



## Self-organizing Ad-hoc Architecture as a Solution for Coverage Issues in WiMAX Metropolitan Area Networks

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**Abstract.** New WiMAX technology offers several advantages over currently available (GSM or UMTS-based) solutions. It is a cost effective, evolving, and robust technology providing quality of service guarantees, high reliability, wide coverage and non-line-of-sight transmission capabilities. All these features make it especially suitable for densely populated - urban environments. In the paper we discuss design and implementation difficulties concerning network coverage, discovered in the test-bed implementation during measurements and tests. We point out unexpected “coverage white spots” - not characteristic to WiMAX technology. As one of possible solutions of this significant drawback of the very promising technology we consider reconfigurable mesh organization of WiMAX base stations. We also suggest directions for further development of this kind of network operation, partly based on our practical experience.

### Introduction

The new WiMAX technology, based on IEEE 802.16 standard [1], offers 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 only. The technology supports different modulation and coding schemes coupled with their adaptive adjustment of transmission parameters 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). The standard also specifies a foundation of a mesh-mode in which peer stations participate in self-organizing network structure and/or its connectivity.

All these characteristics make WiMAX an economically appealing solution. Specially, the NLOS capability described above, makes WiMAX a key technology for urban environments, allowing for a relatively small number of BSs working in PtMP mode to cover large areas. However at the same time its complexity significantly

complicates system design, particularly in terms of system coverage prediction and client station capabilities in a given location, with respect to available throughput and specific QoS parameters.

Due to these difficulties there is a need for specialized software tools able to help system designers to assess effective coverage area and exact transmission parameters inside of it.

In the following part of the paper we discuss basic theoretical wireless network design models, pointing out approaches proposed by them in case of NLOS capable WiMAX technology. Next, we describe measurements conducted in our WiMAX test-bed installation which uncovered the “coverage white spots” effect – a phenomenon very disadvantageous to nomadic and mobile users. This previously undocumented effect strongly undermines the popular beliefs concerning excellent performance of WiMAX NLOS mechanisms and can significantly raise cost of network deployment. As such state of affairs is difficult to accept, steps must be taken to solve the problem. So, in the final part of the article we describe our novel solution of this difficulty - a self-organizing ad-hoc WiMAX-based mesh architecture as a solution for coverage issues. Finally, we also propose mechanisms necessary for the mesh mode to effectively counter the “coverage white spots” in case of nomadic and mobile networks.

## 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).

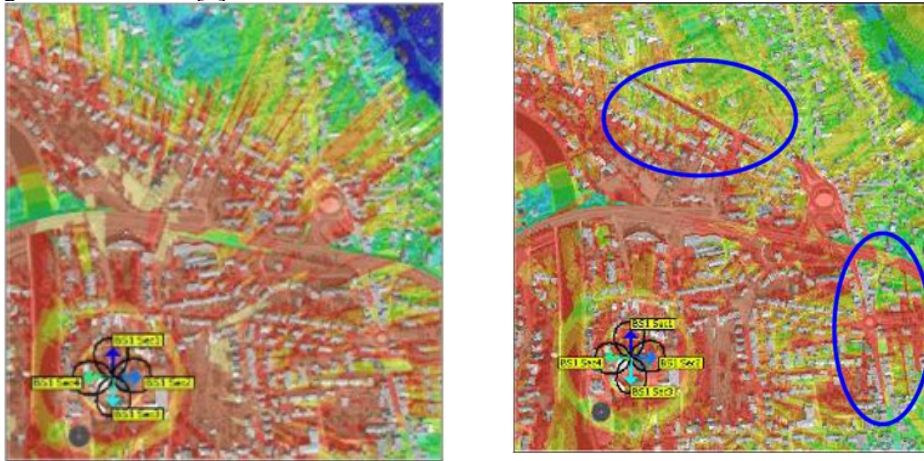
There are two basic types of propagation models employed in wireless systems design [2,3]:

- 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). [2]. 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 fig. 1), thus a dedicated software model is required to give exact results [4].



**Fig. 1.** Results of WiMAX BS coverage simulation: general model (left) and specialized WiMAX coverage model (right).

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 [5]. 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 [6].

### Test-bed installation and example measurements

From both modeling procedures and hardware manufacturers' tests it follows that WiMAX technology is indeed very well suited for metropolitan environment and generally offers good coverage, even in highly urbanized areas [7]. 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 [8] 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. They also handle a real-time, initial data analysis to help measurement teams to optimize their work.

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) [8] 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 [6].

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 some points 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 (fig. 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 hole effect – measured coverage of WiMAX base station in 3.5 GHz band. Stable modulation profile chosen by client terminal: white X - no communication, “1” – BPSK, “2” – QPSK, “3” – QAM16, “4” – QAM64 1/2, “5” – 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.

## Network design considerations

In the case of simple WiFi (IEEE 802.11 [9]) - wireless local area network - installations 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, 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 under 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 [10].

Furthermore, commercial products, based on ray-tracing and ray-launching models [2], 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 [3]. 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:

- heterogenous 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.

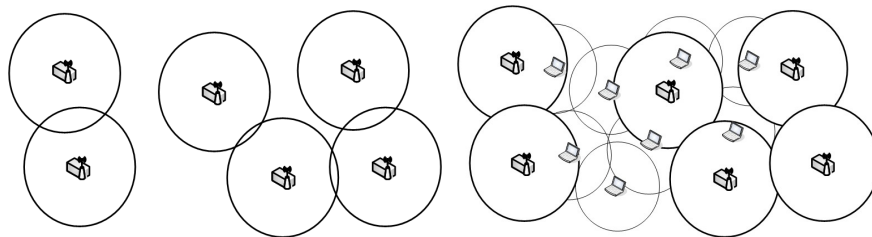
Currently there is a strong trend towards creation of heterogeneous systems, where users can use a variety of connectivity technologies [11].

The emerging IEEE 802.21 standard [12] 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 [13].

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.

## 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 (fig. 3). 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. 3.** Coverage comparison of PtMP and mesh mode with equal number of operator provided base stations/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 [14].

Due to relatively high complexity the WiMAX-mesh mode is not yet specified in the IEEE 802.16 standard and there are still ongoing research and design works. This fact (lack of detailed specification) gives us a possibility to incorporate into the created



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 (fig. 4). We are currently working on a simulation model of WiMAX-based self-organizing mesh network, resistant to the topology stability issues, described above.

## 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 stationary 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.

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