Relay vs. Repeater Architectures in WiMAX

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Abstract. This paper aims at describing the advantages of using relay and repeater elements in a wireless network and especially in a network based on WiMAX technology. Apart from a description of the relay and repeater entities, a comparison between them is presented based on computer simulations. All presented material is based on the findings and results of the FP7-REWIND project.

Keywords: Relay, Repeater, WiMAX, Performance, REWIND.

1 Introduction

The high cost of communication spectrum has forced telecom operators in designing even more efficient frequency reuse schemes. These schemes maintain acceptable levels of network performance in terms of both capacity and service quality, without the expenses that obtaining new frequencies would induce. The concept of microcellular architecture is a widely used approach in network design and is being used by many operators for both indoor and outdoor coverage. The introduction of low cost base stations (micro BS) within the coverage area of a Macro base station can result in significant improvements in coverage, capacity and provided quality of service. The above mentioned architecture is sometimes described as "Overlay/Underlay" and is depicted in Figure 1.

As depicted in the figure, the "macro" base station participates in the Overlay architecture and provides coverage to a wider area, while the Underlay structure comprises of "micro" base stations that are positioned near areas with increased capacity demands or areas that cannot be adequately covered (e.g. due to obstacles) by the macro base station [1].

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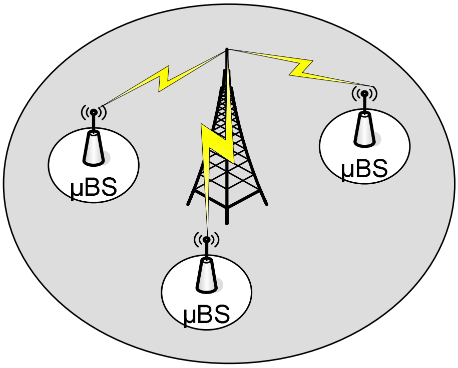


Fig. 1. Overlay/Underlay Architecture

Relay and repeater entities can be easily introduced in an already existing network to meet the increasing demand in traffic capacity [2]. The latter is advantageous for Brownfield networks, where the initial network planning needs to be enhanced without the costs of redesign and frequency reallocation. The usage of underlay structures can be used upon an existing network in order to fill coverage gaps or to increase the capacity of specific locations [3].

2 Usage of Underlay Elements in WIMAX Networks

The advantages of overlay structures are even more important when used in networks that implement adaptive modulation and coding schemes, in which the radio link quality directly affects the total data throughput. When a link has low Signal to Interference and Noise Ratio (SINR), low modulation and coding schemes are used and this severely affects the radio resource allocation and hence system's performance. When a single base station covers an entire area, optimum resource allocation will be realized only for the subscribers that are located near it. This will be achieved by means of high modulation and coding schemes that consequently provide high spectral efficiency. As far as the rest of the subscribers are concerned and because of the presence of factors that degrade link quality (e.g. adjacent cell interference), modulation and coding will be of lower efficiency and therefore the resource allocation will not be optimal. By introducing underlay network elements such as Micro, Pico or Femto base stations, the number of subscribers located near base stations and correspondingly the subscribers using the spectrum in a more efficient way increases [4].

Figure 2 illustrates the modulation used by subscribers when a single base station serves an entire cell, in comparison with the case where the base station is supported by nine underlay base stations. It can be seen that introducing the underlay architecture, not only improves the average modulation scheme that is used by the subscribers served, but also significantly reduces the number of MSs that cannot be

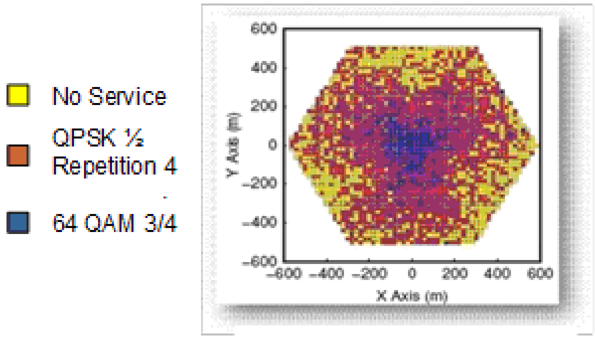


Fig. 2a. Subscriber modulations using Macro Base Station only

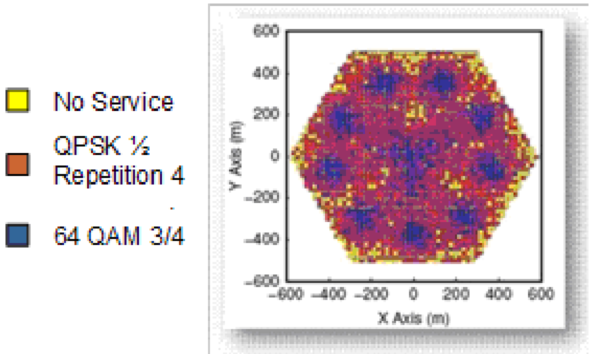


Fig. 2b. Subscriber modulation using Base Station with nine underlay Base Stations

served within the cell. Those subscribers are most of the times located near cell boundaries and service cannot be provided to them either because of range limitations or by interference from adjacent cells.

One of the major issues of using underlay structures in cellular systems is the backhaul link that connects the Micro/Pico/Femto base station with the core network. The cost of a leased line or a wireless link could significantly increase the cost of such a base station and this is a major concern for operators that must install large numbers of underlay elements for their network. The latter becomes even more significant in cases where the required bandwidth is high and hence the cost of operation for the backhauling infrastructure can be higher than that of the entire base station.

An alternative flexible approach to the high costs of backhauling is the usage of relay elements with self backhauling capabilities or even repeaters that amplify the signal within a cell and improve the overall link performance. Even though relays and repeaters are similar in terms of not requiring a dedicated backhaul connection, there are significant differences between them in resource allocation and capacity enhancement.

3 Radio Resource Optimization Using Underlay Structures

Although a first approach might show that the resources of the main base station are depleted in case a relay is served as well, it is the opposite that is true. By using underlay elements, the total radio resources are used in a more efficient way and hence more bandwidth can be provided to the subscribers. In order to illustrate how an underlay structure can improve the radio resource allocation in a cell, we will consider a simplified case with only two modulation and coding schemes. The high modulation scheme will be 64QAM ¾, while the low modulation scheme will be QPSK ¾. The only factor that the system uses to choose between the two available schemes is the SINR of the base station to subscriber station link. It will also be assumed that by using underlay structures, users that had bad link conditions with low modulation schemes will be moved to high modulation because of the SINR improvement. As a result of the highest modulation scheme, the spectral efficiency is improved by a factor of 4 [5].

For example, we will consider a radio frame with 24 time units that are used by the base station for providing data to multiple subscribers in a TDMA way, while for sakes of simplicity we will only consider the downlink part of the frame and that data requirements of each subscriber are equal within each frame. Figure 3a shows the allocation of resources in a radio frame when 12 users in total are located in the cell, 8 are served via high SINR links and 64QAM ¾ modulation while the remaining 4 are under inferior link conditions using QPSK ¾ for data transmission [6].

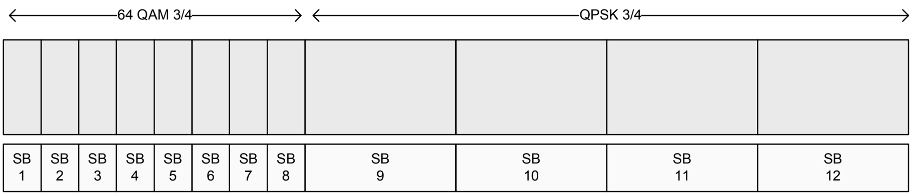


Fig. 3a. Radio Frame usage without underlay elements

The addition of an overlay entity improves the link conditions of the low SINR subscribers and this improves their modulation scheme to 64QAM, increasing thus their spectral efficiency by a factor of 4. The latter results in freed radio resources that can be reallocated to either provide more bandwidth to the subscribers or serve new subscribers within the cell. Figure 3b shows the new allocation of resources when an underlay entity is used.

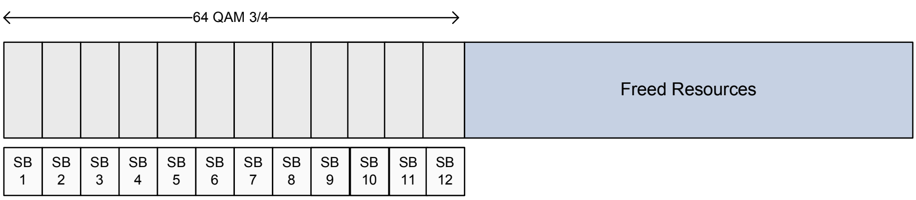


Fig. 3b. Radio Frame usage with underlay elements

Depending on the number of subscribers that were using low modulation schemes, the percentage of freed resources can vary. This proves that a properly installed Micro/Pico/Femto base station that improves as many low quality links as possible can be beneficial for total cell performance. Table 1 shows the percentage of freed resources that can be achieved by using underlay structures, depending on the number of subscribers under low modulation schemes when no such structures are present.

Table 1. Freed resources using underlay structures

64QAM 3/4 Links	QPSK 3/4 Links	Time Slots Used before	Time Slots Used after	Freed Resources
8	4	24	12	50,0%
4	5	24	9	37,5%
0	6	24	6	25,0%

4 Using Repeaters for Performance Improvements

Repeaters are passive elements that are mainly used for coverage extension within a cell. A major usage scenario for repeaters is extending coverage to indoor environments. Even though outdoor repeaters are common as well, the extension of a cell inside a building by means of a repeater is widely used. A repeater uses a directional link to establish connection with the donor base station and an omni-directional antenna for providing services to subscribers. Repeaters can be pure analogue, amplifying the received signal and noise, or digital where noise is removed and only the digital signal is regenerated and amplified. The repeater is totally transparent to both the base stations and mobile subscribers and this is considered a major advantage since no adaptation is required in the already installed equipment. An additional advantage of repeaters is the relatively low cost compared to active equipment such as relays and the ease of installation compared to solutions that do not have self backhauling capabilities [7].

On the other hand, the passive nature of the repeater requires careful planning of installation in order to keep the interference at acceptable levels. Proper configuration of downlink and uplink repeater gains will allow all users to operate in an efficient way (keeping SINR high) irrespectively of their position in the cell. The downlink gain is usually configured high so that the coverage is extended within the cell. The uplink gain is in most of the cases configured lower so that the directional link with the donor base station does not affect cell's performance by introducing excessive levels of thermal noise towards the BS.

Some more advanced repeater implementations can operate using transmission power control schemes and start transmission only when there are subscribers served by it. In case no subscribers exist, the repeater stops transmitting, reducing thus the interference levels for the rest of the subscribers located inside the cell and served directly by the BS. Relays can be used not only in a distributed topology inside a cell but also in a cascaded scheme where a chain of repeaters continuously amplify the signal and extend maximum cell coverage. It has to be mentioned that a limiting factor in the number of repeaters that can be cascaded, apart from the interference levels, is the delay introduced from one hop to the next. The total delay of data transmission should be kept within reasonable levels so all types of applications can be supported, both real time and non-real time. As mentioned above, repeaters are transparent elements inside a network and so no mobility procedures are triggered when a user is being served by one repeater and then from another. This means that no extra delays are introduced for moving subscribers compared to the case where individual BSs would serve the area [8].

5 The Relay as a Self-backhauled Element

BTS Relays are sometimes regarded as similar to repeaters since they are both underlay structures that can be used to extend the coverage of a cellular network. This is partially correct but there are significant functionality aspects that make relays different than repeaters. Since a relay operates as a self backhauled BTS, it is an active network component and can be considered as a full featured base station. This results to the creation of extra capacity for the network in a way similar to the concept of cell splitting that is used in almost every cellular network.

Even though optimization of radio resources is realized in both repeater and relay networks, the usage of relays can increase the total number of subscribers and throughput of a cell. A relay station must be considered as an entity that is closer to a base station rather than a repeater. Relays follow the same rules as base stations as far as network planning is concerned, while from a monitoring perspective their management can be the same as that of the base stations of the network and this is an important factor for telecom providers that require unified management and monitoring systems for their networks. A relay station can operate either in Time division Transmit and Receive (TTR) or in Simultaneous Transmit and Receive (STR) mode.

In the first case, the relay station uses a part of the available timeframe for communicating with the donor base station and the rest for access purposes with the MSs. On the other hand, STR relay stations require dual antennas and radios, increasing thus the final cost of the relay. In both STR and TTR configurations the relay functions as a self-backhauled BTS without the support of additional infrastructure. This is achieved by allocating a part of the available radio resources for communication with the donor and another part for communication with the subordinate elements that can either be subscriber terminals or other relay stations that are connected in a cascaded topology with it [9], [10]. Figure 5 illustrates the basic operation of the relay station and its in-band backhauling functionality.

An additional aspect of relay implementations is the layer of operation. Packet forwarding can be performed on layer 2 or layer 3. The implementation using layer 2 relaying is relatively simpler than that of layer 3 but using layer 3 relays does not require changing the protocol stacks of existing network entities and so can be easily incorporated into already deployed networks.

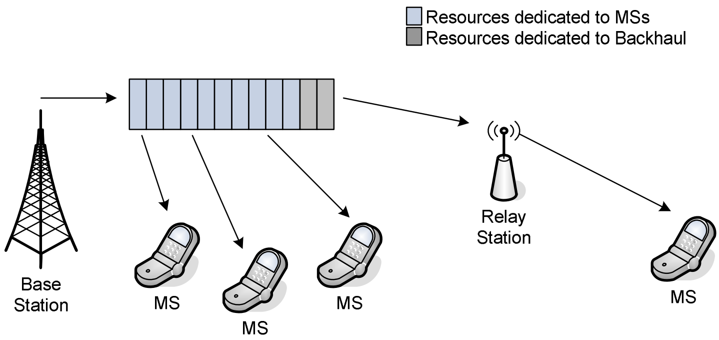


Fig. 5. Self-Backhauled BTS Concept

6 Relay vs. Repeaters Throughput Enhancement

As described in the previous sections, the optimization in radio resource allocation achieved by the introduction of underlay structures in a network, results in the increase of total throughput. In order to quantify the differences in throughput enhancement, simulations were run in a Matlab custom simulator and estimated the total throughput of a single sector, taking into consideration the Manhattan grid. Interference is also considered in terms of SINR. SINR stands for Signal to Interference plus Noise ratio. The scenarios that were considered included: no underlay structures in the cell, two repeaters in each sector, two TTR relays in each sector and two STR relays in each sector. The network used for the simulations consisted of a canonical cell distribution, comprising of 19 three-sector cells. Figure 6 shows the network layout that was used for relay and repeater performance comparison.

The distance between base stations located at the centre of each cell was set to 1000m. The location of the corresponding underlay structures is shown in Figure 7. Two repeater/relay stations were assumed per sector (6 in total per cell) while their distance from the base station was set to be 2/3 of the maximum cell radius. The simulation assumes that in each area where relays are installed, obstacles exist that deter the link conditions for subscribers located near it.

The subscribers were assumed to belong to either densely populated areas, which were the shadowed areas covered by the underlay structures or normally populated areas that were occupying the rest of the cell. In both areas, a uniform subscriber distribution was used, while the number of subscribers inside shadowed (dense) compared the rest of the cell was greater by a factor equal to the “subscriber’s density ratio”. The total radio spectrum that was used for the simulation was 30MHz, allocating thus 10MHz for each sector that is equivalent to 30 WiMAX channels per sector. Each sub channel can be allocated to a different subscriber station, resulting in 30 subscribers per sector. Concerning the RF parameters of the simulation, a transmit power of 40dBm was taken for the base station, while the receive sensitivity was equal to:

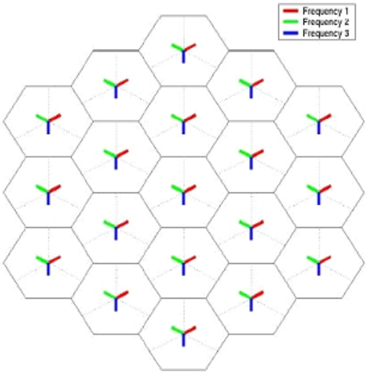


Fig. 6. Topology of the simulated network

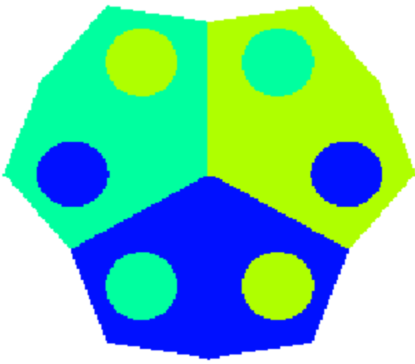


Fig. 7. Location of underlay structures inside a cell

$$\text{Sensitivity} = -174 + 10\log(BW) + NF_{User} + \text{Impl.Loss} \quad (1)$$

NF_{User} is the user's noise figure and an additional implementation loss was considered. The total base station sensitivity was calculated to be -96.7 dBm. A base station with three 120 degree sectors was assumed and the antenna gain was 16 dBi. For the relay station, a transmission power of 30dBm was assumed and the receiver sensitivity was the same as that of the base station. The relay station was assumed to have a 6dBi gain omnidirectional antenna for the access link and a directional antenna for backhaul communication with 16dBi gain [11].

The propagation model of the simulation included two cases. The first one referred to MSs served directly by the base station and assumed that all subscribers are located below rooftop level with NLOS link conditions. Figure 8 depicts the transmission channel for those users.

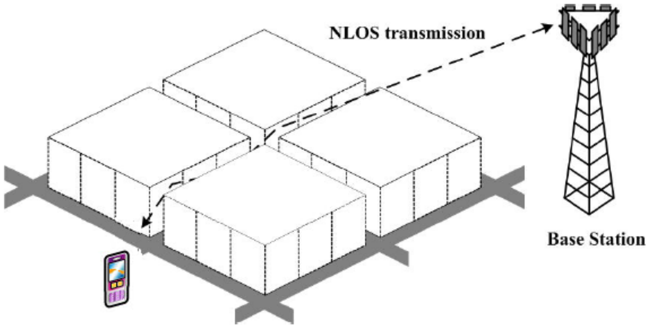


Fig. 8. NLOS transmission of Base Station to Mobile Station

The transmission environment that was chosen was of urban type and the path loss expression was taken as:

$$PL = 38.4 + 35\log(distance) \quad (2)$$

For the subscribers that will be served by an underlay structure, two links were considered. The first one was the base station to relay station (backhaul) link under line of sight conditions while the relay station to subscriber link was assumed to be a non line of sight link. Figures 9a & 9b show the links used for the subscribers served by relay stations.

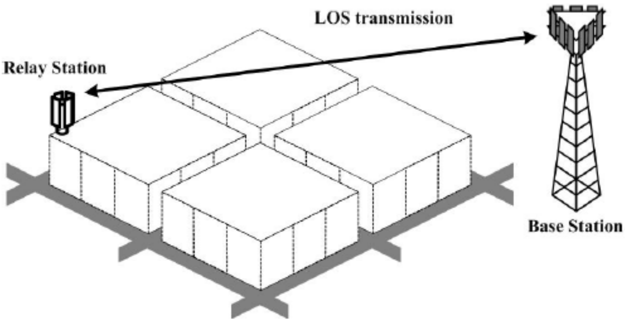


Fig. 9a. Backhaul link for the Relay Station

The propagation model for the relay station to subscriber will be the same NLOS model used for subscribers served directly by the base station. For the backhaul link, line of sight conditions are assumed between the base station and the relay. In addition to the path losses mentioned above, shadowing was taken under consideration with a standard deviation of 4, which better corresponds to the urban environment of the simulation [12-14].

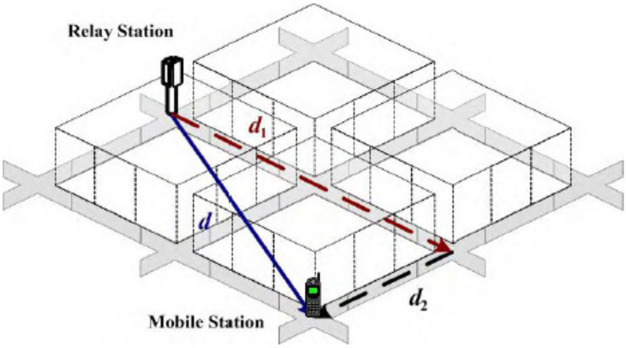
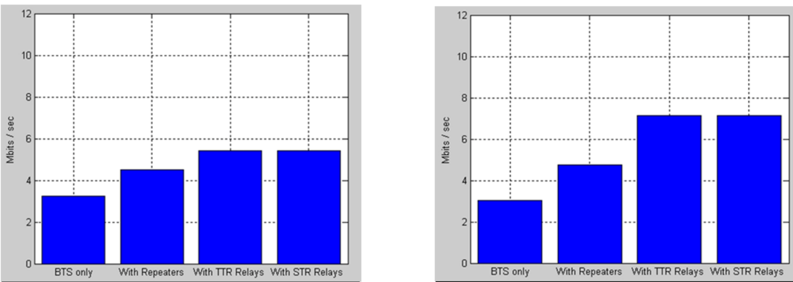


Fig. 9b. Access links for the relay station

The simulation results demonstrate how the total throughput of a sector is improved by using underlay structures. Figure 10a shows the results for the scenario where the radius of the shadowed area is 100m, which means that about 25% of the sector is covered by underlay elements. A fixed obstruction loss of 5 dB was considered, while the number of subscribers in the shadowed areas was 6 times higher than that of the rest of the sector. As a result of the size of the shadowed regions and the subscriber density ratio, the number of users served by relays or repeaters is 40% of the total number of subscribers. The graph shows that by using repeaters there is a 25% improvement in total sector throughput while the introduction of relays (TTR or STR) increases total throughput by 60%.

Figure 10b presents the same scenario but with a higher subscriber density ratio. Because the subscribers served by relays or repeaters is now 60% of the total number, the improvement is greater when relays are used compared to repeaters. The improvement with repeaters is about 60% while relays improve throughput by more that 140%. In this case the improvement provided by STR and TTR relays is the same since the required throughput (according to simulation assumptions) can be fulfilled within the time intervals allowed by the TTR relay and there is no need for the relay to transmit and receive simultaneously, a feature that only STR supports.



Radius of shadowed area [m]	100
Obstruction Loss [dB]	5
Subscriber's density ratio	6
In / Out users ratio [%] (calculated)	40

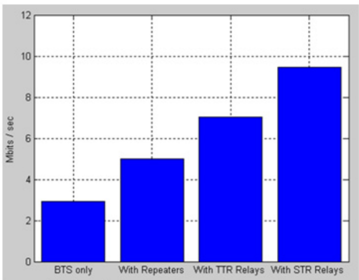
(10a)

Radius of shadowed area [m]	100
Obstruction Loss [dB]	5
Subscriber's density ratio	9
In / Out users ratio [%] (calculated)	60

(10b)

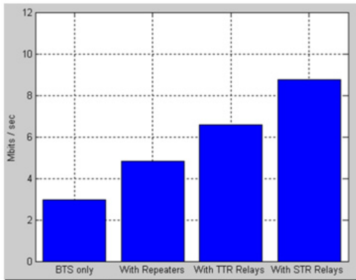
Fig. 10a & 10b. Total sector throughput comparison

When throughput requirements for the shadowed areas increase even more, then relays supporting STR operation outperform all other alternatives. In order to verify the latter, a scenario with double the subscriber density ratio was simulated. If the ratio is increased to 18 then the In/Out users ratio shows that 3 out of 4 subscribers are located in the shadowed areas and hence the capacity requirements for relays/repeaters are even higher. In this case, relays supporting STR can give an enhancement of the order of 220%, TTR relays improve total throughput by 140% and repeaters by 66%. The results obtained are similar when the radius of the shadowed areas is increased to 150 meters, occupying thus about 54% of the total cell area. A difference to the previous case is that the density ratio was again set equal to 9. The results of the simulation are shown in figure 11b. The throughput gain in this case is 10% lower than the gain of the previous scenario but this can be explained by the extended range of the shadowed areas. Because part of the areas is impacted by co-channel interference coming either from other repeaters/relays or neighbouring sectors, the total performance of the relay is inferior, affecting thus the maximum throughput achieved.



Radius of shadowed area [m]	100
Obstruction Loss [dB]	5
Subscriber's density ratio	18
In / Out users ratio [%] (calculated)	74

(11a)



Radius of shadowed area [m]	150
Obstruction Loss [dB]	5
Subscriber's density ratio	9
In / Out users ratio [%] (calculated)	74

(11b)

Fig. 11a & 11b. Total sector throughput comparison (STR operation)

7 Other Advantages of Relays vs. Repeaters

As shown from the simulation results, relays can provide significant throughput improvements in comparison with repeaters. In addition to the throughput, other advantages of relays are summarized below [15]:

- **Capacity Increase** – When the Relay station is operated, the overall capacity utilized by the Macro base-station serving, as the donor for the Relay will be increased by at least 50%. This increase will be experienced if prior to using the relay station, the signal quality available to the subscribers is poor (i.e. only QPSK signals could be received) and that subscribers' distribution around the Macro base-station is uniform.

- **Frequency Re-Utilization** – The Relay Station will backhaul its traffic to a Macro base-station using the same frequency band used for serving its subscribers. If for example a base station works at a frequency f1 and employs two Relay Stations with adjacent frequencies f2 and f3, the whole coverage area will utilize a frequency spectrum including f1, f2 and f3 frequency.
- **Price Target** - A Relay station (STR and TTR) should have a volume operator price-point of less than 20% of a full-scale (3-sector) base-station.

The advantages of Relay Stations include extended coverage and increased throughput with the same QoS as the current networks, without any requirement for changes or upgrade to the user terminal that was defined by the already completed IEEE802.16e standard. The relay station deployment will be cost effective in term of both OPEX (Operational Expenditures) and CAPEX (Capital Expenditures) since its implementation yields inexpensive, small size and simple to install system that do not need any backhaul arrangement or external antennas.

In addition, Relays leave a lot of room for vendor specific implementation for improving capacity, QoS and spectrum utilization by introducing beyond state-of-the -art technologies such as adaptive antenna systems (AAS) and beam forming, close and open loop MIMO spatial multiplexing, novel coding that combines modern Hybrid Automatic Request (HARQ) techniques, smart network radio resource management procedures and improvement of power efficiency of power amplifiers.

8 Conclusions

This paper discussed the concepts of underlay structures, the benefits they could provide to the network and compared relays and repeaters in terms of theory and simulations. Simulation results showed the advantages that relays have over repeaters and the improved throughput enhancement achieved by repeaters operating in TTR or STR mode. The simulations also showed the advantages of an STR relay over a TTR when high capacity is required to be delivered to subscribers. Self-backhauled relays can be a flexible and cost effective solution for many providers that need to extend the capabilities of their existing network or cover locations with high capacity demands. Relays have most of the characteristics required by telecommunication providers and are considered one of the most efficient solutions for the increasing demands of service provisioning with current and upcoming wireless technologies.

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