Accurate Modelling of OFDMA Transmission Technique Using IEEE 802.16m Recommendations for WiMAX Network Simulator Design

Marco Miozzo and Faouzi Bader

Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)
Parc Mediterrani de la Tecnologia (PMT)
Av. Carl Friedrich Gauss 7 - 08860 - Castelldefels (Barcelona) - Spain
{marco.miozzo,faouzi.bader}@cttc.es

Abstract. Worldwide Interoperability for Microwave Access (WiMAX) is the name selected by WiMAX Forum for referring to the standard defined by the IEEE 802.16 task force. The standard introduces several interesting novelties both from PHY and MAC perspective which lead to a complex architecture. In order to understand and investigate its potentialities, analysis is needed. Due to its intrinsic complicated architecture nature, mathematical models may be only applied to portion of the whole system. The same has done for simulation with link level, system and network simulators. However, the new research requirements impose that the model has to be more comprehensive as possible, in order to take care of all the interactions, from physical to application layer. In this paper we propose a novel library for the Miracle extension for ns2 simulator in which, by means of link-to-system mapping (LSM) techniques, the level of details in the PHY layer to be simulated is tuneable in order to take in consideration its important phenomena in a network simulator.

Keywords: IEEE 802.16, WiMAX, OFDMA, ns2.

1 Introduction

In the last years the market for Broadband Wireless Access (BWA) started to grow and nowadays seems to be very attractive for the future, In fact, we are assisting to the proliferation of several new applications and services which requires high quality of service (QoS) and large bandwidth connections. Up to now, the technology which dominates the market is the High-Speed Downlink Packet Access (HSDPA), an extension of Universal Mobile Telecommunications System (UMTS) [1], due to the easy installation (i.e., via USB key) and to the widespread of UMTS accesses. However nowadays, many new technologies are under evaluation in order to obtain better performance thanks to the recent innovations in transmission techniques. Worldwide Interoperability for Microwave Access (WiMAX) and Long Term Evolution [2] (LTE) are the two most interesting ones. The latter one is a standard defined by 3GPP to convey the UMTS radio technology towards the 4G network view, i.e., the next generation of high data rate access network totally based on IP

K. Pentikousis et al. (Eds.): MONAMI 2010, LNICST 68, pp. 258–269, 2011.

flows. These goals are also the ones of WiMAX and it seems that it will be an enthralling challenge on which one will win on the market.

The IEEE 802.16 standard [3] defines the specifications for the WiMAX radio technology related to the lower three layers of the OSI protocol stack. The network is composed by base stations (BSs) in charge of providing connectivity to subscriber stations (SSs) over superframe according to the compulsory procedures defined within the standard. Recently, relay stations (RS) have been introduced to support the BS in the service provisioning. The first functional WiMAX wireless air interface was defined by the IEEE 802.16-2004 [3] targeting only the fixed wireless broadband access systems. Later, with 802.16-2005 [4] (also called 802.16e), it was introduced the support for mobile functionalities thanks to the OFDMA radio transmission technique. With the IEEE 802.16j [5] standard released in the 2006, relay technology has been introduced in the WiMAX architecture. At the time of this writing, the IEEE 802.16 task force is working on the 802.16m draft in the definition of an advanced air interface for high data rates (e.g., 100 Mbit/s mobile and 1 Gbit/s fixed). However, many part of the architecture have been left open to vendor specific implementation (e.g., the scheduling of the packets for the different class of users, the hybrid ARQ schemes, the physical allocation to the users and many others). This means that there is a considerable need of instruments to correctly test the actual performance of the existing solutions and to investigate new enhancements. According to the specific topic under research, this need can be limited to a specific protocol or layer of the OSI stack; for instance, a link level simulator is the best solution for evaluating the coding and modulation performance and more in general PHY aspects. The problem becomes more argued in the upper layers, where the common practice is the adoption of system level simulators or network level ones. The former one models mostly the hardware physical constrains and the link level; in fact, it is commonly exploited by industry during the development of new equipments. Since this kind of solution is usually designed for a specific implementation, it models the hardware constraints and generally does not consider the whole protocol stack interactions. Finally, network simulators account for the whole OSI stack allowing the definition of realistic network topologies and they do not consider hardware aspects. This allows the definitions of scenarios with base stations, servers, routers and clients which exchange flows of data among them, making possible to collect end-to-end performance. We want to note that, network and system level simulators usually rely on the performance obtained by link level simulators in order to model the PHY layer. On this matter, the level of abstraction adopted may differ a lot and we consider that this assumption is becoming a fundamental feature in simulation tools considering the level of details required by most of the new research fields. For instance, the interference and in general the channel state information represent crucial parameters in optimization algorithms at several layers. A few samples are: SINR adaptive coding scheme, TCP optimization and in general smart routing and radio resource management (RRM) schemes.

Democles® project [6] (dynamic resource management for advanced multiple carrier system platform) started with the aim of developing a framework for simulating next generation of wireless networks (e.g., 4G) which exploit multi-carrier techniques. This project also focuses on RRM functionalities in order to better exploit all the PHY and MAC layer characteristics and satisfy the QoS needs of the services by means of cross-layer algorithms. In order to address these goals and considering the discussions above, we decided to implement a simulator for WiMAX networks in the context of this project starting from the Miracle [7, 8] extension for ns2 [9]. This work is called WiMAX for Democles® (WiDe). The rest of the paper is organized as follows. Section 2 introduces the IEEE 802.16 standard. In Section 3 we propose a brief overview of other 802.16 networks simulators. In Section 4 we discuss on WiDe module and we detailed out the implementation process. We note that, we do not present specific implementation details, but rather argue on our simulation methodology in order to highlight the advantages and the limitations due to the complexity adopted. In Section 5 we present interesting research scenarios which can be opportunely described by means of WiDe. Finally, Section 6 concludes the paper.

2 Standard Overview

In this section we summarize the principles of the IEEE 802.16 standard, for a comprehensive view of the architecture the reader may refer to [4, 5]. WiMAX supports both point-to-multipoint (PMP) architecture and mesh topology. The two types of communication systems are similar from PHY layer point of view; they differ mostly in some MAC procedures in order to enable the support to RSs. These changes will be highlighted in this section. The standard defines multiple PHY layers according to the application environment, the most used are: WirelessMAN-OFDM exploiting orthogonal frequency division multiplexing technique (OFDM) and WirelessMAN-OFDMA using orthogonal frequency division multiple access scheme (OFDMA). The PHY layer of WiMAX is organized in frames of fixed length. According to the TDD mode, each frame is divided into two subframes to guarantee the bidirectional communications (i.e., downlink and uplink). In case of relay mode, each subframe is divided into one or more access zones and relay zones. The downlink/uplink access zones are allocated to the transmissions between SS and their access point. The MAC layer is divided into three sublayers: the convergence sublayer (CS), the common part sublayer (CPS) and the security sublayers. CS is in charge of the classification and the mapping of the incoming packets from the upper layers and their transmission to the CPS where classical MAC procedures are applied. The main CPS functionalities are: connection establishment and management, generation of MAC signalling, service flow management and scheduling. One of the main roles of MAC signalling is the negotiation of the bandwidth. This can be done with stand alone bandwidth request messages or piggybacked in data packets. The uplink scheduler at BS side decides which SSs among the ones have requested bandwidth can transmit in the next uplink subframe. Similarly, BS scheduler picks up the packets to transmit in the downlink subframe according to the scheduling services (or QoS classes).

The MAC protocol is connection-oriented: all traffic is mapped onto connections which are uniquely identified by the connection identifier (CID). The registration phase is a two way handshake procedure called *initial ranging*. The downlink map (DL-MAP) and uplink map (UL-MAP) are broadcasted each frame by BS in order to indicate how the accesses have to be managed in the current frame. The downlink channel descriptor (DCD) provides the burst profiles (physical parameter sets) that can be used by a downlink physical channel during a burst, in addition to other useful downlink parameters. The uplink channel descriptor (UCD) does the same as the DCD for the uplink subframe.

In order to transmit and receive data of the service requested, the SS has to establish a connection. Each service flow defines a unidirectional flow of data traffic and is characterized by a set of QoS parameters. In mesh mode, from MAC layer perspective an RS has two operative modes. A transparent RS (T-RS), in which RS does not have to transmit any control messages. In this case, SSs receive broadcast signalling from BS and they are not aware of the RS (i.e., there is not logical connection established), which are in charge to only relay data traffic. In case of non-transparent RS (NT-RS), the RS has to broadcast management messages in its relay zone, that is: the relay DL-MAP (RDL-MAP) and relay UL-MAP (RUL-MAP). This implies that SSs are logically connected to their RS instead of the BS.

3 Related Work

In this section we present a brief overview of the existent WiMAX modules developed for network simulators. We would like to stress that, in this section we are not going to detail the features and gives a practical comparison among them, rather then we are more interested to examine and highlight their approach. The NIST module [10] is one of first developed as extension of the ns2 simulator. It provides functionalities for 802.16 MAC, handover and scheduling. The main drawbacks are that it provides only a simplistic OFDM PHY layer and the absence of an ARQ scheme. The NDSL module [11] focuses mostly on MAC functionalities referring to OFDMA PHY layer, which however is model in a very high level fashion. There are many other extensions provided for ns2, a more accurate exposition can be found in [12]. Recently has been released also a module for the brand new NS3 simulator [13]. The module presents many interesting MAC functionalities but it does not implement any packet error model and it models only the OFDM transmission scheme.

All the modules presented above have a common characteristic: they implement the disk propagation model. In respect to this, many works on IEEE 802.11 have just demonstrated that this model is far from addressing sufficient PHY aspects. In fact, it is designed for a single carrier case and it models the error distribution with a threshold on the power received. However, when we consider modern transmission techniques, such as OFDM, we are referring to multi-carriers systems, where the data is spread over several subcarriers and this assumption might be simplistic. Since these subcarriers are placed at different frequencies, they experience different propagation behaviours and frequency selectivity which implies different degradations.

One of the first modules that try to relax this assumption is the one developed by WiMAX Forum starting from NIST module which, however, is available only to consortium members. Finally also WINSE [12] module is aware of this problematic. WINSE seems to be one of the most complete modules for IEEE 802.16. It has most of the functionalities counted by the standard for the MAC layer, it accurately models both the OFDM and OFDMA PHY layer by exploiting propagation traces generated with dynamic system simulators. However, this solution implies that only scenarios pre-simulated by the system simulator can be then simulated.

4 WIDE

4.1 General Aspects

As done by WiMAX Forum, we implemented WiDe starting from NIST module as extension of the well known network simulator ns2. This choice is based on the fact that NIST extension represents a good solution from MAC layer point of view and, moreover, it has just been integrated in Miracle framework by University of Karlstad [14]. Thanks to the latter feature, this module inherits all the functionalities provided by Miracle. This enables the developing of a fully integrable module without make any changes to the ns2 core, besides it can coexist with other radio technology modules and therefore it allows to simulate scenarios where node are equipped with many of them simultaneously. In fact, WiDe is a simple library which has to be dynamically loaded in the Tcl simulation script (see [7] for more info on dynamic libraries). Another important feature inherited is the support for the PHY layer modelling, which we opportunely adapted to multi-carrier techniques. Finally, a cross layer message engine provides an efficient way to exchange info between MAC and PHY layer, but also to potentially all layers, enabling the easy implementation of RRM schemes. A diagram of WiDe implementation architecture is given in Figure 1.

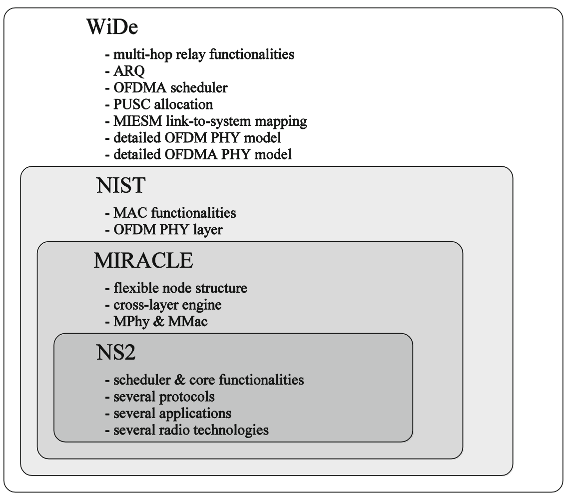

Fig. 1. Diagram of WiDe implementation architecture

4.2 WiDe PHY Layer

In this subsection we explain the solutions we adopted in the implementation of the PHY layer in WiDe. As anticipated in Section 3, OFDM transmissions are affected by complex propagation phenomena due to the time-frequency selective channel nature. This implies that subcarriers may experience frequency selective fading and therefore different channel gains one from each other. We have also to consider that we need to find a trade off between the computational complexity of the simulator and the abstraction level in order to be able to adapt the framework to the specific research scenario we are considering. For instance, in link adaptation schemes and channel aware scheduling algorithms is fundamental to have a clear and detailed view of the channel conditions; while in load balancing scheme or, more in general, in large networks evaluations, these aspects can be neglected (or, usually, have to be relaxed to reduce the computational complexity due to the intrinsic complexity of the scenario). This led us to develop a PHY layer in which the level of complexity is tuneable in order to satisfy different research needs with a reasonable simulation time. This has been obtained by modelling the channel with a different number of logical subchannels, where with modelling we mean the evaluation of the SINR per packet level considering both channel propagation phenomena and the interference perceived counting for all the on-going transmissions. We identified two main different levels of complexity:

- BASIC (standard ns2 behaviour): one single channel simulates all the subcarriers.
- FULL: all the data subcarriers are modelled.

The first model mimics the standard ns2 behaviour where all the transmissions are simulated as performed in the same carrier. This model can be still considered a valid approach in fixed WiMAX, where standard OFDM schemes are applied and therefore all the subcarriers are used simultaneously for the same transmission with the cost of neglecting the frequency selectivity phenomenon. The latter model, called FULL, allows modelling all the aspects involved; in fact, interference and channel gain is counted for each subcarrier. Thanks to the SINR evaluated through the process described above, we implemented an error distribution model which estimates the errors according to the actual SINR frequency profile perceived by the radio during the packet reception. This is done interfacing WiDe with a link level simulator [15] by means of link-to-system mapping (LSM) technique. This allows the relaxing of one of the strongest assumption usually adopted in network simulators: the disk propagation model. This model has a critical limitation: all the transmission schemes have the same performance from error distribution as function of the received power point of view. This behaviour is due to the fact this error reception model marks as corrupted all the packets which have the SINR under a certain threshold, unique for all the transmission types. For instance, the NIST module adopts this solution; in fact, it defines a unique reception threshold below which all the packets are considered corrupted. This implies that the system models all the modulation schemes with the same energy robustness; therefore, for instance, it does not make difference to transmit with the 64-QAM respect to the QPSK from error distribution perspective. We would like to note that, this is the approach adopted by WiMAX Forum [17].

Finally, in order to carefully model the propagation phenomena, the system accounts for fading, shadowing and path loss. Fading is modelled thanks to the Jakes Simulator [17]. Shadowing is modelled according to the Gudmunson model [17], and path loss according to the Hata model [18].

The link level curves exploited are generated by a WiMAX OFDM link level simulator assuming a frequency flat response at given SINR, therefore, in order to

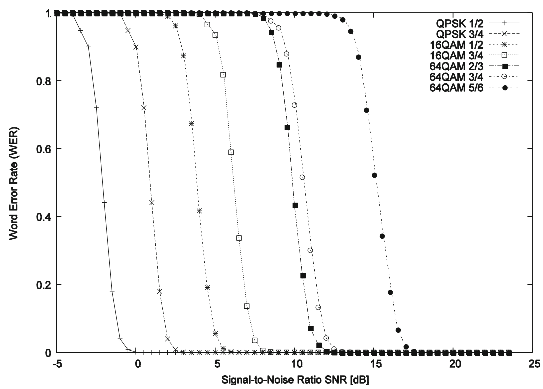

Fig. 2. Example of Word Error Rate curve (example for codewords of 14 bytes)

map SINR values coming from the WiDe PHY layer onto that curves, we need a specific mapping scheme which takes into account of this. This technique is called *effective SINR mapping (ESM).*

In practice, ESM maps the vector of the N SINR values received $\{\gamma_1 \dots \gamma_N\}$ into a single effective SINR (ESNR) value which can be further used to estimate the block error rate (BLER) according to the coding performance curves; in formula, ESNR is approximated with functions of the type

$$\gamma = \theta^{-1}\left(\frac{1}{N}\sum_{n=1}^{N}\theta(\gamma_n)\right)$$

where γ is the ESNR, N is the number of subcarriers, γ_n is the SINR perceived by the n and the particular function θ depends on the wireless technology being used. Several ESM schemes has been proposed to model the link performance, the most interesting ones are: exponential-effective SINR mapping (EESM) [19] and mutual information effective SINR mapping (MIESM) [20]. According to [20], MIESM is the one with the best performance from PER prediction accuracy point of view and therefore we have selected it in our implementation. The idea behind this solution is to compute mutual information metric based on the samples of SINRs of the different subcarriers as function of the specific modulation, in our case it is called received bit mutual information rate (RBIR). Thanks to RBIR value we may have the word error rate (WER) through the curves of the coding simulator [15]; a sketch of the MIESM approach is given in Figure 3. An example of WER curve is given in Figure 3 where it is clearly depicted how the modulation and coding scheme strongly impact on the performance in the reception and justify our concerns on the single threshold model, previously adopted. This is clearly demonstrated by Figure 4, where the standard disk propagation model is adopted for simulating the data rate perceived by the application in a downlink connection with the OFDMA PHY layer. In Figure 4 we may observe that all the modulation and coding schemes have the performance as function of the distance between the SS and the BS, this is due to the fact that the reception model is a single threshold on the received power unique for all the transmission profiles. In Figure 5 we plot the results for the same simulation scenario with the LSM scheme implemented and the impact of the introduction of the WER curves is not negligible in the in the end-to-end performance; in fact the curves follow the same behaviour of the respective ones with the flat response presented in Figure 2.

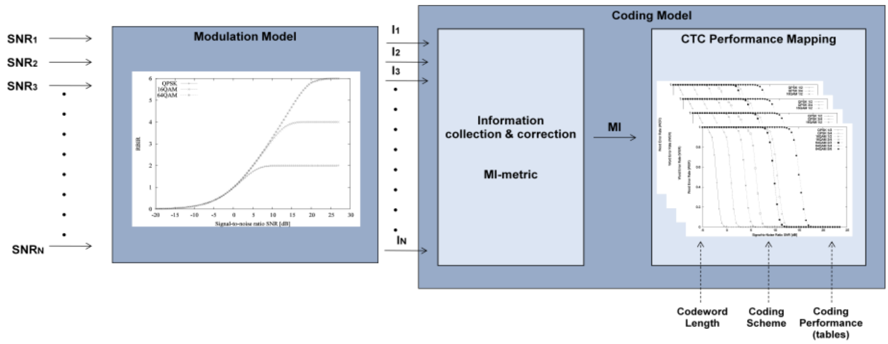

Fig. 3. Diagram of the MIESM link-to-system mapping procedure

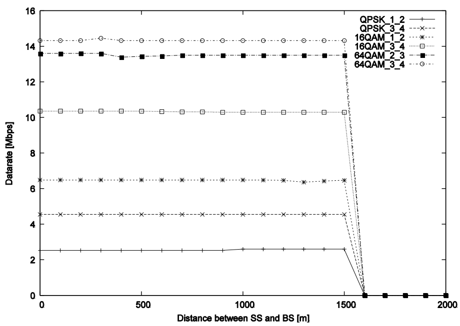

Fig. 4. Data rate perceived in the downlink connection with disk propagation model

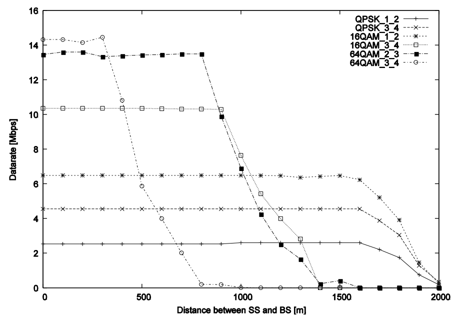

Fig. 5. Data rate perceived in downlink connection with LSM approach

The OFDM transmission scheme is the first real implementation of WiMAX and is the one which nowadays is exploited in all the fixed WiMAX commercial equipments. It supports both TDD and FDD, but in our model only TDD is implemented. It exploits 256 subcarriers and they can be used only simultaneously by the transmission entity. In this case, starting the NIST implementation of the OFDM PHY layer, we improved error model according to the LSM technique described above. In Table 1 we report the main OFDM parameters of WiDe. The OFDMA layer model is the standard adopted by mobile WiMAX and is the model we adopt as reference in our implementation. In case of TDD combined with OFDMA techniques allows to duplex transmissions both in time and frequency. The latter one is obtained by allocating different set of subchannels to each transmission. The standard defines several combination of number of subcarriers supported, in order to provide scalability features. In the particular version of the standard we are referring to (i.e., IEEE802.16m) the mandatory number of the subcarriers is fixed to 1024. From the

1024 subcarriers, we have to remove the ones exploited in the guard bands and the one reserved as central null subcarrier. The result is that OFDMA guarantees 840 subcarriers for actual information transmissions (i.e., data and pilot subcarriers). In order to manage the allocation of the subchannels, several sub-channelization schemes have been defined. In the following we concentrate in the partial usage of the subchannels (PUSC), which is the one adopted in WiDe. PUSC defines 30 logical suchannels, each of one composed of 24 subcarriers for the data and 2 reserved for pilot signalling. The subcarriers involved in the subchannels are selected in a non adjacent fashion with a technique of two levels of permutation and grouping. This is due in order to obtain incorrelation among the subcarriers exploited in the same subchannel.

In our implementation we have modelled PUSC sub-channelization and we are able therefore to track the transmissions on subcarrier level. In this case, we implement a third level of complexity called PUSC which models 30 channels as the 30 logical channels defined by PUSC. This implies that the interference can be accounted per subchannel level but still the frequency selectivity is not modelled. This model can be useful for simulating scheduling scheme in single cell scenarios where the subchannels are common for all the devices.

In Figure 6 we provide statistics on the computational complexity of this technique considering the OFDMA PHY layer. We plotted the simulation time as function of the number of the users for a single simulation run in a single processor Intel Pentium 4 machine. Consider that, the curves refer to a simulation of 30 seconds of simultaneous transmissions of the users involved. Since the rate of the data to be transmitted is set to saturate the channel, we may consider this as a worst case scenario. From the curves we can see how the computational complexity grows with the number of subchannels/ subcarriers simulated as expected. With the FULL model, the simulation time increases very rapidly and therefore it might be difficult to use it in large simulation scenarios. However, it can be still useful to test small scenarios in which a high level of details simulated is required; for instance in interference limitation scenarios such as: compatibility tests between radio transmission technologies and channel aware packet scheduling algorithms. Thanks to the PUSC model we instead have, at a reasonable simulation time overhead, enough information to correctly model the interference in the different subchannels.

4.3 WiDe MAC Layer

In the MAC layer, we worked mostly on addressing the limitations of the NIST library. Due to the realistic error model introduced, we implemented an ARQ scheme in order to mitigate its effect on the end-to-end performance. The standard ARQ implementation in WiMAX, considers dividing the flow into blocks of variable in order to identify the portion of the flow which lacks at the receiver side and subsequently asks for their retransmission. Retransmissions are requested by the receiver according to different policies, the actual algorithm implementation is left to vendor definition. In our implementation a receiver can acknowledge set of adjacent blocks received correctly in a cumulative fashion or specify the sequence of blocks received correctly but non adjacent thanks to the sequence maps.

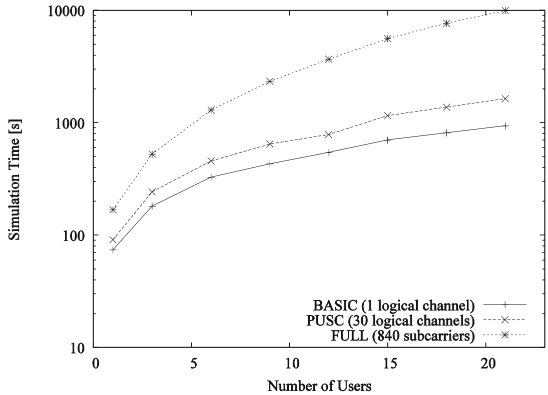

Fig. 6. Computational complexity for OFDMA PHY layer

Finally, we introduced all the functionalities to manage the relay node in mesh mode. In this case we designed two new entities: the relay stations and the subscriber station connected to a relay station. This implies also the extension of the functionality of scheduling from the BS also to the non-transparent RS in order to allow the transmissions both in access and relay zone. In Table 1 we report the main MAC parameters of WiDe.

Table 1. Wide principal features

PHY Layer
SINR traced per each packet in fly at subcarrier grade MIESM link-to-system mapping Packet Error Model with modulation and CTC OFDM with 1 channel OFDM with 256 simulated subcarriers OFDMA with 1 channel (BASIC mode) OFDMA with 30 PUSC subchannels (PUSC mode) OFDMA with 1024 simulated subcarriers (FULL mode)
MAC Layer
MAC management messages: DL-MAP, UL-MAP; DCD, UCD Relay functionalities ARQ scheme (feedbacks and transmission window) ARQ tunable size blocks Bandwidth request: standalone and piggy-backed Best Effort BS scheduler SS scheduler
Connectivity Service Network
Network entry procedures (initial ranging and registration) Connection establishment messaging: dynamic service management Handover

5 Research Scenarios

Thanks to Miracle framework, WiDe inherits a very flexible definition of the node architecture. For instance, it is possible to define mobile device equipped with

WiMAX and also other radio technologies. On top of the network level, several transport protocols can be used, such as Transport Control Protocol (TCP), User Datagram Protocol (UDP) and Real Time Protocol (RTP). Regarding the latter, a set of applications are just ready to be connected to transport layer, such as: VoIP and Video codec (both of them incorporate instruments to evaluate the quality perceived after the decodification) with constant bit rate (CBR) and conversation-like behaviour. For instance, we have integrated in Wide the support for the Evalvid tool [21], which is a set of applications designed to manage video streaming flows, simulate their transmission and collect end-to-end statistics, such as picture signal to noise ratio (PSNR), packets losses and jitter.

Cross-layer messaging represents a suitable framework for the improvement of several algorithms, especially when combined with a detailed view of the link and network condition, as described in [22].

From users' point of view several research topics can be carefully investigated. For instance, scheduling algorithms can take advantage of the information on the actual conditions of the channel at subcarriers grade in order to implement more efficient allocation schemes. In fact, WiDe PHY layer models the channel at single subcarrier level both from propagation phenomena and interference perspectives. This paradigm can be exploited also by upper layers, where RRM modules, transport protocols and applications can adapt their algorithms to the channel or radio conditions (e.g., smarter TCP transmission windows updating, variable bit rate video codec and triggers to RRM handover decision making policies).

Finally, thanks to WiDe we may now evaluate relay architectures by carefully taking in account for the interference in the whole system and exploiting the relay functionalities of IEEE 802.16j. One of the big challenges is to find how to optimally split the intelligence between cognitive terminals and cognitive networks. From network perspective, schedule transmissions both in time and frequency [23] among the entities is another interesting research topic by considering a more flexible partitioning of the frequency bands thanks to admission of a tolerant interference. Both of the last points allow further to consider also energy saving problem, part of the emerging research field known as *green communication*, an evergreen topic in wireless systems due to the intrinsic battery limitations of the handleable devices.

6 Conclusions

In this paper we presented a novel implementation of WiMAX for network simulation called WiDe. According to the trend of the research community, we carefully implemented the PHY layer with a tuneable level of detail specification in order to take into account for interference and propagation phenomena up to subcarriers grade. We demonstrated that this does not introduce too much computational complexity. In fact, with a full level of details it is still possible to simulate intra cell scenarios with a reasonable simulation time. Thanks to these features, WiDe allows the accurate simulation of several new research scenarios, such as cross-layer optimization schemes and green communication, where the knowledge of PHY conditions at simulation run-time is a crucial aspect.

References

1. Holma, H., Toskala, A.: HSDPA/HSUPA for UMTS. John Wiley & Sons, Chichester (2006)
2. Sesia, S., Toufik, I., Baker, M.: LTE – The UMTS Long Term Evolution - From Theory to Practice. John Wiley & Sons, Chichester (2009)
3. IEEE Std. 802.16-2004, IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed Broadband Wireless Access Systems (October 2004)
4. IEEE Std. 802.16e-2005, IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed Broadband Wireless Access Systems - Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in License Bands (February 2006)
5. IEEE Std. 802.16j, Air Interface for Fixed Broadband Wireless Access Systems: Multihop relay specifications (July 2008)
6. DEMOCLES® - Simulation-based testbed for dynamic RRM, `http://www.cttc.es/en/projects/testbeds/project/DEMOCLES.jsp`
7. ns-MIRACLE: Multi InteRfAce Cross Layer Extension for ns-2, `http://telecom.dei.unipd.it/download`
8. Baldo, N., Miozzo, M., Guerra, F., Rossi, M., Zorzi, M.: Miracle: The Multi-Interface Cross-Layer Extension of ns2. EURASIP Journal on Wireless Communications and Networking, Article ID 761792, 16 pages (2010)
9. The Network Simulator - ns2, `http://www.isi.edu/nsnam/ns/`
10. The Network Simulator ns-2 NIST add-on - IEEE 802.16 model (MAC+PHY), Technical report, National Institute of Standards and Technology (June 2007)
11. Chen, J., Wang, C.-C., Tsai, F.C.-D., Chang, C.-W., Liu, S.-S., Guo, J., Lien, W.-J., Sum, J.-H., Hung, C.-H.: The design and implementation of WiMAX module for ns-2 simulator. In: WNS2, Pisa, Italy (October 2006)
12. Sayenko, A., Alanen, O., Martikainen, H., Tykhomyrov, V., Puchko, O.: WINSE: WiMAX NS-2 Extension. In: SIMUTools, Rome, Italy (March 2009)
13. Farooq, J., Turletti, T.: An IEEE 802.16 WiMAX Module for the NS-3 Simulator. In: SIMUTools, Rome, Italy (March 2009)
14. NS2 Miracle Wimax, `http://sourceforge.net/projects/ns2miraclewimax/`
15. Pfletschinger, S., et al.: D2.2.3 Modulation and Coding schemes for the WINNER I System. IST-4-027756 WINNER II
16. WiMAX Forum White Paper, WiMAX System Evaluation Methodology (July 2008)
17. Stüber, G.L.: Principles of Mobile Communication. Kluwer Academic Publishers, Dordrecht (2003)
18. Goldsmith, A.: Wireless Communications. Cambridge University Press, Cambridge (2005)
19. Mumtaz, S., Gamerio, A., Rodriguez, J.: EESM for IEEE 802.16e: WiMaX. In: ICIS, Portland, Oregon, USA (May 2008)
20. Brueninghaus, K., Astely, D., Salzer, T., Visuri, S., Alexiou, A., Karger, S., Seraji, G.A.: Link performance models for system level simulations of broadband radio access systems. In: IEEE PIMRC 2005, Berlin, Germany (September 2005)
21. EvalVid - A Video Quality Evaluation Tool-set, `http://www.tkn.tu-berlin.de/research/evalvid/`
22. Akyildiz, I.F., Wang, X.: Cross-Layer Design in Wireless Mesh Networks. IEEE Transactions on Vehicular Technology 57(2), 1061–1076 (2008)
23. Debbah, M.: Mobile Flexible Networks: The challenges ahead. In: IEEE ATC (October 2008)