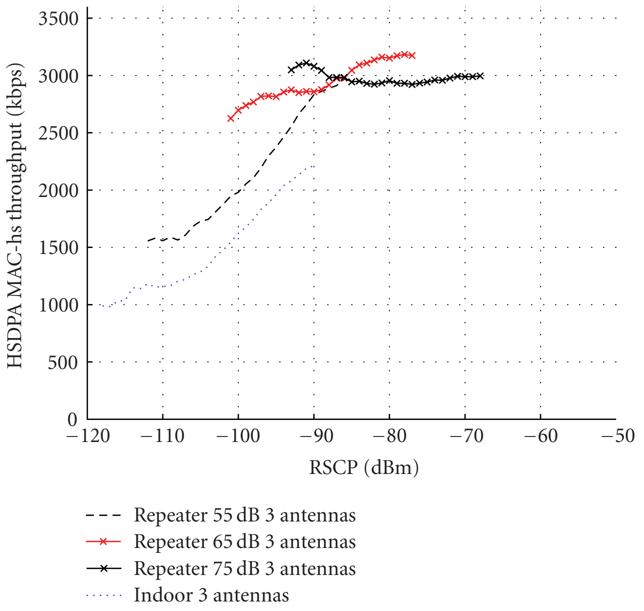


Figure 6: Average of all TP samples for each RSCP value, office corridor. Repeater and indoor systems, 3 antenna configuration.

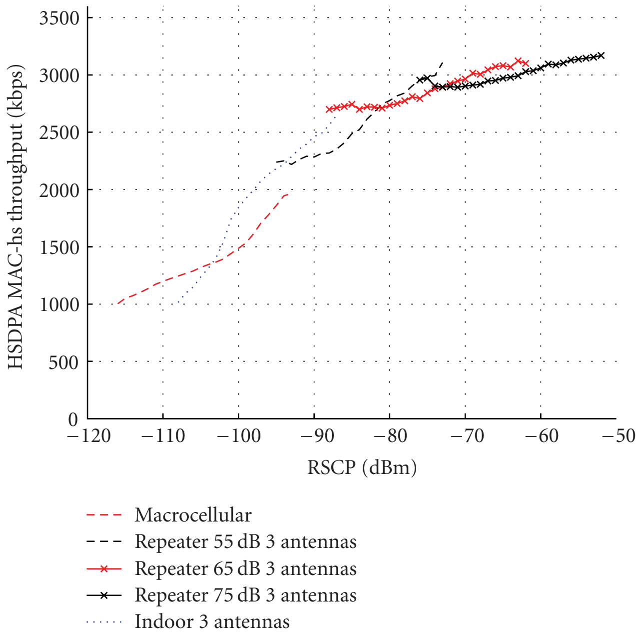


Figure 7: Average of all TP samples for each RSCP value, open corridor. Macrocellular, repeater and indoor systems, 3 antenna configuration.

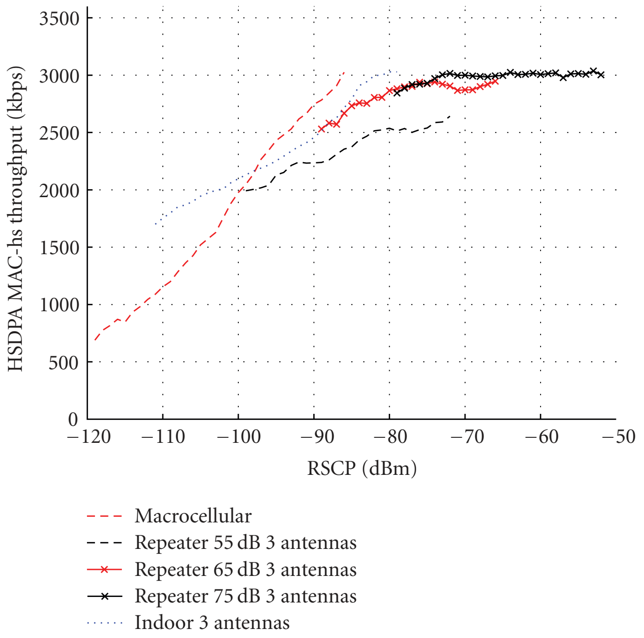


Figure 8: Average of all TP samples for each RSCP value, open area. Macrocellular, repeater and indoor systems, 3 antenna configuration.

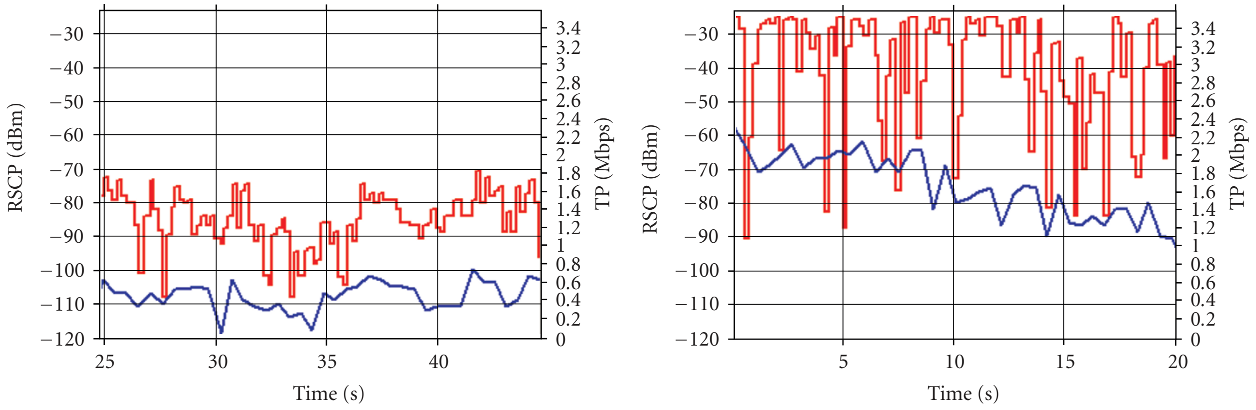
all repeater configurations are shown. To improve reliability, RSCP values that have less than about 30 corresponding throughput samples are discarded.

Measurements for the dedicated indoor system show that with RSCP −110 dBm, average throughput is at a level from 1200 kbps to 1700 kbps, depending on the environment. Average throughput increases rather linearly with RSCP up to −90 dBm, where throughput between 2200 and 2500 kbps can be achieved.

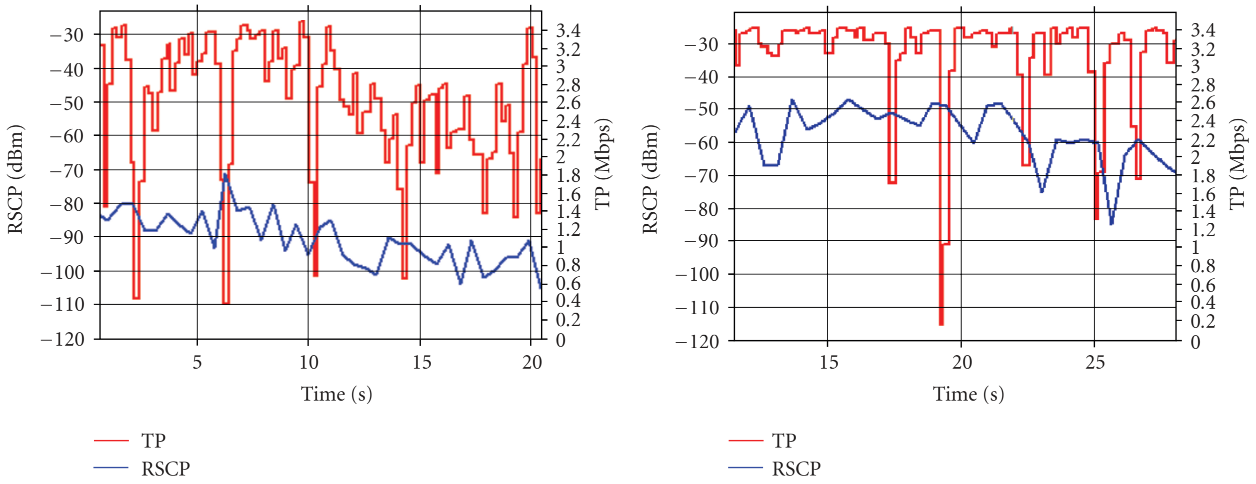
Measurements with repeaters with a gain between 55 and 75 dB in an office corridor show that at a level of RSCP −110 dBm, −90 dBm, and −70 dBm, average throughput of 1600 kbps, between 2700 and 3100 kbps, and 3000 kbps, respectively, can be achieved (Figure 6). Similarly, in an open corridor, RSCP −90 dBm and −70 dBm provides average throughput of 2300 kbps and between 2900 and 3000 kbps, respectively (Figure 7). In an open area, average throughput results for RSCP −90 dBm and −70 dBm are 2400 kbps and between 2800 and 3000 kbps, respectively (Figure 8).

Additionally, measurements of the macrocellular coverage in indoors show that achieved throughput with certain RSCP is approximately at the same level via a repeater or from an indoor system. Moreover, it can be noted that from macrocellular Node B, an average HSDPA throughput of more than between 2000 and 2500 kbps can be achieved in indoor locations, where RSCP is above −92 dBm (Figures 7 and 8).

From the results overall, it can be summed up that RSCP −110 dBm provides average HSDPA throughput above 1000 kbps. Improving the coverage until approximately RSCP −80 dBm improves HSDPA throughput up to between 2500 and 3000 kbps. Measured average throughput at RSCP −50 dBm is between 3000 and 3200 kbps, thus improving coverage above RSCP −80 dBm does not seem to provide clear enhancement in HSDPA throughput, although some improvement is visible (Figures 7 and 8). The given pilot coverage thresholds for different average expected HSDPA throughput values can be used as input for indoor coverage planning. It has to be noted that the presented coverage thresholds are tied to the used power allocation of



(a) Macrocellular (b) Repeater 55 dB



(c) Indoor (d) Indoor, not attenuated

Figure 9: Examples from raw measurement data for open area environment, 1 antenna configuration. Captured on the second half of the measurement route, antenna located on the left hand side.

HSDPA and common pilot channel presented in Table 1, and also differences between different user equipments can appear.

4.5. *Examples of measurement data*

In Figures 9(a)–9(c), illustrative measurement examples of three different scenarios and additionally one example outside the measurement campaign in Figure 9(d) are presented. All the examples are screen shots from the measurement tool, measured in the open area environment with 1 antenna configuration. Each measurement is started below the antenna, and measured to the end of the measurement route (except in the macrocellular scenario, where the signal is coming directly from an outdoor Node B).

In the measurement tool, sampling resolution for RSCP is 600 milliseconds and for throughput is 200 milliseconds. In the physical layer, the radio interface indicators are measured, the CQI is formulated and reported, and the modulation and coding scheme (throughput) is changed every 2 milliseconds (transmission time interval). Thus, the measurement data provided by the measurement tool is roughly averaged, and the throughput and RSCP do not always correlate perfectly. In macrocellular network (Figure 9(a)), RSCP varies between −100 dBm and −120 dBm, and throughput varies between 500 kbps and 1800 kbps.

Figure 9(b) is an example of repeater measurements with 55 dB repeater gain. While walking away from the antenna, RSCP drops from −60 dBm to −90 dBm. At RSCP −60 dBm, throughput repetitively hits the maximum, but the continuous drops/fades cause the average throughput to remain below 3000 kbps. When the local average of RSCP falls below −80 dBm, a small drop is visible in the throughput curve, but maximum throughput is still reached once in a while.

Finally, examples of dedicated indoor system measurements are shown. Figure 9(c) illustrates the behavior of throughput, when RSCP decreases from −80 dBm to −115 dBm, starting from 3000 kbps, and dropping down to a level of 2000 kbps. Figure 9(d) shows an example measured with indoor system without the 30 dB attenuation. Close to the antenna, throughput continuously hits the maximum, but still fades of radio interface prevent HSDPA throughput to remain continuously at the maximum value. This indicates that if continuous maximum throughput is needed, planning threshold for RSCP should be even above −50 dBm.

5. CONCLUSIONS AND DISCUSSION

In the paper, capabilities of an outdoor-to-indoor analog WCDMA repeater are set against a dedicated indoor system, and coverage requirements for performance of high-speed downlink packet access is studied.

In the measured indoor locations, macrocellular outdoor network provided poor coverage. By implementing an outdoor-to-indoor repeater or a dedicated indoor system, the coverage and HSDPA performance in indoor locations were significantly enhanced. The measurements show that if certain coverage thresholds can be ensured, an analog outdoor-to-indoor repeater is able to provide similar HSDPA performance as a dedicated indoor system. However, with dedicated indoor system, the coverage requirements are easier to achieve with higher available transmission power compared to the repeater.

The measurement results provide basic guidelines for pilot coverage planning indoors. From an HSDPA performance point of view, improving the coverage provides a clear benefit up to RSCP −80 dBm, where the average throughput of at least 2500 kbps (500 kbps per code) was always achieved. Moreover, for ensuring average throughput values higher than 3000 kbps (600 kbps per code), RSCP −50 dBm is needed. Of course, the pilot planning thresholds may change if different channel power allocations are used.

Increasing the repeater gain improves downlink performance, but already the lowest measured repeater gain clearly provided improved indoor coverage and capacity. The best HSDPA indoor performance was achieved with the highest measured repeater gain, but a high rise in uplink interference level at the mother cell was caused. Thus, the optimal repeater gain is a compromise between repeater serving area performance and mother cell performance.

In addition, the measurements show that misorientation of the repeater donor antenna reduces HSDPA indoor performance significantly, and special attention should be paid to finding an optimal location and orientation for the repeater donor antenna. Finally, increasing the antenna density in the serving distributed antenna system has a clear positive impact on system coverage and HSDPA capacity.

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REFERENCES

[1] H. Holma and A. Toskala, Eds., *HSDPA/HSUPA for UMTS*, John Wiley & Sons, New York, NY, USA, 2006.

[2] E. Dahlman, S. Parkvall, J. Sköld, and P. Beming, *3G Evolution: HSPA and LTE for Mobile Broadband*, Academic Press, Oxford, UK, 2007.

[3] S. Aguirre, L. H. Loew, and Y. Lo, “Radio propagation into buildings at 912, 1920, and 5990 MHz using microcells,” in *Proceedings of the 3rd Annual International Conference on Universal Personal Communications (ICUPC ’94)*, pp. 129–134, San Diego, Calif, USA, September-October 1994.

[4] “Digital Mobile Radio Towards Future Generation Systems,” COST 231 Final Report, 1998.

[5] S. R. Saunders, *Antennas and Propagation for Wireless Communication Systems*, John Wiley & Sons, New York, NY, USA, 1999.

[6] Y. P. Zhang, “Indoor radiated-mode leaky feeder propagation at 2.0 GHz,” *IEEE Transactions on Vehicular Technology*, vol. 50, no. 2, pp. 536–545, 2001.

[7] Z. Uykan and K. Hugl, “HSDPA system performance of optical fiber distributed antenna systems in an office environment,” in *Proceedings of the 16th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC ’05)*, vol. 4, pp. 2376–2380, Berlin, Germany, September 2005.

[8] J. Lempiäinen and M. Manninen, Eds., *UMTS Radio Network Planning, Optimization and QoS Management*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2003.

[9] C. Seltzer, “Indoor coverage requirements and solutions,” in *Proceedings of IEE Colloquium on Antennas and Propagation for Future Mobile Communications*, pp. 3/1–3/4, London, UK, February 1998.

[10] T. Isotalo, J. Niemelä, and J. Lempiäinen, “Measurements for distributed antennas in WCDMA indoor network,” in *Proceedings of the 9th International Symposium on Wireless Personal Multimedia Communications (WPMC ’06)*, pp. 183–187, San Diego, Calif, USA, September 2006.

[11] T. Isotalo and J. Lempiäinen, “HSDPA measurements for indoor DAS,” in *Proceedings of the 65th IEEE Vehicular Technology Conference (VTC ’07)*, pp. 1127–1130, Dublin, Ireland, April 2007.

[12] K. Hiltunen, B. Olin, and M. Lundevall, “Using dedicated in-building systems to improve HSDPA indoor coverage and capacity,” in *Proceedings of the 61st IEEE Vehicular Technology Conference (VTC ’05)*, vol. 4, pp. 2379–2383, Stockholm, Sweden, May-June 2005.

[13] R. Anderson, B. Arend, and K. Baker, “Power Controlled Repeaters for Indoor CDMA Networks,” White paper, Qualcomm Inc., 2003.

[14] “UTRA repeater planning guidelines and system analysis,” 3GPP Technical Specification, TS 25.956, Version 7.1.0, Release 7.

[15] J. Borkowski, J. Niemelä, T. Isotalo, P. Lähdekorpi, and J. Lempiäinen, “Utilization of an indoor DAS for repeater deployment in WCDMA,” in *Proceedings of the 63rd IEEE Vehicular Technology Conference (VTC ’06)*, vol. 3, pp. 1112–1116, Melbourne, Australia, May 2006.

[16] K. Hiltunen, “Using RF repeaters to improve WCDMA HSDPA coverage and capacity inside buildings,” in *Proceedings of the 17th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC ’06)*, pp. 1–5, Helsinki, Finland, September 2006.

[17] P. Lähdekorpi, T. Isotalo, A. Mazhar, and J. Lempiäinen, "Improving HSDPA indoor performance using outdoor repeater," in *Proceedings of the 11th International Symposium on Wireless Personal Multimedia Communications (WPMC '08)*, Lapland, Finland, September 2008.

[18] "High Speed Downlink Packet Access (HSDPA); Overall description; Stage 2," 3GPP Technical Specification, TS 25.308, Version 5.7.0, Release 5.

[19] "UE Radio Access capabilities definition," 3GPP Technical Specification, TS 25.306, Version 5.9.0, Release 5.

[20] Anite, "Anite Nemo Outdoor Product description," 2008, http://www.anite.com/nemo.

[21] Radio Frequency Systems, "Base station antenna specifications: "RFS APXV206515-7"".

[22] Powerwave technologies (Allgon), "WCDMA channel selective repeater: "AR6560"".