Paper

A hybrid-mesh solution for coverage issues in WiMAX metropolitan area networks

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Abstract—The new WiMAX technology offers several advantages over the 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 (NLOS) transmission capabilities. All these features make it particularly suitable for densely populated urban environments. In this paper we discuss the design and implementation difficulties concerning network coverage discovered in a test-bed implementation of WiMAX. We point out the presence of unexpected "white spots" in the coverage, which are not inherently characteristic of the WiMAX concept. As a possible remedy to this significant drawback of the otherwise 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. Despite the clear advantages of the mesh mode in WiMAX networks, its development is currently at an early stage, due to the high complexity of the necessary mechanisms. In this situation, we propose an original, much simpler solution: the so-called support-mesh mode.

Keywords— IEEE 802.16, WiMAX, coverage, mesh, measurements.

1. Introduction

The new worldwide interoperability for microwave access (WiMAX) technology, based on the IEEE 802.16 standard [1], offers reliable, fast and quality of service (QoS) aware transmission over significant distances. It provides both line-of-sight (LOS) and no-line-of-sight (NLOS) solutions. The LOS solution allows transmissions at rates over 70 Mbit/s over distances up to 50 km (or even more), as long as the antennas of both devices have a direct (not shaded) view of each other. The second solution provides connectivity using reflected signals when the path between the antennas is obstructed. In such a case the range is limited to about 5 km only. The technology supports different modulation and coding schemes coupled with adaptive adjustment of transmission parameters in order to maximize the stable coverage area. Other strong advantages of WiMAX systems include high security, reliability and integrated QoS support, which together allow operators to guarantee their users a contracted 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 the foundation for a mesh mode whereby peer stations participate in self-organizing the network structure and/or its connectivity. All these characteristics make WiMAX an economically appealing solution. Especially, the NLOS capability makes WiMAX the key technology for urban environments, making it possible to cover a large area with a relatively small number of BSs working in PtMP mode. However, at the same time, its complexity significantly complicates system design, particularly in terms of coverage prediction and client station capabilities at a given location, with respect to the available throughput and specific QoS parameters. These difficulties pose a need for specialized software tools that would help system designers assess the effective coverage area and accurately estimate transmission parameters within it.

We shall start from a discussion of the basic theoretical models for wireless network design, from the viewpoint of their possible application to NLOS-capable WiMAX systems. Next, we shall describe measurements conducted in our test-bed installation of WiMAX, which uncovered the white spots effect, a phenomenon very disadvantageous to nomadic and mobile users. This so far undocumented drawback of WiMAX strongly undermines the popular highly favorable opinion regarding the performance of its NLOS mechanisms and can significantly raise the cost of network deployment. As this kind of deficiency is difficult to accept, steps must be taken to resolve the problem. To this end, we shall describe a self-organizing ad hoc WiMAX-based mesh architecture as a solution for the coverage issues and propose mechanisms necessary for the mesh mode to effectively counter the white spots effect for nomadic and mobile networks.

Unfortunately, the mesh mode of WiMAX is currently at an early stage of development, and the requisite mechanisms necessary for it to operate appear numerous and complicated. For these reasons the idea of a WiMAX mesh network receives at best a limited support from hardware manufacturers, and we will probably wait for a long time to see it in a fully functional standardized form. In this situation, we propose an alternative and original solution combining the classical WiMAX point to multipoint mode with the mesh architecture. This hybrid solution is relatively simple, easy to incorporate into current hardware, and it can coexist seamlessly with the standard unmodified equipment.

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 practically relevant accuracy. Thus, there is a need for methods to verify provisional results obtained through theoretical calculations. Two basic approaches are popular with the current design practices. The first one requires a test-bed installation and depends entirely on empirical measurements. The second one relies on software tools able to estimate the system coverage with the use of one of the available propagation models. As the first method is rather time consuming and costly, 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).

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

- Empirical (or statistical) models based on a stochastic analysis of a series of measurements conducted in the area of interest. They are relatively easy to built but not very sensitive to the environmental geometry.
- Site-specific (or deterministic) models, which are far more accurate and need no signal measurements. However, they require a huge amount of data concerning environment geometry, terrain profile, etc., and pose high computational demands.

Owing to the fact that WiMAX systems are intended to provide effective coverage in highly urbanized environments, we are mostly interested in deterministic models, as they can produce sufficiently accurate results for such areas.

Of course, there is always a theoretical possibility to calculate the exact propagation characteristics by solving sets of Maxwell's equations. However, this method would require complex data and very high computational power, causing it to be very inefficient. Therefore, current software tools, based on deterministic propagation models, usually employ simplified simulations: mostly ray-tracing or ray-launching techniques based on uniform geometrical theory of diffraction (UTD) [2]. Such an approach brings about a significant simplification in calculations, making the model an efficient design tool, albeit with a loss of accuracy.

The coverage characteristics of WiMAX differ significantly from those associated with other wireless network technologies employed in similar environments, mainly due to the NLOS capability of WiMAX (see Fig. 1). Thus, a dedicated software model is required to give accurate results [4].

Regardless of the theoretical models employed and their accuracy, experience in wireless systems design and implementation suggests a necessity for empirical measurements in order to confirm that the system design and theoretically obtained parameters are correct [5]. In accordance with 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].

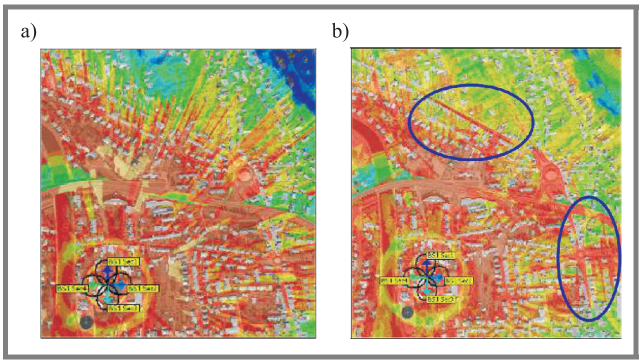

Fig. 1. Results of WiMAX BS coverage simulation: general model (a) and specialized WiMAX coverage model (b).

3. Test-bed installation and example measurements

Both the modeling procedures and tests carried out by hardware manufacturers indicate that the WiMAX technology is indeed very well suited for metropolitan environments and generally offers good coverage, even in highly urbanized areas [7]. To verify these statements and prove the accuracy of the available software design tools, as well as to gather practical design experience, we prepared a test-bed installation consisting of a single WiMAX BS located at Gdańsk University of Technology. We employed a BreezeMAX micro base station [8] provided by the Alvarion company using 3.5 GHz licensed frequency band. We also developed a dedicated software package consisting of a number of control and monitoring tools. These tools communicate with the 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 the measurement teams optimize their work. We have been monitoring long-term operation parameters of the WiMAX installation, with the use of an simple network management protocol (SNMP)-based monitoring system developed especially for this purpose. It allows us to collect and present over 200 parameters concerning BS, SSs and the provided services.

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

– measurements of the BS signal strength in physical layer;

– modulation and coding profile usage as a function of signal quality;

– efficiency of transmission in the medium access control layer (BER, PER);

– quality of service contract adherence for transport layer services.

The tests were performed with the assistance of a 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. In the case of LOS, using the equipment mentioned above, we could expect a reliable communication up to 30 km, and 5 km in the majority of cases related to NLOS scenarios [6].

Such general conclusions sound promising. However, we also made quite unexpected observations. It turned out that in the case of NLOS communication the network did not cover entirely the tested area. We were able to identify some points, dubbed “while spots”, that were not covered by our BS. At the same time, we also detected many locations at which the measured coverage (signal parameters) differed significantly from the theoretical estimates. In some places the coverage was a result of repeatedly reflected signals or signals reflected by various objects either impossible or difficult to map, like trees, billboards, trains, trucks, etc. Other places exhibited lack of coverage, even though the obstacles between the BS and the client terminal were relatively minor (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 WiMAX system design a very difficult task, requiring empirical measurements to validate the project.

Fig. 2. WiMAX coverage hole effect: measured coverage of the WiMAX base station in 3.5 GHz band. Stable modulation profile chosen by client terminal: × – no communication; 1 – binary phase-shift key (BPSK); 2 – quaternary phase-shift key (QPSK); 3 – quadrature amplitude modulation 16 (QAM16); 4 – QAM64 1/2; 5 – QAM64 3/4.

The described effect of white spots demonstrates difficulties faced by attempts to precisely predict the coverage and QoS parameters of any non-trivial real system. If a service provider is interested in a complete and continuous coverage of an area, they may have to accept and absorb a higher system deployment costs. Also, there is no efficient way to validate the coverage without explicit and detailed measurements.

The problem becomes even more serious for a mobile operator, because mobile terminals can loose and regain connectivity as they move. Such effects can be especially laborious in WiMAX, where each network entry operation is complicated and consumes a significant amount of network and terminal resources (bandwidth, BS processing power, battery).

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

4. Network design considerations

The WiMAX poses considerably more complex network design problems than other technologies of lesser coverage. For example, a wireless fidelity (WiFi) [9] wireless local area network can be deployed and verified with a relatively simple, authoritative, and complete set of test measurements. Its typical range (50–300 m) makes such an approach possible. In the case of WiMAX, where the range is measured in kilometers, this solution is not viable, as it is practically impossible to compile a full, empirical coverage map by inspecting all relevant points within the system’s range. In a dense metropolitan area with WiMAX NLOS capability, we would have to measure an extremely thick layout of points. Also, as we pointed out in the previous section, we would need a resolution of under 20 m horizontally. Moreover, restricting the measurements to 2-dimensional would not work, because there are significant variations of the effective signal strength related to the vertical placement of the client station, particularly prominent near ground level.

Computational propagation models can help us highlight potential trouble spots and hint at relevant measurement points. They offer a great support during the design process. Regretfully, 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 equipped to detect coverage anomalies as small as the described white spots. Our research shows that in order to detect them we must employ a very high resolution of modeling, often higher than the popular resolution of 3-dimensional maps [3]. At such resolution, the simplifications inherent in (and shared by) those 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 the detection of all anomalies.

Whether we are able to detect all coverage holes or not, the actual number of BSs needed to provide consistent coverage of the area is higher than inferred from the theoretical modeling. Also, in many places such coverage holes may be impossible to eliminate without a large and economically impractical number of BSs.

There are at least two basic approaches that could be proposed as possible solutions to this problem:

– heterogeneous approach: use a combination of different connectivity technologies;

– homogeneous approach: base the network on a single wireless technology, i.e., WiMAX.

Currently there is a strong trend towards creation of heterogeneous systems, where users can choose from 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 focus on the homogenous approach, limited to the WiMAX technology, considering WiMAX mesh architecture as a possible solution.

5. The WiMAX-mesh mode

In the mesh mode of WiMAX, there is no prominent BS, but SSs communicate directly with their neighbors forming a dynamic, self-organizing, multi-hop network. This way, a client station need not be in range of one of the relatively few BSs, but it is sufficient for it to be in range of any other participating client station. The number of those devices is usually much higher than the number of BSs (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) as new clients join the pool.

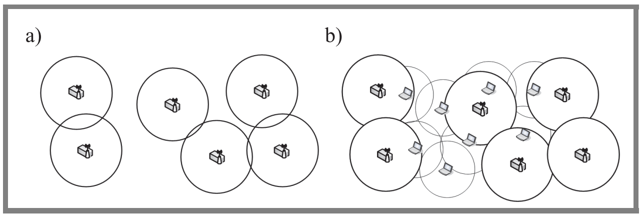

Fig. 3. Coverage comparison of (a) PtMP and (b) mesh mode with the same number of operator provided base stations/nodes.

Unfortunately, this 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 the case of wireless ad hoc mesh architecture, these mechanisms (medium access control, security, etc.) have to be significantly extended and able to operate in a distributed environment. Also the following new mechanisms, not required in a PtMP setup, 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 a large number of derived characteristics (path lengths, bandwidth available, network capacity, transmission delay, error rates, etc.).
- Route discovery: the set of mechanisms employed to find a route through network nodes to any required destination within and outside the wireless mesh. In WiMAX, it should be able to provide paths with specific QoS guarantees.
- Data forwarding: responsible for retransmitting received traffic addressed to remote nodes, in accordance with QoS guarantees and based on the routing information obtained from the discovery mechanisms.

Most studies on mesh networks, including test implementations, exploit short-range wireless technologies (WLANs or sensor networks) to ensure wide area coverage and high reliability. We claim that, also in the case of a wireless metropolitan network (WMAN) of a much higher intended range, WiMAX-based ad hoc mesh architecture can provide the required functionalities and become practical and economically viable [14].

Due to the relatively high complexity, the WiMAX-mesh mode is not yet specified in the IEEE 802.16 standard. The lack of detailed specification gives us the opportunity to incorporate into the created standard new mechanisms, which will make IEEE 802.16 especially attractive for metropolitan environments, being 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 a sufficient number of client stations will participate in the network. It will tend to provide a much better terrain coverage than a typical PtMP WiMAX installation. Also the infrastructure cost will be significantly lower.

With the currently observable trends regarding the user demand and manufacturer support for the technology, one can safely predict that the density of client stations will pose no problem in a typical metropolitan environment. It is also likely that the price of a mesh-capable subscriber station will be similar to that of a classical PtMP WiMAX terminal.

The WiMAX-based ad hoc mesh network can provide much better terrain coverage and its development costs are significantly lower than in the corresponding coverage scenario supported only by standard BSs operating in PtMP mode. Of course, there is still a need for a number of operator-provided network nodes as a foundation of the network. Moreover, mesh architecture can provide high reliability due to the high number of redundant network devices, wireless links, and paths to most destinations. It will also scale well, because any participating node brings in additional resources to the network pool.

While the white spots problem can be solved by a sufficiently dense network of mesh nodes and their redundant links, the network control mechanisms need to be able to deal with the rapidly changing mesh topology. In a static mesh configuration (as in a static PtMP scenario), the problem is not serious, as in most cases the placement of network nodes can be pre-optimized. However, with mobile mesh nodes, even a small movement can lead to unpredictable breakdowns and reappearance of inter-node links.

Mobility can significantly reduce the efficiency of network mechanisms, e.g., leading to frequent activation of the discovery mechanisms of the underlying ad hoc routing protocol, which will flood the network with control traffic. Also QoS guarantees are very difficult to maintain in such an environment, as fast and frequent, short-term connectivity losses can occur.

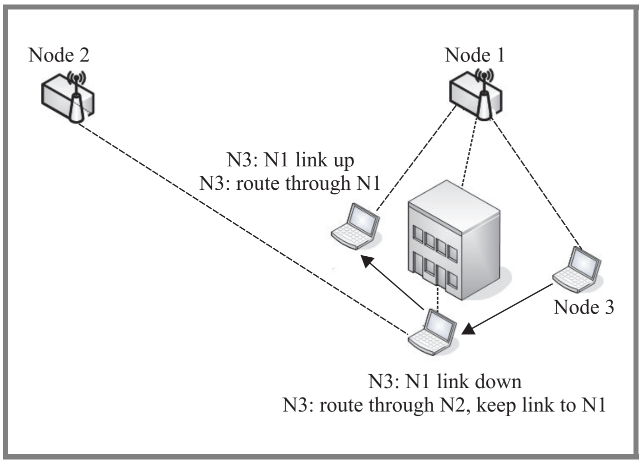

Fig. 4. Short-period link losses and a possible solution with redundant path routing and coverage hole aware topology control.

Fortunately the massive redundancy present in a sufficiently dense mesh network can be harnessed to offset the effect without losing transmission reliability and QoS guarantees. Furthermore, our observations and measurements tell us that signal losses and the corresponding link breakdowns caused by the coverage hole effect are mostly short term events and as such can be efficiently countered with properly designed network control mechanisms. Our work leads us to believe that efficient topology control, taking into account the 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.

6. Support-mesh mode

The main problem with the solution sketched above is the fact that the specification of full WiMAX mesh mode is far from completion. Moreover its development does not receive the attention and support necessary to obtain a practicable solution in the predictable future. Because of this situation we would like to propose an alternative solution, which we call WiMAX support-mesh mode (SMM). It is a hybrid solution utilizing both the standard PtMP architecture with a base station and a self-organizing mesh to support the standard network architecture to eliminate the coverage problems. Our main concern has been to keep the necessary modifications to the existing systems at a minimum. Unfortunately, this goal is in contradiction with the postulate of system efficiency, because the PtMP environment of WiMAX is strictly controlled by the BS. Thus, without a modification of those functions, it is very difficult to arrive at an efficient solution. In this situation we considered two approaches:

- **Variant 1**. A completely transparent solution that requires no alternations to BS hardware or software, only slight modifications in SS functionality.
- **Variant 2**. Requires a slight modification of both BS and SS software, but promises higher system efficiency and robustness.

Both variants allow for seamless coexistence of standard and modified subscriber stations.

In most circumstances the operation of an installation equipped with the support-mesh mode does not differ from that of a classic WiMAX PtMP system. Only in the case of low quality link or connectivity loss between SS and BS the new functionality comes into play (Fig. 5).

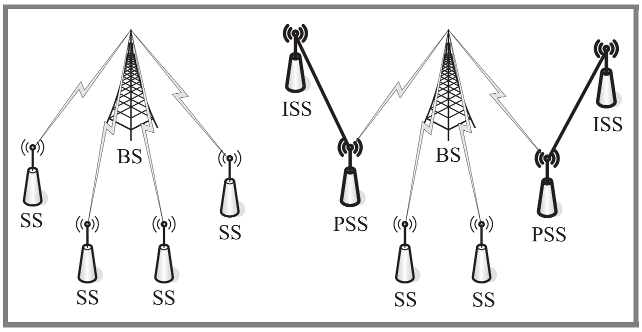

Fig. 5. WiMAX support-mesh mode usage.

In such a case, a 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 the WiMAX PtMP system. The SMM-SS acting as a proxy (PSS) is then responsible for providing communication between the BS and its connected SMM-SSs (indirectly connected SS – ISS). It is even possible to create multiple layers of proxies in the situation when the PSS loses connectivity to the BS and becomes an ISS itself, without abandoning its PSS role (Fig. 6). Such a multilayer network layout is not particularly efficient and should be avoided by ISSs, which should try to find an alternative (directly connected) PSS, but it is nonetheless admissible and can be useful with low-bandwidth, high-reliability applications.

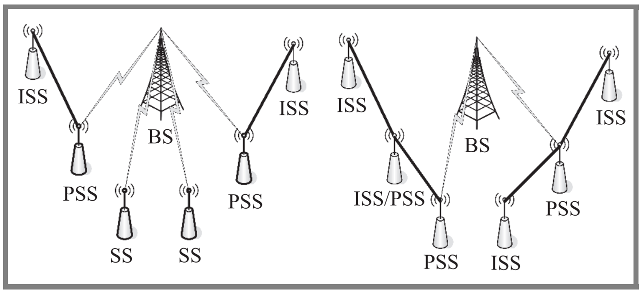

Fig. 6. Multilayer proxying example.

For the system to function effectively, it is recommended that the stations (most importantly PSSs) use omnidirectional antennas. The field of coverage achieved with directional antennas would be very limited and the advantage of employing such PSSs would be questionable. This requirement is currently in conflict with the large volume of WiMAX hardware available on the market, but the situation in likely to change, as a strong trend towards omnidirectional antennas is being noticed.

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.

The PSSs will advertise their capabilities by emulating BS frame structure inside their allocated transmission times, which will allow prospective ISSs to detect them, connect to them, and expedite their traffic. This task may seem highly hardware intensive, as the PSS will need to conduct network maintenance tasks similar to that of the BS. However, there are many simplifications that can be made, taking into account the small expected number of ISSs and their narrow range. Advanced physical transmission control, QoS, and the network control mechanisms can be radically simplified or, in some cases, removed. If only SMM-capable SSs are allowed to connect to proxy stations (and unmodified SSs are prohibited even from connecting to PSSs), the simplifications can be even greater. The exact extent of simplification is currently a subject of our research.

Connecting ISSs can choose their PSSs according to a number of criteria and, possibly, use multiple simultaneous links to several PSSs to enable dynamic soft handover.

6.1. Support-mesh mode – variant 1

This variant is fully compatible with existing unmodified WiMAX systems. Because of this assumption, the PSS makes all requests to the BS, to accommodate its own needs as well as those of the ISSs served by it.

Because the ISSs are not visible to the BS, the PSS is expected to:

- authenticate the connecting ISSs and grant them resources using its own authentication and access control mechanisms;
- obtain bandwidth from the BS, necessary to: service its own traffic, communicate with its connected ISSs, and retransmit the ISS traffic to and from the BS;
- handle the PSS-ISS communication and correctly retransmit unidirectional traffic between the ISS and the BS.

Detailed aspects of the authentication and access control mechanisms are beyond the scope of this paper. Many solutions (strictly local and centralized or distributed) can be employed to address these issues.

The remaining problem is the support for PSS-ISS communication within the constraints of the strictly controlled WiMAX PtMP environment. The WiMAX downlink phase is exclusively controlled by the BS, according to the traffic contracts of the connections and the level of currently buffered traffic awaiting transmission. When the BS does not have traffic to transmit through a particular connection, there is no downlink transmission time allocated for it. In such a case, it is impossible to use the downlink phase of WiMAX for communication with the ISS: it has to be conducted during the uplink phase.

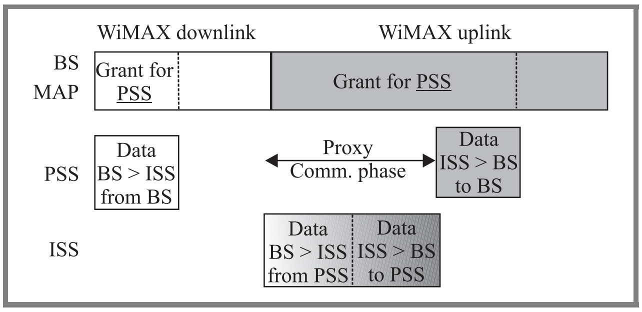

Fig. 7. SMM – variant 1: transmission organization.

Transmission time in the uplink phase is also granted by the BS, according to the traffic contracts of the SSs, but there are no optimizations made by the BS. That makes it possible for the PSS to obtain the necessary transmission time.
In variant 1 of SMM, the PS reserves uplink time to handle (Fig. 7):

– its own uplink traffic to the BS;

– retransmissions of the ISS uplink traffic from the PSS to the BS;

– ISS uplink traffic to the PSS;

– PSS downlink traffic to the ISS.

In variant 1 of SMM presented above, the only stations that require software modification and are aware of the SMM operation are the indirectly connected subscriber stations (ISSs) and their respective proxy subscriber stations (PSSs). The base station and other subscriber stations are neither modified nor aware of the SMM operation.

6.2. Support-mesh mode – variant 2

For variant 2 of SMM, we extend the BS functionality to make it aware of the indirectly connected subscriber stations. While this requires a modification of BS software, it also offers significant advantages in terms of efficiency and system control (Fig. 8).

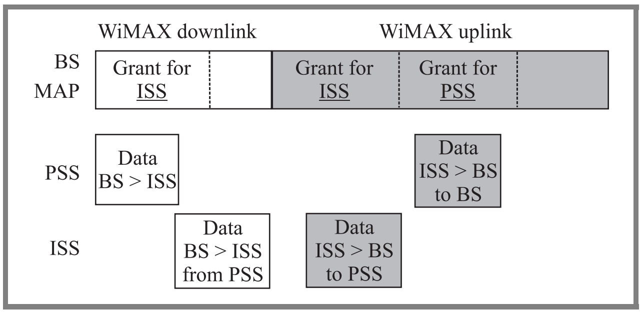

Fig. 8. SMM – variant 2: transmission organization.

In this case, ISSs communicate with the BS, with the proxy stations acting as repeaters, by retransmitting both control and user traffic between the ISS and the BS. This allows the ISSs to participate in the standard network entry procedure, establish WiMAX connections, and issue their own bandwidth requests. This approach allows us to retain the security and management capabilities of the classic PtMP WiMAX system, as the ISS stations are fully recognized by the BS. It also makes it possible to utilize both the downlink and uplink phases for communication with the ISSs, resulting in their much more balanced usage. This balance improves system reliability and can significantly improve the efficiency of WiMAX hardware implementations, which do not support a dynamic change of WiMAX frame division (a dynamic change of the uplink and downlink phase duration ratio).

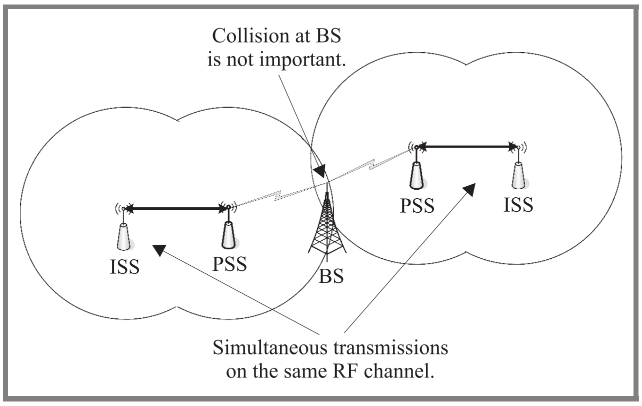

Fig. 9. Use of SDMA in variant 2 of SMM.

In this variant, there is also a possibility of utilizing spatial division multiple access (SDMA) to allow the utilization of a single frequency channel by many PSSs and ISSs at the same time (Fig. 9). This can be done due to the BS's complete knowledge of its network structure (including ISSs), by utilizing an additional raging phase to gather more information about the spatial separation of nodes. Ranging is the process of measuring the quality of the link between the BS and the SS, conducted during the time period especially reserved for this purpose in each WiMAX frame. This time period can be used by the BS to locate those SSs that are unable to interfere with each other, by conducting measurements of link presence and quality between pairs or groups of SSs. This task could be also accomplished by passive measurements by the SSs of the 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.

7. Support-mesh mode – simulation results

To verify the usefulness of our solution we carried out 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 the observed white spots and thus unfit for the task. Thus, we developed a modified propagation model. Its operation is supplemented by a file containing empirical real-world coverage data. 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 5–6 story buildings, 3.5 km^2: the Gdańsk-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: the Gdańsk-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 the results of coverage modeling as the percentage of the previously uncovered area, which now has been 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%.

It is evident from these data that the support-mesh mode subscriber stations can provide a significantly better coverage in urbanized areas than a pure PtMP setup. It advantage is in the distributed layout of PSSs, which cover the target area from varied angles. The result is especially promising in the case of the relatively small number of large obstacles (area *B*). These results convinced us that WiMAX SMM could efficiently solve the coverage issues. Thus, we built simulation models for both of its variants. We employed a relatively simple WiMAX simulation model covering in detail only the ISO-OSI layer 2 network mechanisms, with very simplified layer 1 modeling. We are currently developing a more thorough simulation tool.

Our experiments confirmed the basic operation principles of the WiMAX support-mesh mode, but they 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 proxies. Additional layers refuse to function due to the strict timing constraints of the system. Moreover, there is an additional, up to 8% per layer, performance degradation resulting from the repeated retransmission of data. This degradation applies only to indirectly connected stations and does not impact SSs in the classical PtMP setup.

Variant 2 provides better service and has been tested for up to 5 layers of proxy stations, at which point it was till operable. The loss of performance for indirectly connected stations was about 5% per proxy level, but in this case the BS could compensate for the loss and provide the ISS with a respectively higher bandwidth.

In both cases (variants 1 and 2) there is also a need for retransmission of data by PSSs, which is the main source of performance degradation, halving the bandwidth with each proxy level. Because of that, the performance of variant 2 with SDMA mechanisms is in most cases drastically better, as it allows the stations to conduct multiple retransmissions simultaneously. The exact results depend on station locations and terrain layout.

8. Conclusions

Based on our theoretical research and practical experiments, we observed a detrimental 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 among the most popular wireless network design support tools used today. They can lead to lower than expected service levels, requiring repositioning or installation of additional hardware and can be especially harmful for mobile users who will experience periodic losses of connectivity.

Despite the fact that the same coverage problem would affect mesh nodes (especially the mobile ones) 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 the holes. The problem would be very difficult to fix in the classical BS-based architecture without large additional hardware costs.

We have proposed WiMAX mesh networks as a viable method of dealing with coverage difficulties in metropolitan areas. This kind of solution provides additional crucial advantages, e.g., well-scaling high network capacity, high reliability based on multiple redundancy, low cost of deployment.

As a fully functional mesh mode requires a significant number of additional, advanced mechanisms, and is still in a very early stage of research and development, we developed a hybrid PtMP-mesh solution dubbed the support-mesh mode. It provides the subscriber stations with proxy capabilities, thus bringing about many of the mesh mode advantages (including coverage and reliability) with considerably simpler mechanisms. Both variants of our solution require only limited modifications to subscriber station software, and only the more advanced variant 2 requires a modification of base station software.

Operation of both variants of our solution have been studied by simulation 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 the upcoming versions of WiMAX hardware.

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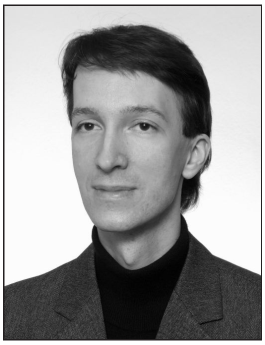

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