Indoor Planning for High Speed Downlink Packet Access in WCDMA Cellular Network

Tero Isotalo, Jukka Lempiäinen, and Jarno Niemelä

Abstract— **The aim of this paper is to show the special characteristics of the indoor environment related to radio propagation and furthermore to radio network planning. The aspects of the radio network planning are highlighted especially for Wideband Code Division Multiple Access (WCDMA) radio access technology that is used widely in the third generation mobile networks. Moreover, the detailed planning parameters in indoor environment are studied for High Speed Downlink Packet Access (HSDPA) in order to support high throughput data applications in Universal Mobile Telecommunications System (UMTS). The final target of the paper is to compare pico cell, distributed antenna system (DAS), and radiating cable network configurations in indoor environment to provide the optimal radio conditions for the data applications, and thus to serve highest number of mobile users.**

Several measurement campaigns with different antenna configurations have been conducted in order to study the effect of multi path related parameters, as delay spread of the signal. Also other capacity related parameters as received signal levels, interference, throughput, and transmit power levels have been studied in order to find out the optimal solution for HSDPA in UMTS. The results clearly show that pico cells and distributed antenna system have outstanding performance in indoor propagation channel compared to radiating cable. In sense of signal quality, pico cell performance is slightly better compared to distributed antenna system. However, measurements with HSDPA indicate that practical capacity of DAS outperforms pico cells. The measurements also show that -separation of the antennas is a key capacity related parameter when planning WCDMA based indoor systems.

Index Terms—**Indoor planning, WCDMA, HSDPA.**

I. Introduction to Indoor Planning

NEW requirements for data communications in mobile networks have accelerated the evolution of the mobile communication systems. This evolution includes first the change from the analogue communications (1st generation of mobile networks) to digital systems (2nd generation as European GSM, and US TDMA systems). Secondly, radio access technologies have been changed from frequency division multiple access (FDMA, 1st generation) through time division multiple access (TDMA, 2nd generation) to code division multiple access (CDMA, 3rd generation) in order to provide more flexibility to have different services for mobile users.

The most recent 3rd generation systems as European UMTS and US CDMA2000 both utilize CDMA radio access technology. The (W)CDMA radio access is based on the code separation between users while using the same frequency all over the radio network. Hence, the (W)CDMA based system is interference limited, and arises new planning aspects compared to more traditional FDMA or TDMA access technologies. [1-5]

In WCDMA based radio network, the transmit power in the uplink and downlink directions is used to get a communication link (coverage) between the system and mobile user. Simultaneously, the required transmit power to get the connection depends strongly on the interference level, and thus on the number of the users in the mobile network. Moreover, it can be concluded that the transmit power of the base station or mobile station in WCDMA system always represents network coverage, or system capacity in the downlink or uplink directions, respectively.

The transmit power and the relation between coverage and capacity have to be taken into account in different phases in the radio planning process of the WCDMA based networks [5]. The cellular planning begins from the definition of the power budget (called also link budget) for the downlink (forward) and uplink (reverse) directions. In this phase, the key task is to solve maximum allowable path loss (maximum attenuation between the base station and mobile station antennas) in the downlink and uplink directions. Simultaneously, the average required transmit power can also be solved in both directions. Moreover, the maximum transmit power from the base station and from the mobile station in practice should also be known, and the power requirements for the common control channels (pilot channels, synchronization channels, broadcast channels) have to be taken into account [3]. Power budget typically also includes some WCDMA specific positive and negative margins (gains and losses) as fast fading margin (loss), and macro diversity gain [6-8]. Finally, pilot coverage planning threshold can be defined after calculating power budget and deciding all required margins to be added to the final planning value.

Pilot coverage planning is the preliminary phase before the final coverage and capacity planning for the WCDMA network. The target of the pilot coverage planning is to find out suitable base station locations such that neighbor (called also adjacent) cells (sector in US) are overlapping enough to

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obtain continuous service. Pilot coverage planning is used because pilot signal is a reference signal for soft handovers needed in WCDMA based network. However, pilot coverage planning does not give the final solution for the network layout.

The final coverage and capacity planning is done together in WCDMA planning, and this planning phase can be called topology planning [5] because all planning actions are related to control interference between neighbor cells. The topology planning phase includes static Monte Carlo type of simulations or dynamic simulations where a certain amount of mobiles using a certain type of services are randomly spread over the coverage area defined mainly from the pilot coverage planning. The final results of the simulations contain service probabilities (probabilities for the coverage and capacity) as a function of load (total traffic) in the network. The maximum performance can be achieved when the optimal network layout and configuration are selected. Thus, the simulations are also providing the final network topology as a result.

Topology planning phase can also be based on measurements in order to study the influence of different antenna placements. In practice, indoor planning is typically done based on test measurements since measurement campaigns are pretty fast to conduct in limited indoor area compared to complicated settings of simulators.

The final network performance depends strongly on a few radio propagation channel related parameters as described in the downlink load equation:

$$\eta_{DL} = \sum_{i=1}^{I} \left[\frac{\rho_i R_i v_i}{W} \left((1-\alpha_i) + \sum_{n=1, n\neq m}^{N} \frac{L_{m,i}}{L_{n,i}} \right) \right] \tag{1}$$

where I is the number of mobiles in a cell, W is the system chip rate (3.84 Mcps in UMTS system), ρ_i is the E_b/N_0 requirement of ith user, R_i is the bit rate of the ith user, and v_i is the service activity of the ith user. Moreover, α_i is the orthogonality factor and $L_{m,i}$ and $L_{n,i}$ are the path losses from the serving cell m and from the neighbor cell n (inter-cell interference in the downlink direction) to the mobile i.

In the downlink direction, multi path propagation reduces the orthogonality of the spreading codes resulting in interference. Orthogonality is better when there is less difference between multi path components of the signal. Thus meaning also less delay spread between the signal components, and moreover lower utilization of RAKE receiver fingers. In planning environment, these requirements for higher orthogonality take place when the distance from the base station is shorter, or when the mobile is in indoor or microcellular propagation channel. [9]

The second key parameter related to the characteristics of the radio propagation is energy per bit over noise spectral density (E_b/N_0) which defines the required signal level compared to noise and interference level in order to get the sufficient bit error rate for the service. The required value of E_b/N_0 depends, for example, on the service type (data rate), on the speed of the mobile, and on the fading statistics of the signal (also utilization of the diversity reception). The main source for the variation of the E_b/N_0 is the fading of the signal, that is furthermore dependent on whether the propagation channel is the type of frequency-selective fading or flat fading. [3]

The third capacity related key parameter in (1) is inter-cell interference defining the “signal leakage” between neighbor cells. In optimal situation, the signal from the serving cell covers only the area where mobile users are using the connection from this particular cell. In practice, the signal continues propagation and causes interference in the neighbor cells. This interference can be reduced by avoiding too close base station locations, and too high antenna positions. Additionally, antennas can be dropped clearly below the rooftops (micro cells) in order to prevent propagation by buildings [5]. Separate indoor systems are, of course, pretty well separated from the outdoor networks due to indoor penetration losses through walls and windows. Moreover, especially interference in outdoor macro cellular networks can be reduced (but not avoided) by using proper antenna down tilting [10]. As a conclusion, the amount of inter-cell interference depends strongly on the base station and antenna configurations of the network, and it has to be optimized in topology planning phase.

In indoor environment, the characteristics of the WCDMA radio channel of UMTS system are special ones compared to outdoor environment. First of all, the UMTS radio channel is mostly flat fading due to small delay spread (<< 0.26 µs) [5]. 0.26 µs is the smallest delay between multi path components to enable separation of them. This leads to the fact that multi path diversity cannot be exploited in indoor environment, and antenna diversity should be implemented in order to use less transmit power, and thus to have higher capacity [11]. System is considered wideband if system bandwidth is clearly wider than coherence bandwidth of the channel. The coherence bandwidth of the channel can be defined from delay spread:

$$\Delta f_c = \frac{1}{2\pi \cdot \sigma} \tag{2}$$

where Δf_c is the coherence bandwidth of the channel, and σ is the delay spread of the channel [5].

Next, the signal in indoor propagation channel is more strongly time and space variant which means that signal variations occur even if the mobile is stationary [12]. In order to improve the average received signal level, the signal should be transmitted simultaneously from different antenna locations. Moreover, orthogonality can also be improved if more antennas are implemented (distance from the base station antenna to the mobile is always shorter). On the other hand, delay spread may be increased in some locations over two RAKE receiver fingers if the delay from different antennas is >> 0.26 µs (>> 78 m in distance), and this may again reduce orthogonality.

Indoor networks have typically been implemented by using separate cells (pico cells), distributed antennas systems (DAS), or radiating cables [13-14]. Pico base stations for pico cells are small in scale which causes pretty small transmit powers and coverage areas in the downlink direction. On the other hand, small base stations are easy to install, and each of them represents a capacity resource. Correspondingly, distributed antenna systems are mostly used with coaxial cables, or with optical fibers. The coverage area of each cell is flexible with DAS because each cell contains several antennas. Moreover, each antenna is providing a certain gain for the antenna line, and the cable loss is typically less compared to radiating cable. Finally, radiating cables offer smooth coverage (less standard deviation of the signal) everywhere where they are implemented if there is not too high attenuation due to cable itself [15]. Thus, the radiating cable could be a proper solution if the implementation area is not too wide.

Final requirements for the indoor planning are coming from the system technology as, for example, from UMTS based HSDPA system specifications [16]. The key characteristics of the systems are typically related to (soft) handovers, radio resource management (channel allocation), and to signal-to-interference ratio (SIR) requirements. For example in HSDPA, soft handovers are not available in the first system releases, and the channel allocation could follow round robin or proportional fair algorithms depending on the propagation environment. Moreover, certain SIR requirements are specified in order to achieve maximal bit rates in a certain radio propagation channel.

The aim of this paper is to provide a performance comparison between pico cell, DAS, and radiating cable configurations for indoor systems when targeting high throughput data services in WCDMA based networks. In measurement campaign, all relevant coverage and capacity related parameters have been measured with different antenna configurations in typical indoor corridor environments. Finally, different configurations are compared to each other as a function of signal levels, interference, delay spread, transmit powers, and HSDPA throughput.

II. Quality Indicators for Indoor Propagation Channel

A. Coverage, interference and delay spread

The received signal power reflects to the system characteristics and configurations – the denser the network is in terms of base station density, the better is the available network coverage. However, in WCDMA, large coverage overlapping between cells leads to high level of inter-cell interference, and thus to lower system capacity [15]. In case of a single, isolated indoor cell (i.e., a single antenna, DAS, or radiating cable), no inter-cell interference is present. During the network evolution and possible capacity limitations of a single indoor cell, more cells should be possibly added for the indoor network. In this scenario, inter-cell interference has to be taken into account when allocating the antennas between the cells, or when placing new antennas for the indoor network. Moreover, inter-cell interference has to be analyzed always when pico cells are implemented.

Throughout this paper, the coverage is mainly analyzed with the received signal code power (RSCP) of the primary common pilot channel (P-CPICH). It measures the absolute coverage level that can be achieved under different antenna configurations. Moreover, energy per chip over noise spectral density (E_c/N_0) on P-CPICH is used as a coverage quality indicator. E_c/N_0 is defined as a ratio of RSCP and received signal strength indicator (RSSI):

$$\frac{E_c}{N_o} = \frac{RSCP}{RSSI} \tag{3}$$

Interference level is indicated with signal-to-interference ratio (SIR) of the P-CPICH that can be defined as

$$SIR_{P-CPICH} = SF_{256} \frac{\frac{P_{P-CPICH}}{L}}{\frac{P_{TOT}}{L}(1-\alpha) + I_{inter} + p_n} \tag{4}$$

where SF_{256} is the processing gain for P-CPICH, $P_{P\text{-}CPICH}$ is the transmit power of P-CPICH, P_{TOT} is the total transmit power from of serving base station, I_{inter} is the received inter-cell interference power, p_n is the received noise power, and L is the path loss from serving base station.

The instantaneous root mean square (RMS) delay spread σ_{RMS} is evaluated in this paper from scanner measurement according to following definition:

$$\sigma_{RMS} = \sqrt{\tau^2 - \bar{\tau}^2} \tag{5}$$

where

$$\tau^2 = \frac{\sum_k a_k^2 \tau_k^2}{a_k^2} \tag{6}$$

is the mean excess delay and

$$\bar{\tau}^2 = \frac{\sum_k a_k^2 \tau_k}{a_k^2} \tag{7}$$

is the mean delay with a_k as the amplitude of k th multipath component and its' a relative delay of τ_k .

B. Signal level variations and diversity

The standard deviation of the signal level (i.e., slow fading) affects the required planning margin. Moreover, especially in indoor environment, where the signal level variations are typically stronger than in outdoor environment, the stability of the signal is important. An indication for this argument was obtained in [17], where a larger soft handover (SHO) window was observed to provide better system capacity. As a result of strong signal level variations from a single cell, partly uncorrelated fading between two cells (involved in SHO) improved the signal level considerably. Hence, due to the lack of multi path diversity in indoor environment, the SHO diversity became extremely important. In pico cell measurements of this paper, the optimal SHO parameter values *add_window* = 6 dB, *drop_window* = 9 dB, and *time-to-trigger* = 160 ms (add), 1280 ms (drop) [17] are used in order to improve signal levels (to reduce deviation of the signal), and to reduce interference.

Absolute coverage can be improved by using multiple antennas in one cell or by having several cells because gain against slow fading can be provided by soft handovers. However, by using a passive signal distribution, the effective isotropic radiated power (EIRP) per antenna is decreased when more antennas are added to the antenna system. On the contrary, an active distribution system based on a fiber optical transmission is able to deliver the same EIRP per antenna independent of the number of antennas. Because DAS (passive or active) does not provide any micro diversity, it does not improve the received E_b/N_0. However, longer distances between antennas in a DAS might increase the delay spread observed by the mobile, and therefore reduce the code orthogonality. In the most interesting case, delay spread is more than chip duration thus causing even higher reduction of orthogonality but simultaneously providing again multi path diversity.

C. HSDPA Capacity

HSDPA throughput varies depending on the channel quality. Base station has an estimate of downlink channel quality based channel quality indicator (CQI) measurements that mobile constitutes based on several indicators, such as RSCP and (E_c/N_0). Scale of CQI measurements is from 1 to 30, where higher value means better channel quality. Based on CQI value, base station decides suitable coding and modulation scheme (MCS) for the DL transmission. In case of 5 code 1.8 Mbps HSDPA transmission used in the measurements, only QPSK (quadrature phase shift keying) modulation is being used, thus MCS is not changing. [18] MAC (medium access layer) throughput gives a good indication of physical layer throughput with about 5 % overhead.

III. Measurement Setup

A. Measurement environment

All measurements were carried out in a typical office building in Tampere, Finland (new building of Department of Information Technology, Tampere University of Technology). The main corridor (the maximum length of 100 m, and width of 10 m) was selected as a measurement route for *wide corridor* measurements, and a narrower office corridor environment for *dense corridor* measurements. Also all base station antennas were placed in the wide corridor and office corridor.

Measurements were conducted during the day time thus having effects of dynamic environment (several persons walking through the corridor, and opening doors) on the radio propagation. Measurements were repeated with the same configuration several times in order to obtain statistical reliability.

B. Measurement system

Measurements were performed in UMTS test system including two base stations and RNC/MSC (radio network controller / mobile switching centre) simulator. RNC simulator included handover and power control functions as well as resource management functions. Other radio resource management (RRM) related functions as admission control, load control, and packet scheduler were not considered. Both RNC and base stations were based on UMTS specifications.

The measurement equipment consisted of a radio interface measurement tool, which was connected to a mobile and scanner. A test mobile was calibrated only for commercial use, and thus a continuous error exists in all absolute values of the RSCP and E_c/N_0 measurements. However, these absolute values are not highlighted but the results are compared to each other. In delay spread measurements, the resolution of half chip (0.26 µs / 2 = 0.13 µs) was sufficient because only information about the possible multi path diversity was required.

The downlink measurement equipment (scanner or mobile) were at the height of 1m without body effect (on a measurement tray), and the receiving antenna (linear polarization) was on the horizontal direction.

RSCP and E_c/N_0 measurements were done in wide corridor environment, under the same measurement route as shown in Fig. 1, by having mobile-to-mobile calls, and a mobile in idle mode in office corridor. SIR, and delay spread were measured by using a scanner. Fig. 2 shows the values of P-CPICH downlink transmit power, and the losses of the antenna line, as well as the gain of the antenna for the power budget comparison. The target was to use equal transmit power for the

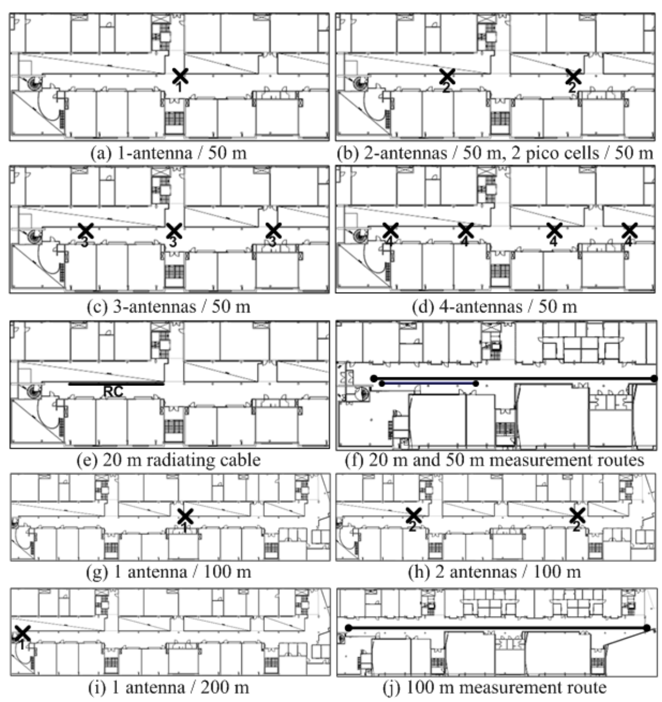

Fig. 1. Measurement routes and antenna placements for wide corridor measurements.

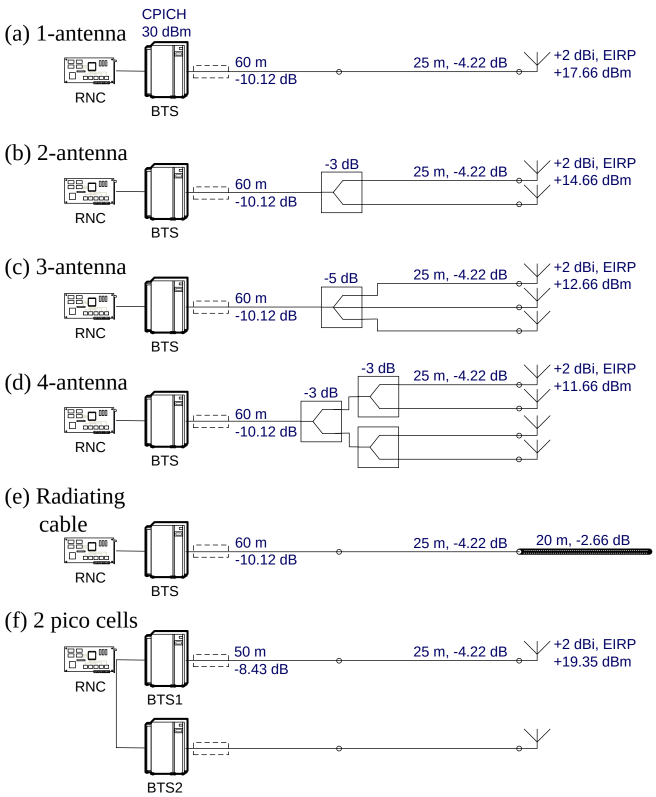

Fig. 2. Antenna lines for the different configurations.

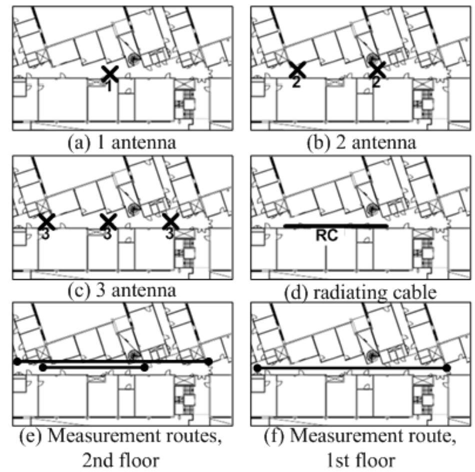

Fig. 3. Measurement routes and antenna placements for dense corridor measurements

different configurations, and to see the effect of losses of the antenna line in the received signal levels when the number of the antennas was changed.

For the HSDPA measurements, a fully functional RNC, and a category 12 HSDPA terminal [19] (maximum physical layer throughput 1.8 Mbps) were used. Measuring mobile requested full downlink HSDPA throughput and no other users were connected. HSDPA throughput was carried out by HTTP download from a server.

C. Measurements

1) Measurements in wide corridor environment

DAS, pico cell, and radiating cable configurations were measured in wide office environment. Pico cell and DAS configurations were measured over the same measurement route, and a shorter route was used for radiating cable. Fig. 1 shows the measurement routes and antenna placements in all these three different scenarios in wide corridor environment. In pico cell measurements, antenna configurations of (b) and (h) (Fig. 1) were used representing the density of two cells per 50 and 100 meters, respectively. In DAS measurements, antenna configurations (a) – (d) were mainly used to represent the separation of two antennas from 12.5 m to 50 m. DAS measurements were performed also with (g) – (i) configurations in order to see the results of longer separation of antennas. Correspondingly, the length of the radiating cable was 20 meters over the measurement route.

All measurements were repeated several times, and the measured values were averaged over the measurement route. Also local average (average over 10 m) was used in order to see the local variations.

2) Measurements in dense corridor environment

DAS and radiating cable configurations were measured also in denser office environment. Measurements were conducted on two floors; on the same floor with the antennas with almost continuous line of sight (LOS) connection, and one floor below, in order to see the impact of pure non-line of sight (NLOS) environment. Antenna placements for are shown in Fig. 3. (a) – (d). Measurements were performed under the antennas (e), and with one floor attenuation (f).

3) HSDPA measurements in wide corridor environment

Measurements for HSDPA were performed in selected scenarios (a) – (d), (g) (Fig. 1) in wide corridor environment to measure the practical HSDPA performance in indoor DAS and pico cell configurations. The antenna line configuration (Fig. 2) was slightly modified; In order to emphasize the differences between antenna configurations in sense of HSDPA throughput, an attenuation of 30 dB was added to the antenna line (Fig. 2, dashed line).

IV. Measurement Results

A. Measurements in wide corridor environment

All averaged results for wide corridor measurements are gathered in Table I (extended from [20]). The obtained results show that RSCP is at the highest level in pico cell configuration. This is caused partly by better power budget (no power splitters in the antenna line compared to DAS). Moreover, the improvement of the RSCP level in DAS is saturated when antenna density is increased enough. Table I shows that DAS of 12.5 m antenna separation offers the highest RSCP but the result is only 0.76 dB better compared to the configuration of 25 m antenna separation. Also standard deviation of the signal in DAS is saturated at the level of 5.24 - 5.67 dB. Correspondingly, signal deviation is higher in pico cell configuration even if optimal SHO parameters (wide SHO areas) were used.

When levels of RSCP and deviation of RSCP of pico cell

TABLE I
MEASUREMENT RESULTS FOR WIDE CORRIDOR

	RSCP [dBm]	RSCP std [dB]	E_c/N_0 [dB]	SIR [dB]	DS [µs]	UL TX pwr [dBm]	DL Tx Power [dBm]
2 Pico cells / 50 m	-54.97	6.81	-4.40	21.68	0.32	-35.57	23.04
2 Pico cells / 100 m	-56.75	7.04	-4.71	21.16	0.33	-29.51	25.66
DAS 4 antennas / 50 m	-56.74	5.67	-4.11	22.28	0.33	-32.08	21.43
DAS 3 antennas / 50 m	-57.43	5.94	-4.14	21.63	0.33	-32.78	21.71
DAS 2 antennas / 50 m	-57.50	5.24	-4.03	21.93	0.30	-32.49	21.74
DAS 1 antenna / 50 m	-60.04	5.93	-4.07	21.84	0.33	-31.20	22.11
DAS 1 antenna / 100 m	-64.10	9.21	-4.15	21.92	0.35	-27.06	22.25
DAS 1 antenna / 200 m	-68.83	11.81	-3.96	21.93	0.38	-21.01	22.87
DAS 2 antennas > 78 m	-65.71	9.28	-4.18	22.50	0.33	-24.59	22.03
Radiating cable	-73.50	3.66	-4.10	22.01	0.39	-17.24	21.90

configurations are compared to the results of DAS and radiating cable configurations, it can be noted that pico cells are offering superior RSCP in both measurements. The standard deviation of the signal is the lowest with radiating cable but the antenna line losses are much higher compared to the gain obtained from the STD of the received signal.

Thus, pico cells and distributed antenna system are clearly superior configurations in indoor propagation channel compared to radiating cable, and pico cells are slightly better compared to DAS as a function of losses and gains related to RSCP.

In Fig. 4, it is shown the local variations of RSCP in measurement configurations (a) – (b), and with radiating cable (e) (Fig. 1). It can clearly be noted that radiating cable provides the lowest variation of the RSCP, and the variation can be reduced in case of pico cells and DAS when density of antennas is increased.

Table I shows also the behavior of the E_c/N_0 and signal-to-interference-ratio (SIR). The lowest E_c/N_0 values can be reached in DAS and radiating cable configurations as expected due to lack of inter-cell interference from the neighbor cells. In case of pico cells, the interference level is already slightly increased even if there is no other traffic in indoor cells (low load of the network). Also SIR values are lower in case of pico cells. Moreover, it has to be noted again that pico cell measurement results are based on the optimal soft handover parameter settings, and thus interference should be minimized.

In Fig. 5, the local variations of SIR are presented in measurement configurations (a) – (b), and with radiating cable. Again, it can be seen the minimum variation in case of radiating cable, or with two antennas / 50 m.

Delay spread results in Table I are all close to 0.26 µs as expected. In case of DAS of 2 antennas / 100 m antenna configuration, delay spread is also close to 0.26 µs even if the delay should be > 78 m, and multi path components should be received by two RAKE fingers. In this case, some multi path

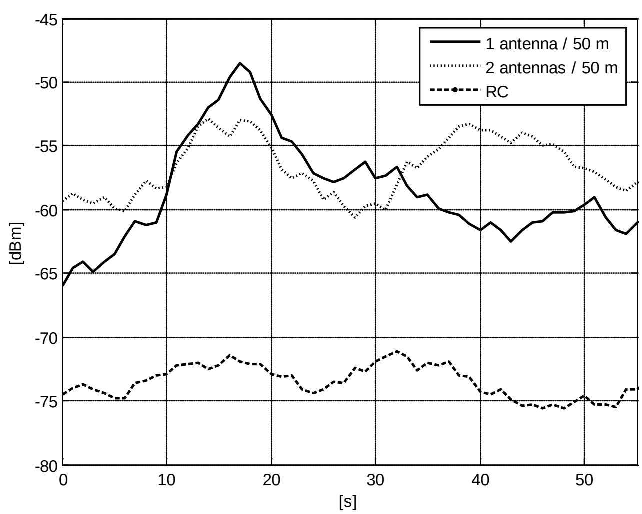

Fig.4 RSCP in different scenarios with 8 s (10 m at 3 km/h) averaging window (sample rate 0.33 s).

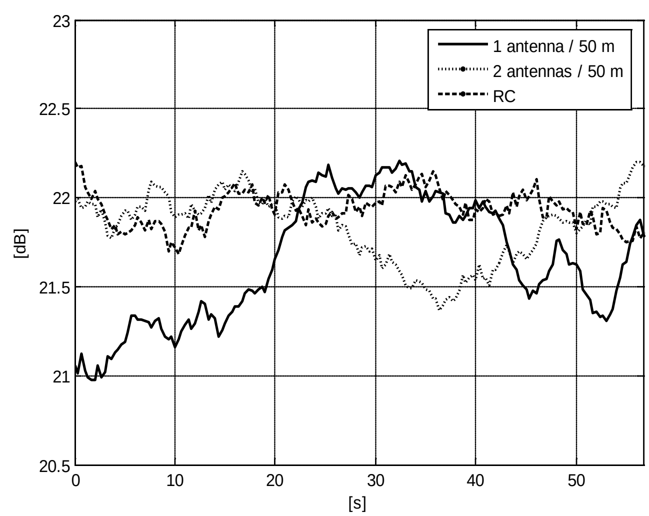

Fig.5 SIR in different scenarios with 8 s (10 m at 3 km/h) averaging window (sample rate 0.33 s).

diversity should also be seen in RSCP levels in Table I. Moreover, even if other delay spread results are also slightly over 0.26 µs, it has been seen in delay profile that majority of the signal power is received during one chip duration, and multi path diversity does not really exist at values close to 0.26 µs. Thus, all configurations are equal except DAS with >78 m antenna separation (Fig. 1 (h)).

Finally, uplink and downlink transmit powers are presented in Table I to show the power range during the measurements, and thus finally to compare the capacities of the different configurations. Downlink transmit powers can be compared with SIR values, and with RSCP values in order to get the total comparison related to the need of transmit power for different configurations. Table I shows that pico cell configurations provide superior RSCP but with slightly higher transmit downlink power compared to DAS configurations. The additional communication links in soft handovers are the reason for higher transmit powers in pico cells. However, the final performance of pico cells is slightly better than DAS configuration.

B. Measurements in dense corridor environment

All averaged results for dense corridor measurements are gathered in Table II. RSCP values below the antennas (2nd floor) are at rather high level due to almost continuous LOS connection. Signal coverage is improved by 3.7 dB from 1 to 3 antennas. Although distance between radiating cable and mobile antenna is below 2m, the average signal level from radiating cable is more than 20 dB lower compared to 1 antenna case. RSCP std is decreased from 1 antenna to 3 antenna configuration by 1.64 dB, and radiating cable provides clearly the smoothest coverage. SIR and E_c/N_0 are slightly varying but expectedly no major differences are visible. Also delay spread measurements are in line with the wide corridor measurements, except the deviant value with 3 antenna configuration.

RSCP values measured one floor below (1st floor) the antennas show similar behavior as measurements right below the antennas. However, the differences between DAS configurations are smaller (1.87 dB improvement from 1 to 3 antennas), i.e. the 1 antenna configuration seems to suffer the least from the longer propagation path and missing LOS component. Average RSCP with radiating cable is at the level of -90.98 dBm, which indicates incipient coverage problems that are also visible in increased E_c/N_0. RSCP std is again decreasing as a function of number of antennas. Furthermore, variation between RSCP std results is increased thus differences between antenna configurations are better visible. RSCP std of 4.39 dB at 3 antenna configuration is even better than the one measured below the antennas. Difference between 1 and 3 antenna configuration is 3.72 dB. It can be also observed that radiating cable is not anymore providing the smallest RSCP std (smoothest signal). SIR measurements are in line with the observations made below the antennas, except a little diverging value from radiating cable.

TABLE II
MEASUREMENT RESULTS FOR DENSE CORRIDOR [21].

	RSCP [dBm]	RSCP std [dB]	E_c/N_0 [dB]	SIR [dB]	DS [µs]
Dense corridor, 2nd floor (below the antennas)					
DAS 3 antennas / 50 m	-41.74	5.34	-4.05	21.40	0.38
DAS 2 antennas / 50 m	-44.05	6.18	-4.10	21.26	0.29
DAS 1 antenna / 50 m	-45.44	6.98	-4.12	22.27	0.31
Radiating cable	-67.59	3.97	-4.01	22.14	0.34
Dense corridor, 1st floor (1 floor attenuation)					
DAS 3 antennas / 50 m	-67.27	4.39	-4.14	22.79	0.31
DAS 2 antennas / 50 m	-68.49	5.00	-4.12	21.79	0.30
DAS 1 antenna / 50 m	-69.14	8.11	-4.21	21.74	0.32
Radiating cable	-90.98	7.47	-4.49	20.83	0.38

C. HSDPA measurements in wide corridor environment

Averaged measurement results for HSDPA measurements are gathered in Table III. Transmit power values are not shown because constant downlink transmit power is used in HSDPA connection. RSCP improvement from 1 to 4 antennas is 3.36 dB, and pico cells provide 2.98 dB better coverage compared to 2 antenna DAS configuration. RSCP std values are little higher compared to UMTS measurements, but remaining inside 1 dB in all antenna configurations in 50 m measurement route. P-CPICH E_c/N_0 values are higher because of added interference level caused by the HSDPA transmission, and also reduced coverage due to 30 dB attenuated antenna line.

HSDPA throughput is increased by about 100 kbps when increasing the number of antennas from 1 to 4. The impact of RSCP (coverage) on throughput is visible in the results. Although the antenna line was attenuated and average RSCP values rather low, the throughput is remaining close to maximum at major part of the measurement route, and only cell edge areas constitute the differences between measurements. Impact of reduced coverage on throughput is clearly visible in 1 antenna / 100 m configuration. 10.15 dB drop at RSCP from 1 antenna / 50 m configuration causes about 500 kbps drop in throughput. Indicated CQI values are in line with the throughput measurements. 2 pico cell configuration is providing 2.98 dB better signal coverage, compared to 2 antenna configuration, which is also indicated by slightly better CQI values. Regardless of better RSCP in pico cell configuration, the throughput values are about 100 kbps worse compared to 2 antenna DAS. This is mainly caused

TABLE III
HSDPA MEASUREMENT RESULTS FOR WIDE CORRIDOR [22].

	RSCP [dBm]	RSCP std [dB]	E_c/N_0 [dB]	Throu-ghput [kbps]	CQI
2 Pico cells / 50 m	-79.43	7.99	-7.99	1303	16.02
DAS 4 antenna / 50 m	-82.68	6.55	-7.96	1502	16.37
DAS 3 antennas / 50 m	-84.19	7.42	-8.22	1469	15.81
DAS 2 antennas / 50 m	-82.41	7.75	-7.92	1397	15.89
DAS 1 antennas / 50 m	-86.04	7.62	-7.46	1403	15.70
DAS 1 antenna / 100 m	-92.38	10.73	-8.48	1000	13.05

by unoptimized handover procedure, which is causing long break in data transmission. Therefore, pico cell performance could be improved with optimized handover management. Increased inter-cell interference might also affect channel quality, if the load of neighboring would be higher. In an empty network differences are small as seen in almost equal E_c/N_0 values.

V. Conclusions

In this paper, different indoor radio network configurations, of distributed antenna system, pico cells, and radiating cable, were compared for high data throughput applications in varying indoor environments. The target was to measure signal and interference levels, and thus to find out the optimal configuration for indoor planning when, for example, HSDPA technology in UMTS mobile networks will be implemented. In addition, also practical HSDPA throughput values were measured.

The obtained results show that pico cells and DAS provided always the lowest interference level, and the highest signal level, thus saving the transmit power and simultaneously offering higher capacity from the network. Radiating cable offers a good solution against fast and slow fading but the losses of the cable are much higher thus leading to the reduced received signal levels, indicated as incipient coverage problems in office corridor with 1 floor attenuation, i.e. the practical coverage of radiation cable is rather short. However, measurements were made without any traffic load in neighboring cells, and thus inter-cell interference will be increased in case of pico cells.

In pico cell and DAS configurations, the antenna placement and antenna density are critical for obtaining the maximum capacity from the system. In this study, only the corridor environments were used, and thus antenna placement is not having too much freedom compared to more open type of indoor environments. Moreover, the higher antenna density of the DAS did not increase the capacity of the network linearly.

Delay spread remained almost constant in all configurations from 2 antennas / 12.5 m to the configuration of 2 antennas / 100 m, even if multi path difference was > 78 m, and two fingers can be utilized in RAKE receiver. In this particular case, the capacity of the indoor DAS should be slightly increased due to better multi path diversity. However, the measured delayed multi path components were at that low level that in practice impact is minimal.

HSDPA measurement in poorer signal conditions show that increased number of antennas has positive impact on HSDPA throughput, as expected based on signal the quality measurements. Also the sensitivity of HSDPA throughput on channel quality is visible. In decent channel conditions cell capacity remains good, but decreased coverage causes significant drop in throughput. Finally, comparison between DAS and pico cell show that practical capacity of distributed antenna system outperforms pico cells, and emphasizes the importance of handover optimization also in HSDPA planning.

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