Client-based Relay Infrastructure for WiMAX MAN Networks

Gierłowski, Woźniak and Nowicki
Gdansk University of Technology
Poland

1. Introduction

New WiMAX technology, based on IEEE 802.16 (IEEE, 2004) standards family, offers several advantages over currently available metropolitan-area wireless access solutions, which are mainly GSM or UMTS-based. It is cost effective, evolving, and robust – able to provide reliable, fast and Quality of Service (QoS) aware transmissions over significant distances. WiMAX technology provides both line-of-sight (LOS) and no-line-of-sight (NLOS) solutions. The LOS solution allows transmissions with rates over 70 Mbps over distances up to 50 kilometers (or even more), as long as antennas of both devices have straight (not shaded) view of each other. The second one supplies a connectivity using reflected signals when a path between antennas is shaded by various obstacles. In such case the range is limited to about 5 kilometers. The technology also supports different modulation and coding schemes coupled with their adaptive adjustment in order to maximize stable coverage area.
Other strong advantages of WiMAX systems include high security, reliability and integrated QoS support, which jointly allow operators to guarantee their users a required level of network services.
The most popular WiMAX system architecture follows a point-to-multipoint (PtMP) data communications model with a coordinating base station (BS) and participating client terminals (subscriber stations - SSs). Such architecture has undisputed advantages of easy monitoring and management, relatively simple (and cheaper) client terminals and well developed methods of deployment. It also proves adequate for most real-world scenarios.
Unfortunately, measurements conducted in our WiMAX test-bed installation uncovered the "coverage white spots" effect – small areas lacking satisfactory signal quality, located within otherwise well covered area. This effect strongly undermines the popular beliefs concerning excellent performance of WiMAX NLOS mechanisms and can significantly raise cost of network deployment – about the only solution, if we want to provide good coverage (especially for nomadic and mobile users) in PtMP environment, is to install additional base stations.
As the alternative to PtMP mode, the standard also specifies a foundation of a mesh-mode in which peer stations participate in self-organizing network structure by creating logical links between themselves and utilize multihop transmission mode. Such infrastructure provides many unique advantages, including better coverage, as any connecting client will serve as

BS and provide service to others. Scalability of properly configured mesh network is also very good, as any connecting client extends available network resources and massive redundancy makes it extremely resistant to malfunctions.

Regrettably WiMAX mesh mode is currently at very early stage of development while mechanisms necessary for it to function trend to be both numerous and complicated. Because of these reasons the idea of WiMAX mesh network receives at best limited support of hardware manufacturers and we will probably wait for a long time to see it in fully functional, standardized form. Instead, a relay-based approach is gaining momentum and we should expect operational solution very soon.

In the following chapter we describe difficulties encountered in estimating the WiMAX installation coverage by either theoretical or empirical methods. We propose our original approach to fast WiMAX coverage estimation with use of standard subscriber equipment.

Moreover, we describe characteristics of existing WiMAX architectures and propose an alternative, original solution based on both classical point to multipoint (PtMP) and mesh/relay architectures, intended to offset aforementioned "coverage white spot" effect. Our solution extends WiMAX subscriber station functionality to provide it with an ability to act as relay and provide access to other clients. Furthermore, the relay architecture may consist of several levels of relays, forming easily reconfigurable tree-like structure.

The proposed solution was designed to be as uncomplicated as possible and provide maximum compatibility with existing installations. Therefore there is no deed for client terminal modification to provide it with an ability to use our relaying clients for communication. Moreover, in compatibility mode (one of our extension's two basic modes of operation), BS requires no modification and is not even aware that relay nodes are present in the system.

Simulation tests proved that described system can provide solid coverage in vast majority of difficult scenarios including countering the "coverage white spots" effect and can also be used to extend range of a WiMAX system without need for additional, costly BSs. Automatic tree reconfiguration ability makes it resistant to wide range of malfunctions, if sufficient number of relay nodes is present. It is also simple, cost effective and retains most advantages of a mesh mode, while the necessary mechanisms are much easier to design, implement, operate and maintain.

2. Theoretical coverage models

In all types of wireless systems, including WiMAX, prediction of their coverage area is a very challenging task, especially when we want to mark out the coverage with a required accuracy. Because of this there is a need for methods to verify provisional results, obtained via theoretical calculations. There are two basic methods used for current design practices. The first one requires a test-bed installation and depends entirely on empirical measurements. The second one includes software tools able to estimate system coverage with use of one of available propagation models. As the first method is rather time consuming and costly, the software tools are widely used to support coverage calculation for wireless systems, such as short range local area systems (WLANs) or more complex wide area networks, consisting of multiple BSs (WMANs, WWANs).

There are two basic types of propagation models employed in wireless systems design [2,3]:

- empirical (or statistical) models, which are based on a stochastic analysis of series of measurements conducted in the area of interest. They are relatively easy to implement but not very sensitive to environment's geometry,
- site-specific (or deterministic) models, which are far more accurate and do not need signal measurements. However, they require huge amounts of data concerning environment geometry, terrain profile, etc. and high computational efforts.

WiMAX systems should usually provide effective coverage in highly urbanized environments. Following this requirement we are mostly interested in deterministic models, as they can give us results sufficiently accurate for such areas.
Of course, there is always a theoretical possibility to calculate exact propagation characteristics solving sets of Maxwell's equations. However, this method would require very complex data processing and very high computational power, causing such solution to be very inefficient. Due to this fact, current software tools, based on a deterministic propagation model, usually employ simplified simulations: mainly ray-tracing or ray-lunching techniques, based on Uniform Geometrical Theory of Diffraction (UTD) (Sarkar T. K. et al., 2003). Such approach enables significant simplification in calculations, making the model an efficient design tool, but with a loss of accuracy.
WiMAX technology coverage characteristics differ significantly from other wireless network technologies that are employed in similar environments (mainly due to its NLOS capability – see Figure 1), thus a dedicated software model is required to give exact results (ATDI, 2007).

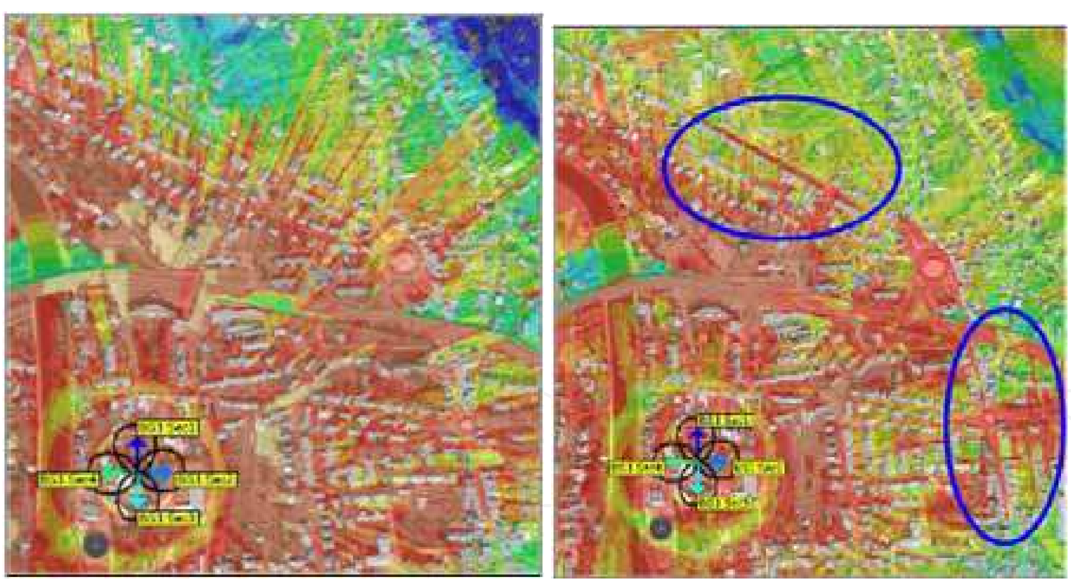

Fig. 1. Comparision of WiMAX coverage estimation results. Left picture – standard propagation model, right picture – specialized, WiMAX propagation model.

Regardless of employed theoretical models and their accuracy, experience in wireless systems design and implementation suggests a necessity of conducting empirical measurements in order to confirm that the system design and theoretically obtained parameters are correct (Olejnik R., 2007). In accordance with a good design practice we implemented a test-bed installation of WiMAX with one base station, and conducted extensive measurements and tests of its coverage and transmission parameters (Gierłowski K. & Nowicki K., 2006).

3. Test-bed installation and example measurements

From both modeling procedures and hardware manufacturers' tests it is clear that WiMAX technology is indeed very well suited for metropolitan environment and generally offers good coverage, even in highly urbanized areas (WiMAX Forum, 2007). To verify these statements and prove accuracy of available software design tools as well as to gather practical design experience, we prepared a study test-bed installation consisting of a single WiMAX BS located at Gdansk University of Technology.

We employed a BreezeMAX Micro Base Station (Alvarion, 2006) provided by Alvarion company and using 3.5 GHz licensed frequency band.

We also developed a dedicated software package consisting of a number of control and monitoring tools. They communicate with BS, client terminals, GPS receivers and are able to automate the experiments to a significant degree.

Moreover, we are currently monitoring long term operation parameters of WiMAX installation, with use of SNMP-based monitoring system developed especially for this purpose. It allows gathering and presentation of over 200 parameters concerning BS, SSs and provided services.

One of our main points of interest was the coverage of WiMAX services in a densely populated metropolitan environment. We performed a variety of tests including:

- measurements of BS signal strength in physical layer,
- modulation and coding profile usage as function of signal quality,
- efficiency of transmission in media access control layer (BER, PER),
- quality of service contract adherence for transport layer services.

The tests were performed with use of hardware spectrum analyzer, equipped with an omnidirectional antenna, BreezeMAX PRO BS, SS subscriber stations (PRO and Si models) (Alvarion, 2006) and transmission performance counters of the base station.

Overall test results confirmed that, in case of LOS, using the equipment mentioned above, we could expect a reliable communication up to 30 km, and 5 km in majority of cases related to NLOS scenarios (Gierłowski K. & Nowicki K., 2006).

Such general statements sound promising. However, we also made quite unexpected observations. It turned out that in case of NLOS communication the network did not cover entirely the tested area. We were able to find multiple small areas not covered by our BS ("coverage white spots"). In some cases, using WiMAX specific propagation models, it would be possible to predict such areas - taking into account terrain profiles and buildings layout.

At the same time, we also detected that there are many locations at which the measured coverage (signal parameters) differs significantly from theoretical estimates. In some places the coverage was a result of repeatedly reflected signals or signals reflected by various objects either improbable or difficult to map, like trees, billboards, trains, trucks, etc. Other places showed a lack of the coverage despite of relatively minor obstacles between BS and a client terminal, thus creating coverage white spots (Figure 2). Our measurements also showed that even a very small displacement (20 m horizontal and/or 3 m vertical) of a client station can result in a dramatic degradation of the transmission parameters - from the best possible modulation and coding profile (QAM64 3/4) to the complete loss of connectivity. This effect makes a WiMAX system design a very difficult task, requiring empirical measurements to validate the project.

Fig. 2. WiMAX coverage white spot effect. Measurements taken in testbed employing a single BS working in 3.5 GHz band. Colors show stable modulation chosen by a terminal: x – no connectivity, blue – BPSK, green – QPSK, yellow – QAM16, orange – QAM64 1/2, red – QAM64 3/4.

The described "coverage white spots" effect shows difficulties in precise prediction of a real system coverage and system parameters. If a service provider is interested in a complete and continuous coverage of an area it can lead to higher system deployment costs. Also, there is no efficient way to validate this kind of coverage.

In case of a mobile operator the problem becomes even more serious, because mobile terminals can loose and regain connectivity as they move. Such effects can be especially laborious in WiMAX, because in this technology each network entry procedure is complicated and consumes significant network (bandwidth, BS processing power) and client terminal (battery) resources.

Summarizing measurement results we can state, that while WiMAX NLOS capability indeed makes it fit for highly urbanized areas, it is not without disadvantages and requires a careful design and troublesome practical validation.

4. Empirical coverage assessment

The above theoretical analysis and practical measurements clearly show, that an empirical coverage assessment should be performed to verify and supplement simulation modeling.

In case of WiMAX network however, such coverage measurements can be difficult, time consuming and not very precise.

The problem originates in WiMAX ability to function in strictly NLOS environment and to very efficiently utilize reflected signals. This characteristic causes WiMAX coverage area to be a rather abstract concept – in densely urbanized areas the coverage area consists of many small separate regions where good quality signal is present, neighboring regions where there is none available (aforementioned "white spots"). Up to 30 dB of SNR difference has been observed over distances of about 20 m.

To accurately measure coverage in such environment, we require a specialized equipment – for example:

- a spectrum analyzer equipped with an omnidirectional antenna, both able to support an RF band correct for our WiMAX installation,
- a sensitive GPS receiver (in case of densely urbanized area equipped with external antenna),
- a hardware or software analysis solution, able to calculate coverage based on readings from the above devices.

Such equipment tends to be costly (with a possible exception of a GPS receiver) and thus available mostly to larger, commercial network operators. However in case of small installations where specialized equipment is unavailable, we can still employ standard WiMAX subscriber station hardware to obtain a rough assessment of our BS coverage. During our research, we have developed an original method of assessing WiMAX coverage in such way.

Each WiMAX subscriber station must be able to precisely measure BS signal in order to support WiMAX mandatory physical layer control mechanisms, but there are two difficulties which can prevent us from easily exploiting this SS ability to conduct coverage measurements:

- user interface of a particular SS model may not allow access to signal measurement results,
- most of WiMAX client hardware available on the market is intended for use a stationary equipment and thus outfitted with directional antennas.

If user or installer interface of SS provides access to measured values of BS signal quality, we can utilize a laptop with a local application, which captures measured values from SS, geographic location from GPS receiver and records them in database. Such measurements can later be used to create coverage map, provided that enough measurements were made and their spatial layout adequately covered our area of interest – ideally measurement points should form a dense (about 10-20 meters apart) grid. In a real situation we should approximate such grid as closely as possible. Such high density of necessary measurements is a result of unpredictability of WiMAX coverage (discussed earlier).

To help with the task we have developed our original application, which is able to perform the function described above in fully automatic manner. It obtains signal quality measurements from WiMAX client equipment with use of SNMP protocol or, if it is unavailable, by parsing www/telnet output of user/installer interface. In our measurements we decided to use signal to noise ratio (SNR) as it directly influences modulation scheme choice for a given SS. Geographic location is obtained from a standard GPS receiver with use of NMEA protocol.

In case when our WiMAX client equipment is unable to provide us with measured values of signal quality, our application can still be employed in its alternate mode of operation. In this mode it works in cooperation with our second software product – WiMAX base station monitoring system.
The monitoring system is able to gather and record in database over 200 of performance parameters reported by base station, which can be used for both short term monitoring and long term performance tuning. Ability to analyze data in varied time-frames makes it a useful tool in both didactic/research testbed (second by second monitoring) and commercial installation (both short and long term analysis) environment.
Based on gathered data system administrator can create any number of different graphs (Figure 3), by choosing BS parameters to include and additional characteristics such as graph type, X/Y scale, time period, colors, size etc. Defined graphs are then organized in "profiles" – pages which can be configured as a whole – for example: a change of profile time period changes time period of all included graphs.

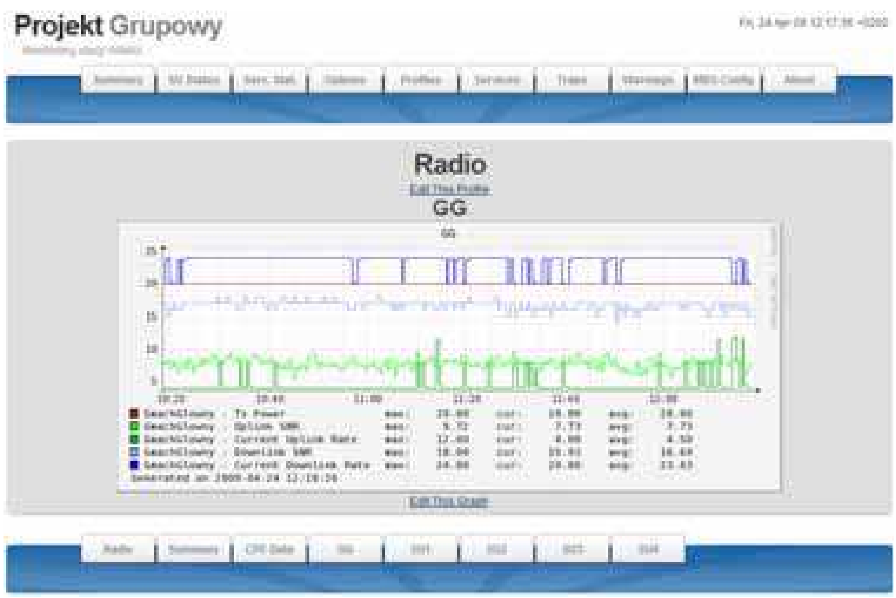

Fig. 3. WiMAX monitoring system – "GG" terminal RF parameters graph.

Such approach allows administrator to customize the visualization for his needs in various situations, for example a dedicated profile can be created to monitor: a given set of subscriber stations, overall RF environment of BS or statistics of transmitted network traffic, system's conformance with its traffic contracts etc.
The system is also able to automatically monitor configured parameters and issue alerts in a number of forms: visual, audio, email, script execution etc.
With such functionality, the monitoring system is a comprehensive solution, able to fulfill most of the monitoring-related tasks necessary in case of a small WiMAX installation.
To further expand system's capabilities, we are currently developing a number of additional modules able to take action in case of WiMAX installation failure or inefficiency to automatically solve the problem by altering configurable BS configuration parameters.
The monitoring system is also able to assist in WiMAX coverage assessment, especially in case when client terminal equipment is does not allow access to measured values of signal

quality parameters. In that case the remote (client side) software package of our design does not perform any signal measuring or analysis tasks – the only function it performs is gathering location data from GPS receiver and transmitting it, accompanied with appropriate timestamps, to the monitoring system by any network link supporting IP traffic. Apart from independent connectivity providers, the measured WiMAX link can be used for this purpose, as the application is able to buffer the data for extended periods of time in case of link failure. There is even a possibility of conducting a completely offline measurement with no network connectivity whatsoever, and then sending data to the monitoring system as a standard file.
It is a straightforward task for the monitoring system to correlate location data from the remote application with its own (BS provided) measurements of link quality to a given terminal, to calculate coverage data.
This method allows us to conduct measurements even in case of a very simple terminal, unable to provide user with measured values of signal quality, but it has its limitations. The most important one is its inability to record signal quality parameters that are below the level necessary for a client terminal to successfully connect to BS, as BS can provide the monitoring system only with performance parameters of active terminals.

The second problem that we face if we plan to use standard WiMAX client equipment for coverage assessment is the type of installed antenna. Very often the only equipment that we have at our disposal is a terminal designed for stationary installation and thus outfitted with directional antenna. This is a serious difficulty, as the measurements will only describe quality of signal coming from a particular direction, which most probably will not be the optimal one and manual reorienting antenna at each measurement point is impractical. Moreover, due to NLOS characteristics of WiMAX operation, we are unable to predict which antenna position will be most appropriate at a given location.
To solve this problem in an efficient way, while still retaining an accuracy of measurement sufficient for coverage assessment, we propose to employ a multi-pass method.
We should start with analysis of our antenna beam characteristics, to assess how many separate orientations will be sufficient to roughly cover all angles (relative to our movement vector) from which we expect the signal at any of measurement points.
Then we set antenna to first of these orientations and perform measurements along our patch through a grid of measurement points. When this first pass is finished, we set antenna to second orientation and repeat the same exact patch through the grid. We repeat this process for each antenna orientation. As a result, we have a set of grid measurements, which can be aggregated to provide an assessment of signal quality at measurement points.
In our experiments we employed a simple maximum as aggregating function, which resulted in ample approximation of our installation's coverage, which we verified by comparing the results with detailed measurements conducted with use of dedicated, physical layer measuring equipment.
Our test measurements covered Wrzeszcz district of the city of Gdansk (Poland). It is a district with dense concentration of 5-6 floor buildings, with a number of small open areas present (city squares). Such terrain is a very complex environment for WiMAX coverage assessment.
In our measurements we have often encountered areas where SNR changes reached 30dB at 20 meter distance. It clearly shows that precise statements declaring WiMAX transmission

range in urbanized environment should be threaded as a very rough approximation and the real coverage area is by no means uniform or even continuous. A good illustration of this unpredictability is presented in Table 1, which shows SNR value for a number of measurement points located in a straight line from the BS.

Distance from BS [km]	SNR [dB]
0.30	20
0.70	32
1.23	3
1.37	24
1.64	0
2.30	20

Table 1. WiMAX base station signal SNR at measurement points located in a straight line from base station.

An example visualization (created in Google Earth environment) of measurements obtained with use of our software and described method of employing WiMAX client equipment with directional (90 degree) antenna is shown below (Figure 4).

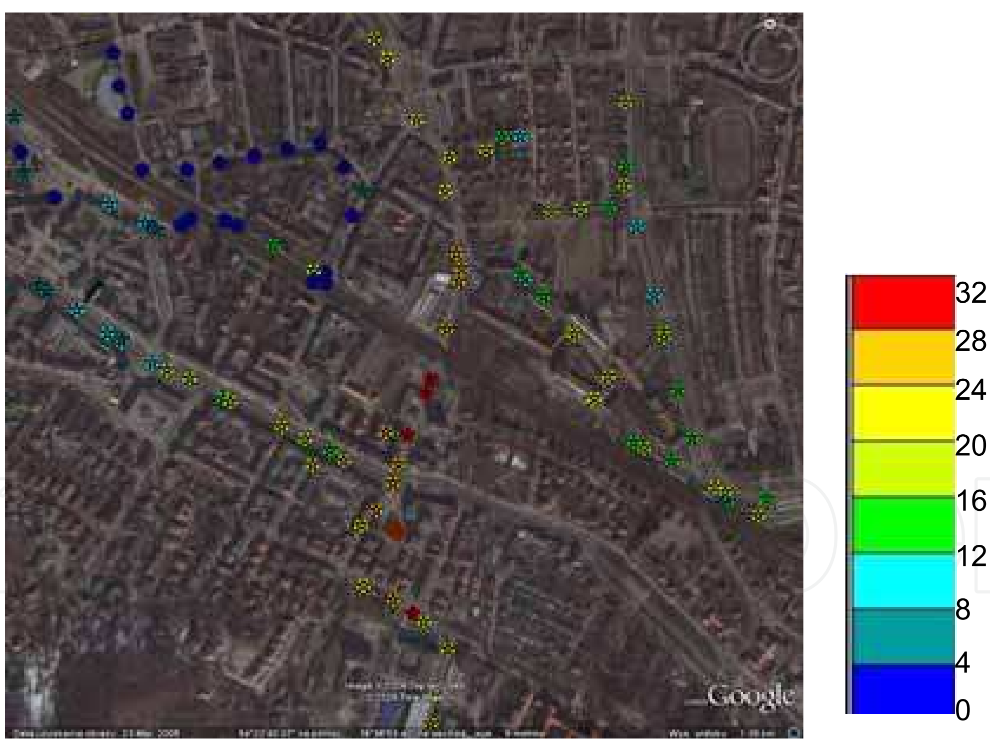

Fig. 4. Example results of WiMAX coverage fast assessment method (results in dB). Standard client equipment with 90 degree directional antenna, 4 measurement passes.

Comparison of results obtained with our method and measured with use of dedicated equipment with omnidirectional antenna shows up to 10 dB (after taking into account different antenna gains) differences. In majority of the measurement points (over 85%) this

error is below 4 dB (accuracy strongly depends on proper selection of employed antenna orientations).
Moreover, our method tends to underestimate measured signal quality, so the assessment can be considered a worst case scenario while assessing BS coverage. It should be clear however, that our method is only intended as a very rough, fast assessment solution, to be used when dedicated equipment is not available.

5. Network design considerations

In the case of simple WiFi (IEEE 802.11) (IEEE, 1999) - wireless local area network - we use test measurements to appropriately design a system. Its usual 50-300 m range makes such approach possible. In case of WiMAX technology, where the range is counted in kilometers such solution seems to be highly impractical, as it is almost impossible to compile a full, detailed, empirical coverage map, by measuring all meaningful points within system's range. In a dense metropolitan area with WiMAX NLOS capability we would have to measure an extremely thick layout of measurement points. Also as we pointed out in the previous section we would need a resolution of about 10-20 m horizontally. Moreover we should not limit such measurements to a 2-dimensional case, because there are significant variations of effective signal strength related to a client station vertical placement, especially prominent near ground level.
Computational propagation models can help us in highlighting potential trouble-spots and suggest important measurement points. They offer a great support during the design process. Regrettably, their application can be costly, because they usually require detailed 3-dimensional digital maps, which may be expensive or even unavailable for the area of interest (Hewitt M. T., 1993).
Furthermore, commercial products, based on ray-tracing and ray-launching models (Sarkar T. K. et al., 2003), are not well suited to detect coverage anomalies as small as the described "coverage hole effect". Our research shows that in order to detect them we must employ a very high resolution of modeling – often higher than popular 3-dimensional map resolution (Rossi J. P. & Gabillet Y., 2002). In case of modeling at such resolution, the simplifications common for these models no longer work in our favor. This leads to the need for much higher computational power and longer modeling time and still does not guarantee detection of all significant anomalies.
Wherever we are able or not to detect the coverage holes, to provide consistent coverage of the area we need much higher number of BSs than we can expect from theoretical modeling. Also, in many places such coverage holes are almost impossible to eliminate without installation of economically impractical number of BSs.
There are at least two basic approaches that could be proposed as possible solutions to this problem:

- heterogonous approach - a number of different connectivity technologies are used in order to provide services for the user,
- homogenous approach - only one wireless technology, i.e. WiMAX is employed.

Currently there is a strong trend towards creation of heterogeneous systems, where users can use a variety of connectivity technologies (Matusz P. et al., 2005).
The emerging IEEE 802.21 standard (IEEE, 2007) is devoted to a seamless handover between networks of the same or different types. In this case the best connection (ABC strategy –

Always Best Connected) is automatically selected at a given user location and the handover is performed without losing quality of service, if possible (Machań P., 2007).
This approach takes into account several different wireless technologies and we will not consider it here. We will concentrate on the homogenous approach, limited to WiMAX technology, considering WiMAX mesh architecture, as a promising solution for coverage issues.

6. WiMAX Mesh Mode

In WiMAX-Mesh mode, there is no prominent BS, but SSs communicate directly with their neighbors forming a dynamic, self-organizing, multi-hop network. In this way a client station does not need to be in range of one of relatively few BSs, but it is sufficient to be in range of any other participating client station and number of these devices is usually much higher (Figure 5). Moreover, with correctly designed control protocols and effective methods of joining the network by new stations, its available capacity can be increased instead of going down.

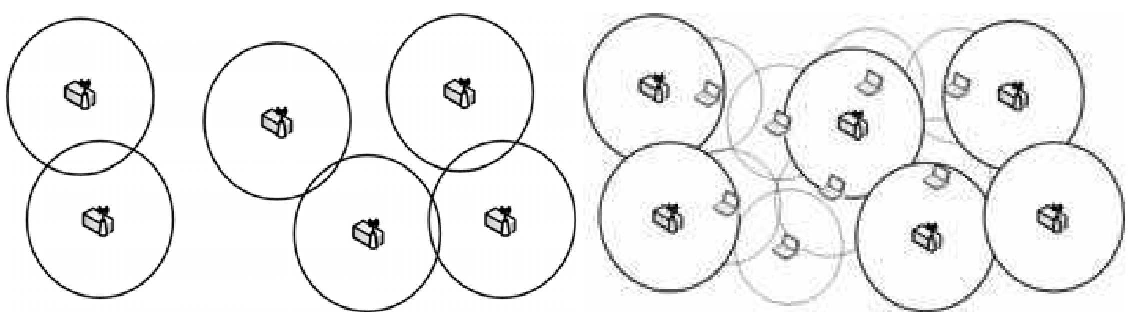

Fig. 5. Coverage comparison in case of classical PtMP mode and mesh mode, for the equal number of operator-provided nodes.

Unfortunately such network architecture requires much more advanced support mechanisms than a simple PtMP setup, where a single entity (BS) sees and controls all the network activity. In case of wireless ad-hoc mesh architecture, these mechanisms (medium access control, security…) have to be significantly extended and be able to operate in a distributed environment. Also new mechanisms (listed below) not required in PtMP setup (which utilizes star architecture), are necessary:

- Topology control – selects logical network node neighborhood based on its physical neighborhood. Running in all network nodes, it is responsible for overall network topology and vast number of derived characteristics (path lengths, bandwidth available, network capacity, transmission delay, error rates…).
- Route discovery – set of mechanisms able to find a route through network nodes to any required destination within and outside wireless mesh. In case of WiMAX, it should be able to provide paths that able to provide specified QoS guarantees.
- Data forwarding – responsible for retransmitting received traffic addressed to remote nodes, with accordance to routing information obtained from discovery mechanisms and QoS guarantees.

In majority of research works and test implementations a mesh network utilizes short range wireless technologies (WLANs or sensor networks) to ensure wide area coverage and high reliability. We claim that, also in case of a wireless metropolitan network (WMAN) of much higher basic range WiMAX-based ad-hoc mesh architecture can provide required functionalities and become practical and economically viable solution (Gierłowski K. & Nowicki K., 2007).

Due to relatively high complexity the WiMAX-mesh mode is not yet specified in the IEEE 802.16 standard. This fact (lack of detailed specification) gives us a possibility to incorporate into the created standard new mechanisms which will make 802.16 especially attractive for metropolitan environments - being definitely its prime areas of deployment.

Our research related to IEEE 802.16 and measurements in the test-bed shows that mesh architecture based on WiMAX metropolitan area network is likely to solve the coverage-hole problems, as long as sufficient number of client stations will participate in the network. In such case it will provide much better terrain coverage than reasonably designed PtMP WiMAX installation. Also the costs of infrastructure will be significantly lower.

We predict that in metropolitan environment the number of client station will not pose a problem, with currently observable user demand and manufacturers' support for the technology. It should also be possible to keep prices of mesh-capable subscriber stations similar to classical PtMP WiMAX terminals.

WiMAX-based ad-hoc mesh network can provide much better terrain coverage and its development costs are significantly lower than in corresponding coverage scenario supported only by classical BSs in PtMP mode. Of course, there is still need for a number of operator-provided network nodes as a foundation of the network.

Moreover, mesh architecture can provide high reliability due to high number of redundant network devices, wireless links and paths to most destinations. It will also scale well, because any participating node brings additional resources to an overall network poll.

The coverage hole problem can be solved by sufficiently dense network of mesh nodes and their redundant links, but network control mechanisms need to be able to deal with rapidly changing mesh topology. In a static mesh configuration (as in static PtMP scenario), the problem is not dangerous, as in most cases the placement of network nodes can be optimized, but in case of mobile mesh nodes even small movement (as mentioned before) can lead to unpredictable breakdowns and reappearances of inter-node links.

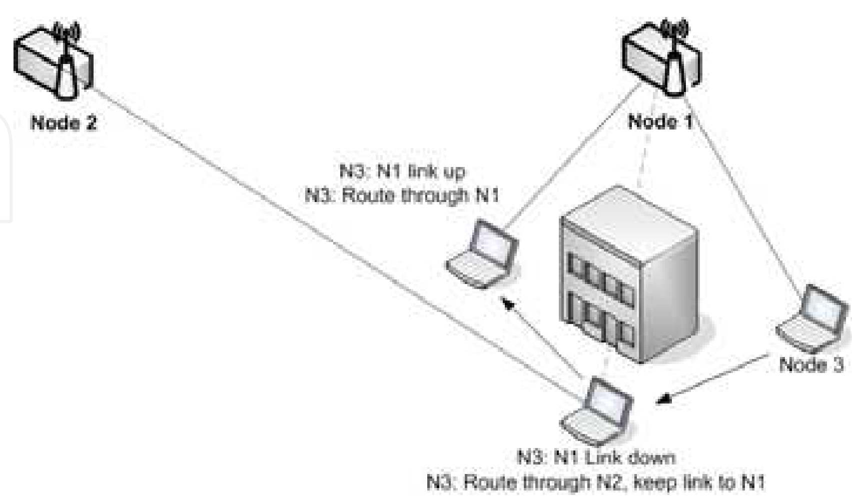

Fig. 6. Use of redundant path routing and coverage hole aware topology control as a solution for short-period link losses at mobile stations.

Such environment greatly lowers efficiency of network mechanisms leading to, for example, frequent activation of ad-hoc routing protocol's discovery mechanisms, which flood the network with control traffic. Also QoS guarantees are extremely difficult to maintain in such environment as fast and frequent, short-term connectivity losses can occur.
Fortunately massive redundancy which exists in a sufficiently dense mesh network can be used to offset the effect without losing transmission reliability and QoS guarantees. Furthermore, our observations and measurements tell us, that signal losses and corresponding link breakdowns caused by coverage hole effect are mostly short term events and as such can be efficiently countered with properly designed network control mechanisms.
Our present research leads us to believe, that efficient topology control, taking into account possibility of short-time disappearance of network links, coupled with redundant path routing and stability-aware routing metric can solve the described problem (Figure 6). We are currently working on a simulation model of WiMAX-based self-organizing mesh network, resistant to the topology stability issues, described above.

7. WiMAX Relay Usage

As the full WiMAX mesh architecture is far from completion and the advantages of having multiple network nodes supporting BS functionality scattered through our area of interest are undisputed, a less complicated solution has been proposed. Instead of creating a dynamic network of mesh-capable subscriber stations, a number of relay stations is to be deployed by network operator.
Relay station (RS) is a simplified version of a full base station, which can provide similar functionality to subscriber stations, but only in cooperation with a fully capable BS.
Due to significant simplifications in its functionality RS is much cheaper than full BS. It also does not require a direct connection to a network backbone, because RS connects to its parent BS via a WiMAX connection. The only external resource required is electrical power.
These characteristics make RS an economical solution, when we are interested in extending range of our WiMAX installation (Figure 7), especially in areas lacking decent communication infrastructure (for example: rural areas). Moreover, such regions do not have a high user density, so the controlling BS should have no problem with allocating enough resources to support its connected RSs.

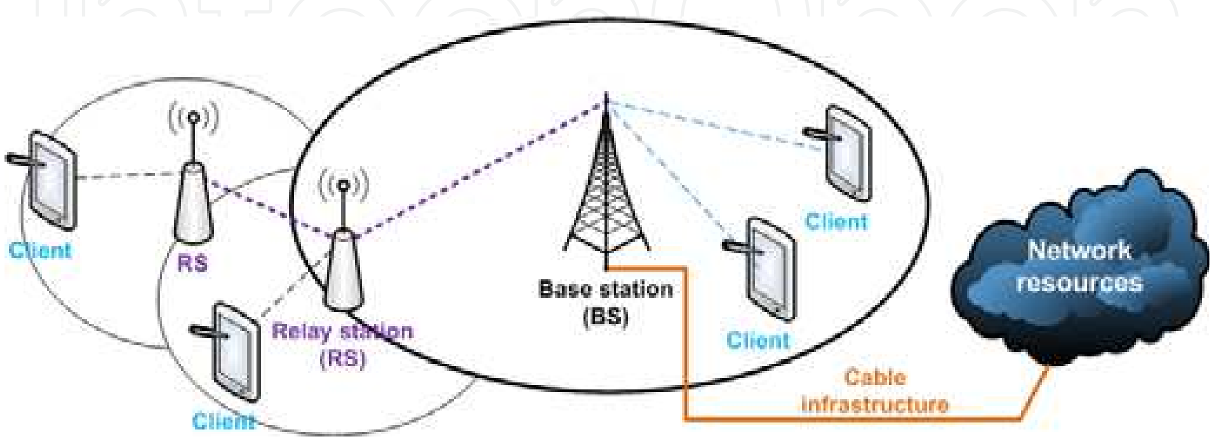

Fig. 7. WiMAX BS coverage extension with relay station infrastructure.

While coverage range extension is very desirable in areas of sparse user density, for example rural ones, it has limited utility in case of densely urbanized areas. In this case we are often interested in limiting the range of a single BS, as such approach allows the network to support a higher number of users. It is possible mainly due to division of area into independent cells in which radio-frequency resources can be reused and by dividing medium access control mechanisms workload between multiple controlling BSs.
In such environment, we can also profit from deploying RS, as they allow us to divide area maintained by a single BS into smaller regions, at least partially controlled by dedicated RSs. A higher number of entities able to provide coverage and service to users (BSs and RSs) helps to eliminate coverage white spots and can also allow a higher number of subscriber stations to connect (Figure 8), due to transference of a part of BS's management functions to cooperating RSs.

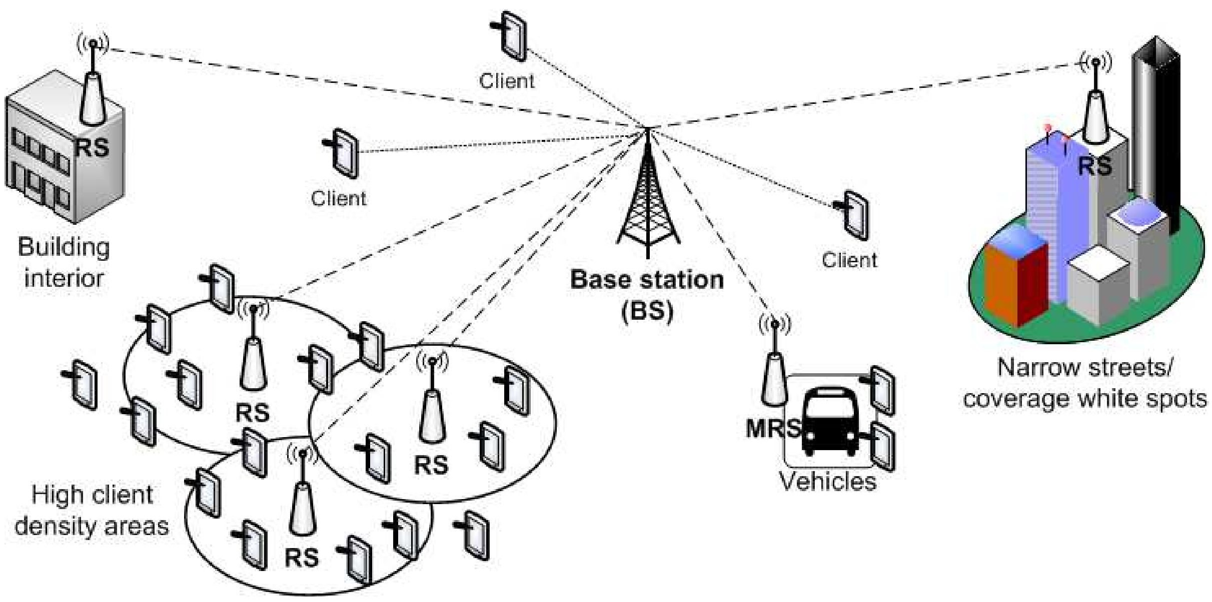

Fig. 8. Different scenarios of relay station (RS) and mobile relay station (MRS) deployment.

The advantages of employing relay stations in WiMAX environment are considerable. The complication of necessary mechanisms and their number is much lower than in case of fully capable mesh architecture. Despite this relatively low complication, there are two main tasks which must be addressed: BS-RS communication and resource management.
There are two basic methods of BS-RS communication, each providing certain advantages and bringing specific complications:

- In-band communication – in this scenario RS communicates with BS using the same physical channel that it uses to provide service to connected clients. Such RSs are significantly cheaper, but their efficiency is limited, especially if deployed in areas of high user density.
- Out-of-band communication – links that connect RSs and BS (thus creating local "backbone") are established using physical channel different from the one utilized for RS-client communication. The gain in efficiency is obvious and considerable, but the costs of equipment (processing power, multiple radio modules, etc.) and

operation (multiple licensed RF bands, etc.) are also significantly higher than in case of in-band communication scenario.

The second, even more important and complex problem in implementing relay station infrastructure is network resource management organization. One of the main advantages of WiMAX system is its ability to provide QoS guarantees to users, by means of careful resource monitoring, management and access scheduling. At the same time, such approach makes advanced reservation and physical medium access control mechanisms strictly necessary. As we are interested in minimizing complexity and cost of relay stations, there are two popular approaches to implementing resource reservation and medium access control mechanisms in BS-RS architectures:

- Centralized scheduling – relay stations tunnel requests from clients to BS and BS's responses to clients in a transparent manner. All monitoring, scheduling and control mechanisms are located at BS. Such approach allows us to employ very simple and cheap relay stations. Unfortunately, we do not gain any additional system capacity or performance, because BS is unable to offload its tasks to RSs. Moreover, it must handle additional load due to a need to coordinate RS infrastructure. There is also a necessity to maintain a low latency communication between client and BS, which is still the only control entity in the system. This requirement drastically limits number of consecutive RS which can be chained (see Figure 7) and creates a likely point of failure.
- Distributed scheduling – relay stations are fully capable of receiving clients' requests and performing scheduling / medium access control tasks for their clients. Relay stations coordinate their actions with BS, which performs overall resource management tasks across its entire controlled area, but does not need to handle work-intensive client-related work. In this scenario BS workload is drastically lower and there is no latency in interpreting client's requests as they are handled by its serving RS. This solution allows easy extension of both system's coverage area and its capacity. Moreover, relay stations can be safely chained, due to their relatively infrequent and not time-critical control communication with BS.

Relay architecture seems to be a promising solution for WiMAX networks. While it does not have the remarkable and diverse advantages of fully capable mesh architecture, it is much easier to implement. As such we should expect its rapid standardization (currently in progress as IEEE 802.16j amendment to a base IEEE 802.16 standard) and appearance in production grade systems. At the same time we hope, that popularity of relay architecture will not hinder standardization work on the full WiMAX mesh mode, concurrently planed as an optional part of IEEE 802.16m specification.

8. Client-based Relay Infrastructure

Relay-based WiMAX architecture is an economical and easy to deploy alternative for utilizing a high number of expensive base stations, which would otherwise be necessary to provide (more or less) continuous coverage in dense urban environment. However, these relay stations are still financed, deployed and maintained by a network operator. As such they are deployed in limited numbers, according to operator's coverage plan.

We would like to propose a slightly different solution, which we call WiMAX support-mesh mode (SMM). It is a relay-based solution designed to utilize modified client equipment to

create simple relay stations, while maintaining compatibility with a standard WiMAX system. The solution can be deployed by clients on their own initiative (for example: to provide indoor WiMAX coverage) and should not negatively impact network access experience of other clients.
Our main priority in creating this solution was keeping necessary modifications of existing systems to minimum. Unfortunately, this goal is in contradiction with resulting system's efficiency, as WiMAX PtMP environment is strictly controlled by BS and without modification of functions obtaining efficient solution is very difficult. In this situation we decided to take two approaches:

- Variant 1 – a completely transparent one, which requires no alternations to BS hardware or software, only slight modifications in functionality of SS that is to function as a relay-station.
- Variant 2 – requires slight modification of BS software, but promises higher system efficiency and robustness.

Both variants allow seamless coexistence of standard and modified subscriber stations, which significantly raises practicability of the solution.
In most circumstances the operation of support-mesh mode enabled installation does not differ from classic WiMAX PtMP system. Only in case of low quality link or connectivity loss between SS and BS the new functionality is utilized (Figure 9).

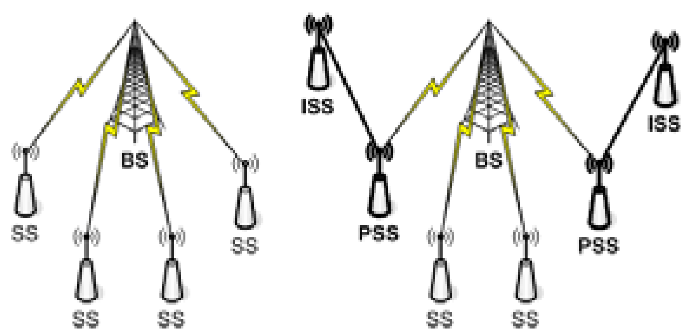

Fig. 9. WiMAX support mesh mode.

In such case support-mesh mode enabled subscriber station (SMM-SS) can connect to another SMM-SS instead of BS and use it as a proxy to maintain its presence in WiMAX PtMP system. The SMM-SS used as a proxy (PSS) is then responsible for providing communication between BS and its connected SMM-SSs (Indirectly connected SS – ISS).
It is even possible to create multiple layers of proxying in case when PSS loses connectivity to BS and becomes an ISS itself, without abandoning its PSS role (Figure 10).

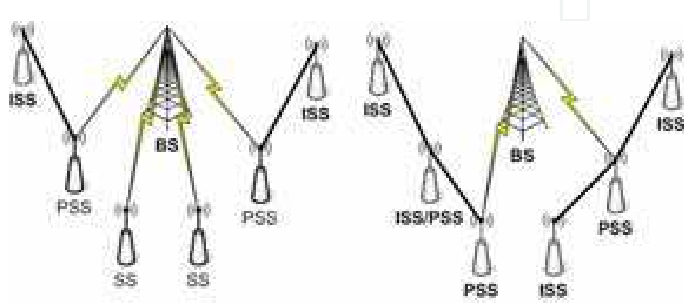

Fig. 10. Multilayer proxying in WiMAX support mesh mode.

Such multilayer network layout is not especially efficient and should be avoided by ISSs by finding alternative (directly connected) PSS, but it is possible which can be useful in case of low-bandwidth, high-reliability applications.

For the system to function effectively it is advisable for the stations (most importantly PSSs) to utilize omnidirectional antennas – in case of directional antennas their field of coverage will be very limited and advantage of employing such PSS is questionable. This requirement is currently in contrast with a large percentage of WiMAX hardware available on the market, but the situation in going to change as there is a strong trend towards omnidirectional antennas.
Proxy-capable subscriber stations work in the same frequency channel as their main BS, and need to perform all operations in their allocated (by BS) transmission times. That includes:

- their own traffic to/from BS,
- receiving transmissions form ISS and retransmitting them to BS,
- receiving transmissions from BS and retransmitting them to ISS,
- maintenance of their own proxy-WiMAX cell.

PSSs will advertise their capabilities by emulating BS frame structure inside their allocated transmission times, which will allow potential ISSs to detect them, connect and transmit traffic. This task may seem highly hardware intensive, as the PSS need to conduct network maintenance tasks similar to that of BS, but there are many simplifications that can be made, taking into account a small expected number of ISSs and small range. Advanced physical transmission control, QoS, network control mechanisms can be radically simplified or, in some cases, removed. If we will allow only SMM-capable SS to connect to proxy stations (in contrast to allowing even unmodified SSs to connect to PSS), the simplifications can be even greater. The exact degree of simplification is currently a subject of our research.
Connecting ISSs can choose PSS according to a number of factors and it is possible use multiple simultaneous links to many PSSs (as described in earlier chapter) to perform dynamic, soft-handover for mobile ISS.

8.1 SMM infrastructure – Variant 1

In this variant our main priority is compatibility with existing, unmodified WiMAX systems. Because of this requirement PSS makes all request to BS – both to accommodate its own needs and needs of ISSs it serves.
Because ISSs are not visible to BS, it is responsibility of PSS to:

- Authenticate connecting ISSs and grant them resources using its own authentication and access control mechanisms.
- Obtain bandwidth grants from BS, necessary to: service its own traffic, communicate with its connected ISSs, retransmit ISS traffic to and from BS.
- Handle PSS-ISS communication and correctly retransmit unidirectional ISS-BS traffic.

Detailed aspects of authentication and access control we consider out of scope of this paper, because there are many appropriate solutions (both strictly local and centralized or distributed) which can be employed.
The remaining problem is conducting PSS-ISS communication within constraints of strictly controlled WiMAX PtMP environment.

The WiMAX downlink phase is exclusively controlled by BS according to both connections' traffic contracts and level of currently buffered traffic waiting transmission – when BS does not have traffic to transmit through a particular connection, there is no downlink transmission time allocated for it. In this situation it is impossible to use WiMAX downlink phase for communication with ISS – all such communications need to be conducted during uplink phase (Figure 11).
Transmission time in WiMAX uplink phase is also granted by BS according to SSs' traffic contracts, but there are no optimizations made by BS. That makes it possible for PSS to obtain necessary transmission time.

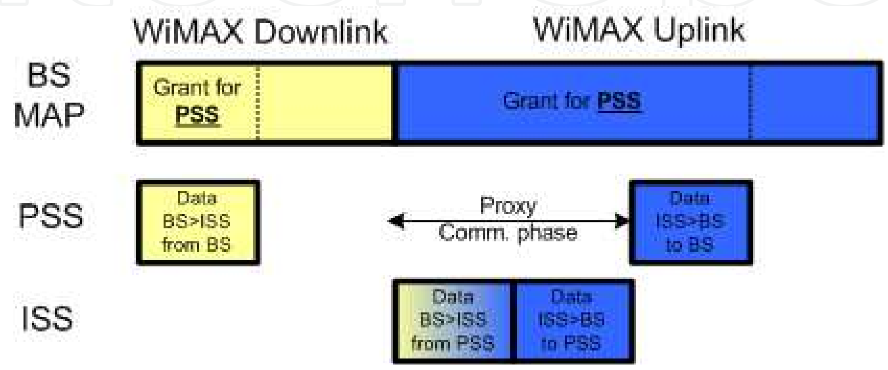

Fig. 11. SMM Variant 1 – transmission organization.

In variant 1 of SMM, PS reserves uplink time to handle (Figure 11):

- Its own uplink traffic to BS,
- Retransmission of ISS uplink traffic from PSS to BS,
- ISS uplink traffic to PSS,
- PSS downlink traffic to ISS.

In presented SMM variant 1 the only stations which require software modification and are aware of SMM operation are indirectly connected subscriber stations (ISSs) and their respective proxy subscriber stations (PSSs). Base station and other subscriber stations are not modified nor aware of SMM operation.

8.2 SMM infrastructure – Variant 2

In event of SMM variant 2 we extend WiMAX BS functionality making it aware of indirectly connected subscriber stations. While it requires BS software modification, it also provides vast advantages in terms of efficiency and system control.
In this case ISS communicate with BS with proxy stations acting as repeaters by retransmitting both control and user traffic between ISS and BS. This allows ISSs to participate in standard network entry procedure, establish WiMAX connections and make their own bandwidth requests (Figure 12).

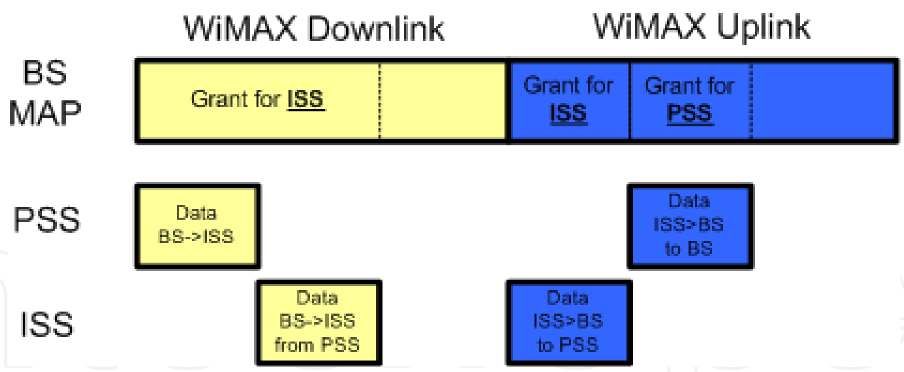

Fig. 12. SMM Variant 2 – transmission organization.

This approach allows us to retain security and management capabilities of classic PtMP WiMAX system, as ISS stations are fully recognized by BS. It also brings us an ability to utilize both downlink and uplink phases for communication with ISS, resulting in their much more balanced usage. Such balance improves system reliability and can provide a big increase in efficiency in case of WiMAX hardware implementations which does not support a dynamic change of WiMAX uplink and downlink phase duration ratio.

In this variant there is also a possibility of utilizing a spatial division multiple access (SDMA) to allow utilization of a single frequency channel by many PSSs and ISSs at the same time (Figure 13). This can be done due to BS's complete knowledge of its network structure (including ISSs), by utilizing additional raging phase to gather additional information about spatial separation of nodes.

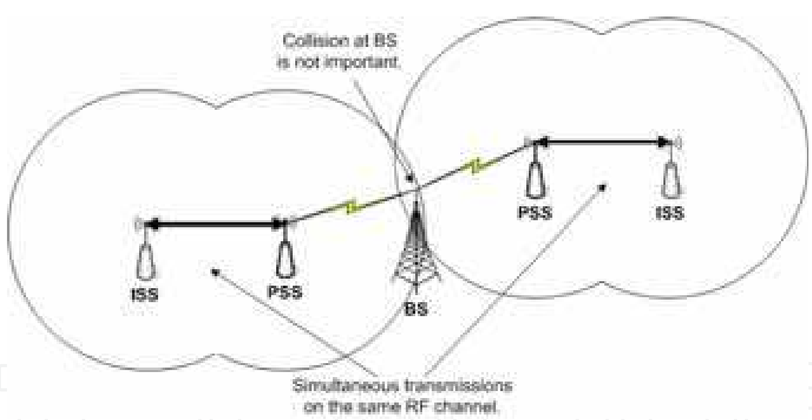

Fig. 13. Use of SDMA in SMM Variant 2.

Ranging is the process of measuring quality of link between BS and SS, conducted during a time period especially reserved for this purpose in each WiMAX frame. This time period can be used by BS to locate SSs which are unable to interfere with each other, by conducting measurements of link existence and quality between pairs or groups of SSs. This task could be also accomplished by SS passive measurements of normal traffic generated by other stations, but the use of ranging mechanisms makes the process independent of station activity and their physical transmission characteristics, such as dynamically adjusted power and modulation.

9. Simulation results

To verify usefulness of our solution we conducted a series of coverage tests, using a modified, WiMAX NLOS-compatible propagation model.
As stated before, the classical propagation models are inefficient in detecting anomalies as small as "coverage white-spots" and thus unfit for the task, we developed and employed a modified version. Its operation is supplemented by a data file containing real-world coverage measurements, which allows localized increase of modeling accuracy. That way the model is able to check the presence of small "white-spots", while still keeping calculation costs within acceptable limits.
We considered two urbanized area types:

- Terrain A: dense urbanized area with blocks 5-6 floor buildings, 3.5 km^2 – Gdansk-Wrzeszcz area.
- Terrain B: sparse residential area with 12 story buildings (building length 30-300 m) and a limited number of smaller buildings and objects, 4 km^2 – Gdansk-Zaspa area.

In these areas we randomly distributed 30 SMM-SS in two scenarios:

- Scenario 1: 30 stationary SMM-SS on rooftops and building walls.
- Scenario 2: 20 stationary SMM-SS on rooftops and building walls, 10 mobile SMM-SS slowly moving at street level.

Below we include results of coverage modeling in percent of previously uncovered area which is now covered by SMM-capable subscriber stations.

- Area A, scenario 1: 80%
- Area A, scenario 2: 85%
- Area B, scenario 1: 95%
- Area B, scenario 2: 100%

Form these scenarios it seems evident, that support-mesh mode subscriber stations can provide significantly better coverage in urbanized areas, that strictly PtMP setup. It vast advantage is a distributes layout of PSSs, which cover target area from varied angles, maximizing chances of archiving through coverage. The result is especially promising in case of relatively small number of large obstacles (area B).

The results above convinced us that WiMAX SMM can efficiently solve coverage issues, so we prepared simulation model of both its variants. We employed a relatively simple WiMAX simulation model, covering in detail only ISO-OSI layer 2 network mechanisms, with very simplified layer 1 modeling, as that was the only such model available to us. We are currently working on development of more through simulation tool.
Simulation test confirmed basic operation principles of WiMAX support-mesh mode, but also uncovered some limitations.
Variant 1 of SMM, from the beginning designed as temporary, low-efficiency, emergency solution proved operable for up to 2 layers of proxying. Additional layers refuse to function due to strict timing constraints of the system. Moreover there is an additional, up to 8 % per layer, performance degradation over one expected from the need for repeated retransmission of data. This degradation applies only to indirectly connected stations and does not impact SSs in classical PtMP setup.
Variant 2 provides better service and was tested for up to 5 layers of proxy stations, at which point it still remained operable. The loss of performance for indirectly connected stations is

about 5% for level of proxying, but in this case BS can compensate for it, and provide given ISS with suitably higher bandwidth.
In both cases (variant 1 and 2) there is also need for retransmission of data by PSSs, which is a main source of performance degradation, halving bandwidth with each level of proxying. Because of that, performance of variant 2 SMM with SDMA mechanisms is in vast majority of cases drastically better, as it allows to conduct multiple retransmissions simultaneously. The exact results depend on station locations and terrain layout.

10. Conclusions

Based on our theoretical research and practical experiments, we observed a possibly dangerous effect present in wireless networks based on WiMAX technology, resulting in small coverage holes in areas of otherwise good coverage. Such white spots are difficult to predict, even with the use of deterministic propagation models, which are amongst the most popular wireless network design support tools, used today.
Such situation can lead to lower than expected service level, requiring repositioning or installation of additional hardware in case of stationery users and can be especially harmful for mobile users that will experience periodic losses of connectivity.
Despite the fact that the same coverage problem would affect mesh nodes (especially in case of mobile nodes) potentially leading to topology instability, it is possible to design network control mechanisms to counter the effect. That would allow WiMAX mesh networks to provide continuous coverage of a given area eliminating "coverage holes", which is very difficult in classical BS-based architecture without large additional hardware costs.
We propose WiMAX mesh networks as viable method of dealing with coverage difficulties in metropolitan areas as they are simultaneously providing additional crucial advantages, such as: well-scaling high network capacity, high reliability based on multiple redundancy, low cost of deployment etc.
As a fully-functional mesh mode requires a significant number of additional, advanced mechanisms and in case of WiMAX network is still in very early stage of research and development, we developed a client-based relay solution (support-mesh mode). It provides subscriber stations with proxying capabilities thus providing many of mesh mode advantages (including coverage and reliability) with use of considerably simpler mechanisms. Both variants of our solution require only limited modification to subscriber station software and only in case of more advanced variant 2 there is a need for modification of base station software.
Operation of both variant of our solution have been confirmed by simulation test and yielded satisfactory results. Variant 1 should be treated as a temporary/emergency solution for currently available systems, while variant 2 can be considered for further development and incorporation as an option in upcoming versions of WiMAX hardware.

11. References

Alvarion (2006). BreezeMAX Whitepapers and Manuals, http://www.alvarion.com/

ATDI, (2007), The WiMax technologies with ICS telecom: Fixed, Nomadic and Mobile! http://www.atdi.com/

Gierłowski K. & Nowicki K. (2006). Test Installation of WiMAX-based Wireless Network on Gdansk University of Technology (in Polish), In: Multimedia in economy and education, L. Kiełtyka (Ed.), pp. 269-277, DIFIN, ISBN 83-7251-673-1, Warszawa.

Gierłowski K. & Nowicki K. (2007). Wireless Networks as an Infrastructure for Mission-Critical Business Applications, Notes in Computer Science Vol. 4658, pp. 49-58, ISBN 3-540-74572-6, Regensburg, September 2007, Springer-Verlag, Berlin

Hewitt M. T. (1993). Surface feature data for propagation modeling, Proceedings of IEEE Colloquium on Terrain Modelling and Ground Cover Data for Propagation Studies, pp. 4/1 - 4/6

IEEE (1999), IEEE 802.11-1999: IEEE Standard for Information Technology – Telecommunications and Information Exchange between Systems – Local and Metropolitan Area Networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, IEEE Explore.

IEEE (2007). IEEE P802.21/D05.00: Draft IEEE Standard for Local and Metropolitan Area Networks: Media Independent Handover Services, IEEE Explore.

IEEE, (2004). IEEE 802.16-2004: IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems, IEEE Explore.

Machań P. et al. (2007). IEEE 802.21 Standard – mobility support mechanisms, Telecommunication Review and Telecommunication News, No 7/2007, July 2007, pp. 211-216

Matusz P. et al. (2005). Heterogeneous wireless networks - selected operational aspects, Telecommunication Review and Telecommunication News, No. 8-9/2005, August 2005, pp. 284-295, ISSN 1230-3496

Olejnik R. (2007). Methods of designing wireless networks and parametric design method (in Polish), Computer Networks – T. 1: New technologies, pp. 347-356, Wydawnictwo Komunikacji i Łączności, Warszawa.

Rossi J. P. & Gabillet Y. (2002). A mixed ray launching/tracing method for full 3-D UHF propagation modeling and comparison with wide-band measurements, IEEE Transactions on Antennas and Propagation, Vol. 50, Issue 4, April 2002, pp. 517 – 523, ISSN 0018-926X

Sarkar T. K. et al. (2003). A Survey of Various Propagation Models for Mobile Communication, IEEE Antennas and Propagation Magazine, Vol. 45, No. 3, ISSN 1045-9243

WiMAX Forum (2007). WiMAX Forum Whitepaper Library, http://www.wimaxforum.org/

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It has been many decades, since Computer Science has been able to achieve tremendous recognition and has been applied in various fields, mainly computer programming and software engineering. Many efforts have been taken to improve knowledge of researchers, educationists and others in the field of computer science and engineering. This book provides a further insight in this direction. It provides innovative ideas in the field of computer science and engineering with a view to face new challenges of the current and future centuries. This book comprises of 25 chapters focusing on the basic and applied research in the field of computer science and information technology. It increases knowledge in the topics such as web programming, logic programming, software debugging, real-time systems, statistical modeling, networking, program analysis, mathematical models and natural language processing.