Bridging Solutions for a Heterogeneous WiMAX-WiFi Scenario

Romano Fantacci and Daniele Tarchi

Abstract: **Recently, the metropolitan area network (MAN) has attracted much attention in telecommunication research and has emerged as one of the most important research topics in the community. Several standards representing the first step for developing metropolitan networks have been published; IEEE 802.16 (WiMAX) has taken a relevant role in reaching the goal of realizing a full-service network all over a urban and suburban area. At the same time, the wireless local area networks (WLAN) have been widely used for in-home or short range communications, mainly basing on the IEEE 802.11 (WiFi) standard. A consequence is the increasing interest in interworking technology, that allows an interconnection between different standards by maintaining certain properties, mainly in terms of quality of service (QoS). One of the major issues is to design bridging devices capable of transparently interconnect different wireless technologies. In this paper, we propose two interconnection bridging solutions between WiMAX and WiFi links; the first is more based on the concept of maintaining a certain end-to-end QoS level independently from the wireless technologies used. The second method is more devoted to the reduction of the implementation complexity at the cost of no QoS assurance. The performance of the two methods are compared by resorting to computer simulations showing the advantages of each one technique.**

Index Terms: **Heterogeneous networks, IEEE 802.11, IEEE 802.16, quality of service (QoS) management.**

I. INTRODUCTION

Wireless technologies characterize our way of life deeper and deeper in the modern culture: This has lead to a sensible improvement of research, development, and investments in communications that does not need a physical wired link. Starting from the wireless personal area networks (WPAN), through wireless local area networks (WLAN) we are actually facing the problem of covering a big area (like a metropolitan or a country scenario): The use of radio-link communications is due to the very low costs of implementation and the lack of natural obstacles to overcome, while covering an entire city means a newer and easier way of human communication. For these reasons, the 3G networks have been created with the aim of covering an entire country, achieving good reliability and acceptable data rates. In order to improve these rates, wireless metropolitan area networks (WMAN) standards have been realized, introducing a easier way to manage the network and a medium to carry information faster than in 3G networks.

The IEEE 802.16 standard [1], supported by the WiMAX commercial consortium, concerns the physical (PHY) and medium access control (MAC) layers specifications for a broadband wireless access (BWA) communication protocol [2]: Its characteristics provide WiFi-like data rate (near 50 Mbit/s) on a 50 km average range; for these reasons IEEE 802.16 will become the best way to carry BWA connections in remote areas, where the wired links would be too expensive, realizing the so-called *wireless ADSL last mile*.

On the other hand, the WLANs based on the IEEE 802.11 standard [3] emerged as the most widely deployed technology for the broadband wireless access; the key features of 802.11 WLANs are simplicity, scalability, and robustness against failure [4]. One of the main drawbacks of the IEEE 802.11 standard is the inability to provide priority support for those applications requiring QoS: The IEEE 802.11 MAC layer does not offer a specific treatment for each application running within the WLAN. To this extent, recently has been finalized the IEEE 802.11e-2005 standard [5], in order to enhance the original IEEE 802.11 MAC layer to support QoS, by improving the capabilities and efficiency of the basic 802.11 MAC protocol by defining a mechanism for QoS support to the different types of traffic, in order to satisfy their specific service level requirements.

One of the main advantages that can be achieved would be a seamless integration between heterogeneous networks within an urban area; the interworking optimization issue of different networks has been considered in the past when wireless access was not widely used [6], [7]. With the introduction of the modern wireless networks, the possibility of use jointly more than one of them has been often suggested in the literature, as for resource optimization as for wider area coverage. In particular in [8] and [9], two interworking solutions between 3G cellular networks and WLAN have been proposed, while in [10] and [11] two interworking solutions for WLAN/WMAN integration have been proposed.

In this paper, we propose two bridging solutions for a WiFi/WiMAX interconnection by taking into account two main goals: Traffic priority and implementation issues. The first solution is more based on the concept of maintaining a certain end-to-end QoS level independently from the wireless technologies used to link them. In that sense, the primitives of the MAC layer of the two protocol stacks have been considered in order to assure the requested QoS level for a certain connection. The second solution is more devoted to the reduction of the implementation complexity at the cost of no QoS assurance by optimizing the MAC primitives connection and limiting the protocol adaptation between the two stacks.

The paper is organized as follows. In Section II, the most

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The authors are with the Department of Electronics and Telecommunications, University of Florence, Firenze, Italy, email: romano.fantacci@unifi.it, tarchi@lenst.det.unifi.it.

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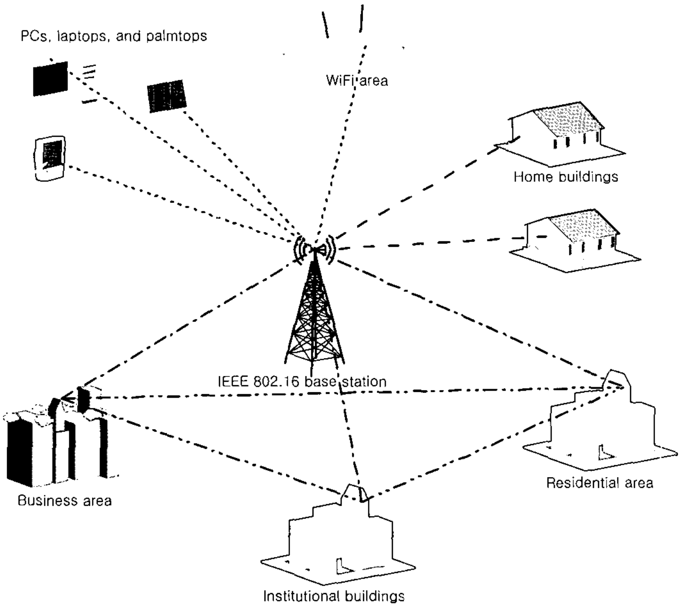

Fig. 1. A WiMAX typical scenario.

important characteristics of the IEEE 802.16 and IEEE 802.11 standards are introduced, while in Section III a brief explanation on the WLAN traffic model used for our aims is done. In Section IV, the proposed interconnection models are introduced, and in Section V numerical results obtained via computer simulations are reported, showing the effectiveness of the proposed bridging solutions. Finally, conclusions are drawn.

II. IEEE STANDARD FAMILY

A. *IEEE 802.16x (WiMAX)*

The IEEE 802.16 standard defines the MAC and PHY layers specification of the wirelessMAN air interface for BWA. A wireless MAN provides network access to buildings and residential areas through an external antenna system based on a central radio station (i.e., base station—BS) and a variable number of user devices (i.e., subscriber stations—SS), and it offers a very useful alternative to cable connection, realizing less-expensive high-speed radio link communications (see Fig. 1).

The IEEE 802.16 standard was first developed in order to create the so-called wireless ADSL: In the last few years, the availability of broadband home connections has become more and more requested and in this way we have attended to a great expansion of DSL covering range in easy to reach areas. Unfortunately, some residential areas are difficult to reach and realizing a cable DSL coverage is too expensive: In these cases, the possibility of obtaining high data rate, with certain quality of service requirements and security bounds through a low cost connection easy to install and maintain, is the best way to solve the problem. For all these reasons, WiMAX has kept the interests of all the major Internet service providers (ISPs) and networks developers of the world and it has grown from a simple way of realizing LMDS-like links [12] to a brand new protocol for all kinds of WMAN with the purpose of introducing devices mobility inside the covered area (competing then with WWAN networks standards like UMTS and WCDMA).

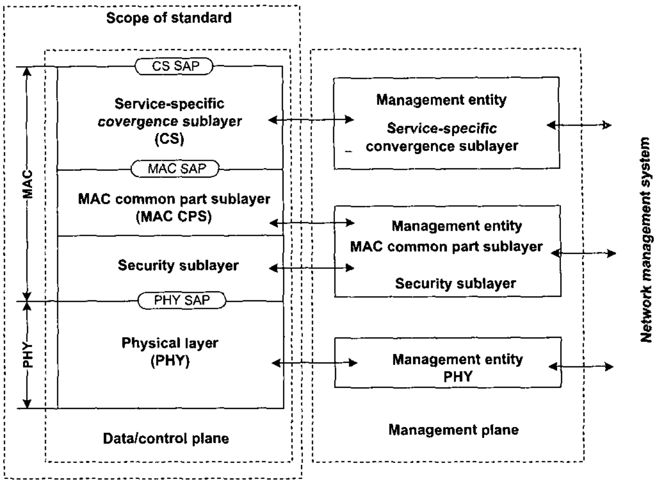

Fig. 2. IEEE Std. 802.16 protocol layering.

Table 1. Transmission parameters for a 1 ms frame.

Channel size [MHz]	Symbol rate [MBaud]	Bitrate QPSK [Mbit/s]	Bitrate 16-QAM [Mbit/s]	Bitrate 64-QAM [Mbit/s]
20	16	32	64	96
25	20	40	80	120
28	22.4	44.8	89.6	134.4

The former standard, i.e., IEEE 802.16-2001 [1], addressed frequency from 10 to 66 GHz, where extensive spectrum is available in all the world countries, even though the realization costs and the highest frequencies introduce serious problems. The other versions, from the IEEE 802.16a [13] to the recent IEEE 802.16-2004 [14] and IEEE 802.16e-2005 [15], instead, cover either the 10–66 GHz (LMDS and, generally, LOS links) band or a 2–11 GHz band, including license-exempt frequencies, enabling NLOS communications (this characteristic fits best a metropolitan scenario) and mobility support.

As we said before, IEEE 802.16 standard defines MAC and PHY layers of the air interface for a BWA (see Fig. 2).

The PHY layer can be divided in two significant parts: The first including 10–66 GHz frequencies and the second regarding the 2–11 GHz band. For the 10–66 GHz, the line-of-sight (LOS) propagation is needed due to the high working frequencies while the 2–11 GHz band is driven by the need for non-line-of-sight (NLOS) operation. The access protocol can be either time division multiplex (TDMA) or frequency division multiplex (FDMA), with both time division duplex (TDD) and frequency division duplex (FDD). The 2–11 GHz band is designed for NLOS operations and can be divided in:

- WirelessMAN-SC2: Using a single-carrier modulation.
- WirelessMAN-OFDM: Using an orthogonal frequency division multiplexing with a 256-point FFT.
- WirelessMAN-OFDMA: Using an orthogonal frequency division multiple access with a 2048-point FFT.

In Table 1, the physical parameters considered for our purposes are shown; WiMAX uses channel bandwidth of 20, 25, or 28 MHz, a Nyquist square-root raised-cosine pulse shaping with a roll-off factor of 0.25, the possibility of QPSK, 16-QAM, and

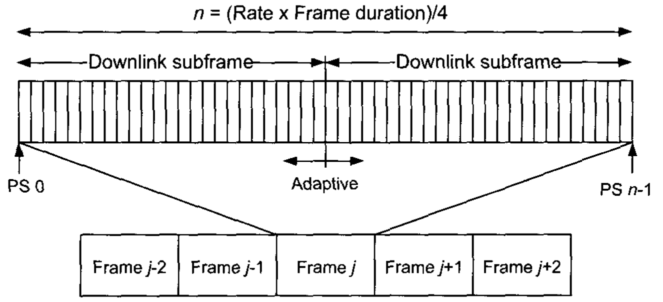

Fig. 3. TDD frame structure.

64-QAM modulations and frame durations of 0.5, 1, and 2 ms.

The MAC layer can be divided in three parts: Convergence sublayer (CS), for the specifications of ATM and IP networks interfaces, common part sublayer (CPS), that is the kernel of all the MAC characteristics, and privacy sublayer (PS), that manages the authentication and crypting procedures. It is very important, for our purposes, the CS, because it has the following functionalities:

- It can classify the service data unit (SDU) from the upper layers to the appropriate MAC service flow with a particular connection identifier (CID);
- it implements the payload header suppression (PHS) by which it is possible to eliminate a redundant part of the header of the payload the CS SDU;
- it delivers the CS packet data unit (PDU) to the MAC service access point (SAP) according to the associated QoS level.

In particular, the standard defines two CS for mapping the services on the MAC connections: The ATM CS for the ATM services and a packet CS for Ethernet, IPv4, IPv6, and other packet services. After the MAC classification, the data is sent within a service flow, that is defined as an unidirectional packet flow having the same QoS management. Each service flow can be managed separately, by considering its requirements in terms of requested rate, maximum delay, or other QoS parameters.

The CPS implements the IEEE 802 MAC primitives, and can be easily connected with other networks exploiting the IEEE 802 specifications. It uses different ways of managing PDUs from the upper layers: Specifically, a data unit, arriving from the upper layers of an ATM or IP network protocol, can be fragmented, packed, and concatenated. After that, the PHY support is defined: TDD or FDD (half and full) can be adopted and the framing structure is determined, including the synchronization between uplink (UL) and downlink (DL) subframes.

In this paper, the TDD framing is used as represented in Fig. 3: The UL and the DL subframe are firmly separated by an adaptive threshold, and each subframe is divided in a finite number of physical slot (PS); the DL subframe comes first because it contains the bandwidth requests and the transmission informations directed from SSs to the BS, which has to schedule the UL resources between all the users.

In the following, the scheduling services are described: It's important to underline that IEEE 802.16 does not specify any scheduling policy, neither in UL nor in DL.

In the IEEE 802.16 standard, WiMAX a particular attention is paid to the QoS by classifying traffics in four service classes:

1. **UGS** (unsolicited grant services): Constant bit rate (CBR) and CBR-like flows like VoIP. This kind of applications needs constant bandwidth allocation, without request.
2. **rtPS** (real-time polling services): Real-time variable bit rate (VBR) and VBR-like flows such as MPEG video or teleconferences. These applications need minimum bandwidth granted and have to request transmission resources by polling (contention and piggybacking are not allowed).
3. **nrtPS** (non-real-time polling services): Non-real-time flows like bandwidth intense FTP. For these traffic, polling bandwidth requests are allowed when minimum bandwidth requirements are needed; otherwise, contention and piggybacking are allowed.
4. **BES** (best effort services): Best effort flows like HTTP, email, and short length FTP. These applications can make bandwidth request only with contention and no minimum resources allocation is granted.

As said before, each service type has its own requirements of bandwidth and bit rate and each flows have different way of requesting band. For these reasons, the IEEE 802.16 determines how to make bandwidth request: Every SS has to use a specific data unit, composed only of the header (that has a particular structure), and the request can be forwarded using polling, contention, and piggybacking. The BS, once received all the requests from SSs, applies an *ad-hoc* scheduling algorithm in order to establish how many resources have to be allocated to a defined user terminal. Finally, dealing with SS without addictive explanations could be misleading: In fact, the IEEE 802.16 can manage traffic either from single device user or terminals grouped in a LAN; we refer to both of them, considering a diverse metropolitan scenario (see Fig. 1).

B. *IEEE 802.11x (WiFi)*

The IEEE 802.11 standard [3] for WLANs is the most widely deployed WLAN standard. This standard defines two access schemes at the MAC layer: The distributed coordination function (DCF), based on carrier sense multiple access scheme with collision avoidance (CSMA/CA), and the contention-free point coordination function (PCF) in which the access point (AP) controls all transmissions based on a polling mechanism. This second access scheme was conceived in the IEEE 802.11 standard in order to support real-time services, but it was shown to have serious limitations in supporting QoS and implementation feasibility [16].

According to the basic 802.11 MAC access scheme, DCF, a wireless station (WSTA) first senses the wireless medium: If the channel is idle for a minimum duration time called DCF interframe space (DIFS), then the WSTA can immediately send its data frame. Otherwise, as soon as the wireless medium becomes idle, the WSTA starts a backoff procedure before starting transmission: The WSTA generates an additional waiting time which is multiple of a slot-time. The duration of the backoff time is chosen from the interval $[0, CW]$ [3], with the parameter CW (contention window) in the range $[CW_{\min}, CW_{\max}]$.

B.1 IEEE 802.11e MAC

The QoS can be managed in an IEEE 802.11 LAN by resorting to the IEEE 802.11e subversion [5]. It implements a specific hybrid coordination function (HCF) that combines the DCF and PCF defined in the IEEE 802.11b standard with some other features for providing QoS support. HCF uses a contention-based channel access method, also called enhanced distributed channel access (EDCA), that operates concurrently with a polling-based HCF-controlled channel access (HCCA) method. EDCA is designed to provide prioritized QoS by enhancing the contention-based DCF. It is foreseen to use frames with 8 different priority levels, derived from IEEE 802.1D specifications. Each IEEE 802.11e access point (AP) implements four different access categories (AC), and each priority class is mapped in one access category. The various AC differs from some parameters, among which the most important are the minimum DIFS (now named arbitrary inter-frame space—AIFS), the contention window (CW) length and the maximum waiting time before transmitting after the right.

Enhancements to the above described IEEE 802.11 MAC have been introduced in the IEEE 802.11e standard [5], which considers the HCF for QoS support, consisting of two access schemes, namely:

- The enhanced distributed channel access (EDCA), an extension of the DCF, which provides differentiated, distributed access to the wireless medium for 8 priorities;
- the HCF controlled channel access (HCCA), a modification of the existing PCF which provides a contention-free access to the medium, based on polling scheme.

Regarding the EDCA, the 8 available user priorities (UP), are grouped into 4 access categories (AC), each one is an enhanced version of the IEEE 802.11 DCF: Thus, a quality station (QSTA), which is a wireless station (WSTA) supporting the IEEE 802.11e MAC protocol, accesses the medium with a variable priority, according to the AC of the frame which is going to be transmitted. The mapping of UP into AC used in our work follows the recommendation suggested in [5]. The mapping from UPs in ACs is defined in Table 2.

Each AC is assigned to a different type of service according to its QoS requirements, namely conversational, streaming, interactive, and background. The prioritized medium access of the EDCA in IEEE 802.11e is provided by the differentiation of the values of the contention parameters DIFS (now called AIFS), $CW_{\min}$, and $CW_{\max}$. Lower values of contention parameters are assigned to an AC with higher priority, in order to ensure that, with greater probability, a higher-priority AC will be able to transmit before lower-priority ones.

In each QSTA, up to four ACs are permitted: Possible internal contentions are solved by choosing and transmitting the highest priority frame, while the other frames enter into the backoff procedure.

Besides the service differentiation provided by the above described EDCA, a polling-based access scheme, similar to the legacy IEEE 802.11 PCF, is included in the IEEE 802.11e standard. This mechanism, developed in order to support QoS for some types of interactive and synchronous services, is controlled by a centralized hybrid coordinator (HC), which is normally located in the AP.

Table 2. User priority to access category mappings.

UP	AC	Designation
1	0	Background
2	0	Background
0	1	Best effort
3	2	Video
4	2	Video
5	2	Video
6	3	Voice
7	3	Voice

III. WLAN TRAFFIC MODELING

Network traffic analysis and an effective model development have recently found a renewed interest. A novel approach, based on the fractal paradigm, has been successfully applied to the traffic statistics characterization, giving rise to the so called self-similar traffic modeling [17].

As a matter of fact, the data traffic carried out in an actual network highlights a significant parameter variance, usually named burstiness that appears quite unchanged on a wide range of time scale, typically up to four or five orders of magnitude. Since this behavior has been verified through wide-range observations performed within several network scenarios, it seems to constitute an omnipresent feature, as explained in [18].

In particular, it has been noticed that the traffic in a typical Ethernet network or Internet world wide web (WWW) applications strictly follows the self-similar paradigm, due to the aggregation of elementary data bursts (i.e., a file) according to the user behavior and the network policies. This empirical evidence has been generally invoked in order to find fault with the classical Poisson traffic modeling. Accordingly, the aggregate traffic should become, instead, smoother as the aggregation order increases.

Finally, regarding generic real-time traffic (e.g., VBR video, video phone, video conferencing, or motion picture), the *long range dependency* (LRD) between entities (as scenes or frame) are commonly highlighted. In this case, the polynomial decay of the autocorrelation function can be explained by means of the data processing, mainly the codec entropic compression, that preserves the original frame correlation [17].

In order to model the traffic generated by multiple terminals within a WLAN, we have resorted to an ON/OFF model, that is constituted by the presence of N independent bursty traffic sources. It is possible to demonstrate that, in this case, the output traffic follows the behavior of a WLAN [19].

IV. INTERCONNECTION OF HETEROGENEOUS NETWORKS

As explained in Section II, the IEEE 802.11 standard and IEEE 802.16 standard have different characteristics in terms of traffic management. Even if the upcoming IEEE 802.11e has some QoS management policies, the IEEE 802.16 supports natively different QoS streams. In this section, two interconnection methods for an heterogeneous environment will be introduced, by exploiting the functionalities of both standards.

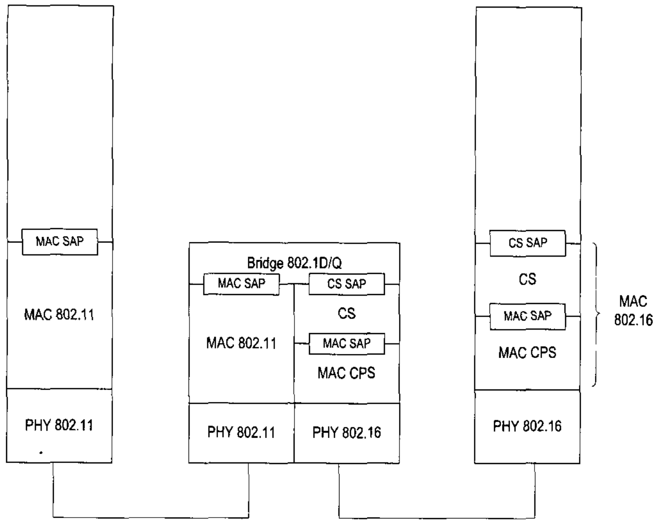

Fig. 4. Interconnection of IEEE 802.11 and IEEE 802.16 MAC layer with an IEEE 802.1D/Q bridge.

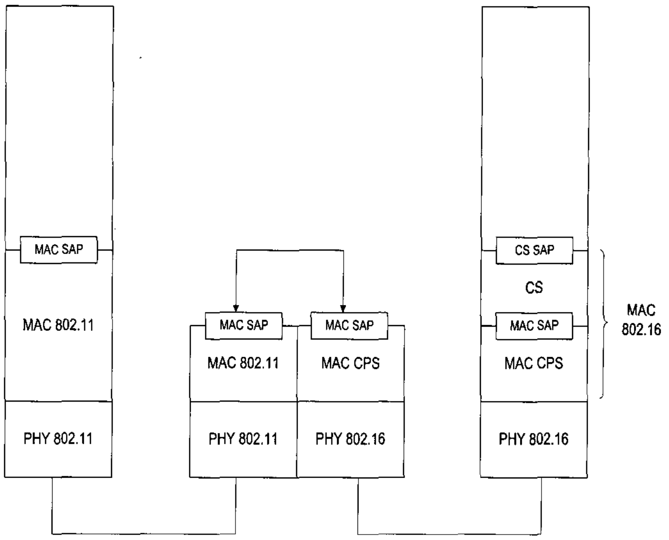

Fig. 5. Direct interconnection of IEEE 802.11 and IEEE 802.16 MAC layer through SAP.

In this work, we propose two interconnecting methods for an heterogeneous environment where IEEE 802.16 and IEEE 802.11 operate. The main difference between the two standards at the MAC layer consists in the presence of a convergence sublayer in the IEEE 802.16 protocol stack mainly devoted to the traffic classes management. The CS cannot be connected directly to the MAC service access point (SAP) of the IEEE 802.11 stack because they have different primitives mapping. For this reason, our idea is to preserve the QoS, in the first method, or connect directly the two MAC SAP but avoiding QoS management, in the second method.

The first mechanism is based on a MAC bridge that follows the IEEE 802.1D/Q [20], [21] specifications, as shown in Fig. 4, allowing the QoS mapping between IEEE 802.11e access categories and IEEE 802.16 service flow classification to the bridge.

By using the proposed mechanism the LLC and upper layers operate transparently onto the two networks, except than the QoS management, that differs between IEEE 802.16 and IEEE 802.11e. The IEEE 802.1D/Q bridge supports 8 priority levels, each one implementing one FIFO queue between the two MAC levels, where 8 corresponds also to the number of the IEEE 802.11e access categories; the frames within a certain queue can be sent only if the queue with higher priority are empty. In some cases, there can be less than 8 queues, leading to a different mapping between priority classes and traffic classes. It is possible to note that the IEEE 802.11e priority classes almost corresponds to the IEEE 802.1D classes, leading to a simplified interoperability.

The rationale behind this solution is that, differently from IEEE 802.16, in the IEEE 802.11e standard a convergence sublayer for the QoS mapping from upper layers does not exist, requiring some more implementing issues. We propose to use an IEEE 802.2 LLC interface, that allows to map the DSCP field of IP header with the TCID of the IEEE 802.11e MAC header. This can be done by using the LLC primitives `DL-UNITDATA.request()` and `MA-UNITDATA.request()` that contain a priority field. The first is used by the network layer for requesting to the LLC layer the forwarding of a link SDU, while the second is used by the LLC layer to MAC layer for requesting the sending of a MAC SDU.

When an IEEE 802.11e MAC frame is received from a IEEE 802.1D/Q bridge, it is classified, filtered, and sent, basing on the priority class, considering that an IEEE 802.1D frame can be allocated in a specific priority queue according to its traffic class. Finally, the frame is sent through a specific IEEE 802.16 MAC frame. In order to be correctly classified by the IEEE 802.16 MAC layer, and correctly mapped to a specific priority class, the frame that came out must be formatted as an IEEE 802.3ac frame, because, in this case, the VLAN tag header can specify the priority. In particular, the tag control identifier (TCI) contains the information regarding the user priority, specified by the IEEE 802.1D frame.

An alternative mechanism for interconnecting an IEEE 802.16 network and an IEEE 802.11a/b/g network is proposed. It differs from the previous one mainly because of the absence of any priority mechanism during the interconnection. In this case, a simplified model can be used, by interconnecting directly the two MAC layers, as shown in Fig. 5.

The rationale of this solution is to simplify the protocol stack interconnection by limiting the primitives mapping to the elementary matching. This solution could simplify a lot the management between the two networks, at the cost of not maintaining any priority classification. If we think to a scenario where the sender and the receiver belongs to a WiFi area, the WiMAX interconnection can be seen as a level 2 tunnel, letting the two WiFi areas be a unique network entity. The frame addressing issue to the right connection identified by a CID, can be solved by mapping the IEEE 802.11 primitives with the IEEE 802.16 primitives. For the link from WiFi to WiMAX, we can map the `MA-UNITDATA.indication()` with the `MAC_DATA.request()`. This allows a direct transit of the data from a network to the other. For the reverse link, a mapping of the `MAC_DATA.indication()` with the

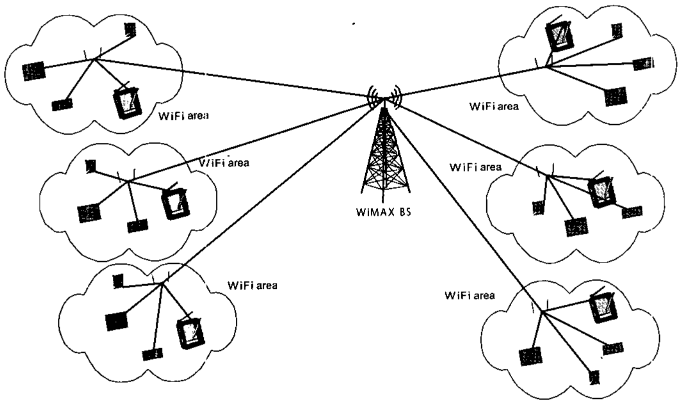

Fig. 6. Simulation scenario.

`MA-UNITDATA.request()` can be used.

V. NUMERICAL RESULTS

In order to validate the effectiveness of the proposed interconnection models, we have resorted to computer simulations. The considered scenario is composed by one or more WiFi areas connected to one or more WiFi areas via one or more WiMAX links, as represented in Fig. 6. The WiFi access point is supposed to have a second interface that works as a subscriber station for the WiMAX connection.

In order to optimize the bandwidth allocation, we need to fill as much as possible the payload area of the PDU generated at the transmitting WLAN; the payload length is specified by the WiMAX SS so that we have resorted to an analysis and optimization of the fragmentation and packing phase at the WiFi-WiMAX MAC layer interconnection. In this phase, our aim is to fragment the longer SDU and packet together the shorter in order to optimize the PDU length.

For what concerns the fragmentation, it is initialized by each SS in order to maintain a certain QoS target; each fragment is associated with a certain fragmentation subheader (FSH) in order to allowing the SDU fragment reconstruction at the receiver side. The packing phase varies if the SDUs have a fixed or variable length. If they have a fixed length, the MAC header contains informations about the amount of SDUs contained in the payload area; in this case, it is not needed any more information about SDU, so that they are transparently inserted in the payload area. In the case the SDUs have a variable size, a packing subheader (PSH) is inserted before each SDU within the payload area; this is due to the fact that now it is not known a priori when each SDU begins and ends.

By optimizing the fragmentation and packing phase, it is possible to optimize the resource allocation and reduce the bandwidth wastage. Both packing and fragmentation have been considered herein, by including the PDU construction algorithm shown in Fig. 7. The impact of this solution is to optimize the performance be choosing the optimal size for the PDU at the MAC layer.

The integrated scenario of WiFi areas and WiMAX coverage has been considered constituted of

- two transmitting WLANs with an offered loading equal to 1;

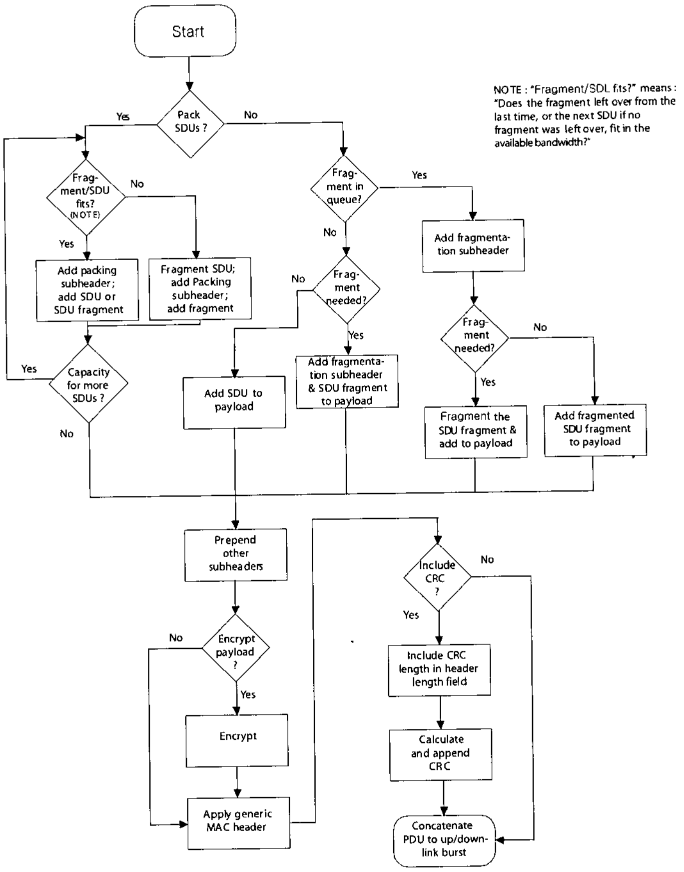

Fig. 7. MAC PDU construction algorithm.

- two receiving WLANs with an offered loading equal to 0.3;
- one WiMAX interconnection with variable bit rate.

The offered loading corresponds to the percentage amount of traffic generated by each WLAN; for what concerns the transmitting WLANs, the offered traffic can be divided between internal traffic and external traffic. This percentage has been used as a parameter for the simulation results in the following. For what concerns the receiving WLANs, the offered traffic corresponds to the amount of traffic that remains internally; as it will be shown in the following, this supplementary traffic represent a limit to the total amount of traffic at the input of the WLANs. The WiMAX system has the following characteristics:

- Channel bandwidth equal to 25 MHz;
- constant modulation equal to 16-QAM;
- gross bit rate equal to 80 Mbit/s;
- frame duration equal to 1 ms;
- physical slot in one frame equal to 5000.

In order to model the traffic generated by multiple terminals within a WLAN, we have resorted to an ON/OFF model, that is constituted by the presence of N independent bursty traffic sources. It is possible to demonstrate that, in this case, the output traffic follows the behavior of a WLAN [19]. The WLAN traffic has been generated by using an aggregated ON/OFF source model with the following characteristics:

- 200 ON/OFF sources for each WLAN traffic generator;
- a shaping factor for the Pareto distribution of ON/OFF times equal to 1.4;

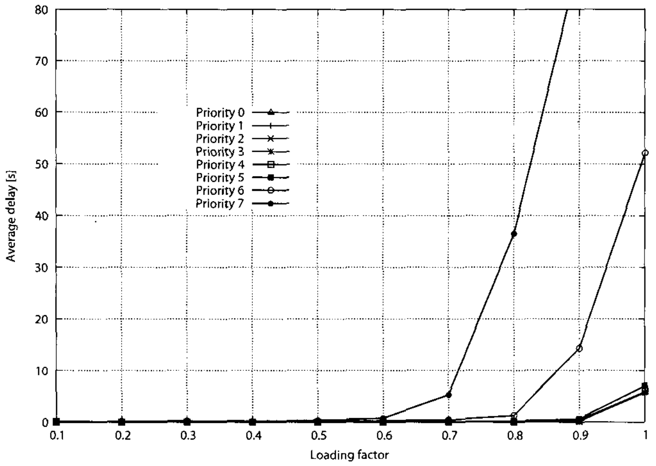

Fig. 8. Packet delay for the whole path for different loading factor at the transmitting WLAN.

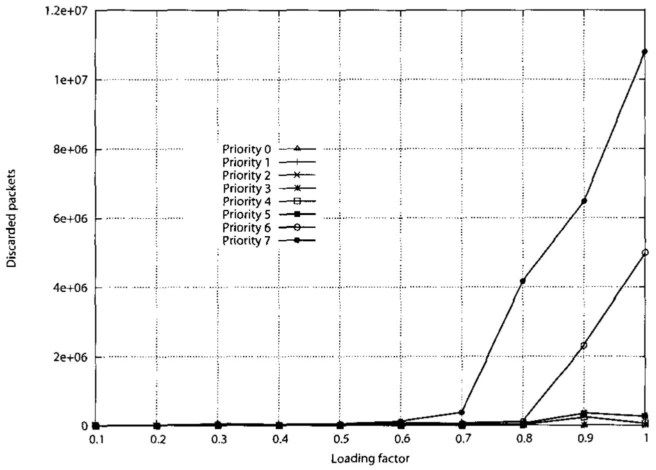

Fig. 9. Packet loss for the whole path for different loading factor at the transmitting WLAN.

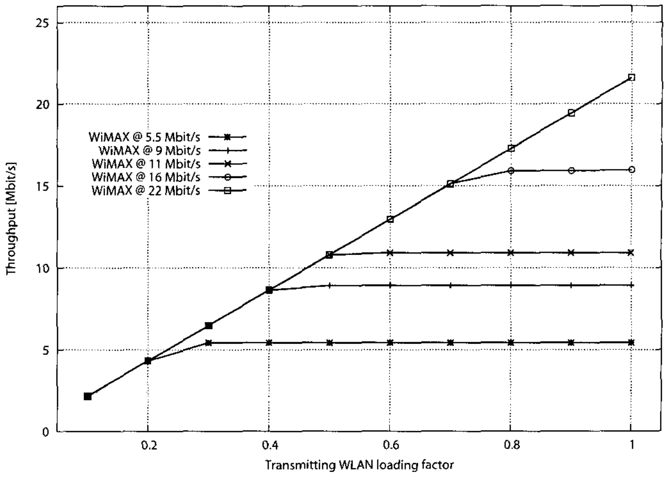

Fig. 10. Throughput of the WiMAX connection.

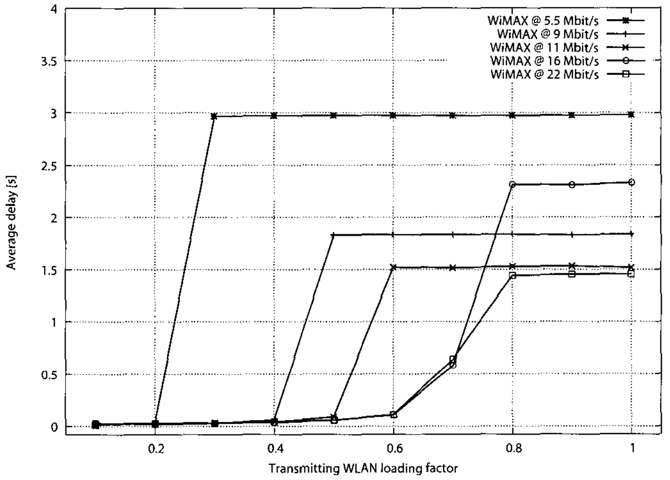

Fig. 11. Packet delay for the whole path WiFi-WiMAX-WiFi.

- packet length uniformly distributed between 34 and 2346 bytes.

As a result, the average burst length is equal to 4000 bytes.

In Figs. 8 and 9, the performance results for the interconnection of the MAC layers of a IEEE 802.11 and a IEEE 802.16 networks by an IEEE 802.1D/Q bridge are shown.

It has been supposed to have 8 WiMAX connections, each one with a maximum rate equal to 2.75 Mbit/s, for a total rate of 22 Mbit/s; each one WiMAX connection will carry one priority class at a time. The priority scheduler works in a non-preemptive way by serving the higher priority class until it has data to transmit; the packets for a certain priority queue can be sent only if higher priority queues are empty. Even if not properly fair this scheduling technique allows us to the the bridging solution in a multi-priority scenario.

We have then considered the performance results of the WiFi-WiMAX interconnection by using a direct MAC connection. In Fig. 10, the performance in terms of throughput offered by WiMAX links for different data rate, and considering different loading factors for the transmitting WLANs is shown.

In Fig. 11, it is shown the packet delay during the whole path from a terminal in the transmitting WLAN to a terminal in the receiving WLAN. The performance has been considered for different loading factors and for different WiMAX link rate. It is possible to note that, apparently surprising, the delay for 16 Mbit/s has higher values that 11 Mbit/s and 9 Mbit/s connections. This fact can be explained if we focus our attention on the main components in which the whole delay can be split, that are the delay at the transmitting buffer of the WiMAX connection and the delay suffered in the buffer at the WiMAX-WiFi bridge. In Figs. 12 and 13, the performance in terms of packet delay, focusing on high loading factor and for 11 Mbit/s, 16 Mbit/s, and 22 Mbit/s are reported.

For what concerns the behavior of the buffer at the WiMAX transmitting side, as expected, it shows a higher delay in the case a lower connection rate is considered, as in Fig. 12. The opposite effect occurs if we analyze the delay behavior of the packets in the buffer at the WiMAX-WiFi bridge. This is mostly due to a bottle effect at the bridge, due to the lower supported throughput in the WLAN, and because we have supposed that the WLANs have a maximum data rate equal to 11 Mbit/s, and each WLAN generate some traffic that remains internally. By varying these parameters, e.g., WLAN rate and internal traffic, it is possible to mitigate the bottle effect, anyway it is important

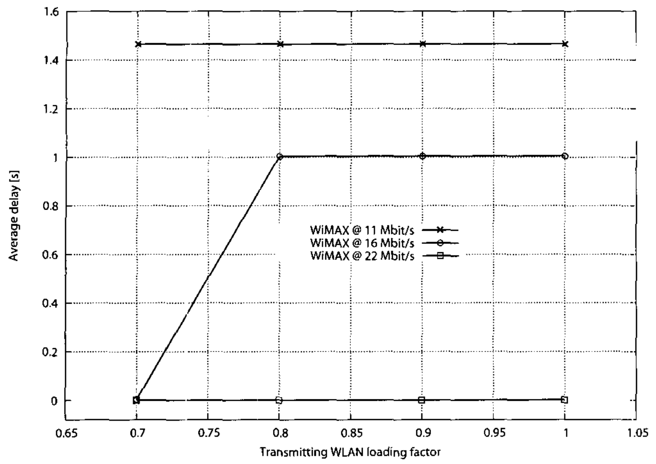

Fig. 12. Packet delay at the WiMAX transmitting buffer.

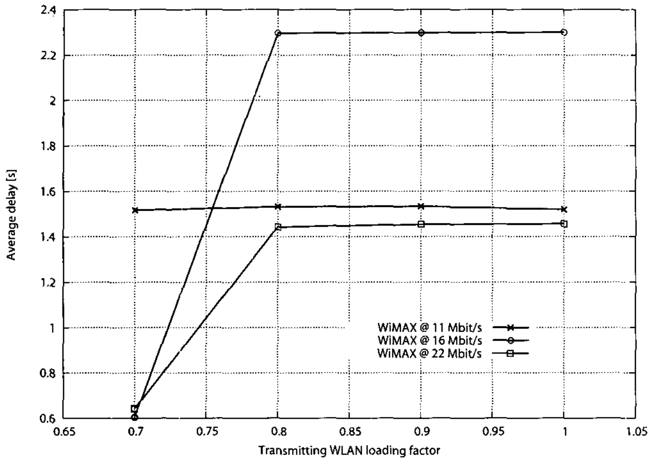

Fig. 13. Packet delay at the WiMAX-WiFi bridge buffer.

to pay attention that in the case the WiFi area has a lower data rate than the WiMAX connection, a similar effect may occur. It is worth to notice that in our case, we have not consider the effects of the flow control introduced by a TCP connection.

In Fig. 14, the two introduced interconnection methods are compared, by considering the overhead percentage respect to the useful data in the framing structure.

VI. CONCLUSION

In this paper, two bridging interconnection solutions for an heterogeneous environment where a WiMAX coverage and multiple WiFi zones coexists. One method aims to interconnect multiple IEEE 802.11e WLANs with a WiMAX link by maintaining the priority classes, while in the other method a simpler solution that allows a direct interconnection between the two MAC layer, at the cost of no priority maintenance, is proposed. For the proposed method, some numerical results are presented by resorting to computer simulations, showing the advantages of the two proposed solutions.

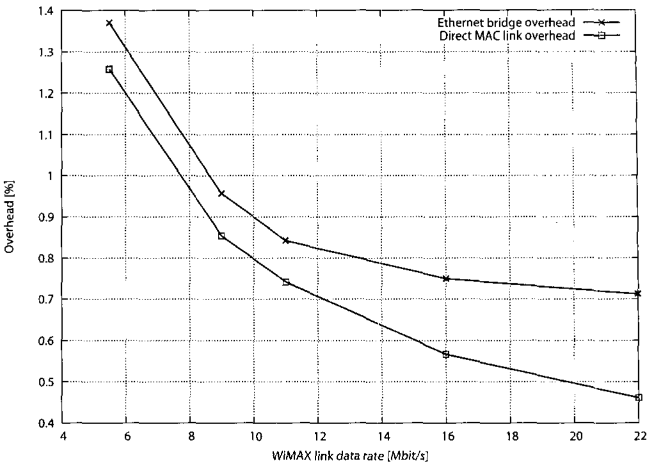

Fig. 14. Overhead introduced by the two bridging methods.

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Romano Fantacci born in Pistoia, Italy, graduated from the Engineering School of the Università di Firenze, Florence, Italy, with a degree in electronics in 1982. He received his Ph.D. degree in Telecommunications in 1987. After joining the Dipartimento di Elettronica e Telecomunicazioni as an assistant professor, he was appointed associate professor in 1991 and full professor in 1999. His current research interests are digital communications, computer communications, queuing theory, satellite communication systems, wireless broadband communication networks, ad-hoc, and sensor networks. He has been involved in several European Space Agency (ESA) and INTELSAT advanced research projects. He is the author of numerous articles published in prestigious communication science journals. He guest edited special issues in IEEE journals and magazines and served as symposium chair of several IEEE conferences, including VTC, ICC, and GLOBECOM. Professor Fantacci received the IEE IERE Benefactor Premium in 1990 and IEEE COMSOC Award Distinguished Contributions to Satellite Communications in 2002. He is currently serving as a editor for Telecommunication Systems, International Journal of Communications Systems, IEEE Transactions Communications, and IEEE Transactions on Wireless Communications.

Daniele Tarchi was born in Florence, Italy, in 1975. He received the M.Sc. degree in Telecommunications Engineering and the Ph.D. degree in Informatics and Telecommunications Engineering from the University of Florence, Italy, in 2000 and 2004, respectively. He is now a research fellow at the University of Florence, Italy. His research interests are in both physical layer and data link layer, with particular interests to resource allocation algorithms in wireless networks, link adaptation and adaptive modulation and coding techniques, neural networks application to multiuser detection, and MAC protocols in ultra-wide band systems (802.15.3) and ad-hoc networks. He has been involved in several national projects (rescue, pattern, and women) as well as European Network of Excellence (Nexway, Newcom, Satnex). He is involved in COST289 European Union action. He has been a symposium co-chair for Wirelesscom 2005, and TPC member for IEEE VTC 2004-Spring, IEEE ICC 2005, and IEEE GLOBECOM 2006.