Applicability of repeaters for hotspots in UMTS

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Abstract—**The aim of this paper is to assess the applicability of repeaters for downlink capacity improvement in hotspots through field measurements. Deployment of repeaters in capacity-limited scenarios requires more careful radio network planning compared to the traditional approach for operation in coverage-limited environment. The results of the field measurements conducted in an urban UMTS network reveal that a proper configuration of a repeater can provide a substantial downlink capacity gain, which indicates the suitability of the repeaters also in capacity-limited environments. Besides, obtained outcomes show that repeaters can improve dominance in pilot polluted areas, which on the contrary reduces SHO rates. Moreover, utilization of repeaters might improve the performance of location techniques as well.**

Keywords-Capacity, field measurements, positioning, radio network planning, repeaters, UMTS.

I. INTRODUCTION

The usage of repeaters for extending network coverage in cellular radio systems reduces significantly the overall network deployment expenses by decreasing the required number of base stations. Additionally, utilization of repeaters for capacity enhancements could provide very flexible and cost-efficient solutions for varying traffic conditions or for temporary load variations. However, deployment of repeaters in capacity-limited UMTS (Universal Mobile Telecommunications System) networks differs fairly from implementation in conventional frequency channelized cellular systems due to assignment of users to the same carrier frequency [1]. Hence, the utilization of repeaters becomes more complicated, since repeaters have a potential to affect the performance of the whole network.

The majority of the conducted research concentrates on the deployment of repeaters in a traditional way, i.e., for providing service coverage within dead spots (areas without sufficient coverage) [2]-[6]. Applicability of repeaters for coverage extension along highways was analyzed by simulations in [2] with a conclusion that repeaters can slightly increase the system capacity by reducing other-to-own-cell interference in the UL (uplink). In [3] and [4], repeaters were studied for enlarging coverage in dead spots with results that repeaters have a potential to decrease the UL capacity by acting as a new source of interference. A repeater system, which is automatically switched on if traffic is detected under its coverage area, was proposed in [5]. Such a repeater system does not amplify the noise in the UL when there are no users transmitting the data, thus reducing the average interference contribution. An indoor deployment approach for repeaters was

considered in [6]. The paper concentrates on the evaluation of the impact of repeaters' noise figure on the shrinkage of the mother cell coverage. Additionally, positive outcomes from measurement trials were published in [7]-[8], where the results confirmed the relevance of repeaters in coverage-limited areas. Moreover, the unsuitability of repeaters was also emphasized for capacity-limited areas [7]. Measurements conducted in [8] revealed that repeaters are able to improve the signal quality in pilot polluted areas. On the contrary, an unconventional idea of using repeaters for capacity enhancements was proposed in [9]. Applicability of repeaters for hotspots was evaluated for the UL and DL (downlink) through Monte-Carlo simulations. Repeaters were shown to be able to provide service for almost double number of users under hotspots. However, the effect on the UL capacity was not as outstanding. Simultaneously, the importance of optimum repeater gain was highlighted, since wrong settings can significantly reduce the network performance.

In this paper, the applicability of repeaters for enhancing the DL capacity in hotspots is assessed through field measurements conducted in an urban UMTS network. Performed analyses include also a study of the improvement of dominance areas and reduction of SHO (soft handover) rates in pilot polluted areas. Moreover, applicability of cellular mobile location techniques for networks equipped with repeaters is evaluated.

II. UMTS CAPACITY EVALUATION

The system capacity of the configurations without and with a repeater is estimated from the sensitivity of the network configuration for an increase of the load. Basically, the network configuration, which is the most robust for interference increase, provides also the highest capacity. A suitable parameter for indicating interference conditions in the DL, and a parameter that can be easily extracted from the measurements, is CPICH (common pilot channel) E_c/N_0 (energy per chip over interference spectral density), shown in (1). E_c/N_0 provides a convenient value for evaluation of the DL interference increase when RSCP (received signal code power) is at the adequate level, i.e., as long as the contribution of thermal noise is minimal. Without other users' interference, RSSI (received signal strength indicator) consists of signals from the serving sector (p_{own}), of a small contribution from common channels from neighboring cells (p_{other}), and of thermal noise (p_n). However, if the load of a cell increases, also the level of RSSI rises due to increase of the own-cell interference. On the other hand, a mobile in neighboring cells will also increase the power of interference in the DL. In any

case, the interference contribution of other mobiles in the network is observed as a decrease of E_c/N_0 values.

$$\frac{E_c}{N_0} = \frac{RSCP}{RSSI} = \frac{RSCP}{p_{own} + p_{other} + p_n} \qquad (1)$$

Measurement results of E_c/N_0 from two different load situations of the same network configuration provide information about the sensitivity of the network configuration for increase of load. Thus, the maximum DL capacity can be estimated, if the values of the average DL throughput of each mobile, SIR (signal to interference), and the noise rise (ΔNR_{DL}) due to additional load ($\Delta \eta_{DL}$) are known. However, utilization of load equation requires a rough estimate of the DL orthogonality factor (α). Finally, the load equation (2) can be fitted to match the measured values using other-to-own-cell interference (i_{DL}). The relation of the load equation and the noise rise is given in (3). Finally, the maximum DL capacity of a cell can be estimated by setting the maximum allowable noise rise. The correlation between the theoretical noise rise of (3) defined by (2) and measured values has been observed to be at the sufficient level [10].

$$\eta_{DL} = \sum_{n=1}^{N} \frac{\left(\dfrac{E_b}{N_0}\right)_n R_n \nu_n}{W} \left[(1-\hat{\alpha}) + \hat{i}_{DL}\right] \qquad (2)$$

$$\Delta NR_{DL} = -10\log_{10}(1-\Delta\eta_{DL}) \qquad (3)$$

III. MEASUREMENT SCENARIO

The repeater [11] was deployed for capacity-limited environment in an urban UMTS network. The sites of the network are deployed in 3-sectored manner with 400 m mean site spacing. The base station antenna height exceeds occasionally the average rooftop level, thus presenting a combination of macro and microcellular environments. A part of the network layout with the repeater location is shown in Fig. 1. The donor and the serving antennas were installed at 10 m height and in an approximate distance of 500 m from the mother cell. The donor antenna was mounted in the location with LOS (line of sight) connection with the mother cell. The corresponding path loss was 100-105 dB. For the donor antenna, the horizontal and vertical half-power beamwidths were 65° and 6.5°, respectively, with gain of 17.1 dBi [12]. A properly isolated [1] serving antenna was located at 100 m distance from the hotspot (Fig. 1). For the serving antenna, horizontal and vertical beamwidths were 62° and 13° together with a gain of 15 dBi [13]. Moreover, the serving antenna was downtilted electronically 12° and mechanically 5°. Total losses of cables and connectors used in the repeater system did not exceed 4 dB. Three repeater gain settings were applied in the measurements, namely 65 dB, 70 dB, and 75 dB.

An artificial hotspot was located in LOS conditions with respect to the serving antenna (Fig. 2). Without the repeater, the radio conditions in terms of pilot pollution were quite
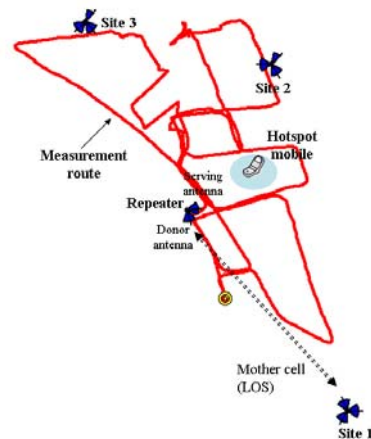

Figure 1. A part of the network with the location of the repeater and the measurement route.

Figure 2. The deployment environment of the serving antenna and the hotspot area.

fascinating in the hotspot area, since occasionally 8 pilots were hearable simultaneously almost at equal level. However, even without the repeater 'the mother cell' was the most dominant one in the hotspot area. Hotspot traffic was generated by a static high speed packet data mobile downloading with a speed of 384 kbps (background service class). The hotspot mobile was placed inside a car, where the RSCP level was roughly -85 dBm. The non-coverage-limited conditions of the measurement route and repeater location were confirmed by tracking the mobile transmit power, which maintained on average at the level of -22 dBm over the whole route.

The measurements were performed over the route covering areas under the mother cell, repeater cell, and neighboring cells (Fig. 1). The measurement equipment consisted of a laptop PC with air interface measurement software connected to the test mobile and to the GPS receiver. The test mobile was set to download also with 384 kbps speed (background service class). Thus, the simultaneous maximum throughput requested under 'the mother cell' was 768 kbps. Also the test mobile was placed inside a car. The measurement statistics were gathered with and without the hotspot mobile. All the measurements were performed during the same day. Presented results are averages of measurements outcomes obtained during two rounds of the defined route.
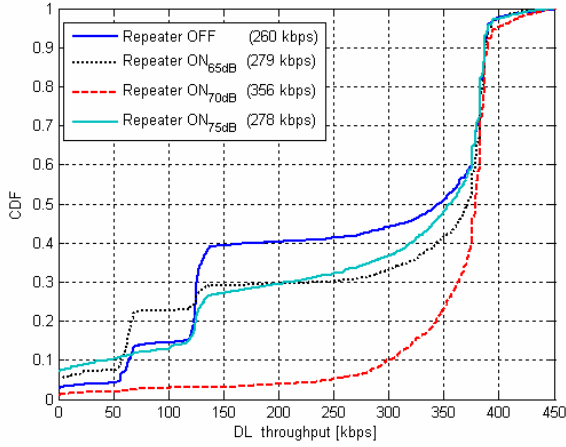
Figure 3. The cumulative distribution function (CDF) of the throughput under considered configurations in the mother cell. Average throughput values are provided in parentheses.
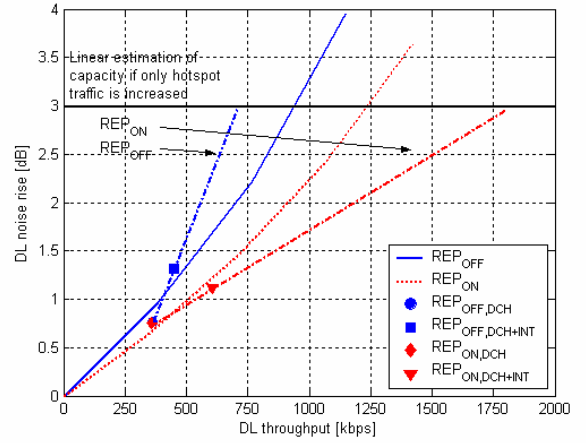

Figure 4. The estimation method of the maximum mother cell throughput without and with the repeater (gain 70 dB) in the measured configurations.

TABLE I. DL AVERAGE THROUGHPUT OF THE TEST AND HOTSPOT MOBILE UNDER MEASURED NETWORK CONFIGURATIONS IN THE MOTHER CELL.

DL throughput [kbps]	Repeater OFF	Repeater ON 65 dB	Repeater ON 70 dB	Repeater ON 75 dB
Test mobile	260	279	356	278
Hotspot mobile	223	287	257	195
TOTAL	**483**	**566**	**613**	**473**

TABLE II. DL AVERAGE THROUGHPUT AND E_c/N_0 WITHOUT AND WITH THE HOTSPOT MOBILE IN THE MOTHER CELL AND IN THE NEIGHBOR CELLS.

Repeater OFF		Without hotspot mobile	With hotspot mobile
Mother cell	E_c/N_0 [dB]	-4.55	-5.26
	DL throughput [kbps]	364	451
Neighbor cells	E_c/N_0 [dB]	-5.37	-6.17
	DL throughput [kbps]	368	296
Repeater ON (Gain 70 dB)			
Mother cell	E_c/N_0 [dB]	-4.68	-5.23
	DL throughput [kbps]	356	613
Neighbor cells	E_c/N_0 [dB]	-4.77	-5.00
	DL throughput [kbps]	363	363

IV. MEASUREMENTS RESULTS AND ANALYSIS

Fig. 3 shows the throughput variations and average values of the test mobile without the repeater and with different repeater gain settings (65 dB, 70 dB, and 75 dB). Moreover, Table I gathers the average DL throughputs of the test and the hotspot mobile. The results show that a suitable deployment of the repeater significantly enhances the average DL throughput of the hotspot mobile and test mobile. The highest total throughput was achieved with 70 dB repeater gain. However, the worst throughput is achieved already with 75 dB repeater gain, hence illustrating the importance of the repeater gain setting. The variations in throughputs for all other configurations except repeater gain 70 dB were caused by downgrading of spreading factor by the RRM (radio resource management) functions (Fig. 3). Moreover, most of the spreading factor downgrades were concentrated in the mother cell area, indicating insufficient amount of radio resources. Nevertheless, the difference in the maximum measured DL throughput can not be directly converted into DL capacity gain, since it might include errors produced by a non-optimal functioning of the RRM functions. Naturally, the source of the decision for the spreading factor lies in the radio conditions. Therefore, it is strongly assumed that the configuration of 70 dB repeater gain provides the best DL capacity for the mother cell. More detailed measurements were conducted with this repeater gain setting.

The impact of the repeater configuration on the mother cell capacity is evaluated through the sensitivity analysis presented in Section II. In the analysis, the comparison of differences of the E_c/N_0 reductions under the mother cell allows an estimation of the maximum throughput. Fig. 4 compares the estimated load curves for the DL without and with the repeater (gain 70 dB). The load curves are based on the measured DL average throughputs, SIR targets, and noise rise (based on the reduction of the average E_c/N_0). The average DL orthogonality was assumed to be 0.7 for both configurations. Moreover, the load curve was fitted to the measured points by changing i_{DL}.

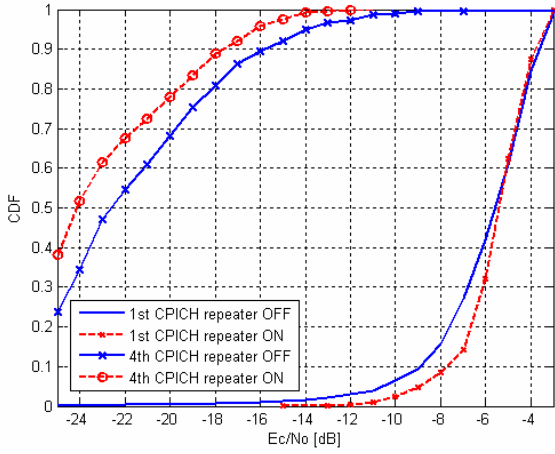The lower operation points (circle and diamond) in Fig. 4 show the measurement results when only the test mobile was

Figure 5. The effect of the repeater (gain 70 dB) on the first and the fourth CPICH E_c/N_0 over the whole measurement route.

Parameter	Repeater OFF	Repeater ON 65 dB	Repeater ON 70 dB	Repeater ON 75 dB
Mean active set size	1.20	1.10	1.10	1.08
SHO probability [%]	17.2	8.9	8.6	7.2

loading the cell (the same throughput with the noise increase). Obviously, within the measurement route, both configurations are able to provide almost the maximum throughput with roughly 0.7 dB noise increase[1]. However, taking into account the resources required for the hotspot mobile, the contribution of it is considerably smaller if the repeater is in operation (indicated in the Fig. 4 as square for repeater off and triangle for repeater on). Linear estimation of the maximum available throughput (dashed-dotted lines) is applied in order to estimate the impact of additional throughput only from the hotspot area. This would result in 700 kbps maximum throughput without the repeater and 1800 kbps with the repeater, which would correspond to over 150% capacity gain. However, note that requesting more throughput from the hotspot area provides an estimate of the upper-limit of the capacity enhancement (hotspot and the repeater close to the cell edge). In order to provide a fair comparison between these configurations, an average capacity enhancement is estimated by fitting the load curve to pass the middle point of the measured load points. Utilizing configuration without the repeater results in 940 kbps cell capacity (with 3 dB noise rise) and 1230 kbps with the repeater. Hence, the available average capacity gain of using repeater would be still 30%. This figure should actually provide more realistic estimation, since, in practice, the throughput distribution between the mother cell and repeater vary. Nevertheless, the evaluated absolute capacity values form a reasonable estimation of the capacity for a macrocell [14].

The positive impact of the repeater configuration on the DL capacity is a contribution of multiple factors. Firstly, the
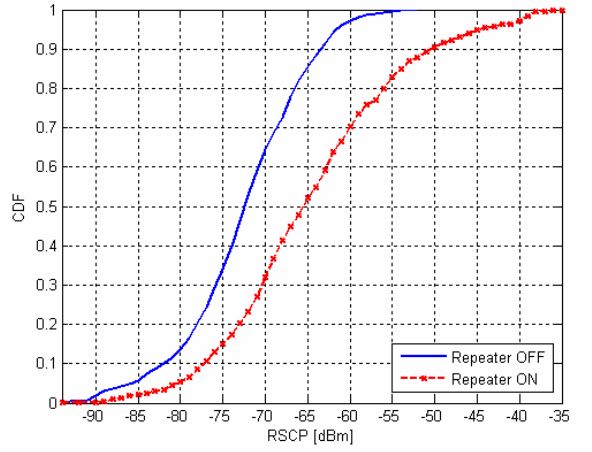

Figure 6. CDF of RSCP in the mother cell without and with the repeater (70 dB gain).

achieved capacity gain is caused by a lower DL transmit power for the hotspot mobile through the repeater. This should intuitively reduce also the DL interference in the neighboring cells, which can be verified by investigating the noise rise in the neighboring cells. It appears that without the repeater, the interference increase in the neighboring cells is 0.8 dB (Table II). On the other hand, the corresponding increase with the repeater is merely 0.23 dB, even thought the average throughput for the hotspot mobile was higher (Table I). Secondly, the improved DL capacity might be also caused by improvement of the DL orthogonality. Intuitively, the time dispersion under repeaters' dominance area should be smaller, which on the other hand improves the DL code orthogonality.

The results illustrate also that a properly deployed repeater reduces SHO probability (Table III). Obviously, the repeater implementation improves the cell dominance area and thus it can reduce pilot pollution problem. Therefore, improvements in the quality (E_c/N_0) of the connections were observed within the whole measurement route as shown in Fig. 5. First of all, the level of the first pilot is enhanced slightly. Secondly, also the level of the fourth visible pilot is reduced. Hence, the measurement results confirmed the applicability of repeaters for avoidance of the pilot pollution problem [8].

Performed evaluation of the effectiveness of repeaters gives positive outcomes also if mobile positioning applications are considered. The signal transmitted through a repeater is seen by the UE (user equipment) as an additional multipath component of the mother cell. However, in a typical dense network deployment, the UE can recognize whether the pilot has not been received directly from the mother cell, since the delay introduced by the repeater is sufficient (5 μs). Therefore, in mobile-based positioning methods utilizing OTDOA (observed time difference of arrival) information of the received pilots [15], the UE can take into account the repeater delay in the range equations. Then, the positioning accuracy is not decreased if the system and propagation delays introduced by the repeater are precisely defined and constant. Similarly, in network-based location approaches exploiting RTT (round trip time) measurements [16], an enormously large RTT report can be recognized as measured through the repeater, and thus the corresponding range equations can be adequately tuned.

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[1] The absolute noise increase of 0.7 dB was verified by idle mode measurements.

The deployment of the repeater enhances the RSCP levels for the mobiles under the mother cell, and therefore LOS conditions might be improved (Fig. 6). The mean values of the RSCP without and with the repeater configuration (70 dB gain) were -72.13 dBm and -64.1 dBm, correspondingly. Better LOS conditions will result in a better accuracy for majority of time-biased location techniques. In turn, the achieved reduction of shadowing in the area served by the repeater should contribute positively to the positioning approaches employing signal strength measurement data. Another interesting point in the repeater deployment is that previous studies [17] have indicated disagreement between topology planning from capacity and mobile positioning perspective. However, deployment of repeaters seems to constitute an infrequent example when the performance of network-based location techniques does not suffer in case of prioritizing on network capacity.

V. DISCUSSION AND CONCLUSIONS

In this paper, the applicability of repeaters for hotspot capacity was evaluated by field measurements conducted in an urban UMTS network. The measurement results indicated that repeaters are highly feasible solutions for extending the mother cell capacity in the DL. Simultaneously, a properly deployed repeater produces less interference towards the neighboring cells. The estimated maximum throughput with 3 dB DL noise rise increased from 700 kbps to 1800 kbps (over 150% capacity gain), if the hotspot traffic was dominating. However, more moderate assumption of the capacity increase was around 30% (equal loading of the whole cell). Thus, the final capacity gain in the DL is expected to be within this range. However, already with 75 dB repeater gain setting, the average throughput in the DL was lower, hence indicating the importance of the repeater configuration. In general, the capacity enhancements are based on smaller required DL transmit power, which automatically reduces interference towards the other cells and the required DL power in neighboring cells. A part of the DL capacity enhancement of the mother cell could be also achieved by better average DL code orthogonality. The increase of the DL capacity was evaluated from differences in the DL noise rise due to the hotspot load without and with the repeater. The errors in presented analysis can be caused by noise rise approximation based on two measurement points. Moreover, the impact of the repeater might have been different if, e.g., antennas with different characteristics were deployed or the serving antenna was not downtilted (more interference towards neighboring cells).

The measurement results showed also that repeaters constitute a feasible solution for avoidance of pilot pollution, as in this configuration the hearability of the fourth pilot can be reduced with concurrent increase of the first pilot dominance. Improved dominance decreases the overlapping between the cells, which results in smaller SHO rates around the repeater area. Moreover, analysis of topology planning from mobile positioning point of view demonstrated that implementation of repeaters does not pose problems to cellular mobile location techniques. It is expected, that enlargement of areas with LOS conditions caused by deployment of a repeater positively affects the accuracy of most of the proposed approaches for mobile positioning. Further studies should include more detailed verification of networks with repeaters (including phenomena in the UL) and field trials in more complex environments such as indoor.

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