UNIVERSITY
OF TRENTO

DEPARTMENT OF INFORMATION AND COMMUNICATION TECHNOLOGY

38050 Povo – Trento (Italy), Via Sommarive 14
http://www.dit.unitn.it

QVBR-MAC: A QoS-Oriented Medium Access Control Strategy MAC Protocol for Variable-Bit-Rate MC-CDMA Wireless LANs

Giovanni Berlanda-Scorza, Claudio Sacchi, Fabrizio Granelli, and Francesco G.B. De Natale

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INDEX

Abstract

Multicarrier Code Division Multiple Access (MC-CDMA) techniques were originally proposed at mid of 90's for wideband multi-user communications in wireless environments characterised by hostile propagation characteristics. Problems still to be solved are related to the provision of efficient resource channel allocation in variable-bit-rate transmission. In this work, the design of a MC-CDMA-based WLAN infrastructure is considered. The great advantage of MC-CDMA, i.e. the capability of supporting asynchronous multi-user variable-bit-rate (VBR) transmission over multipath channel with conventional detection, is exploited, jointly with an efficient and real-time Medium Access Control (MAC) strategy, in order to allow a significant number of VBR users to share the same bandwidth with different QoS profiles. Different classes of users will be labeled by the MAC level that has to plan a controlled access to the channel on the basis of the users' requests and to check the possibility of assuring to them a certain Qos degree. The paper presents an overview of the system and tests its performance through extensive simulation.

I. Introduction

The provision of Wireless Local Area Network (WLAN) connections in small environments represents one of the most growing business fields of telecom market. In fact, old wired Ethernet connections for computer networks in houses, offices and buildings are gradually being replaced by wireless connections, keeping into account the necessity of providing local connectivity also for laptops. The most popular WLAN standard is currently IEEE 802.11 (known also as *Wi-Fi*), based on Direct Sequence Spread Spectrum (DS/SS) transmission [2] and Carrier Sense Multiple Access – Collision Avoidance (CSMA/CA) multiple access protocol [2]. The frequency band used by such a standard is the 2.4GHz ISM band. In its first realize, the topic bit-rate allowed by IEEE 802.11 was fixed to 2Mb/s [1]. An improved version, namely IEEE 802.11b, can provide transmission rates up to 11Mb/s. Another standard for WLAN connections is Bluetooth [3], based on Frequency Hopping Spread Spectrum (FH/SS) transmission. In such a standard, the transmission rate is limited to 1Mb/s, allowing remote connections mainly between laptops and wireless peripherals (e.g. keyboards, mouse, joysticks, etc).

The employment of robust Spread Spectrum modulation both in IEEE 802.11 and Bluetooth standard clearly suggests that WLAN and WPAN transmission is performed in a hostile propagation environment. Indoor channel is a very problematic transmission environment, due to the presence of walls, doors, people, chairs, etc., each one acting as a "scatterer" for the transmitted signal. So frequency selective multipath fading and consequently inter-symbol interference (ISI) are commonly encountered. In such a context, R&D is studying more and more innovative standards able at providing the true wideband (namely: ultra-wideband) to WLAN connections. The unclaimed objective is to transmit over wireless indoor networks at rates comparable to Fast Ethernet ones (i.e. 100Mb/s). At the present moment such an objective is yet quite far, but not so far as few years ago. The exploitation of multicarrier modulation [4] can be regarded now as one of the turning points allowing ultra-wideband connectivity. Orthogonal Frequency Division Multiplexing (OFDM) raised since late 50s a great interest among researchers and developers due to its well-known fading resistance, [5]. Actual implementation of OFDM systems is allowed since few years (beginning of '90s) and one of first commercial applications of OFDM was IEEE 802.11a, dated at end of 1999 [6]. IEEE 802.11a employs the same MAC protocol used by IEEE 802.11 and IEEE 802.11b, but the physical level was designed for OFDM modulation in the

5GHz ISM band. The topic rate value allowed is equal to 54Mb/s [6] that is truly quite close to the wired Fast Ethernet one. More recently, the new IEEE 802.11g standard brought the top data-rate of 54Mb/s in the 2.4GHz ISM band by using an OFDM-based modulation scheme. IEEE 802.11g can also provide co-existence of OFDM transceivers with “old” DS/SS 802.11b devices.

The aim of this paper is to investigate the possibility of exploiting the spread spectrum extension of OFDM, i.e. the Multicarrier CDMA (MC-CDMA) for indoor transmission in order to allow multi-user communications in WLAN connections at very high-bit rates. Particularly, multiple access management aspects are faced in the dealing, trying to investigate an optimal strategy for resource allocation. MC-CDMA techniques, whose basic concepts were introduced by Yee and Linnartz in 1993 [7], are strictly derived by OFDM ones. MC-CDMA are classified as Spread Spectrum techniques, as a single data bit is modulated over orthogonally-spaced multiple carriers, with a consequential spectral spreading of the transmitted signal. Moreover, MC-CDMA exhibits a natural inclination to variable-bit-rate (VBR) transmission. VBR services can be easily managed by assigning to each user a variable-cardinality set of subcarriers depending on each bit-rate request [8]. Due to such good properties, MC-CDMA is a serious candidate for supporting physical layer in future WLAN systems. Nevertheless some relevant problems are still to be faced. The provision of variable-bit-rate services can be managed by assigning to different users different-cardinality subcarrier sets. The subcarrier set can be regarded as the resource assigned to users for controlled multiple access. As clearly shown in [8], performance bounds for what concerns fastest users (i.e. employing the lowest-cardinality subcarrier set) are imposed by multi-user interference (MUI), that is the most relevant factor of capacity limitation in MC-CDMA systems, as well as in every kind of CDMA system.

A relevant topic in the field of wireless transmission becomes the management of the radio resource, and thus primary importance is devoted to the MAC layer. In [9], the main issues regarding broadband WLAN (B-WLAN) systems, focusing on a scheme based on OFDM-CDMA technique are presented. Relevant references on the topic of MAC for MC-CDMA are just a few: [13], where a MAC protocol is presented for supporting Qos in synchronous frame transmission employing an IntServ/RSVP approach; [14], where access is granted through a token-passing approach.

In this paper the design of a MC-CDMA WLAN infrastructure for indoor applications is investigated. A physical layer suitable for variable-bit-rate (VBR) multi-user asynchronous

MC-CDMA transmission is designed upon the issues already shown in [8], i.e. a different set of orthogonal subcarriers with different cardinality is assigned to each VBR users, depending on his rate requests.

The problem that the MAC layer has to manage consists in the resource assignment control, in order to discipline the access to the channel of users with different Qos. profiles. In a WLAN scenario, the requests of simultaneous users of accessing the channel by using a certain number of subcarriers depending on the required bit-rate should be checked and allowed (or not allowed) in order to avoid channel congestions, involving unacceptable BER values, huge packet errors and finally dramatic throughput decreases for all users. The presented approach is hybrid (centralized/decentralized) and it involves different classes of Qos, which are mapped into different configurations of transmission bitrate, delay and error probability. Requests for QoS are sent to a resource arbiter, which dynamically assigns transmission slots and MC-CDMA channels to the mobile terminals on the basis of the knowledge of the combination of users transmitting in the same time period.

Points of strength of the paper are: (1) no MAC is available for VBR MC-CDMA wireless networks; (2) the paper gives an overview of the performance of the system from the physical up to the transport level; (3) few papers on MC-CDMA provide a reliable performance evaluation through simulation.

The paper is structured as follows: Section 2 briefly describes the proposed WLAN infrastructure and some outlines on the VBR MC-CDMA physical layer design. Section 3 is focused on QVBR-MAC, while Section 5 shows simulation results. Finally conclusions are drawn in Section 6.

II. Description of the WLAN Infrastructure

The proposed WLAN infrastructure, as widely assumed [9], is defined through a protocol stack consisting of four layers:

- The service layer;
- The adaptation layer;
- The MAC layer;
- The Physical Layer.

The service layer (usually the Internet Protocol, IP) ensures packetization and transmission over the network. In order to provide support for QoS, a priority field is used to partition traffic into different priority classes.

The adaptation layer maps IP traffic into MAC PDUs and performs splitting/merging of PDUs on the basis of the characteristics of the MAC layer. In the case presented in this paper, the adaptation layer is mainly responsible for mapping IP traffic priority classes into the MAC QoS classes (discussed in section 4).

The MAC layer manages the access to the transmission medium and, in the proposed architecture; it provides the physical layer with the proper parameters that maximize the use of the transmission channel by the highest possible number of users, while providing support for the different QoS requirements.

The physical layer is the interface with the actual transmission channel, and in the considered case implements the MC-CDMA scheme presented in detail in the next section. In Figure 1, a pictorial scheme of the proposed MC-CDMA-based WLAN infrastructure is shown. The different typology of interconnected devices suggests that different QoS requests could be forwarded to the network manager by network users.

In this paper, a VBR MC-CDMA transmission scheme very similar to one presented in [8] and [12] (implemented by a full-digital FFT signal processing architecture) is employed. The pictorial graph of Figure 2 can easily describe the subcarrier allocation strategy chosen for the VBR transmission.

The number of subcarriers attributed to the m-th user for signal multiplexing in the frequency domain is equal to N_m. Such a value can be regarded as the actual processing gain of the m-th user MC-SS transceiver. As a fixed amount of bandwidth is employed for transmission, each user's modulator is provided by a different number of orthogonal sub-carriers N_m, depending on the user's bit-rate. The users transmitting at the highest bit-rate will receive the smallest number of carriers, whereas the users transmitting at the lowest bit-rate will receive the highest number of carriers, thus complying with the usual trade-off between transmission speed and protection against channel noise.

Following a common approach (see e.g. [10]), C classes of variable-bit-rate users are assigned as follows:

$$r_c = 2^{c-1} r \quad c = 1,..C \quad (1)$$

where r is the symbol-rate of the slowest users (i.e. class 1). In the present dealing, we consider a BPSK modulation for all users and hence the symbol-rate is equal to the bit-rate. The formula providing the correct orthogonal spacing of the subcarriers for the m-th user of class c_m is given by:

$$f_{m,i} = F/2\left(2^{c_m-1} - 1\right)r + iFr_{c_m} \quad i = 0..N_m \quad (2)$$

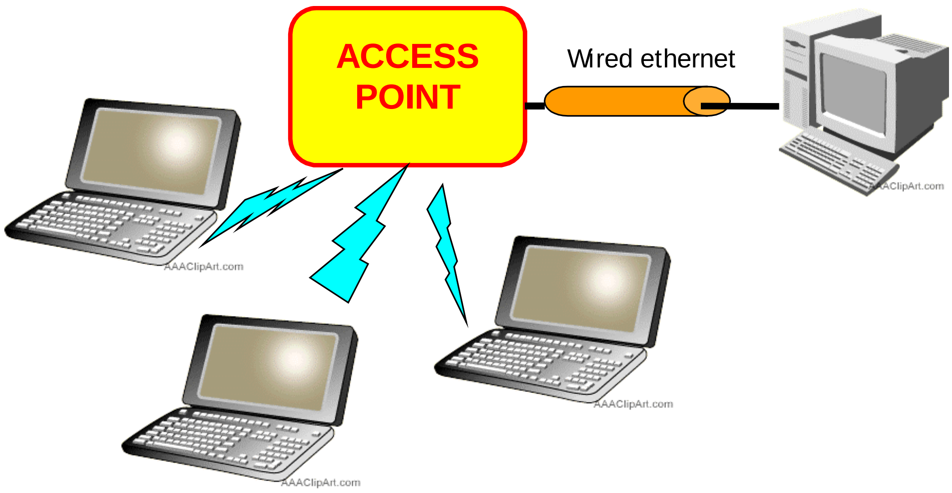

FIG.1. MC-CDMA-BASED WLAN INFRASTRUCTURE

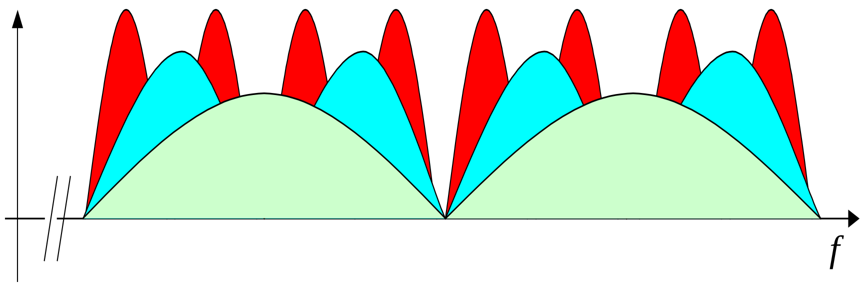

FIG.2. VBR MC-CDMA CHANNEL ALLOCATION STRATEGY

In the present dealing, we considered the lowest subcarrier spacing factor (F=1), in order to achieve the maximal spectral efficiency in wideband transmission. The signature codes has been chosen in the tree-structured mutually orthogonal and variable-length set described in [10], usually employed in UMTS systems. The set of codes at each level of the tree is a mutually orthogonal Walsh set. Couples of codes belonging to different levels of the tree are also mutually orthogonal, excepting in the case when one of the codes belonging to a higher level is father of one or more codes belonging to a lower level [10]. It is supposed that the digital modulation employed by the OFDM block is the BPSK one. The transmission frequency considered for the considered application belongs to the usual 2.4GHz ISM band (2.4GHz-2.4385GHz), already exploited for IEEE 802.11 and Bluetooth transmission. The indoor channel has been modelled by a tapped delay line (frequency selective model [2]) and parameterized on the basis of the experimental data provided in [11]. Thus, the channel delay spread has been fixed at 500nsec (corresponding to a coherence bandwidth of 2MHz) and the Doppler spread at 2Hz (corresponding to a coherence time of 500msec). The receiver has been implemented by following a simple sub-optimal Equal Gain Combining (EGC) strategy [7], supposing ideal carrier and timing synchronization.

III. QVBR-MAC: Differentiated VBR Access to the Transmission Resources

MC-CDMA allows the coexistence of several user transmissions in the same frequency band, and it was demonstrated to support multiple data-rates with different bit-error-rates (see [8] for further details). Drawing from the results of previous investigations [12] and taking into account the peculiarities of MC-CDMA transmission, the proposed WLAN infrastructure is aimed at providing differentiated access to the transmission resources through centralized mapping different QoS classes into physical layer transmission parameters.

The considered QoS classes are the following:

- 1 Best-Effort (BE) class, not arbitrated and without specific constraints on QoS;
- 3 QoS-Guaranteed (QoSG) classes, managed in a centralized fashion, so that specific constraints on bitrate, transmission delay and error probability can be supported.

The user classes considered for the simulations have been listed in Table 1. In this table, channel rate and bandwidth is listed for each class, together with the constraints in terms of BER (bit error rate), and transmission delay.

TAB.1. Variable-Bit-Rate (VBR) user classes

USER CLASS	CHANNEL RATE	BANDWIDTH/SUBCARRIER NUMBER N_M	PER	DELAY
BE	8192 kbps	73.7MHz / 8	None	None
QoSG-1	512 kbps	66MHz / 128	$<10^{-2}$	$<10^{-2}$s
QoSG-2	1024 kbps	66,6MHz / 64	$<10^{-2}$	$<10^{-2}$s
QoSG-3	2048 kbps	67,7 MHz / 32	$<10^{-2}$	$<10^{-2}$s

The baseline idea of the MAC protocol is to properly assign a set of carriers and spreading sequences to each user transmission on the basis of the QoS constraints each user needs (see Table 1 for an example). Such set of parameters is defined a-priori and stored in a table (PT), which is available to each terminal in the WLAN environment (with a simple lookup operation; for, example downloaded after registration in the WLAN domain).

In general, each terminal belonging to the WLAN could contain a queue of packets belonging to each QoS class. For sake of a simpler study and without losing generality, in this work we assume that each terminal transmits traffic belonging to only one QoS class.

Figure 3 shows a conceptual scheme of the proposed MAC strategy. The available bandwidth (the *physical channel*) is dynamically partitioned into several *logical channels* by the combination of currently employed transmission parameters.

One logical channel (the *Shared Channel*, *ShCh*) is allocated to best effort traffic and reservations: it is further partitioned in the time domain into 2 intervals, of which one (T_{res}) is reserved for terminals interaction with the resource arbiter (which can be the gateway router for connection to other networks) and the other (T_{con}) is left for best effort access through CSMA. The partitioning is repeated with period ($T_{res}+T_{con}$). T_{res} contains a header and a trailer (generated by the resource arbiter) in order to "advertise" the reservation of the interval.

The remaining channels are left for QoS traffic.

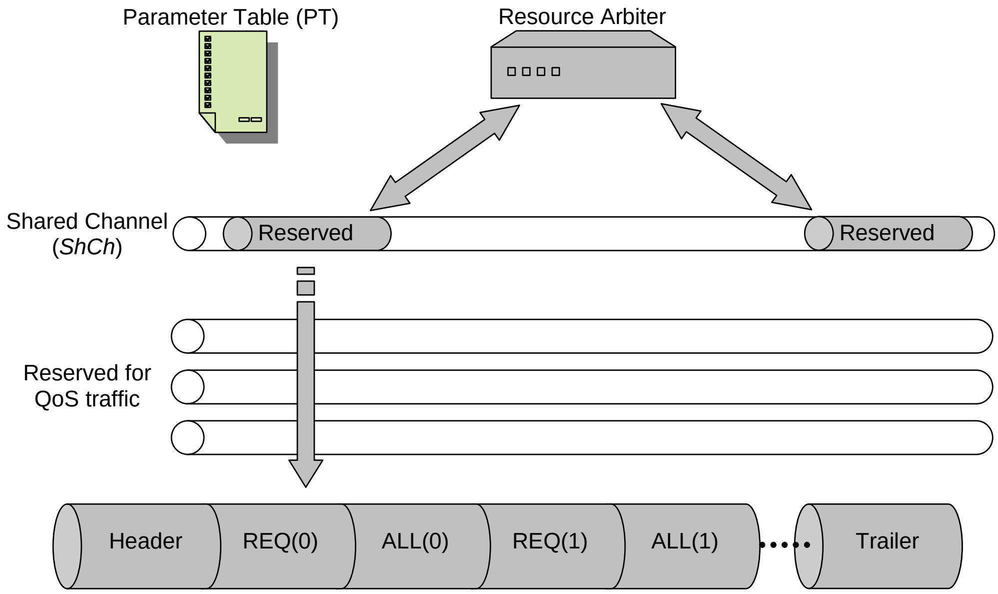

FIG.3. CONCEPTUAL SCHEME OF THE PROPOSED MAC PROTOCOL

Resource allocation is based on a hybrid centralized/decentralized reservation approach:

- for QG traffic, the requesting terminal accesses *ShCh* (during T_{res}) for sending the requests for transmission at a given QoS (using a REQ frame) and for receiving information about the allocation of resources (ALL frame). The corresponding frame description is presented in fig. 4. Transmission of QoS traffic is then performed on the logical channel allocated to the mobile device by the resource arbiter;
- the T_{con} interval on *ShCh* is left for BE traffic. In this case, resources are directly available without the need for reservation, but employing a CSMA discipline. Such channel provides

a high data rate and low access delay (in case of low load on the network). As usual in CSMA-based access, when the traffic on the network grows, performance on this link decreases.

The capacity available for BE traffic is given by:

$$C_{BE} = \left[1 - \frac{T_{res}}{T_{res} + T_{con}}\right] \cdot 8Mbps \quad (3)$$

Summarizing, one logical channel (ShCh) is used for best-effort transmission and QoS requests. The remaining resources are dynamically allocated by the Resource Arbiter to QoS-oriented transmissions.

Access to the channel for QoS requests is arbitrated using a round robin discipline: each terminal has a time slot available for sending its QoS requests to the resource arbiter. The request (see fig. 4) is represented by a MAC frame containing the source ID of the requesting terminal (the MAC address of the device), the type of service requested (the User Class in table 1), the bitrate, the length of data to be transmitted (in terms of number of time intervals to use) and a CRC for error detection.

REQ Frame Format:

MAC Address (16 bit)	Service (8 bit)	Bitrate (8 bit)	Requested Capacity (32 bit)	CRC (32 bit)

ALL Frame Format:

MAC Address (16 bit)	Params (8 bit)	Bitrate (8 bit)	Granted Capacity (32 bit)	CRC (32 bit)

FIG.4. FORMAT OF THE REQ AND ALL FRAMES

The resource arbiter then grants access to the transmission medium by assigning the MC-CDMA transmission parameters to the terminals in their own ALL slot (on the basis of the content of PT). Only the resource arbiter can send data in the ALL(x) slots. The MAC frame used by the resource arbiter contains the ID (MAC address) of the requesting source, a pointer to the corresponding transmission parameters on PT, the bitrate granted to the mobile terminal, the allocated time slots and the CRC (see fig. 4). The reader should note that the allocation algorithm is itself a parameter of the protocol and it can be defined at the resource arbiter level. Some guidelines regarding the overall capacity of the link during a given time slots are presented in the experimental results in section 5.

As an example, if the system allows 9 contemporary users to present requests in parallel every 10 ms, it is possible to leave one slot free before and after the REQ/ALL slots in each T_{res} (see fig. 3) thus leading to a total of 96 bits (for a single REQ/ALL frame) x 2 x 10 = 1920 bits to be transmitted every 10 ms. This leads to a reserved capacity of 192 kbps on *ShCh* for reservations, leaving (8192 – 192) kbps = 8000 kbps for BE traffic.

A terminal, which succeeds in resource allocation, can then transmit on the logical channel allocated to it, by using the negotiated physical layer transmission parameters.

IV. Simulation results

Some intensive simulations have been performed in order to test the behavior of QVBR-MAC. The structure of the simulator includes a MC-CDMA frame and physical level simulation (in MATLAB SIMULINK V6.1) and MAC to transport level simulation (in ns-2). The first section provides information about channel performance (BER, PER) to the second, which computes transport-level performance (throughput, delay, etc.)

Different user configurations have been tested by simulations. A fixed C/N_0 equal to 80dBHz has been established for all users, the transmission E_b/N_0 is equal to 11dB for BE users, and it is incremented way-by-way of 3dB for each user class. The configuration characteristics in terms of number of users of different VBR class asynchronously transmitting over the shared bandwidth is listed in Table 2.

The transmission of a number of bits ranging from 5,000 for the slowest users up to 100,000 for the fastest users has been simulated. In Table 3, simulation results are completely shown for all user classes and all configurations (note that a PER equal to 1 means that at least one packet will be missed and throughput reduced). Such results presented in table 3 are useful at the resource arbiter level, since they provide an overview of the different combinations of requests in terms of QoS. It is interesting to underline that simulations at the physical layer demonstrate that it is possible to successfully combine different QoS requests, such as for example configurations no. 2 and no. 3 (table 3).

By using the PER values it is then possible to perform a network simulation to evaluate the throughput and delay of the different traffic flows. For space reasons, just a graph is shown (fig. 5) to depict the normalized throughput of traffic flows at different QoS levels.

TAB. 2. USER CONFIGURATIONS CONSIDERED IN SIMULATIONS

	NUMBER OF USERS			
CONFIGURATION	CLASS 1–BE	CLASS 1–QOSG-1	CLASS 2–QOSG-2	CLASS 3–QOSG-3
1 – BE only	3	-	-	-
2 – QoSG only	-	4	2	1
3 – Mixed traffic	1	2	1	2

TAB. 3. SIMULATION RESULTS ABOUT PHYSICAL LAYER

CONFIGURATION 1 – BE ONLY		
USER CLASS	BER	PER
BE	10^{-5}	10^{-4}
CONFIGURATION 2 – QOSG ONLY		
USER CLASS	BER	PER
QoSG-1	$2*10^{-4}$	$2*10^{-3}$
QoSG-2	$5*10^{-4}$	$4*10^{-3}$
QoSG-3	10^{-2}	10^{-1}
CONFIGURATION 3 – MIXED TRAFFIC		
USER CLASS	BER	PER
BE	10^{-1}	1
QoSG-1	10^{-4}	10^{-3}
QoSG-2	$4*10^{-4}$	$4*10^{-3}$
QoSG-3	$8 *10^{-3}$	$7*10^{-2}$

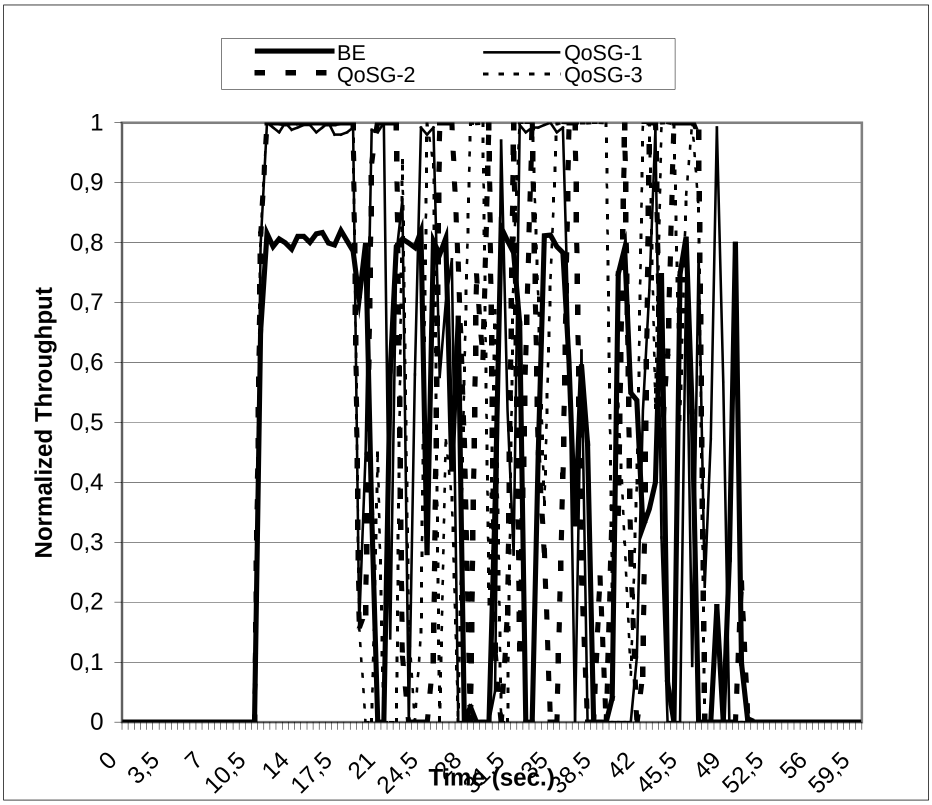

FIG.5. NORMALIZED THROUGHPUT FOR DIFFERENT TRAFFIC FLOWS

V.Conclusions and Future Work

A WLAN architecture based on MC-CDMA is presented and a preliminary version of a dedicated MAC protocol for resource management is proposed that aims at maximizing the use of the transmission medium while preserving constraints on different levels of QoS given to the users. Achieved results underline that with QVBR-MAC it is possible to allocate several traffic flows with different QoS contraints at the same time, thus providing a good efficiency in the usage of the shared wireless medium.

Future work will involve issues related to the receiver design, able at efficiently exploiting the natural diversity provided by MC-CDMA techniques.

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