COMPARISON OF WCDMA UPLINK ANTENNA SOLUTIONS WITH 4 RECEIVER BRANCHES

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ABSTRACT

In this paper the increase of the number of antennas at a base station (BS) receiver is studied as an approach to improve the coverage and capacity in a wideband code-division multiple access (WCDMA) uplink. The effects of the different propagation environments and the BS antenna solutions on the WCDMA base station performance are investigated in macro cellular environment. The number of receiving antenna elements per sector is limited to four.

The studied macro cellular antenna configurations include beamforming, antenna diversity with maximum ratio combining (MRC) and a combination of those two. Based on the results from the link level simulations, the capacity and the coverage of each antenna concepts are compared to a conventional 3-sector BS with two receiving antennas per sector.

The results indicate that no solution is optimal in every sense. However, the 4-branch diversity receiver (4MRC) is somewhat better than the other two methods in terms of overall performance and capacity, especially with high data rates and low mobile speed. From the cell range point of view the 4MRC concept is shown to be particularly better than the other concepts.

1. INTRODUCTION

In the early phase of cellular network deployment, as the operators are building coverage by macro cells, the overall cost of the network should be minimised. Therefore, coverage should be as high as possible. The importance of capacity will increase after the initial deployment when the amount of traffic increases.

Even though the wide bandwidth of WCDMA gives an inherent gain by reducing the fading of the radio signal, the multipath fading and the interference are still major factors in the deterioration of communication quality in mobile communications. Numerous BS solutions have been suggested to overcome these problems. Among the most important methods are the antenna array structures that have been proved to combat multipath fading of the desired signal and to suppress interfering signals, thereby increasing both the coverage and capacity of wireless systems [3]. Uplink antenna arrays, that are considered in this paper, directly affect the receiver sensitivity by improving the energy per bit per noise power density (E_b/N_0) performance. The lower the E_b/N_0 requirement, the less power is needed for the same performance and the larger cell radius can be obtained.

There are several issues that have to be taken into account when selecting the particular antenna configuration, mainly radio channel characteristics (angular spread, delay spread, Doppler spread, multiple access interference, etc.) but also implementation aspects such as the quality of channel estimation and implementation complexity [2]. Since increasing the number of receiving antennas at the BS certainly allows better performance, the basic choice is whether to maximise the number of diversity branches in an array or to maximise the antenna gain in order to achieve the maximal performance.

2. SYSTEM MODEL AND ANTENNA CONCEPTS

Typically macro cell environment is characterised with narrow angular spread and well defined direction-of-arrival (DOA). Also a relatively large number of interfering sources can be assumed to be spread all over the cell, hence interference can be assumed relatively non-coloured. Generally, with small angular spread both an L-element adaptive array and a fixed beam array provide L-fold antenna gain [3]. An adaptive antenna employing optimum combining or beam steering can optimise the beams according to the angular directions, but with fixed beam concept a mobile being between predefined beam patterns does not achieve the maximum array gain due to cusping loss (3 dB). Although, some diversity gain is achieved due to the orthogonality of the beams. The orthogonality is only partial, thereby the signals received from adjacent beams can be somewhat correlated [3].

Diversity combining is different from antenna array processing and beamforming. It increases the signal level without affecting the individual antenna pattern, contrary to beamforming techniques that modify the antenna pattern of the whole array. However, diversity MRC and antenna gain by beamforming can give both the same optimal result, if certain parameters can be estimated, such that DOA for beamforming and channel estimate coefficients of the radio link for MRC [2]. Nevertheless, the more diversity antennas are used the more channel coefficients have to be solved, but still only one parameter of direction in the beamforming case.

In the simulations basically the performance of the diversity gain and the antenna gain with a 4-antenna receiver array are compared. The conventional 3-sector BS is the reference case. The trade-off between the three options is illustrated in Table 1 and the different 4-antenna configurations are shown graphically in Figure 1.

Table 1. Diversity vs. antenna gain trade-off

	4-branch diversity	***2-branch diversity***	***No diversity***
Relative antenna gain with beams	0 dB	3 dB	6 dB
Number of diversity branches in 1-tap channel	4	2	1

Each antenna configuration option studied covers the same 120° angular section. In the case of 4-branch diversity (4MRC in Figure 1a) all widely spaced (or orthogonally polarised) antennas cover the whole sector. In the 2-branch diversity case there are two orthogonal 2-antenna fixed beam arrays, each with 2MRC (2+2 beams in Figure 1b). This concept can be regarded equal with further sectorisation, but in a real 6-sector BS case the 120° sector is halved and two diversity antennas with 3 dB extra directivity are placed separately in each sector. Also in that case the effect of softer handovers and other network functions should be considered. The third fixed beam concept (no diversity) is illustrated in Figure 1c and it consists of 4-antenna array dividing the sector to four fixed beams.

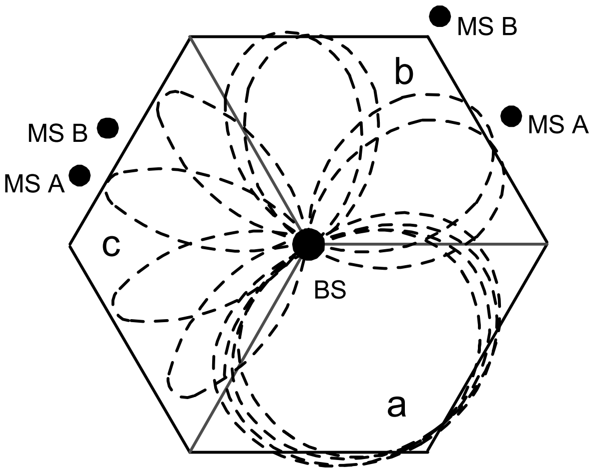


Figure 1. Uplink antenna configurations.

3. Simulation Modelling

The performance of different 4-antenna receiver concepts has been studied by means of Monte-Carlo simulations. The main outputs of the simulations are the required received (Rx) E_b/N_0 per antenna and the required transmission power (Tx E_b/N_0) to achieve the given frame error rate (FER) target. The power rise is defined as the difference between average transmission and reception powers when the average attenuation of the channel equals one [2].

In addition to typical macro cellular assumptions (narrow angular spread and well defined DOA) also the coverage limited situation is assumed in the simulations. This includes the assumption that the users are spread all over the cell range and multi-access interference (MAI) is modelled as AWGN. Accordingly, the loading is presumed to be at low level. Typical values for the load factor in the coverage limited case range from 20% to 50% system loading [2]. In this paper, a static 50% system load factor (3 dB noise rise) is assumed in the capacity calculations for all cases.

The distance between antenna elements and the radio environment, mostly the angular spread define the correlation between antenna elements. Thus, the spatial properties of the radio channel can be characterised by exploiting 1D channel models and introducing correlation and power distribution between them [4]. ITU Vehicular A and Pedestrian A channel profiles used in the simulations are presented in Table 2. ITU Pedestrian A channel model is used in these simulations to study the effect of low multipath diversity case.

Table 2. ITU Vehicular A and Pedestrian A channel models, taps in chip resolution

	Pedestrian A	***Vehicular A***
Tap 1	0.2 dB	0.0 dB
Tap 2	-12.3 dB	-2.4 dB
Tap 3	-	-6.5 dB
Tap 4	-	-9.4 dB
Tap 5	-	-12.7 dB

The 4MRC concept (Figure 1a) is modelled as a four branch Rake receiver with input from four uncorrelated channels. The desired signal is assumed to always be received from the centre of the 120° sector. There are two situations with 2+2 beams and 4 beams approaches, that are shown in Figure 1b and in Figure 1c, respectively. One is MS A being at the centre of a beam and the other MS B being between beams. If MS is placed between beams, a 3 dB cusping loss is assumed. Then, also the correlation (*C*) between beams is varied between 0.0 and 1.0. According to [4] the factor 0.7 is proper average value for the correlation between beams for 4-antenna array in macro cellular environment.

The parameters for the uplink speech and packet data simulations are shown in Table 3.

Table 3. Simulation parameters

Interference modeling	AWGN
Interleaving depth	10 ms, 1 radio frame
Coding	1/3-rate conv. coding, K=9
Power control delay	Inner loop: 1 time slot Outer loop: 1 radio frame
Power control step	Inner loop: 1 dB Outer loop: 0.5 dB
Mobile speeds	3 km/h and 50 km/h
Number of Rake fingers per antenna	2 for Pedestrian A 5 for Vehicular A
Data rate	8 kbps, 144 kbps (Veh. A), 384 kbps (Ped. A)
FER target	1 % (speech), 20% (data)
Power diff. between DPCCH and DPDCH	-3 dB for 8 kbps, -6 dB for 144 kbps, -9 dB for 384 kbps

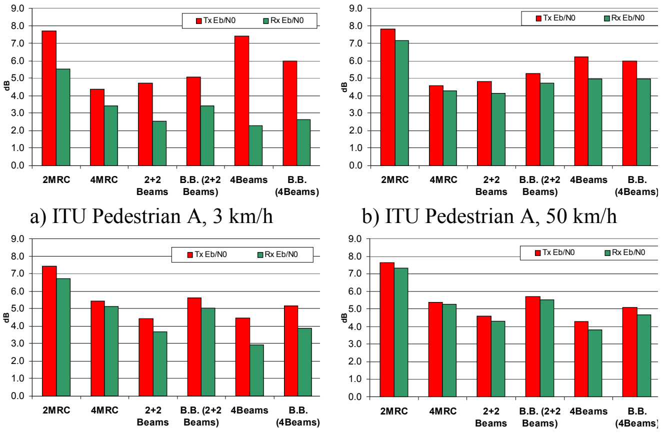
In uplink the smoother type of fixed estimator is used for all simulations cases, i.e., the channel estimates of the previous, current and the next slot are weighted by 0.4, 1.0 and 0.4 respectively.

4. Link Level Simulation Results

4.1. Effect of Multipath and Correlation Between Beams

In Figure 2 the effect of the radio channel is illustrated for 8 kbps speech service. The average E_b/N_0 performance in decibels with PC (both Tx and Rx E_b/N_0 per antenna) are shown for all the studied antenna concepts.

Due to the lack of multipath diversity in Pedestrian A channel, it is obvious that enhanced antenna diversity reduces the transmitted power fluctuation, and thus reduces the average transmitted power. Therefore, the transmitted powers with 4MRC are the lowest.



a) ITU Pedestrian A, 3 km/h b) ITU Pedestrian A, 50 km/h

c) ITU Vehicular A, 3 km/h d) ITU Vehicular A, 50 km/h

Figure 2. Single link E_b/N_0 *performance results with PC for 8 kbps speech service (B.B. between beams, C=0.7).*

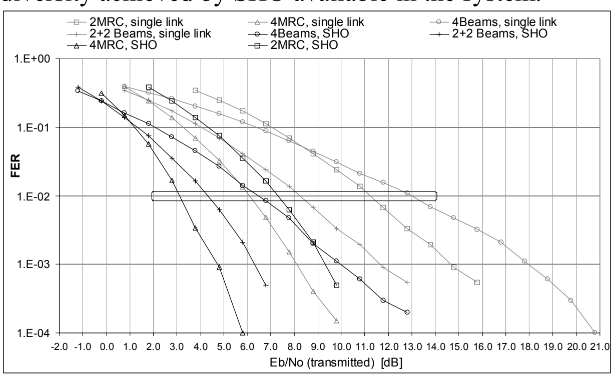
Plenty of path diversity is already available from Vehicular A channel, thus the antenna concepts providing increased antenna directivity gain (2+2 beams and 4 beams) give a better performance improvement (lower E_b/N_0) than 4MRC. Also for the same reason, non-correlation between beams does not compensate the cusping loss as efficiently as in case of Pedestrian A channel.

With ideal channel estimation and with ideal PC the received powers should be the same in all cases. Due to non-ideal channel estimation (lower SNR per finger and more parameters to estimate) the antenna gain by 4MRC is less effective than the antenna directivity gain with the other two concepts. However, the improved channel estimation (adaptive, longer averaging, more DPCCH power) could reduce the relative Rx E_b/N_0 difference between concepts.

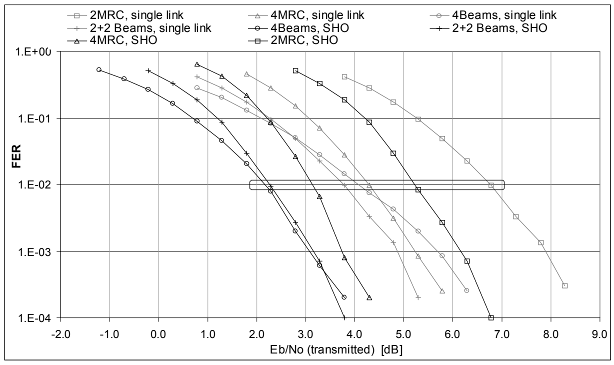
4.2. Effect of Soft Handover

For SHO performance comparison between antenna concepts, simulation results are plotted for 8 kbps speech service in SHO (without PC) with different degrees of channel diversity in Figure 3.

In Figure 3a there is very little both time and path diversity available in the channel. Hence, the 4MRC concept still gives better performance than more antenna gain providing concepts even if there is the extra macro diversity achieved by SHO available in the system.



a) ITU Pedestrian A, MS speed of 3 km/h.



b) ITU Vehicular A, MS speed of 50 km/h.

Figure 3. SHO E_b/N_0 *performance results without PC for 8 kbps speech service with BS power imbalance 0 dB.*

The situation is rather different in Figure 3b. In this case the most diversity (time, multipath) is achieved from the radio channel, thus the gain from increased macro diversity saturates due to less accurate channel estimation. Therefore, the SHO gain is larger for fixed beam concepts than for 4MRC. With a BS imbalance larger than 0 dB the relative differences are obviously smaller and correspondingly less SHO gain is achieved. Log-normal shadowing is not considered in the SHO simulations.

From Figure 3 it is also seen that the required E_b/N_0 values are much higher for low mobile speed. Hence, the low speed is the limiting factor for range because of the higher required power control head room (fast fading margin) [2].

5. System Performance Results

The simulations with power control model the cases where MS transmission power is in its dynamic PC range. In these cases it is difficult to determine the order of superiority between different antenna configurations just based on either Tx or Rx E_b/N_0. Rx E_b/N_0 defines the amount of intra-cell interference that the other users experience from the given MS, thus it defines the maximum number of users that can be supported by one BS. On the other hand, the transmission power of MS (Tx E_b/N_0) defines the interference caused to adjacent cells, i.e., inter-cell interference. Hence, both numbers must be considered in order to find out the multicell capacity.

The coverage in macro cells is determined by the uplink range because the transmission power of MS is much lower than transmission power of BS [2]. Maximum range is obtained when the MS is transmitting with constant full power, whereupon the fast PC cannot compensate for fast fading. The simulations without PC model the cases when the MS transmission power is kept constant (MS at cell edge and transmitting with full power).

5.1. Coverage Increase

In Figure 4 the relative coverage gains (compared with 2MRC) of the different antenna concepts are illustrated. It can be noticed that the configurations providing more antenna gain lead to little better performance gain than enhanced antenna diversity, when the significant path diversity (Vehicular A) exists and velocity of mobile is rather high (50 km/h). The difference is less than 1 dB, though. At low MS speed the 4MRC concept clearly outperforms the other 2 antenna concepts. For example, in Pedestrian A channel with the 4MRC concept there is a 7 dB higher path loss margin in use to extend coverage than with the fixed beam concept.

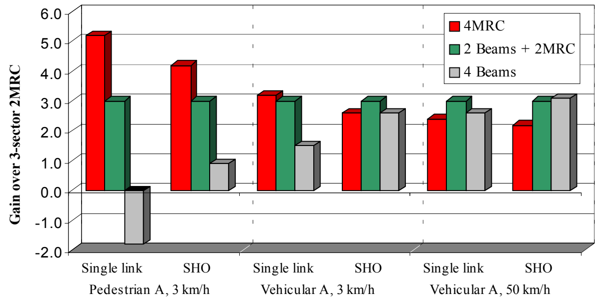


Figure 4. Performance gains in decibels of different antenna configurations compared to corresponding 2MRC values (speech, without PC, FER 1%).

Basically the same simulations as for speech service were carried out for packet data services, respectively. The main intention is to study how the increased FER operation point and increased DPCCH pilot energy affect the E_b/N_0 performance and the relative differences between antenna concepts.

In Figure 5 there is basically the same behaviour as with speech cases (Figure 4), but the relatively higher DPCCH power favours the antenna solutions where SNR per finger is low. That is why 4MRC provides better or equal coverage gain in almost all circumstances compared to the other two approaches. However, for packet data services the relative differences between antenna concepts are much smaller than for speech service due to the higher FER operation point (1% vs. 20% FER).

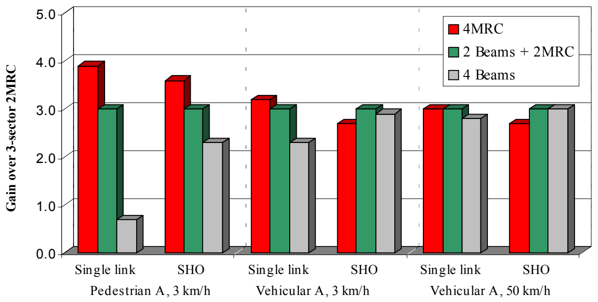


Figure 5. Performance gains in decibels of different antenna configurations compared to the corresponding 2MRC values (packet data, without PC, FER 20%).

5.2. Capacity Increase

Based on [1, 2, 5] the maximum number of simultaneous users M for a particular noise rise NR where the uplink is targeted to operate on one WCDMA carrier can be calculated as

$$M = G_{\mathrm{p}} \cdot \frac{F_{fading}}{v} \cdot 10^{-\frac{E_b/N_{0\,\mathrm{dB}}}{10}} \cdot \left(1 - 10^{-NR_{\mathrm{dB}}/10}\right) + 1 \qquad (1)$$

where G_{p} denotes the processing gain, v is the DTX activity factor, and $F_{\mathrm{fading}}=1/(1+\Delta P(1/F_{\mathrm{non\text{-}fading}}-1))$ is the frequency reuse factor, i.e., ratio between uplink intra-cell interference and the total interference in a fading situation (ΔP is power rise). A typical assumption for the frequency reuse factor F (non-fading) in macrocells is 0.7 [5], thus it has been used in all calculations.

For packet data service the capacity is more convenient to define in terms of physical layer level data throughput rather than the number of users. The throughput can be obtained with the WCDMA uplink load equation and defined as the 'average' number of packet users multiplied by a particular bit rate R. Also the retransmissions due to erroneous frames have to be taken into account. Thus, the uplink capacity equations for packet data can be defined as

$$Throughput = R \cdot (1 - FER) \cdot \left(G_{\mathrm{p}} \cdot F_{fading} \cdot 10^{-\frac{E_b/N_{0\,\mathrm{dB}}}{10}} \cdot \left(1 - 10^{-NR_{\mathrm{dB}}/10}\right) + 1 \right) \qquad (2)$$

where FER is the FER operation point.

Based on the link level simulation results the capacity of a 120° sector (maximum number of simultaneous users) is calculated for each antenna concept, and the results are used to calculate the Erlang capacity.

The Erlang B capacity formula is needed to evaluate the traffic load (the average number of users) that can be supported with a blocking probability of 0.02, and also to consider the effect of different trunking gains between antenna concepts on capacity. 4MRC antennas cover the entire 120° sector, thus the entire channel pool is in use when a new user tries to establish a connection. Instead, with 2+2 and 4 beams concepts, each beam covers 60° or 30° angular section, respectively. Therefore, the size of the channel pool is a half or quarter the quantity of the max. amount of channels, and the trunking gain is smaller.

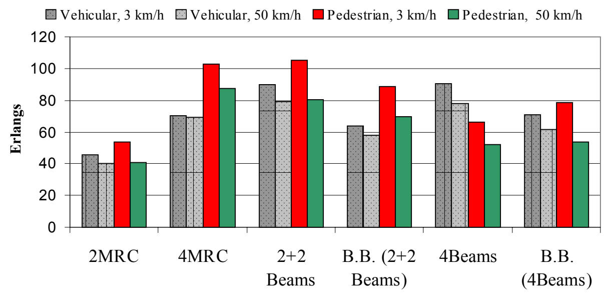


Figure 6. Number of speech Erlangs/carrier/cell.

It is shown in Figure 6 that the lower MS speed in general provides better capacity. This can be explained with better received E_b/N_0 performance. The fast PC is able to follow the fading signal and the required E_b/N_0 target is reduced. The lower target value reduces the overall interference level and more users can be served in the network. The impact of MS speed to coverage is different. The higher speed reduces the required Tx E_b/N_0 and thus the coverage is improved when the MS speed is increased (up to a certain speed).

For a single cell the capacity of the 4 beams concept with 3 km/h speed would be clearly the best due to the lowest Rx E_b/N_0 values (see Figure 2). However, for multicell capacity the inter-cell interference caused by higher transmission powers must be considered, and thus, high power rise decreases the maximum capacity of the 4 beams concept.

For the 4MRC concept the Rx E_b/N_0 values are much higher (2.2 dB – 1 dB) than for 2+2 and 4 fixed beams solutions due to worse channel estimation and less antenna gain. Despite the small power rise of the 4MRC concept, fixed beam concepts seem to provide better channel capacity in Vehicular A channel. In Pedestrian A channel 4MRC and 2+2 beams concepts seem to work quite equally. Although, the adaptive channel estimation could improve, especially the 4MRC concept, in all cases. Note that the real channel capacity for fixed beam cases can be assumed to be somewhere between the results from 'between beams' and 'middle of beam' cases.

5.3. Throughput Increase

For best effort packet data the channel throughput of a 120° sector is evaluated in this section from the link level E_b/N_0 values, and the results are plotted in Figure 7.

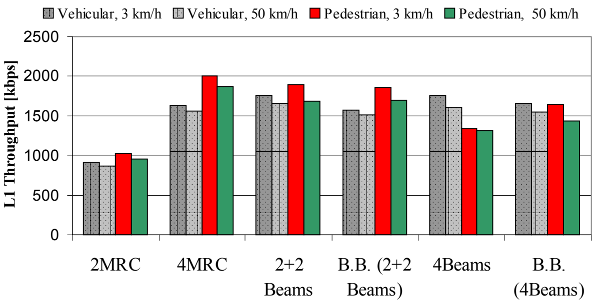


Figure 7. L1 throughput, kbps/carrier/cell.

From Figure 7 it can be seen that enhanced diversity (4MRC) is the clear winner in terms of L1 throughput in radio environments lacking multipath diversity (Pedestrian A). In Vehicular A the differences between antenna concepts are smaller.

6. Discussion

In radio environments with large degree of multipaths the differences between antenna concepts are rather small. However, the 4-branch diversity receiver (4MRC) is somewhat better than the other two methods in terms of overall performance and capacity, especially with high data rates and low mobile speed. From the coverage point of view (low speed) the 4MRC concept is shown to be particularly better than the other concepts.

7. Measurements

An extensive measurement campaign was carried out in Espoo, Finland to verify the gain of 4MRC over normal 2-branch receiver diversity with Nokia WCDMA test system. The results will be presented in [6], but here some of the main findings are shown. An example result on one measurement route is shown in Figure 8.

The 4MRC concept was implemented with 2 physical antennas with 2 slanted (±45) cross-polarisation branches. The reduction of average MS transmission power with 4MRC compared to 2MRC was measured in numerous cases with different BS and MS antenna positions.

The effect of separation between 2 physical BS antennas was one of the main interest in the measurements. Results in Table 4 show that positioning the polarisation antennas in parallel close to each other or vertically on each other did not have much effect on 4MRC performance in given suburban environment.

Table 4. Summary of results for measurements with 3 different BS antenna positions on one route. Mean MS Tx powers shown in dBm's.

BS antenna position	***2RX***	***4RX***	***4MRC gain***
Parallel, 1 m separation	7.90 dBm	4.59 dBm	**3.31 dB**
Parallel, 0 m separation	7.90 dBm	4.86 dBm	**3.05 dB**
Vertically positioned	8.33 dBm	5.13 dBm	**3.20 dB**

As a whole the 4MRC gain in the measurements was 2.1–3.8 dB, and typically between 2.5–3.2 dB. The average gain in the field measurements match well with the simulation results. The antenna separation of 1.0 m performs 0.3–0.4 dB better than the case where antennas are very close to each other. No differences were found between the different mobile speeds in the measurements.

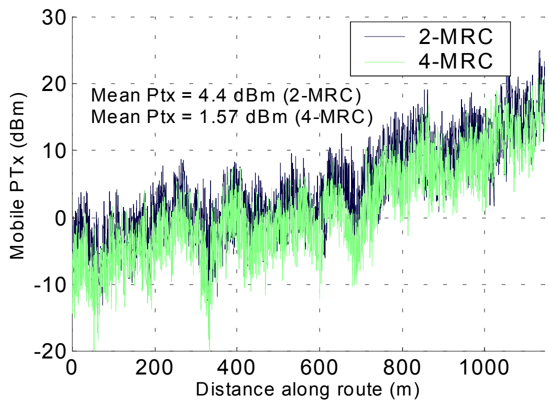


Figure 8. Example of MS Tx power along measurement route.

8. Conclusions

Doubling the number of antennas from two to four is a simple way to increase the coverage and the capacity in uplink. In the coverage limited situation the 3-sector 4MRC concept should be used in uplink to significantly increase the cell range.

9. Acknowledgements

The authors would like to acknowledge the suggestions and the contributions from several colleagues in Nokia Networks.

10. References

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