Dimensioning Cellular Multihop WiMAX Networks

Christian Hoymann, Michael Dittrich, Stephan Goebbels
Chair of Communication Networks (ComNets),
RWTH Aachen University, Faculty 6,
christian.hoymann@comnets.rwth-aachen.de

***Abstract*— WiMAX networks are foreseen to cover diverse geographic regions. On the one hand they shall 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 shall provide access over large geographic regions in remote rural areas, where 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 are foreseen to extend the range of the BS and to increase the cell capacity allowing for a cost-efficient deployment and service.**

This paper discusses an analytical approach to dimension cellular multihop networks based on the WiMAX 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 subsequent time slots as well as simultaneously separated only in space. The following performance evaluation allows to compare singlehop and multihop deployments in terms of capacity. Finally, general guidelines propose to use multihop deployments in some scenarios, whereas is disadvises their deployments in others.

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. Relay stations are foreseen to enhance the link quality leading to throughput enhancements and coverage extensions [1; 2].

For dimensioning, the worst case CINR within a cellular network is relevant. In Downlink (DL), the central BS transmits to the relay, which forwards the decoded 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, SSs, and relays that simultaneously utilize the same frequency channel.

A. Cellular Multi-Hop Scenarios

For the following dimensioning of multi-hop networks, 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 transmit power of all stations is restricted to the Equivalent Isotropic Radiated Power (EIRP) in Germany, 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 [3]. 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 [4].

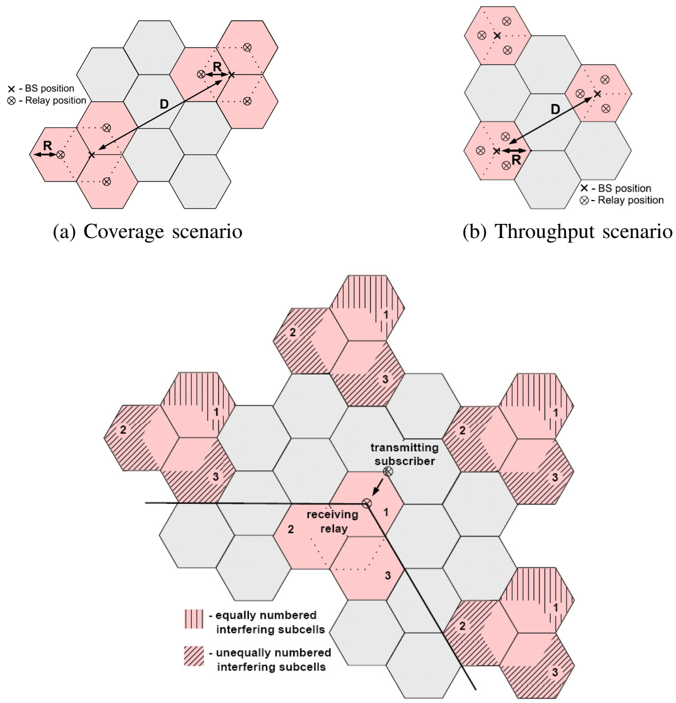
The positioning of relay stations may vary according to the intended benefit. Two different scenarios are distinguished in the following.

- *Coverage scenario*
  In order to extend the coverage area of the cell, relays may be placed at the border of the BS's transmission range. The distance between the BS and the relay equals the original BS cell radius R. Figure 1a 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 $A_{single\,hop}$ 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. Assuming a cluster order k, the co-channel distance of the coverage scenarios can be calculated to $D = 3R\sqrt{k}$.
- *Throughput scenario*
  Placing relays within the BS's coverage, the CINR and therewith the link capacity is increased. The distance between the BS and the relay is half of the cell radius. The co-channel distance can be calculated to $D = R\sqrt{3k}$. From a dimensioning perspective, this scenario equals a singlehop case, since the entire cell area shall be covered by the BS.

SSs are assumed to utilize omni-directional antennas all the time. Directive antennas are optionally used at the relay stations to reduce the 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 suppressed to zero and the forward signal is transmitted undistorted, thus the antenna characteristic is assumed to be perfect. Figure 1c 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



(a) Coverage scenario

(b) Throughput scenario

(c) Coverage scenario with co-channel interferers (directional antennas, cluster order 4)

Fig. 1: Multi hop scenarios

affected by the transmission. At the same time, the number of co-channel interferers is reduced by a factor of $^2/_3$.

B. Interference of Multi-Hop (Sub-)Cells

In DL, BSs are interfered by co-channel BSs, which are centrally located. Relays are interfered by co-channel relays, whose positions are also 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, in the following, UL co-channel interference is assumed to be generated by a planar transmitter instead of a centrally located point source. The planar transmitter has the shape of the interfering cell.

In order to increase mean 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 co-channel cells. In SDM mode, interference is generated by three different sources. In order to explain the sources, relay stations are numbered in figure 1c. 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. 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 hand side.

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 areas of subcells numbered with 2 are at the left hand side of the relay. So some interfering SSs are closer, others are farther.

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.

II. Means to Improve Signal Quality in Cellular Networks

A. Clustering

In order to avoid interference in cellular networks, cells are combined into clusters in which frequency channels are uniquely assigned to cells. Figure 1b shows a cellular network with cluster order four. Assuming a certain cell radius R, the co-channel distance $D = R\sqrt{3k}$ is increased by the cluster order k.

B. Standard Features for Downlink

Beside clustering , several other features may increase the CINR level in multihop WiMAX networks and thus extend the DL coverage. They are listed in the following:

- The *BS transmit power* was aligned to the maximum EIRP allowed in the targeted 5 GHz spectrum. If regulations allow increasing the transmit power, all co-channel BSs may increase their transmit power, too. The signal strength of carrier and interference grows the same way and finally, the Carrier to Interference Ratio (CIR) stays constant. Thus, an increased transmit power will have nearly no effect on the maximum cell radius in scenarios where the system is interference-limited. Nevertheless, the transmit power affects the CINR in noise-limited scenarios. There, it can increase the DL coverage area.
- The mobility amendment of IEEE 802.16e expands *subchannelization* to the DL data transmission. If BSs transmit on a subset of subcarriers only, the number of interferer per subcarrier can be reduced [6]. However, the spectral density [$^{\text{power}}/_{\text{bandwidth}}$] and thus the transmission range stays constant. This feature is beneficial in interference-limited systems.
- During the DL subframe, a BS with adaptive antennas can steer its transmit antenna to the receiving SS so the *BS transmit antenna gain* improves the signal quality [7]. This reduces the inter-cell interference since less power is emitted in undesired directions.
  If regulations allows to exceed the EIRP by focusing the transmission power and thus increasing the spectral density, the received signal strength at the SSs is increased. This is additionally useful in noise-limited systems.

- In a *non-saturated system* not all co-channel BSs are constantly transmitting. This leads to a reduced level of interference.

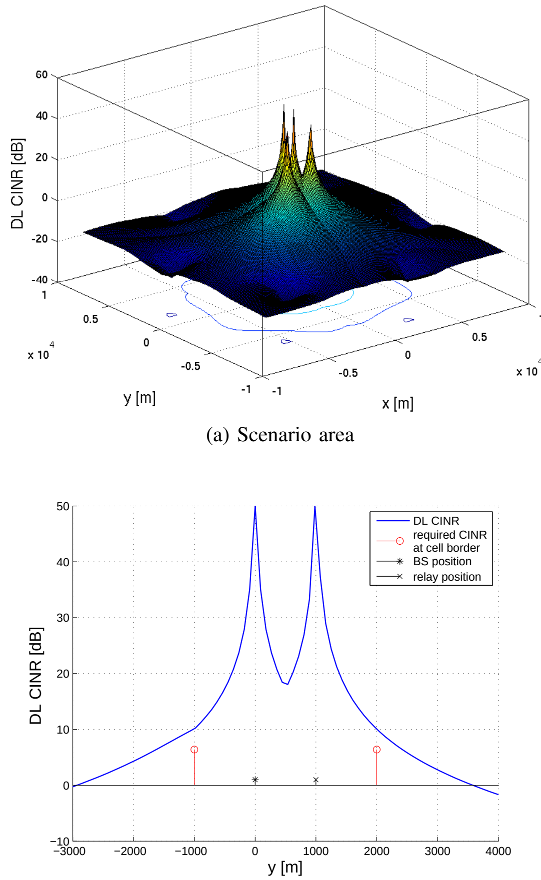
The mentioned features to increase the CINR level are only valid during the scheduled DL data transmission. The synchronized broadcast phase of a cellular WiMAX network, in which all BSs are transmitting omni-directionally on all available subcarriers cannot be enhanced. Thus, a dimensioning approach should focus on this phase as the worst case.

C. Standard Features for Uplink

The IEEE 802.16 standard foresees the following features to increase UL CINR.

- The *SSs' transmit power* was set to the maximum allowed EIRP. Portable and mobile SSs will most probably be battery powered. Their restricted power consumption may force the devices to reduce the transmit power, which will reduce the carrier strength. If all co-channel SSs transmit with reduced power, too, interference is reduced the same way and the CIR stays constant. In interference-limited systems, the possible link distances are nearly the same. In noise-limited systems, a reduced transmit power leads to a reduced coverage.
- *UL subchannelization* is specified for initial ranging, for Bandwidth (BW) requests and for UL data transmission. Subchannelization during ranging and BW request procedures allows focussing the transmit power onto a subset of subcarriers. This increases the spectral density by 12 dB and extends the transmission range significantly [3]. Since this feature increases the carrier signal and reduces interference, it is beneficial in both, interference and noise limited systems.
  If the transmit power per subcarrier stays constant during UL data transmission, interference-limited systems benefits from subchannelization: if all SSs are using a subset of the available subcarriers, the number of interfering stations per subcarrier is reduced.
- In a *non-saturated system* not all co-channel cells have constantly active transmissions. This reduces the number of interferer.
- During the scheduled part of the UL subframe, the BS can focus its receive antenna to the transmitting SS so that the *BS receive gain* improves the signal quality [7]. Since an adaptive antenna can reduce the received interference and increase the receive carrier strength, it is useful in all scenarios. Note that, the receive antenna gain is not restricted by regulations.

Some features to increase the CINR level are applicable during the scheduled UL data transmission, others during the contention based access. Especially subchannelization extends the UL range significantly. If this optional feature is implemented by the manufacturer, the UL transmission is most probably not the limiting factor in a cellular 802.16 network. Thus, the following dimensioning approach will focus on the omni-directional DL broadcast phase.



(a) Scenario area

(b) traversing the cell

Fig. 2: DL CINR in the multihop *coverage* scenario, (TDM, omni antennas, 1000 m cell radius, cluster order 7)

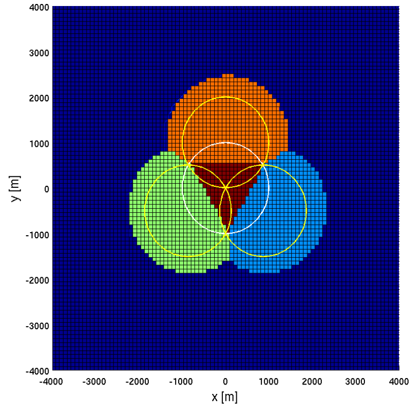
III. Time Division Multiplex of Relay Subcells

This section outlines the dimensionsioning of the coverage scenario in which relays operate in Time Division Multiplex (TDM). Relay stations use omni-directional antennas. The potential subscriber is always connected to the best server, i.e, either the central BS or the relays. Figure 2a shows the CINR of the scenario. Four CINR peaks are visible, which result from the central BS and three relays. The perceived DL CINR of a SS that traverses the scenario area is plotted in figure 2b. It shows the position of the central BS as well as the position of the relay at a distance of 1000 m.

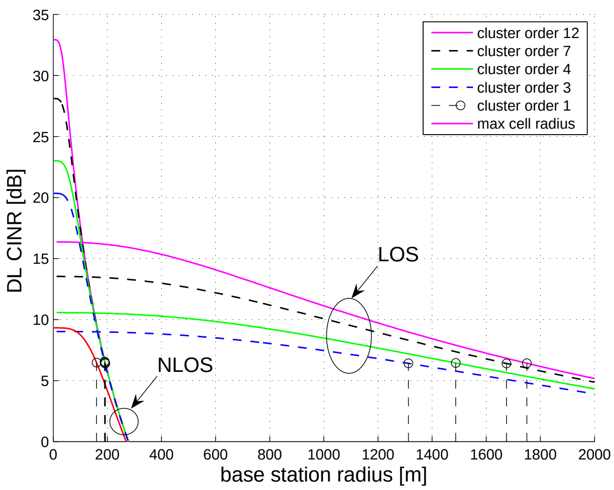
The hight of the two stems at the cell border marks the minimum CINR requirement for the most robust modulation and coding scheme (BPSK½), i.e., 6.4 dB [3]. It can be seen that the actual CINR level at the border is well above the minimum requirement. Thus, the BS radius of 1000 m applied in the particular scenario is valid because it leads to a sufficient CINR at the cell radius. In the following, only the CINR at the cell border is evaluated.

A. LOS Conditions

Figure 3a illustrates the best server, i.e., the BS or relay to which the potential subscriber is associated. Additionally,



(a) Best server (LOS, 1000m cell radius, cluster order 7)



(b) DL CINR at the cell border vs. BS radius

Fig. 3: TDM, omni antennas

circles are plotted, whose radii are the cell and subcell radii as depicted in figure 1a. The best server analysis shows that the inner part of the relay enhanced cell is covered by the BS while the outer cell 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. In distant areas the CINR level is below 6.4 dB.

For dimensioning purposes, the signal quality for the most distant station is crucial. In a relay enhanced cell, this position is at the outer border of a relay subcell. In figure 3a this is at $x = 0\,\mathrm{m},\ y = 2000\,\mathrm{m}$.

In figure 3b, the DL CINR that is perceived by this particular (most distant) SS is plotted versus the BS radius. Note that the BS radius is the radius of the inner cell. The stems indicate the maximum cell radius and the minimum receiver requirement.

Graphs of figure 3b differ by their cluster order and by the propagation condition. With an increasing cluster order, the co-channel distance increases and the interference level decreases. This leads to an increased CINR at the cell border. The size of the cell radius affects the signal quality, too. Larger cell radii lead to decreasing CINR at the border.

In this LOS scenario, where interference is the limiting factor, the system is called *interference-limited*. For all cluster orders larger than one, a valid cell radius can be given. 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 with a BS radius of 1675 m the most distant SS in the multihop deployment is 3350 m away from the BS. Three relays extend the overall coverage area of the BS from 2.598 km^2 to 21.868 km^2, which is a factor of 8.4.

B. NLOS Conditions

Figure 3b also plots the coverage scenario with NLOS propagation conditions. 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). 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 with valid BS radii of 160 m.

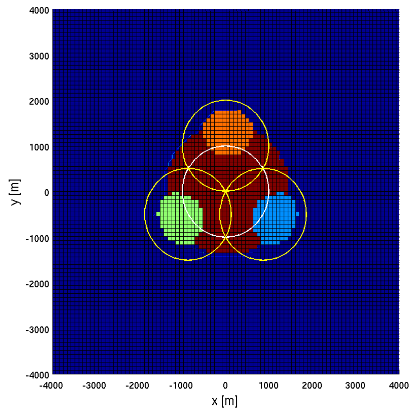
IV. Space Division Multiplex of Relay Subcells

Operating relays in TDM results in high signal quality and large coverage. However, this approach shortens the portion of the MAC frame that is dedicated to each relay station. The mean cell capacity can be increased by operating relays simultaneously. The investigated scenario equals the one of the previous section, except that the three relays transmit concurrently.

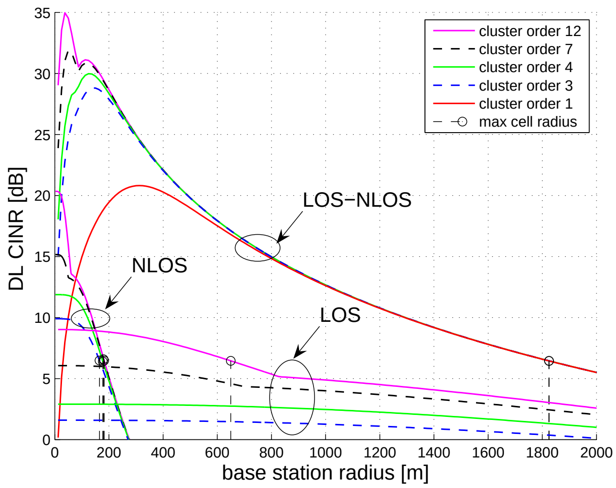
A. LOS Conditions

Figure 4a shows the best server of the relay enhanced cell under LOS conditions. 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 LOS conditions, which is shown in figure 4b 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



(a) Best server (LOS, 1000m cell radius, cluster order 7)



(b) DL CINR at the cell border vs. BS radius

Fig. 4: SDM, omni antennas

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.

B. NLOS Conditions

Figure 4b also plots 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 TDM, the NLOS case is noise-limited. In DL, all cluster orders allow nearly the same maximum cell radius of approximately 175 m.

C. Combined LOS-NLOS Conditions

A simultaneous operation of multiple relays within one cell is not advantageous if the mutual interference of relays cannot be limited. However, in special environments the scenario itself limits the mutual interference. In urban Manhattan scenarios, the source and the destination have a direct LOS connection along the streets. In contrast, the first tier of interferers is shadowed behind buildings, thus a NLOS pathloss results. The same effect occurs in wide-area scenarios when the BSs 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 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.

The best server plot of such a combined LOS-NLOS scenario is nearly the same as with TDM operation shown in figure 3a. The NLOS propagation reduces the co-channel interference of distant cells and the mutual intra-cell interference of relays of the same cell.

Figure 4b plots the DL CINR versus the BS radius of the LOS-NLOS scenario. The shape of the curve differs from the previous ones. Having small radii, the interferers are close and the system is interference-limited. With an increasing radius, the interference attenuates faster than the carrier signal, because they are following different pathloss coefficients. Due to the relative increase of the carrier signal compared to the interference, the CINR increases.

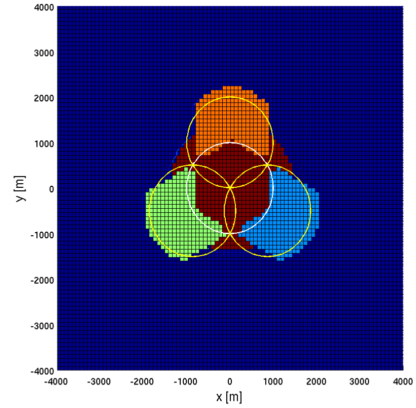
By increasing the radius further, the level of interference becomes small compared to the noise level and the behavior of the system converts to noise-limited. From this point, the attenuation of the carrier signal results in a decreasing CINR. The resulting maximum cell radius lies in the noise-limited part. For all cluster orders the maximum radius in DL is 1825 m. Note that, cluster order one is valid and it results in the same coverage area than all other cluster orders.

V. Space Division Multiplex with Directive Antennas

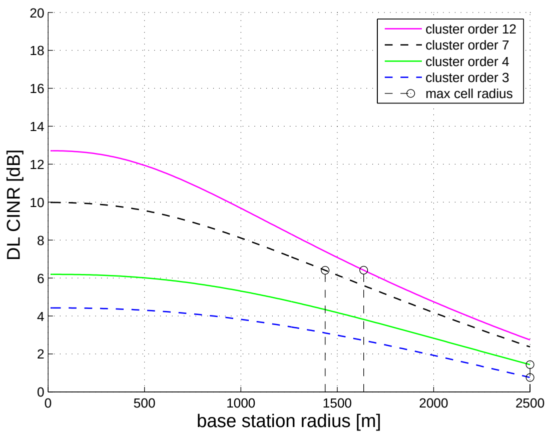
The previous section showed that a simultaneous operation of multiple relays within one cell under LOS conditions, is not advantageous due to heavy mutual interference. In order to control the interference in such scenarios, directive antennas can be used. As shown in figure 1c, the directive antenna 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.

Figure 5a plots the best server of a LOS 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 different. 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 5b plots the DL CINR versus the BS radius for the LOS scenario. Compared to the SDM case with omni antennas, the situation is improved. Cluster orders seven and twelve allow for radii up to 1640 m. This range is close to the radii



(a) Best server (LOS, 1000m cell radius, cluster order 7



(b) DL CINR at the cell border vs. BS radius, LOS

Fig. 5: SDM, directional antennas

of the TDM case shown in figure 3b. However, cluster orders below seven are not sufficient for this setup.

VI. Comparison of Coverage Areas of Cellular Singlehop and Multihop Scenarios

Tables I and II summarize the resulting coverage areas in cellular singlehop and multihop deployments, respectively. The table contains results for different scenarios using cluster order seven. In order to calculate the coverage area, the maximum valid cell radii have been taken from the analysis above. Note that, the coverage of the multihop *throughput scenario* equals the singlehop case. SDM operation using omni-directional antennas in a LOS environment did not result in a valid cell radius. Under all propagation conditions the multihop deployment significantly increases the coverage area.

VII. Capacity of Cellular 802.16 Networks

The CINR in a cellular scenario can be converted into a resulting cell capacity. The link capacity at a certain position $Cap(x, y)$ is a function of the perceived CINR. Reference [8] lists gross PHY data rates for each available PHY mode in the given scenario (20 MHz bandwidth, Cyclic Prefix (CP) of ¼). Minimum receiver requirements (in terms of required CINR)

TABLE I: Maximum BS coverage area in cellular singlehop networks (DL, cluster order 7)

	singlehop coverage	
pathloss	1 sector*	3 sectors
NLOS	0.0889 km^2	0.0938 km^2
LOS	2.5981 km^2	7.2892 km^2
LOS-NLOS	8.6533 km^2	8.6533 km^2
*	applicable to multihop *throughput scenario*	

TABLE II: Maximum BS coverage area in cellular multihop networks (DL, cluster order 7)

	multihop coverage		
pathloss	TDM	SDM omni anten.	SDM dir. anten.
NLOS	0.287 km^2	0.253 km^2	0.281 km^2
LOS	21.868 km^2	*	16.117 km^2
LOS-NLOS	25.960 km^2	25.960 km^2	25.960 km^2
*	no valid cell radius		

for each PHY mode are given in [3]. If perfect link adaptation is assumed, the perceived signal quality can be converted into an achievable data rate. In order to convert PHY data rates into MAC data rates, retransmissions due to packet errors and MAC protocol overhead have to be taken into account. Since the MAC overhead mainly depends on the implemented multihop protocol, which is not yet specified by the IEEE, the following analysis focusses on PHY layer capacity.

SSs that are served by relays perceive a data rate that is influenced by the link capacity of both hops involved. The overall capacity can be calculated by equation 2, in which $Cap_{hop\,1}$ is the capacity of the BS-to-relay link and $Cap_{hop\,2}$ is the relay-to-SS link capacity. In order to increase the link capacity on the first hop, the relay may apply receive antenna gain [2]. This advancement of the first hop converts into an enhanced overall channel capacity.

$$\frac{1}{Cap_{overall}} = \frac{1}{Cap_{hop\,1}} + \frac{1}{Cap_{hop\,2}} \tag{2}$$

Now, the capacity of a SS that is traversing the scenario can be calculated. Figure 6 shows the instantaneous DL capacity while traversing the coverage scenario using omni-directional antennas. The positions of the BS, the relay and the cell edge are indicated. The dashed line shows the TDM case, which corresponds to figure 2b. It can be seen that the main cell is covered by the BS and the relay extends the coverage area to the right hand side.

If the relay station is equipped with an antenna that provides 14 dBi receive antenna gain, it can improve its received CINR on the first hop. This directly converts into an increased link capacity. The dashed-dotted line in figure 6 shows the SDM mode of operation. Here a simultaneous operation of relays decreases the instantaneous channel capacity in a LOS scenario using omni-directional antennas. However, since three relays operate simultaneously, the dotted line indicates the tripled SDM capacity. It can be seen that in some regions the SDM mode is quite beneficial.

Now, the mean cell capacity can be calculated. Reference [9] derives a way to calculate the mean cell capacity of round singlehop cells. This approach has been generalized to

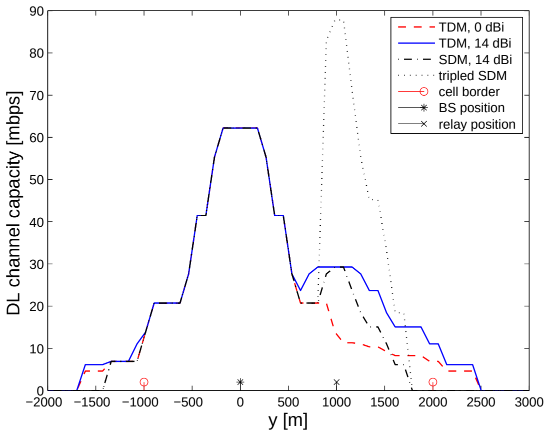


Fig. 6: DL capacity while traversing the scenario (omni antennas, LOS)

calculate the cell capacity of hexagonal singlehop and various multihop deployments. Equation 3 calculates the reciprocal cell capacity as the integral of the reciprocal transmission capacities, which depends on the coordinates x and y of the receiver.

$$\frac{1}{Cap_{cell}} = \int_{cell\ area} \frac{1}{Cap(x,y)}\, dxdy \qquad (3)$$

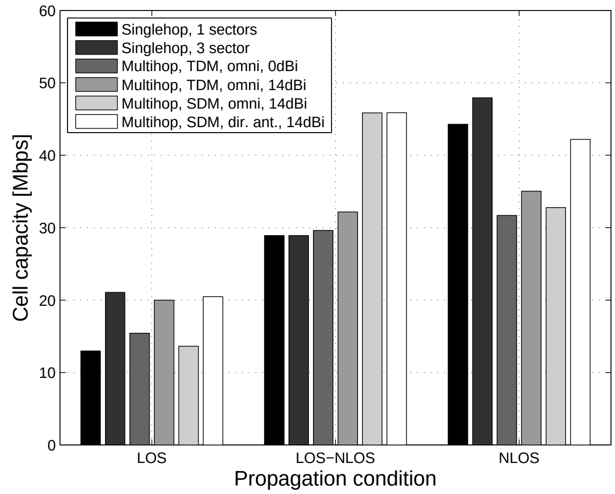
According to the previous dimensioning approach, the cell radius in LOS and LOS-NLOS environments is assumed to be 1000 m. Under NLOS propagation conditions the cell radius is set to 150 m. All entries were calculated for cluster order seven.

Figure 7a visualizes the mean cell capacity of exemplary singlehop and multihop *throughput* scenarios. In singlehop deployments under LOS conditions, sectorization significantly increases the cell capacity, because the system is interference-limited. Under NLOS conditions, the benefit of sectorization decreases. In LOS-NLOS scenarios, which are noise-limited, sectorization is not effective any more because interference is already limited by the propagation conditions. In NLOS environments the cell capacity reaches a maximum, but it has to be considered that the coverage area of the cell is much smaller.

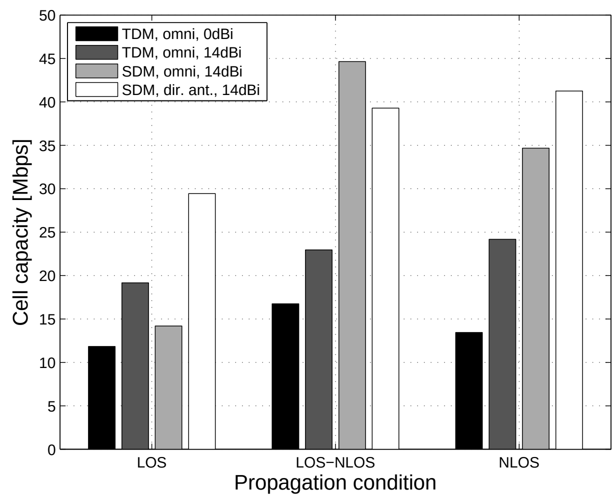
Looking at TDM multihop modes, it can be seen that receive antenna gain at the relay improves the cell capacity under all propagation conditions. SDM operation of relays using omni-directional antennas is only beneficial when the interference can be limited under LOS-NLOS propagation conditions. In LOS and NLOS environments, the mean cell capacity during SDM operation drops below the TDM case.

In order to control inter- and especially intra-cell interference in SDM mode, directive antennas were introduced. In NLOS scenarios they increase the cell capacity beyond the TDM case. Under LOS conditions, directive antennas are only able to increase the cell capacity up to the original TDM mode.

Comparing singlehop and multihop *throughput* scenarios, it can be seen that under LOS and NLOS conditions, the



(a) Singlehop and multihop *throughput* scenarios



(b) Multihop *coverage* scenarios

Fig. 7: Mean cell capacity

multihop capacity is less or equal to the singlehop capacity. If one considers the additional MAC overhead that is needed to control the multihop transmission, a singlehop deployment should be preferred. In scenarios where the relay subcells are highly shadowed from each other, i.e., under LOS-NLOS conditions, a multihop deployment can increase the cell capacity, especially in SDM mode. However, the additional MAC overhead and the cost for deploying and operating the relay devices have to be taken into account.

Figure 7b visualizes the mean cell capacity of selected multihop *coverage* scenarios. Like in the multihop *throughput* scenarios, the introduction of receive antenna gain increases the cell capacity of the multihop *coverage* scenarios under all propagation conditions. Since the relays are located farther apart from the BSs in the *coverage* scenarios, the benefit of receive antenna gain on the first hop is larger than in the previous *throughput* scenarios.

SDM operation of relays using omni-directional antennas can further increase the cell capacity in LOS-NLOS and even in NLOS scenarios. Here, the interference is limited by the propagation conditions. Additionally, the distance between simultaneously operating relay stations is larger in the *coverage* scenarios compared to the *throughput* scenarios. Again, omni-directional antennas at the relays generate too much mutual interference in the LOS environment so that the mean cell capacity during SDM operation drops below the TDM case.

SDM operation of relays with directive antennas outperforms the other modes of operation under LOS and NLOS conditions. A significant increase is visible. In LOS-NLOS environments, the mutual interference of concurrently operating relays is negligible even with omni-directional antennas. Thus, the larger area (360° instead of 240°) that is covered by the relay antenna increases the mean cell capacity.

In order to finally compare singlehop and multihop *coverage* deployments, the different sizes of their coverage areas have to be considered. By simply comparing their area spectral efficiencies, singlehop deployments seem to be beneficial because their mean cell capacities are higher and their coverage areas are smaller. Under all propagation conditions, the maximum area spectral efficiency of multihop *coverage* deployments is lower than the efficiency of singlehop deployments even without sectorization. The true benefit of multihop deployments is the cost-efficient roll-out and operation of such networks. Thus, a fair comparison would have to take Capital Expenditures (CAPEXs) and Operational Expenditures (OPEXs) into account.

VIII. 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.

Regarding the capacity of multihop network, the results are two-folded. In *throughput* scenarios, where relays are placed inside the BS coverage area, an effective capacity enhancement is not possible in pure LOS or NLOS scenarios. Here, the mean cell capacity is decreased compared to the singlehop case. In LOS-NLOS scenarios (Manhattan or antenna tilt) the cell capacity can be increased, especially by combining SDM operation and receive antenna gain at the relay.

In *coverage* scenarios, relays are placed at the original BSs' cell edge. This extends the coverage of the BS. Again, the cell capacity can be enhanced by SDM operation and receive antenna gain. In scenarios where interference affects the signal quality, i.e., in LOS and NLOS scenarios, directive antennas further reduces interference and thus increases the cell capacity.

Acknowledgment

This work has been performed in the framework of the FP6 project FIREWORKS IST-27675 STP, which is funded by the European Community.

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BPSK	Binary Phase Shift Keying
BS	Base Station
BW	Bandwidth
CAPEX	Capital Expenditure
CINR	Carrier to Interference and Noise Ratio
CIR	Carrier to Interference Ratio
CP	Cyclic Prefix
DL	Downlink
EIRP	Equivalent Isotropic Radiated Power
FDD	Frequency Division Duplex
LOS	Line-of-Sight
NLOS	Non Line-of-Sight
OPEX	Operational Expenditure
SDM	Space Division Multiplex
SS	Subscriber Station
TDD	Time Division Duplex
TDM	Time Division Multiplex
UL	Uplink