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TCP OVER WIMAX NETWORKS

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Abstract—**The IEEE standard 802.16, also known as Worldwide Interoperability for Microwave Access (WiMAX), is viewed as a powerful enabler for the massive deployment of high performance metropolitan area networks. It can also be viewed as one alternative to provide last mile access to Internet users, and therefore it is expected that most of its traffic will be TCP/IP. This article intends to overview what are the features of the MAC layer of WiMAX that can affect the performance of TCP traffic, especially with PMP architecture. Mapping of TCP data over WiMAX and a discussion on the impact of different scheduling mechanisms is provided.**

Index Terms—**IEEE 802.16, performance, TCP/IP, transport, scheduling techniques, WiMAX.**

I. Introduction

THE last version of IEEE Standard for Local and metropolitan area networks, 802.16™, has finally been released in October 2004, almost closing a long road of standardization that begun several years ago. With this new revision completed, finished and most important, agreed by the major networking and electronic companies of the industry, the road seems paved for major deployments of WiMAX access networks almost all over the world with the only exceptions of a few countries that still need to free up some spectrum in order to fully utilize all the possibilities offered by this new technology. Generally speaking, WiMAX has a range of up to 30 miles and covers several different frequency ranges with speeds up to 75 megabits per second. The base 802.16 standard is for the 10 to 66 GHz range, but this last version added coverage for the 2 to 11 GHz range. Although WiMAX deployments can be used for private custom networks, the most probable usage of WiMAX will be to provide massive Internet broadband access to business and household users, competing with technologies like ADSL and Cable Modem, especially in those places where the latter two technologies cannot be used or their costs are prohibitive [10]. Furthermore, in countries with a scarce wired infrastructure like India, Mexico, and China, WiMAX can become part of the broadband backbone. According to [11], by 2006, technology based on the IEEE 802.16e standards will be integrated into portable computers to support movement between WiMAX service areas, allowing for portable and mobile applications and services; moreover, in the future, WiMAX capabilities could even be integrated into mobile handsets.

Therefore assuming such a high penetration of WiMAX technology to transport Internet traffic, it became important the study of the behavior of TCP/IP data over this new medium. This new standard has particular complexities on its MAC layer which are very different from the MAC layers of 802.3, or 802.11x, from which studies of TCP/IP performance has been extensively done. The particularities of 802.16 demand for a new assessment of TCP/IP performance over its MAC, to understand what are the major factors and parameters that will impact the performance of TCP, and be aware of them at the moment of design or tune a WiMAX Network that will have to carry mostly TCP traffic. In a recent Gartner major carrier survey in Europe, the Middle East and Africa, 25 percent of the respondents said that WiMAX had already changed their opinion of wireless broadband, and an additional 25 percent indicated that they would test the technology before forming an opinion and since to the author's knowledge the behavior of TCP over WiMAX networks has not been yet researched, this work intend to be an introductory analysis of the topic that can hopefully encourage further theoretical analysis and help understand the result of practical tests.

The rest of the paper is organized as follows: section II, describes the mapping of TCP traffic into the WiMAX MAC; section III, explains how the classifier would work with TCP data; section IV enumerates the service classes natively included in the standard and finally, section V discuss the impact of different scheduling policies on TCP performance.

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II. Mapping of TCP traffic

A. The Convergence Sublayer concept

In order to map the traffic coming from upper layer protocols or applications, the WiMAX standard introduces the concept of service-specific Convergence Sublayers (CS). As it is shown in the reference model of Fig. 1, the service-specific CS sits on top of the MAC Common Part Sublayer (CPS), and its purpose is to make use of the services provided by the

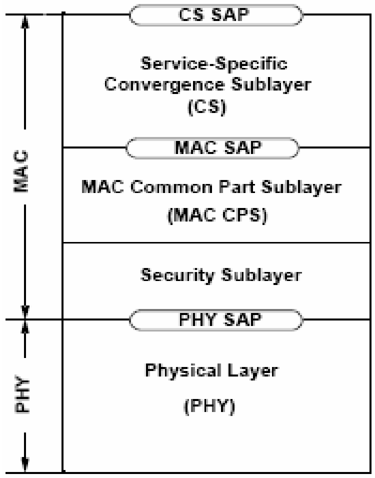

Fig. 1. IEEE Std 802.16 reference model showing SAPs. The MAC comprises three sublayers. The Service-Specific Convergence Sublayer (CS) provides any transformation or mapping of external network data, received through the CS service access point (SAP), into MAC SDUs received by the MAC Common Part Sublayer (CPS) through the MAC SAP.

latter via appropriate MAC Services Access Points (SAP). This idea provides scalability to the standard introducing one more degree of freedom because it is just a matter of building the right CS to transport almost any protocol one can think of. In particular, the standard only defines two CSs: one for ATM (ATM CS) and another for packet services (Packet CS), but leave the possibility open to future specifications. Aside from just accepting protocol data units (PDUs) from higher layers, the service-specific CS also classifies them; performs their processing based on previous classification (if required); delivers CS PDUs to the appropriate MAC SAP and receives the ones coming from peer entities. Regarding the Packet CS, since WiMAX is a connection oriented service, most of the information used for routing a packet becomes redundant once the connection is set up, therefore the Packet CS also provides a packet header suppression (PHS) mechanism in order to avoid the transmission of redundant information over the link. Among all the functions mentioned for the service-specific CS, the most important one for this study is packet classification as will be shown later.

B. *Encapsulation*

As with any other packet based communication system it is always important to understand the encapsulation process prior to any deeper discussion of the functional details of the system. Packets arriving to the service-specific CS from upper layers are called MAC Service Data Unit (SDU), and are processed as is or they can be optionally added a Payload Header Suppression Index as shown in Fig. 2. PHSI header is added only if the Payload Header Suppression option is enabled for the connection. In most cases one can surely assume that TCP traffic will arrive encapsulated within an IP packet which in turn is mapped into an Ethernet frame. For each one of these encapsulations PHS can optionally be used open up several possibilities summarized in Fig. 3.

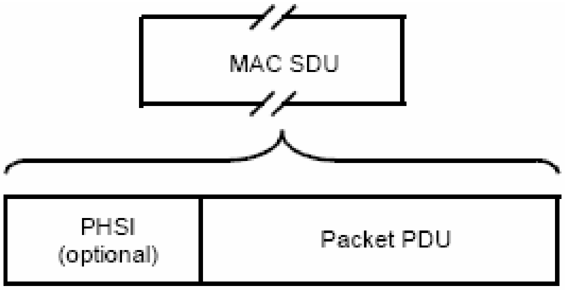

Fig. 2. Generic IEEE Std 802.16 MAC SDU format. According to the standard the 8-bit Payload Header Suppression Index (PHSI) field shall be present only when a Payload Header Suppression (PHS) rule has been defined for the associated connection.

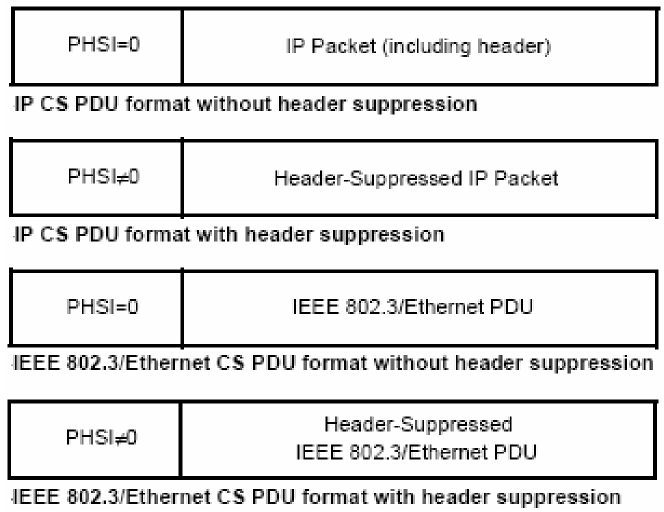

Fig. 3. Encapsulation of IEEE Std 802.3/Ethernet and IP PDUs over IEEE Std 802.16 MAC service-specific CS SDU format.

After classification the SDU is given to the MAC CPS which adds a generic MAC header as shown in Fig. 4.

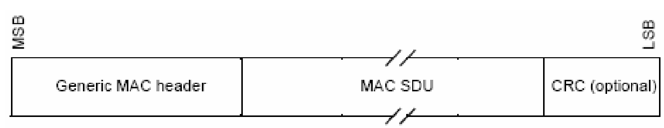

Fig. 4. IEEE Std 802.16 MAC PDU format. A MAC PDU may contain a CRC. Implementation of CRC capability is only mandatory for certain PHY operational modes.

Finally the PHY layer encapsulates the MAC PDUs in a frame whose structure has been nicely putted together in one picture by [12], reproduced in Fig. 5. The frame is divided into DL and UL subframes, where the DL subframe is made up of a preamble, Frame Control Header (FCH), and a number of data bursts. The UL subframe contains a contention interval for initial ranging and bandwidth allocation purposes and UL PHY PDUs from different SS's. The DL-MAP and UL-MAP completely describe the contents of the DL and UL subframes. They specify the SS's that are receiving and/or transmitting in each burst, the subchannels on which each SS is transmitting (in the UL), and the coding and modulation used in each burst and in each subchannel. The highly elaborated structure of the WiMAX frame express the complex architecture of this standard, and since it is not the scope of this work to describe it, we refer the interested reader to [3] for further details on the WiMAX frame structure.

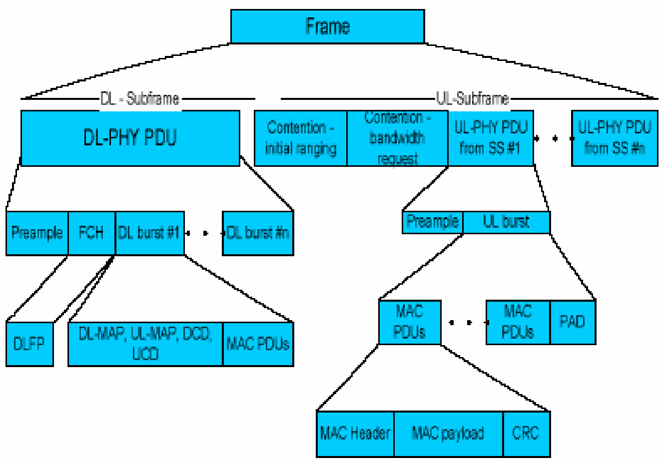

Fig. 5. IEEE Std 802.16 downlink (DL) and uplink (UL) frame structures for a TDD system. In FDD, the DL and UL frame structure looks similar except that the UL and DL are transmitted on separate channels.

III. The Packet Classifier

Classification is another function exercised at the service-specific CS before the packet is delivered to the MAC CPS. Classification is the process by which arriving packets are assigned to WiMAX connections according to their QoS needs. In turn, each connection is associated with a level of QoS, therefore from the point of view of QoS, the most important function of the service-specific CS resides in classification. Each connection is associated with a service flow characterized by a set of QoS Parameters such as latency, jitter, and throughput assurances. Classification consists of a set of protocol-specific packet matching criteria (e.g. destination IP address, IP ToS, transport protocol port, etc), applied to each of the packets serviced by the WiMAX network. A classifier also includes a priority and a reference to a CID. Previous revisions of the standard such us [4] considered an option called Direct Mapping where if as a result of the application of some upper layer policy mechanisms, the packet has already been associated with a particular service flow (i.e. QoS characteristics), that combination associates the packet with a particular connection directly without the need of a classification phase, but this option does not seem to be available anymore in the last release of the standard. Furthermore, implementation of each specific classification capability, as for example, IPv4 based classification, is optional, something that leaves a lot of room for the implementation of custom classification techniques aimed towards a particular performance objective. Table I shows some of the fields considered in the standard. Parameters for each of the matching rules are encoded following the type/length/value (TLV) formatting scheme that adds a tag to each transmitted parameter containing the parameter type (and implicitly its encoding rules) and the

TABLE I
Packet Classification Table Fields

Priority[a]	Classification Parameters[b]				CID/SFID[c]
	802.3	802.1P/Q	IPv4/v6	TCP/UDP	
n	TLV_1	TLV_2	TLV_3	TLV_4	*p/q*

n is 1-byte length; *p* is 2 bytes and *q* is 4 bytes length.

[a]The value of this parameter specifies the priority assigned to a service flow. Given two service flows identical in all QoS parameters besides priority, the higher priority service flow should be given lower delay and higher buffering preference. For otherwise nonidentical service flows, the priority parameter should not take precedence over any conflicting service flow QoS parameter.

[b]Encoded using type/length/value (TLV) formatting scheme.

[c]Connection identifier (CID): A 16-bit value that identifies a connection to equivalent peers in the MAC of the base station (BS) and subscriber station (SS). It maps to a service flow identifier (SFID 32-bit), which defines the Quality of Service (QoS) parameters of the service flow associated with that connection. A service flow is a unidirectional flow of packets that is provided a particular QoS.

length of the encoded parameter. The following parameters are relevant for IEEE Std. 802.3/Ethernet CS classifiers: (TLV_1 in Table I): destination MAC address; source MAC address; Ethertype/SAP; and for IP over IEEE 802.3/Ethernet, IP headers may be included in classification. For IEEE Std. 802.1Q (TLV_2): Priority Range, VLAN ID. For IP (TLV_3): TOS Range/Mask, Protocol, Source Address/Mask, Destination Address/Mask. For TCP/UDP (TLV_4): TCP/UDP Source Port Start, TCP/UDP Source Port End, TCP/UDP Destination Port Start, TCP/UCP Destination Port End. For example, for IP type of service/differentiated services codepoint (DSCP) (IETF RFC 2474) range and mask, the rule specifies three values of one byte each: tos-low, tos-high, tos-mask [3]. Therefore, an IP packet with IP type of service (ToS) byte value "ip-tos" matches this parameter if tos-low ≤ (ip-tos AND tos-mask) ≤ tos-high. If the field is omitted, then comparison of the IP packet ToS byte for this entry becomes irrelevant. Similar rules encode each one of the parameters mentioned earlier for each one of the protocols of Table I. Fig. 6 summarizes the whole procedure.

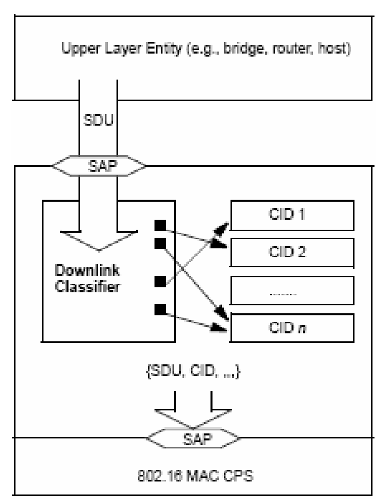

Fig. 6. Classification and CID mappings.

IV. NATIVE QOS SERVICE CLASSES

Once packets are classified they are associated with a service flow that will provide the required QoS, being this process valid for both uplink and downlink traffic. In order to provide upper-layer entities with a global and consistent way to request service flows with the desired QoS parameters, service flow properties are grouped into Service Classes. Service classes are simply identifiers for a specific set of QoS parameters, and according to [3] the use of service classes is optional. Anyhow, using them is beneficial because they permit the modification of the implementation of a given service to local circumstances without changing SS provisioning. For example, some service profiles could be changed by time of day or scheduling parameters may need to be tuned differently for two different BSs to provide the same service. Therefore, service flows can have their QoS parameters specified by explicitly including all traffic parameters or by indirectly referring to them using a Service Class name or by specifying the Service Class name along with modifying parameters (overriding).

Since the concept of service flows is key to the MAC protocol of WiMAX because they are used to provide a mechanism for uplink and downlink QoS management, they may be associated with many PDUs, but a PDU is associated with exactly one service flow. There can be also many service flows that belong to one service class but one service flow can have only one connection associated with it. All these relationships and associations can be putted together using the UML class model showed in Fig. 7 [3]. There is also a configuration and registration function for preconfiguring SS-based QoS service flows and traffic parameters, as well as a signaling function for dynamically establishing QoS-enabled service flows and traffic parameters.

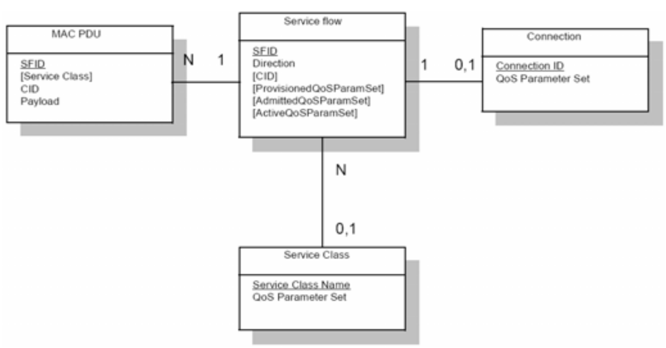

Fig. 7. UML class diagram that depicts the object model that supports the QoS architecture of WiMAX. The major objects of the architecture are represented by named rectangles. Each object has a number of attributes; the attribute names that uniquely identify it are underlined. Optional attributes are denoted with brackets. The relationship between the number of objects is marked at each end of the association line between the objects.

Recalling that subscriber stations (SSs) share the uplink to the BS on a demand basis[1], once the service flows have been created, the MAC has to schedule their transmission in a way so that the QoS characteristics of the flow can be satisfied. In order to accomplish this task, the WiMAX standard defines four scheduling services[2] for upstream traffic, which are implemented using unsolicited bandwidth grants, polling, and contention procedures.

In particular, the WiMAX standard defines the following types of uplink scheduling methods:

1) **Unsolicited Grant Services (UGS):** designed to support real-time data streams consisting of fixed-size data packets issued at periodic intervals.
2) **Real-Time Polling Services (rtPS):** designed to support real-time data streams consisting of variable-sized data packets that are issued at periodic intervals.
3) **Non-Real-Time Polling Services (nrtPS):** designed to support delay-tolerant data streams consisting of variable-sized data packets for which a minimum data rate is required.
4) **Best Effort (BE) Services** (Default): designed to support data streams for which no minimum service level is required and therefore may be handled on a space-available basis.
5) **Undefined** (BS implementation-dependent): vendor-specific implementation-dependent scheduling service type

Scheduling requirements are sent within Dynamic Service Addition (DSA) Request messages by an SS or BS at the creation of a new service flow. If the parameter is omitted, BE service is assumed.

Finally, to completely specify the QoS characteristics of a data service there are a number of mandatory QoS parameters that shall be included in the service flow definition when the scheduling service is enabled for it. Each scheduling service has a minimum number of associated parameters which are listed in Table II.

TABLE II
MANDATORY QOS SERVICE FLOW PARAMETERS

Scheduling service	Parameters	Possible applications
UGS	Maximum Sustained Traffic Rate Maximum Latency Tolerated Jitter Request/Transmission Policy Minimum Reserved Traffic Rate	ATM CBR; E1/T1 over ATM; TDM Voice; T1/E1; VoIP without silence suppression
rtPS	Minimum Reserved Traffic Rate Maximum Sustained Traffic Rate Maximum Latency Request/Transmission Policy	MPEG video; VoIP with silence suppression
nrtPS	Minimum Reserved Traffic Rate Maximum Sustained Traffic Rate Traffic Priority Request/Transmission Policy	ATM GFR; TFTP; HTTP; FTP
BE	Maximum Sustained Traffic Rate Traffic Priority Request/Transmission Policy	E-Mail; P2P file sharing

[1] At this point it is good to remember that the downlink channel is TDM, with the information for each SS multiplexed onto a single stream of data and received by all SSs within the same sector.

[2] Reference [12] call them "Service Classes" but to avoid any confusion with the service classes that groups service flows, this article follows the IEEE standard that call them "scheduling services".

V. Scheduling Algorithms and QoS Classes

The primary purpose of the QoS features described so far were designed to define transmission ordering and scheduling on the air interface. However, these features often need to work in conjunction with mechanisms beyond the air interface in order to provide end-to-end QoS or to police the behavior of SSs. Many higher-layer sessions may operate over the same wireless CID. For example, many users within a company may be communicating via TCP to different destinations, but since they all operate within the same overall service parameters, all of their traffic is pooled for request/grant purposes. Therefore, scheduling in the WiMAX MAC can be viewed as divided into two related scheduling tasks: scheduling the access to the airlink among the SSs through the mechanisms described in section IV, and scheduling of individual packets at the BSs and SSs. The latter, schedules packets from the connection queues into the transmission opportunities allocated to the SS within each frame. The standard does not suggest any solution to this task and leave it completely open to the designer. To the best of the author's knowledge no article has been published proposing a solution although there are many references [7], [8] and [9], that tackle similar problems in other domains.

There are several packet scheduling techniques in use today to manage TCP/IP traffic congestion in wired networks that can be applied satisfactorily to approach the problem in WiMAX networks as well. The most common queuing algorithms to sort traffic are [6]:

- First-in, first-out (FIFO) queuing
- Priority queuing (PQ)
- Custom queuing (CQ)
- Weighted fair queuing (WFQ)
- Class-based weighted fair queuing (CBWFQ)

Basic Store-and-Forward (FIFO) queuing involves storing packets when the network is congested and forwarding them in order of arrival when the congestion end. FIFO requires no configuration and therefore becomes the default algorithm in most of the cases. The problem with FIFO is that it makes no decision about packet priority and the order of arrival determines bandwidth, promptness, and buffer allocation. Furthermore, a full queue causes tail drops and this is undesirable because the packet dropped could have been a high-priority packet. All this make FIFO queuing bad choice to implement the queues of UGS, rtPS and even nrtPS, instead seems a good and simple solution to manage the queues of a BE service.

Priority queuing is designed to give strict priority to important traffic providing flexible prioritization according to network protocol, incoming interface, packet size, source/destination address, and so on. Normally PQ is implemented using four queues, e.g. high, medium, normal or low priority, and packets are distributed according their priority where those that do not fall within this classification are sent to the normal queue. Then during transmission, the algorithm gives higher-priority queues absolute preferential treatment over low-priority queues. With priority queuing, the high-priority queue is always emptied before the medium-priority queue, and so on. As a result, traffic in lower-priority queues might not get forwarded in a timely manner or get forwarded at all. Several factors make PQ inappropriate for use in WiMAX: First PQ queuing does not compensate for inadequate bandwidth. Second, this method is only appropriate for low-bandwidth serial lines and currently uses static configuration which does not automatically adapt to changing network requirements, therefore, the overhead involved makes this queuing strategy unacceptable for higher-speed networks such us WiMAX.

Custom Queing eliminates the potential priority queuing problem by reserving a certain percentage of bandwidth for each specified class of traffic. One can use custom queuing to allocate bandwidth based on a protocol or source interface and bandwidth is shared proportionally between application and users. Custom queuing services a queue until a threshold defined by the number of bytes is reached or until the queue is empty. Then the next queue is serviced. Custom queuing handles its queues in a round-robin fashion, where unconfigured queues or empty queues are skipped during the round-robin packet dispatching. This method could work well administering the queues of an nrtPS service.

WFQ is suitable for situations in which it is desirable to provide consistent response time to heavy and light network users alike without adding excessive bandwidth. The algorithm creates bit-wise fairness by allowing each queue to be serviced fairly in terms of byte count. Therefore, if one queue has 300-byte packets and another 150-byte packets, the WFQ algorithm will take two packets from the latter for every one packet from the former, and this makes the service fair for each queue while ensuring that queues do not starve for bandwidth and that traffic gets predictable service. WFQ apparently seems to be a good solution for the management of rtPS traffic queues but there still some problems. For example, an MPEG video stream that needs half E1 bandwidth will be correctly provisioned if there are only two rtPS flows. As more flows are added, the video stream get less bandwidth because WFQ's algorithm creates fairness, therefore, if there are 10 flows, the video stream will get only $1/10^{th}$ of the bandwidth which is clearly not enough according to the initial supposition, and certainly a mechanism must be set in motion to provide that half E1 bandwidth that video needs.

Class-based weighted fair queuing arises as a possible solution to this problem. The network administrator defines a class, and places the video stream in the class, then tell the network management system (see management entity in [3]) to set up the service-specific CS traffic queues to provide half of the bandwidth (1024 kbps) for the class. Video is now given its required bandwidth while the default class is used for the rest of the flows. WFQ can still be used with the default class to allocate the remainder of the bandwidth. Furthermore, a low-latency queue (LLQ) may be designated, which acts basically as a priority queue (this approach is sometimes called priority queue class-based weighted fair queuing

PQCBWFQ [6]). Low-latency queuing allows a class to be serviced as a strict-priority queue i.e. served before any of the other classes thus covering all the possibilities considered by the rtPS scheduling service.

VI. CONCLUSION

WiMAX technology opens up the possibility to finally provide massive broadband data access at an affordable price to almost every one and to nearly every place including rural areas, something that satellite technology has been promising for years but fails to satisfy. But in order to fulfill such a broad range of possibilities the standard became rather complex, but still plausible thanks to the low cost of today's advance DSP technology.

Since WiMAX was designed to manage a lot of different protocols, this article focused only on how TCP will be serviced by WiMAX, and what are the issues that are still open and can be used to increase the performance of the service. First it was reviewed the mapping of TCP traffic pointing out different encapsulation possibilities. Then, the packet classifier was briefly addressed along with the native QoS classes considered by the standard. Finally, it was discussed how can different congestion-management tools, i.e. queuing techniques can be combined with the MAC scheduling techniques to improve the efficiency of the overall system in the presence of TCP/IP traffic.

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The figures were reproduced from [3] and [12].

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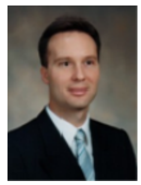

Carlos G. Bilich was born in Santa Fe, Argentina in 1971. He graduated as Electro-Mechanical technician from the Superior Industrial School in 1990. Then he moved to Rosario to study Electronic Engineer at the National University of Rosario, and graduated in 1997. He was working in industry even before graduation as a network system engineer at Carrefour S.A. Soon after his graduation he was appointed as an automation engineer at Techint Corporation for his flat steel division in Argentina, named SIDERAR, where Mr. Bilich implemented several control models for the electric furnaces and water cooling lines of the hot steel rolling mill. In 1999 he was recipient of a Fulbright scholarship award to do his master degree in Telecommunications at the University of Pittsburgh. In 2001 he was at SIDERAR but as a semi-senior network engineer of the systems department. He was involved in performance measuring and tuning of the company intranet as well as working closely with software developers to aid in the design of distributed application that can meet the stringent performance standards of the company. By that time he was also chief architect of the automatic measuring system that was developed to monitor the performance of the J2EE and Microsoft distributed applications developed in SIDERAR. Recently, in 2004 he won a scholarship to pursue a Ph. D. in computer networks and mobility from the University of Trento, Italy. While doing his Ph. D. Mr. Bilich also works as a junior scientist at the Center for REsearch And Telecommunication Experimentation for NETworked communities, CREATE-NET; an International Research Center founded by a group of leading Universities and Research Centers of Europe and America, leading by the renowned Professor Dr. Imrich Chlamtac. Mr. Bilich primary research interests include: Pervasive computing technologies for healthcare, wireless networks, distributed applications and breakthrough technologies for all packet switching photonic networks.