# Dimensioning Cellular WiMAX Part II: Multihop Networks

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*Abstract*— **WiMAX networks are foreseen to cover diverse geographic regions. On the one hand they can cover urban areas where a high density of buildings and indoor usage prevent Line-of-Sight (LOS) propagation conditions. On the other hand WiMAX networks can provide access over large geographic regions in remote rural areas, in which over the rooftop deployment of Tx and Rx antennas allow for LOS conditions. However, in both scenarios it is challenging to cover the entire service area. Either huge parts are heavily shadowed from the Base Station (BS) or the link distances are very large. In both cases relays help to extend the range of the BS allowing for a cost-efficient deployment and service.**

**This paper discusses an analytical approach to dimension cellular multihop WiMAX networks that are based on OFDM technology. A worst case analysis results in valuable indications for dimensioning cellular WiMAX networks within various multihop scenarios. Within these scenarios relays are operating in separate as well as simultaneous time slots.**

## I. Introduction

Every wireless system suffers from challenging radio propagation characteristics, so does WiMAX. The achievable Carrier to Interference and Noise Ratio (CINR) decreases with an increasing link distance. Shadowing, which leads to Non Line-of-Sight (NLOS) communication, further reduces the perceived signal quality. The introduction of relay stations may significantly enhance the link quality leading to throughput enhancements and coverage extensions [1; 2; 3].

For dimensioning WiMAX networks, the worst case CINR within a cellular 802.16 network is relevant. In Downlink (DL), the central BS transmits to the relay, which re-transmits the data to the most distant Subscriber Station (SS). In Uplink (UL), the SS at the cell border transmits to the relay, which forwards the information to the central BS. Interference is generated by BSs and relays that utilize the same frequency channel.

## II. Cellular Multi-Hop Scenarios

The dimensioning approach presented in this paper extends the singlehop dimensioning presented in [4] to multihop networks. Hence, hexagonal cells are regarded that are clustered according to a given cluster order. Inter-cell interference is generated by the six co-channel cells of the first tier. The network operates in the 5 GHz spectrum using a channel bandwidth of 20 MHz. The OFDM-based physical layer allocates resources in Time Division Multiple Access (TDMA). The transmit power of all stations is restricted to the Equivalent Isotropic Radiated Power (EIRP), i.e., BSs, SSs, and relays are transmitting with 1 W. LOS and NLOS propagation conditions are taken into account.

DL and UL channels are perfectly separated either by Time Division Duplex (TDD) or by Frequency Division Duplex (FDD) schemes [5]. According to the design of the multihop enabled MAC frame, transmissions on the first and the second hop are assumed to be perfectly separated in time [6].

The positioning of relay stations may vary according to the intended benefit. Two different scenarios are be distinguished in the following.

- *Throughput scenario*
  Placing relays within the BS's coverage, the CINR and therewith the link capacity can be increased. From a dimensioning perspective, this scenario equals the singlehop case [4], since the entire cell area is covered by the BS.
- *Coverage scenario*
  In order to extend the coverage area of the cell, relays are placed at the border of the BS's transmission range. The distance between the BS and the relay equals the original BS cell radius. Figure 1 illustrates such a scenario. It plots the BS's coverage area with dotted lines. Three relays at the corners extend the coverage area of a singlehop deployment ($A_{single\,hop}$) with respect to the coverage area of a multihop deployment ($A_{multi\,hop}$) by a factor of three.

$$A_{multi\,hop} = 3\,\frac{3}{2}\sqrt{3}R^2 = 3 * A_{single\,hop} \qquad (1)$$

  Due to the extended coverage of a relay enhanced cell, the co-channel distance is enlarged by a factor of $\sqrt{3}$ in these scenarios. It can be calculated to $D = 3R\sqrt{k}$

SSs are assumed to utilize omni-directional antennas all the time. Classical sectorization is not regarded in the multi-hop scenarios since spatial reuse is exploited instead. Directive antennas are optionally used at relay stations to reduce inter- and intra-cell interference. The antenna angle is set to 240 °. The relay antenna look direction always points away from the central BS. The directive antenna's backward signal is

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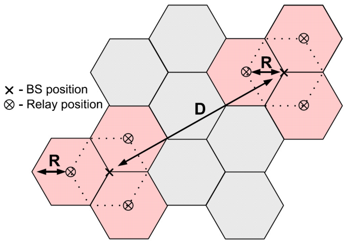


Fig. 1: Coverage scenario (cluster order 3))

suppressed and the forward signal is transmitted undistorted, thus the antenna characteristic is assumed to be perfect. Figure 2 exemplarily illustrates the resulting coverage area of relay stations that use directive antennas. It can be seen, that the angle has been chosen so that the other two relays of the same cell are not affected by the transmission. At the same time, the number of co-channel interferers is reduced by a factor of ⅔.

## III. Mean Interference Generated by Multi-Hop (Sub-) Cells

In DL, BSs' co-channel interferer are co-channel BSs, which are centrally located. Relays are interfered by co-channel relays, whose positions are well known. In UL, co-channel SSs generate interference. Their position is unknown and may vary within the cells coverage area. In order to model the random SS position, UL co-channel interference is assumed to be generated by a planar transmitter instead of a centrally located point source [4]. The planar transmitter has the shape of the interfering BS cell or the relay's subcell. A comparable model for interference in multihop networks has been presented by [7]. However, he assumed circular cells instead of hexagonal and he does not consider the effect of noise. Directive antennas and simultaneous operation of relays have not been covered as well.

Analog to [4], the receive power of a signal that is emitted by a planar transmitter can be calculated. This receive power models the interference more accurate than the assumption of centrally located SSs. According to the method derived in [4] interference correction factors for distant cells and subcells were calculated. The factors depend on the pathloss model, the scenario type and the antenna characteristic. Apart from cluster order one, the factors for omni-directional antennas are positive and the corrections for directive antennas are negative. Hence, the interference of a hexagonal planar transmitter is higher than the centrally generated interference. Using directive antennas, co-channel SSs are located behind the central position of the relay so that their interference level is lower.

In order to increase cell capacity, relays might operate simultaneously in Space Division Multiplex (SDM). SDM operation means that a distinct relay station (station of interest) transmits and receives in parallel to the other two relays of the same cell and in parallel to all relays of the co-channel cells. Interference is generated by three different sources. In order to explain the sources, the relay stations are numbered in figure

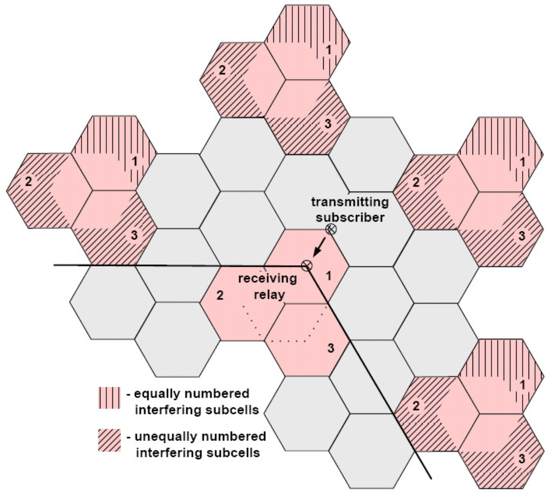


Fig. 2: Coverage scenario with co-channel interferer (directional antennas, cluster order 4)

TABLE I: UL Interference correction of equally numbered, distant multi-hop subcells within LOS scenarios in [%]

| | cluster order → | 1 | 3 | 4 | 7 | 12 |
|---|---|---|---|---|---|---|
| scenario ↓ | antenna ↓ | | | | | |
| coverage | omni | 7.12 | 2.25 | 1.68 | 0.96 | 0.56 |
| coverage | directive | -0.58 | -2.61 | -2.02 | -1.20 | -1.88 |
| throughput | omni | 5.21 | 1.68 | 1.26 | 0.72 | 0.43 |
| throughput | directive | -2.16 | -2.02 | -2.39 | -1.50 | -1.42 |

2. Each relay that is on the BS's upper right hand side is numbered with 1. The relays on the BS's left hand side are numbered 2, and the lower right relays get the number 3.

First, equally numbered subcells of distant co-channel cells interfere. Like in the single hop scenario, each source is equally distant and the subcells look direction is equal to the subcell of interest, e.g., the antenna look direction of subcells numbered with 1 are all pointing to the upper right. Correction factors of these sources are listed in tables I and II. It can be seen that directive antennas reduce the interference compared to a central source, because in general, the SSs are located farther away from the station of interest. Using omni-directional antennas, the correction is comparable to the single hop correction developed in [4].

Second, in SDM operation, unequally numbered subcells of distant co-channel cells interfere. Their distance to the station of interest is varying and the look directions of these sources are different, since they are located at different positions relative to the central BS. For instance, the coverage area of

TABLE II: UL Interference correction of equally numbered, distant multi-hop subcells within NLOS scenarios in [%]

| | cluster order → | 1 | 3 | 4 | 7 | 12 |
|---|---|---|---|---|---|---|
| scenario ↓ | antenna ↓ | | | | | |
| coverage | omni | 21.82 | 6.55 | 4.86 | 2.74 | 1.59 |
| coverage | directive | 7.62 | -1.81 | -1.51 | -0.96 | -2.53 |
| throughput | omni | 15.64 | 4.86 | 3.61 | 2.05 | 1.19 |
| throughput | directive | 2.56 | -1.51 | -2.59 | -1.73 | -1.93 |

TABLE III: Averaged UL interference correction of unequally numbered, distant multi-hop subcells within LOS scenarios in [%]

| scenario ↓ | cluster order → / antenna ↓ | 1 | 3 | 4 | 7 | 12 |
|---|---|---|---|---|---|---|
| coverage | omni | 91.29 | 22.66 | 15.42 | 8.37 | 4.72 |
| coverage | directive | 205.33 | 64.75 | 51.21 | 33.71 | 21.82 |
| throughput | omni | 82.74 | 15.42 | 11.36 | 6.13 | 3.49 |
| throughput | directive | 193.16 | 51.21 | 39.11 | 28.06 | 19.99 |

TABLE IV: Averaged UL interference correction of unequally numbered, distant multi-hop subcells within NLOS scenarios in [%]

| scenario ↓ | cluster order → / antenna ↓ | 1 | 3 | 4 | 7 | 12 |
|---|---|---|---|---|---|---|
| coverage | omni | 503.49 | 80.39 | 50.19 | 25.79 | 14.04 |
| coverage | directive | 1033.30 | 185.50 | 126.00 | 74.60 | 45.80 |
| throughput | omni | 500.44 | 50.19 | 36.09 | 18.44 | 10.25 |
| throughput | directive | 1086.00 | 126.00 | 93.80 | 59 | 39.50 |

subcells numbered with 2 are at the left hand side of the relay. So some interfering SSs are closer, others are farther. Averaged interference corrections that take these effects into account are listed in tables III and IV. Due to the varying distances, these factors are higher than the previous ones.

Third, in SDM operation and with omni-directional antennas, relays of the same cell interfere. This interference is worst since the interfering SSs are close to the relay station of interest. Table V lists the corrections to model this kind of interference.

## IV. Time Division Multiplex of Relay Subcells

In this section, relays operate in Time Division Multiplex (TDM) and they use omni-directional antennas. Figure 3 plots the DL CINR over the scenario. It shows four CINR peaks, which results from the central BS and three relays. The perceived DL CINR of a SS that traverses the scenario area is plotted in figure 4. It shows the position of the central BS as well as the position of the relay at a distance of 1000 m. The hight of the stems at the cell border reflects the minimum required CINR. Since the actually perceived CINR is higher than the minimum required one, all SSs of that particular scenario are able to receive at least with the most robust modulation and coding scheme.

### A. LOS Conditions

Figure 5 illustrates the best server, i.e., the BS or relay to which the potential subscriber is associated due to the most beneficial CINR conditions. Additionally, circles are plotted, whose radii are the cell and subcell radii as depicted in figure 1. The best server analysis shows that the inner part of the

TABLE V: UL Interference correction of multi-hop subcells of the same cell in [%]

| | omni antenna | directive antenna |
|---|---|---|
| LOS | 24.89 | -18.15 |
| NLOS | 89.68 | -16.47 |

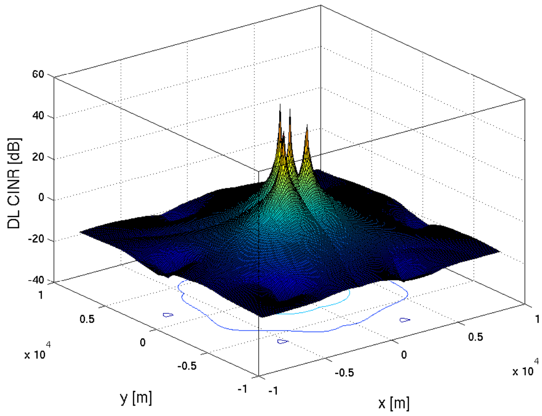


Fig. 3: DL CINR, TDM, omni antennas, LOS

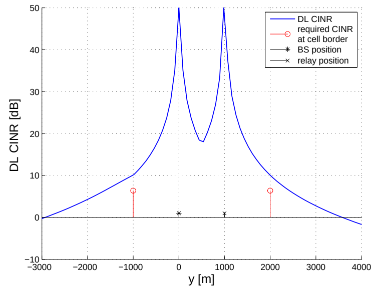


Fig. 4: DL CINR while traversing the scenario

relay enhanced cell is covered by the BS while the outer areas are covered by the relays. Since the relays use omni antennas, the switching points between BS and relay are inside the BS's original cell.

For dimensioning purposes, the signal quality for the most distant station or most interfered station is crucial. In a relay enhanced cell, this position is at the outer border of a relay subcell. In figure 5 this is at the coordinates $x = 0\,m,\ y = 2 * cell\,radius$. In DL, the receiving SS is located at the subcell's border. The transmitter is the central BS or one of the three relay stations, whichever is most beneficial. In UL, the same SS transmits while the BS or one of the relay stations receives. Note that the BS radius, which is used as x-axis parameter in the following is the radius of the inner cell. The overall coverage of the relay enhanced cell is extended by the relay to a maximum radius of twice the original radius (figure 1).

Figure 6 plots the DL case. For all cluster orders larger than one, a valid cell radius can be given. For the single hop case, only cluster orders larger than four were valid [4]. Compared to the singlehop case the valid cell radii can be extended in the multihop scenario. For instance, BS radii of up to 1675 m are possible for cluster order seven. In the single hop case, a radius of 1000 m was the limit. Note that the most distant SS is 3350 m away from the BS. The overall coverage area of the BS is extended from 2.598 $km^2$ to 21.868 $km^2$ (refer to equation 1). Thus, three relays can extend the coverage area by a factor of 8.4.

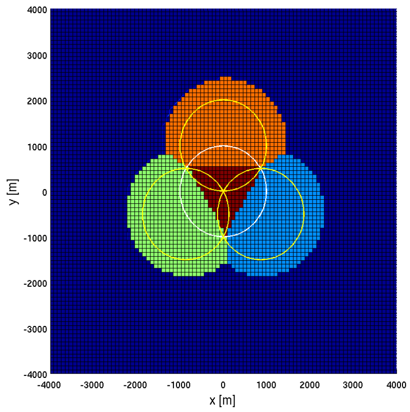


Fig. 5: Best server (TDM, omni antennas, LOS, 1000 m cell radius, cluster order 7)

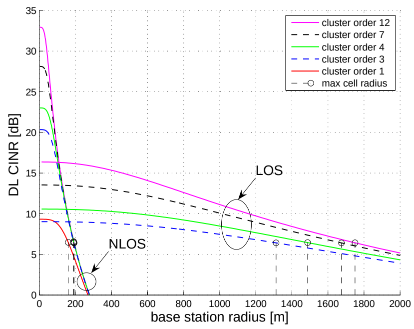


Fig. 6: DL CINR, TDM, omni antennas

The UL case results in similar radii, so it is not plotted here. Reference [4] points out that the UL is not the limiting factor, at least in interference-limited systems. The UL can be improved by optional features, such as subchannelization and BS antenna gain [4; 5].

### B. NLOS Conditions

Figure 6 also plots the coverage scenario with NLOS propagation conditions. The plots for DL and for UL signal quality do not differ, so the UL is not presented separately. In general, the valid cell radii are smaller than for LOS conditions. They range only up to 192 m. Compared to the single hop system the maximum BS radius cannot be significantly extended (only from 185 m to 192 m for cluster order seven [4]). However, the three relay station increase the coverage area from 0.0889 $km^2$ to 0.287 $km^2$, which is a factor of 3.23.

Using NLOS links, the system is noise limited, because modifying the interference by varying the cluster order does not affect the maximum cell radius. It stays nearly constant. The heavy attenuation of inter-cell interference allows cluster order one to provide valid cell radii. Radii of approximately 150 m are possible.

## V. Space Division Multiplex of Relay Subcells

Operating relays in TDM results in high signal quality and a large coverage. However, this approach shortens the

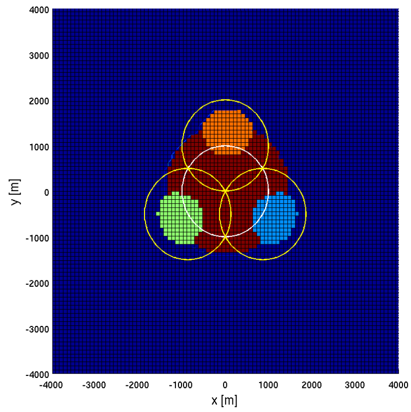


Fig. 7: DL best server (SDM, omni antennas, LOS, 1000 m cell radius, cluster order 7)

portion of the MAC frame that is dedicated to each station. The MAC frame capacity can be increased by operating the relays simultaneously. Like this, the frame needs to be divided only into two parts, one is dedicated to the BS, the other is simultaneously used by the relays. The investigated scenario equals the one of the previous section, except that the three relays and their associated SSs transmit and receive concurrently.

### A. LOS Conditions

Figure 7 shows the best server of the relay enhanced cell. Again, the inner part of the cell is covered by the BS. The BS's situation has not changed, so its coverage is equal to the one in the TDM approach. The outer areas are covered by the relays, but compared to the TDM case, the relays' coverage is seriously shrunken. Some parts of the relay subcell have to be covered by the BS, others are not covered at all. In SDM, relays operate simultaneously and interfere each other. The number of interferer is more than tripled and the two relays of the same cell are quite close. This reduces the CINR and thus the coverage area.

For the DL case of the SDM scenario, which is shown in figure 8 only cluster order twelve is valid. The maximum cell radius is 650 m. For all other cluster orders the CINR never reaches the minimum threshold of 6.4 dB. Furthermore it can be seen that the curves for cluster order seven and twelve change their shapes around the radius of 750 m. With small radii, the receiving SS is covered by the BS although the distance to the relay is much shorter than the distance to the BS. The interference during the relay phase is so high that the perceived CINR from the BS surpasses the CINR from the relay. Passing a certain distance, the relay becomes the best server for the SS of interest.

In UL, the situation is similar. Only cluster order twelve allows valid cell radii, which range up to 663 m. The shape of the curves in figure 9 indicate that the transmitting SS is always covered best by the BS. The inter- and intra-cell interference degrades the CINR during the relay phase. In UL the interference situation is even worse, since the sources

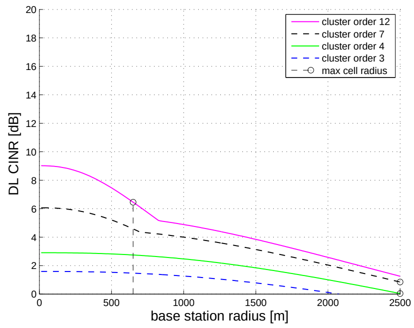


Fig. 8: DL CINR, SDM, omni antennas, LOS

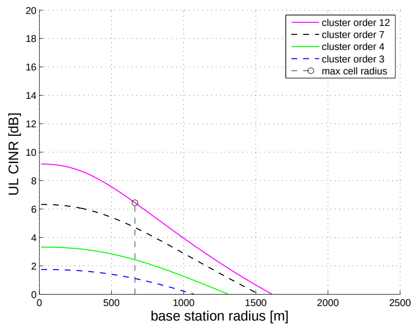


Fig. 9: UL CINR, SDM, omni antennas, LOS

of interference, i.e., the co-channel SSs might be closer to the receiving BS. Thus, the average received interference is increased by the correction factors derived in section III.

### *B. NLOS Conditions*

Figures 10 and 11 plot the SDM scenario under NLOS conditions. The high pathloss degrades the inter- and intra-cell interference so that even cluster order three results in a valid deployment. Like in the previous scenarios, the NLOS case is noise-limited. In DL, all cluster orders allow nearly the same maximum cell radius of approximately 175 m. The UL interference is higher and the valid radius range only up to 95 m.

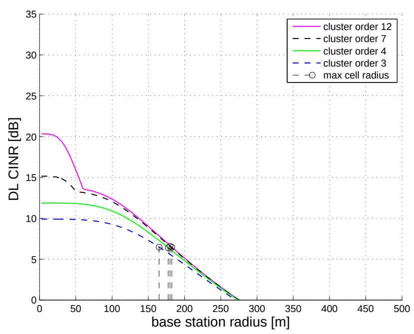


Fig. 10: DL CINR, SDM, omni antennas, NLOS

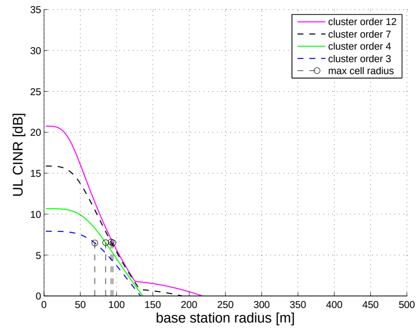


Fig. 11: UL CINR, SDM, omni antennas, NLOS

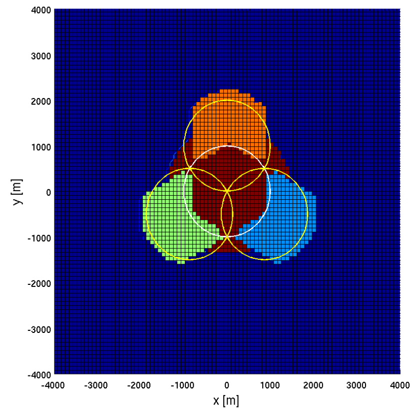


Fig. 12: DL best server (SDM, directional antennas, LOS, 1000 m cell radius, cluster order 7)

## VI. Space Division Multiplex with Directive Antennas

The previous section showed that a simultaneous operation of multiple relays within one cell, is not advantageous due to heavy mutual interference. In order to control the interference, directive antennas can be used. As shown in figure 2, the directive antenna covers the entire subcell area but the relay does not interfere with the two other subcells of its own cell. Like this, the two closest sources of interference are suppressed and the number of distant co-channel SSs is reduced to twelve (refer to figure 2).

### *A. LOS Conditions*

Figure 12 plots the best server of a scenario utilizing directive antennas. Since the BS still uses omni-directional antennas and its operation is separated in time, the BS coverage does not change compared to the previous scenarios. However, the relay coverage looks much better. It can be seen that the SS of interest at the distant subcell border can be covered assuming an example radius of 1000 m. Furthermore, the antenna angle of 240 ° is visible. Due to the ideal antenna shape, the switching point between BS and relay lies at the original (single-hop) BS cell border.

Figure 13 plots the DL CINR versus the BS radius for the LOS scenario. Compared to the SDM case with omni antennas,

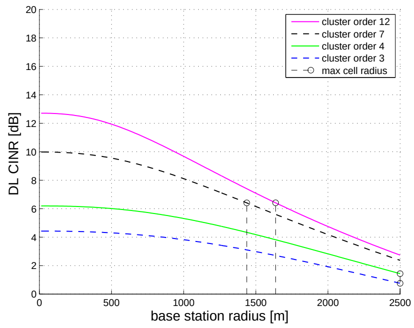


Fig. 13: DL CINR, SDM, directional antennas, LOS

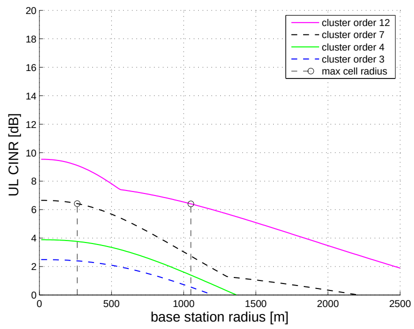


Fig. 14: UL CINR, SDM, directional antennas, LOS

the situation is improved. Cluster orders seven and twelve allow for radii up to 1640 m. This range is close to the radii of the TDM case shown in figure 6. However, cluster orders below seven are still not sufficient for this setup.

In UL, the same cluster orders are valid, but the achievable range is much smaller (refer to figure 14). The positions of interfering SSs cause this decrease.

### *B. NLOS Conditions*

The NLOS scenario is plotted in figure 15. Due to the noise-limited nature of that scenario, the reduced interference has nearly no effect on the cell size. Valid cluster orders between three and twelve allow for radii of up to 960 m. Compared to the TDM operation in section IV, cell sizes are approximately the same. Only a single-frequency network, i.e., cluster order

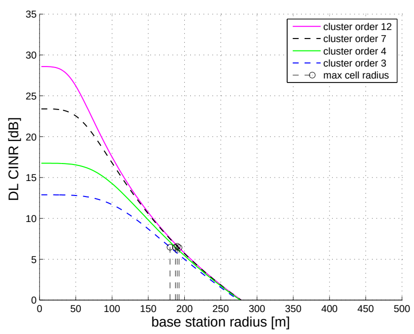


Fig. 15: DL CINR, SDM, directional antennas, NLOS

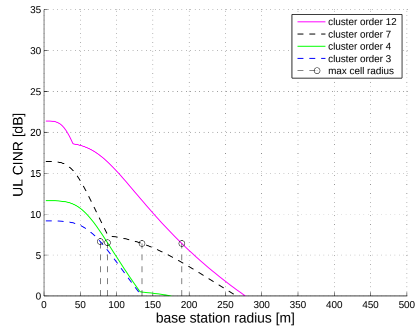


Fig. 16: UL CINR, SDM, directional antennas, NLOS

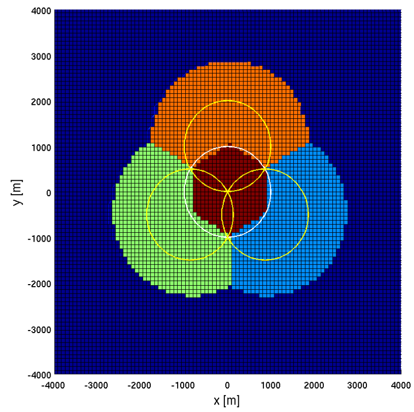


Fig. 17: DL best server (SDM, directional antennas, LOS-NLOS pathloss, 1000 m cell radius, cluster order 7)

one, is not possible.

Beside cluster order twelve, the UL scenario shown in figure 14 shows minor performance than the DL. The transition of the serving station from the BS to the relay causes the change in the shape of the curve and therewith the large variance in the valid UL cell radii.

### *C. LOS-NLOS Conditions*

In urban Manhattan-like scenarios, the source and the destination have a LOS connection along the streets. In contrast, the first tier of interferer is shadowed behind buildings, thus a NLOS pathloss results. The same effect occurs in wide-area scenarios when the BS are deployed with an antenna tilt. Like this, the SSs of the cell have a LOS connection while the SSs of distant co-channel cells do perceive a NLOS attenuation. In both deployments, the carrier signal is attenuated with the LOS pathloss coefficient, while the interfering signals are attenuated with the NLOS coefficient.

Figure 17 plots the best server of such a combined LOS-NLOS scenario. Again, the antenna shape is visible. Due to the reduced co-channel interference, the coverage of the relay-enhanced cell is extended far beyond the cell border. The mutual intra-cell interference between relays is reduced so that the corresponding coverage areas adjoin.

Figure 18 plots the DL CINR versus the BS radius of the LOS-NLOS scenario. The shape of the curve differs from the

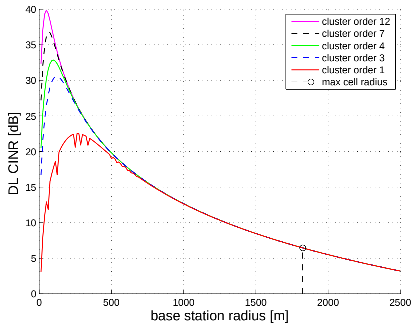


Fig. 18: DL CINR, SDM, directional antennas, LOS-NLOS

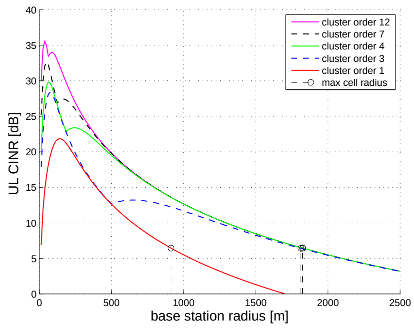


Fig. 19: UL CINR, SDM, directional antennas, LOS-NLOS)

previous ones. Having small radii, the interferer are close and the system is interference-limited. With an increasing radius, the interference attenuates faster than the carrier, because they are following different pathloss coefficients. Due to the relative increase of the carrier signal compared to the interference, the CINR increases. By increasing the radius further, the level of interference becomes small compared to the noise level and the behavior of the system switches to noise-limited. From this point, the attenuation of the carrier signal results in a decreasing CINR. However, the maximum cell radius lies far beyond that switching point in the noise-limited part. For all cluster orders the maximum radius is 1825 m.

The UL case in figure 19 shows the same behavior, which results in the same maximum cell radius of 1825 m. Only cluster order one restricts the radius to 910 m. Furthermore, the shape of the curve indicates that best server transits from the BS to the relay. With small radii the BS provides access while the relays provide access with large radii.

## VII. Conclusion

This paper presents an analytical dimensioning approach for the planning of cellular WiMAX networks within diverse multihop scenarios. The results show the potential of relays to extend the coverage area of BSs in cellular WiMAX networks. Multihop deployments allow to offer ubiquitous broadband services over large geographic regions at low costs.

While separation relays in time, they do not interfere each other. However, the subsequent allocation of resources to relays result in an inefficient utilization of available bandwidth. Thus, it is favorable to let the relays operate simultaneously.

Relays that operate in SDM interfere each other heavily. The severe mutual interference avoids a cellular multihop deployment. Directive antennas reduce the interference by focussing the antenna pattern towards the relay's subcell. The inter- and especially the severe intra-cell interference can be reduced significantly. If multihop enabled systems are deployed so that the co-channel interference perceive NLOS signal attenuation while the carrier signal still has a LOS path the system further benefits. Table VI summarizes the resulting coverage areas in cellular multihop and singlehop deployments in exemplary scenarios.

TABLE VI: Coverage area of a WiMAX BS in cellular singlehop and multihop networks (DL, cluster order 7)

| | scenario | multihop coverage | singlehop coverage [4] |
|---|---|---|---|
| TDM | NLOS | 0.287 $km^2$ | 0.0889 $km^2$ |
| | LOS | 21.868 $km^2$ | 2.5981 $km^2$ |
| | LOS-NLOS | 25.960 $km^2$ | 8.6533 $km^2$ |
| SDM with dir. anten. | | | |
| | NLOS | 0.281 $km^2$ | 0.0889 $km^2$ |
| | LOS | 16.117 $km^2$ | 2.5981 $km^2$ |
| | LOS-NLOS | 25.960 $km^2$ | 8.6533 $km^2$ |

## References


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