MOBILE RADIO ADVANCES IN EUROPE

# A MAC Protocol for a Wireless LAN Based on OFDM-CDMA

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## ABSTRACT

Local access encompasses requirements of high throughput, transfer performance, flexibility, and ease of user/terminal mobility at a relatively low cost. While some of these targets can often be met satisfactorily with wired infrastructures, it is getting increasingly popular to resort to wireless access (wireless LAN), mainly because of its simpler deployment, continuous coverage, availability of ad hoc connectivity, and user/terminal mobility support. This article outlines the proposal of a broadband quality-oriented WLAN system. The basic system characteristics are described, with details given on a MAC protocol supporting IP and exploiting an OFDM-CDMA technique.

## INTRODUCTION

The wireless approach to the local area access, wireless LAN (WLAN), is becoming increasingly attractive, mainly because of its simpler deployment, continuous coverage, availability of ad hoc connectivity, and user/terminal mobility, together with inherent flexibility for delivering full broadband services to end users.

Key developments in software and hardware capabilities within terminals, coupled with sophisticated multiple access schemes and wireless interface protocols, allow a full range of possibilities to be displayed ranging from very economic wireless access for domestic or ad hoc network use (e.g., HomeRF [1], Bluetooth [2], and infrared WLANs [3, 4]) up to very high-performance radio interfaces, such as those targeted by evolving IEEE 802.11 and HIPERLAN standards [5].

Key elements of the success of WLAN systems are:

- Their extreme flexibility to provide access to users moving within a local area and to new users entering that area, either with a fixed infrastructure (radio fixed points) or even without any infrastructure (ad hoc networks)
- Their relatively low cost with respect to wired infrastructures, especially for upgrade toward broadband services and/or new infrastructure deployment
- The possibility to provide flexible services in terms of both resources and quality (e.g., real-time guaranteed service along with best effort transport, broadband multimedia high-quality services, fast Internet, traditional narrowband services)

In this article we describe a broadband WLAN (B-WLAN) system. We discuss the main system issues and trade-offs for broadband wireless access. We outline the proposal of a quality-oriented B-WLAN system based on the orthogonal frequency-division multiplexing (OFDM)-code-division multiple access (CDMA) technique. The focus is on the multiple access scheme.

## LOCAL WIRELESS ACCESS ALTERNATIVES

We discuss the main topics related to a B-WLAN development in the indoor environment. Since very high-performance systems are addressed, we do not consider ad hoc networks.Thus, fixed radio points that collect and broadcast radio signals locally to serve a number of terminals are assumed.

### THE ROLE OF BROADBAND WLAN

Broadband WLANs' area of application is essentially similar to that of wired LANs with respect to public networks: to offer high performance, relatively low price, and easily manageable connectivity for local access. Added values of B-WLANs are the capability to handle roaming and mobile users, and support a mix of real-time strict requirement services along with data communications of mainly best effort quality.

The relative roles and characteristics of B-WLANs, Universal Mobile Telecommunication System (UMTS) — third-generation mobile networks) — and Mobile Broadband Systems (MBS) — a further generation of mobile networks — are given in Table 1. These statements lay down the big picture, although they are necessarily somewhat gross. It is envisaged that the target of B-WLANs is data-oriented traffic transfer. However, multimedia traffic will also play a significant role (think of the variety of high image content information and applications used in an intranet environment, where radio segments could be incorporated). This poses a requirement for much larger bandwidth than UMTS can yield, and hence pushes radio technology up to higher frequency bandwidths, such as the Industrial, Scientific, and Medical (ISM) bandwidth around 2.4 GHz; bandwidth around 5, 17, and 60 GHz has been demonstrated in various testbeds). Very high operating frequencies, coupled with a rather challenging radio channel in indoor environments, call for very robust multiple access techniques, at

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| Parameter | UMTS | MBS | WLAN |
|---|---|---|---|
| Operator | Public and private | Public and private | Private |
| Applications | Indoor and outdoor | Indoor and outdoor | Primarily indoor |
| Operating frequency band | 1885–2025 MHz,<br>2110–2200 MHz | 40 and 60 GHz | 2.4, 5, and 17 GHz, 60 GHz (experimental testbed) |
| Data rates | 2 Mb/s | 2–155 Mb/s | 1–54 Mb/s |
| Range | < 10 km | 100–1000 m | ~ 50 m |
| Communication | Connection (circuit and packet), IP/ATM | Connection and connectionless, ATM | Connectionless (IP), ATM |
| Bearer capability | Variable assignment | Variable assignment | Variable assignment |
| Speed | High-speed vehicle | < 50 km/hr | Very low speed (quasi-stationary) |
| Mobility class | Vehicle, portable, handheld | Mobile, movable, portable | Mobile, portable |
| Mobility | Support UPT | Support UPT | — |
| Services | Data, speech, video, access to IT resources | Data, speech, video, access to IT resources | Data, speech, video, access to IT resources |
| Interworking | PLMN, PSTN, ISDN, Internet | PLMN, Internet | Private corporate networks (intranet), Internet |
| Coverage | Cellular infrastructure with handover | Cellular infrastructure with handover | Local with interconnecting nodes |
| Channel access | W-CDMA, TD-CDMA | FDMA; TDMA; CDMA | TDMA; CDMA; OFDM |

IT: Information technology; TD-CDMA : Time-division CDMA; PLMN: Public land mobile network
UPT: Universal personal telecommunications; W-CDMA: Wideband CDMA

■ **Table 1.** *A comparison of wireless networks.*

*Very high operating frequencies, coupled with a rather challenging radio channel in indoor environments, call for very robust multiple access techniques, at least for high-class products, to achieve the required throughput that can make B-WLANs competitive with wired ones.*

least for high-class products, to achieve the required throughput that can make B-WLANs competitive with wired ones (i.e., hundreds of megabits per second). A second big issue is the capability to support a range of different quality of service (QoS) requirements, going from guaranteed QoS applications (typically those involving some form of audio/video real-time communications) down to best-effort traffic. It is convenient to do this in such a way as to simplify interworking with outside backbone networks (e.g,. IP networks enhanced with IntServ/DiffServ paradigms).

The multiple access technique and MAC protocol structure considered in the following are defined along these distinguishing guidelines for B-WLAN development.

## GENERAL WLAN ARCHITECTURE

A typical WLAN architecture includes a number of base stations (BSs) and a group of fixed or mobile terminals (PCs, laptops, etc.) served by those BSs (Fig. 1). We refer to the radio-related entities inside the terminals as *radio interface units* (RIUs).

The BS provides the functionality to logically control the wireless interface and to perform all the transmission functions (modulation/demodulation, channel encoding/decoding, synchronization, etc.). The BS can be connected to a gateway (GW), possibly shared among all the BSs making up the WLAN. The GW represents the border between the WLAN and the core network, and it manages one or more access points toward other networks: leased lines, frame relay, asynchronous transfer mode (ATM), Internet, and so on.

The terminal functional architecture is split into a radio part, handling the radio interface tasks, as both physical transmission and reception and to carry out lower-layer radio interface protocols, and a control part for dealing with signaling (data and mobility-related signaling) and controlling data transfer over the radio interface.

In Fig. 1, an example of the protocol architecture of a WLAN is shown. Four main layers can be distinguished. The service layer (SL) corresponds to classical network functions (addressing, routing) and traffic handling functions (flow classification/declaration, admission control, traffic policing, and/or shaping). A major example of an SL is the IP layer possibly enhanced with QoS handling capabilities. Another example is ATM, in which case SL classes could be the standard ATM traffic categories constant bit rate (CBR), variable bit rate (VBR), available bit rate (ABR), and unspecified bit rate (UBR).

The adaptation layer (AL) mainly performs the classification of SL packets into medium access control (MAC) service classes. It is to be noted that the SL classes do not necessarily have a one-to-one correspondence with the MAC classes. This is to keep MAC relatively simple, but open to support different networking platforms. Other AL functions are packet segmentation to fit the MAC protocol data units (PDUs) and error detection and recovery by means of automatic repeat request (ARQ), when required.

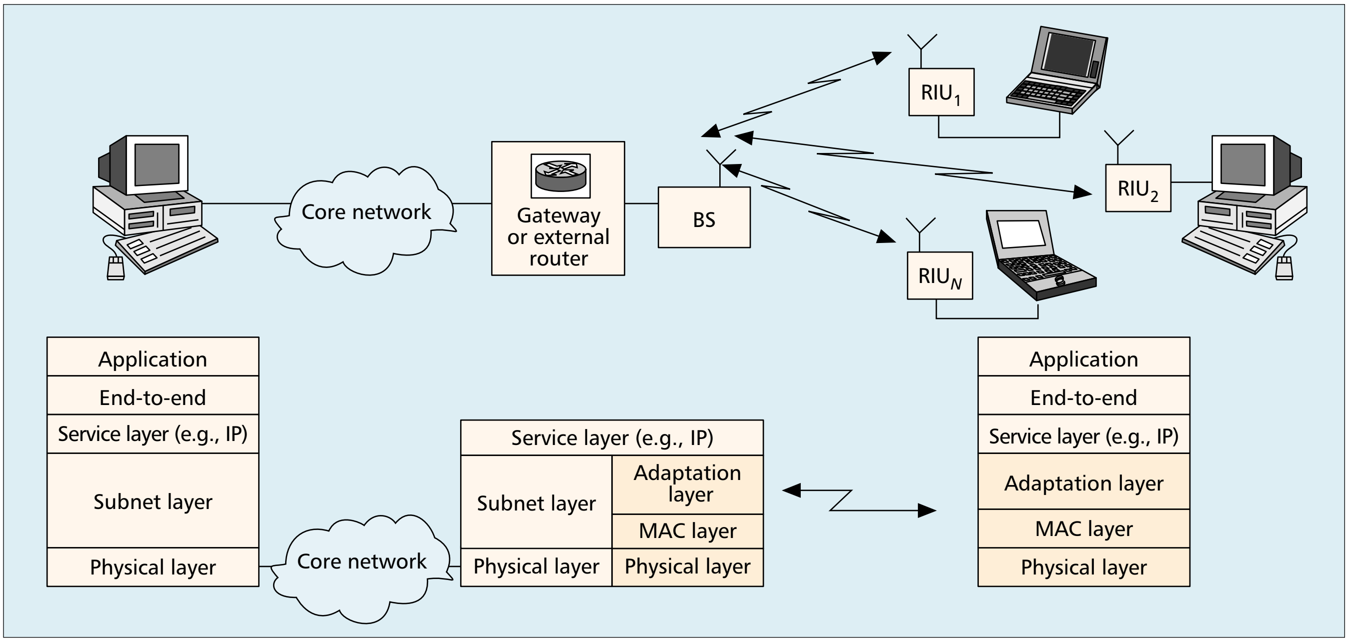

**Figure 1.** *Overall WLAN architecture.*

The MAC layer accomplishes the sharing of radio capacity among packet flows. Capacity assignment can be performed centrally by the BS via a demand/assignment scheme. This allows very sophisticated sharing policies to be implemented.

Finally, modulation/demodulation, channel encoding/decoding, synchronization, and radio frequency transmission functions belong to the physical layer.

## THE INDOOR RADIO CHANNEL

A number of studies address the indoor radio channel characteristics in the millimeter wave region [6–10].

Millimeter wave propagation behaves almost like light. Within closed and irregular indoor environments this leads to very complex signal propagation, dominated by a large amount of multipath fading and delay spread that can impair signal reception significantly at bit rates greater than tens of megabits per second. As an example, measurements carried out at 19 GHz show that delay spreads as high as 150 ns can be reached [7]. Moreover, channel characteristics are strongly time-varying because of changes in the environment surrounding the terminal (e.g., new obstacles moving in, movement of persons or objects).

Another important characteristic is interference from other systems (e.g., in large open space indoor environments or systems operating in deregulated ISM bandwidth) and from other sources of relevant electrical fields (e.g., microwave ovens in domestic applications of WLANs). Quite low signal power values are desirable both to spare terminal batteries and due to regulatory constraints.

Typical countermeasures encompass diversity (spread spectrum communications can be seen as frequency diversity techniques), use of sectored or even smart antennas, error protection/correction mechanisms, and equalization and/or robust modulation techniques (e.g., OFDM).

## MODULATION AND MULTIPLE ACCESS SCHEMES

In analyzing the suitability of a given modulation and multiple access scheme for B-WLAN solutions, certain aspects must be taken into account, including:

- Computational complexity of the digital signal processing components: adaptive equalizers, multicarrier filter banks, and so on
- Sensitivity to carrier phase noise, frequency offsets, and timing errors
- Sensitivity to high-power amplifier nonlinearities
- Flexibility in bandwidth allocation

In B-WLAN applications involving aggregated bit rates on the order of tens of megabits per second in both uplink (UL) and downlink (DL) directions, the equalizer is the most complex element of the signal processing for single-carrier (SC) solutions. Complex adaptive equalizers are needed to cope with intersymbol interference (ISI) caused by multipath propagation in channels which may have delay spreads of several symbol periods (e.g., 5–10). Decision feedback equalizers represent a good solution for B-WLANs operating at millimeter waves, and equalizer coefficients can be adjusted according to the minimum mean square error (MMSE) criterion.

To adapt the equalizer coefficients to channel variations in the DL direction, the slow-convergent and numerically robust Least Mean Square (LMS) algorithm can be used. However, because the BS faces different radio channels corresponding to different users in successive time slots in the UL direction, a fast convergent and more complex fast Recursive Least Squares algorithm is required.

Alternatively, multicarrier OFDM has drawn a lot of attention in the field of radio communications as an effective way to combat frequency selectivity in hostile radio channels. In OFDM, the entire channel is divided into many narrow subchannels transmitted in parallel. By increas-

| Access | SC vs. OFDM | | | | Different OFDM techniques | | |
|---|---|---|---|---|---|---|---|
| | Uplink channel | Adaptive equalizer complexity | Sensitivity to phase noise and frequency offsets | Dominant complexity | Flexibility (minimum assignable bandwidth per symbol interval) | Main PAPR reduction capabilities | Effects of phase noise |
| Single-carrier | Time-varying intersymbol interference | ~ Tens of billions complex operations/s | Moderate | Adaptive equalizer | — | — | — |
| OFDM-TDMA | Slow-time variation<br>Intersymbol interference eliminated by guard interval | ~Billion complex operation/s | High | FTT operations | Aggregated bit rate | Use of redundancy<br>Time domain signal processing | Common rotation of received symbols and inter-carrier interference |
| OFDMA | | | | | Aggregated bit rate/ total number of subcarriers | Use of redundancy is rather complex<br>Time domain signal processing | Multi-user and inter-carrier interference and non-uniformly rotated received symbols |
| OFDM-CDMA | | | | | Aggregated bit rate/ total number of codes | Good results with appropriate code spreading and amplifier backoffs | Multi-user interference and non-uniformly rotated received symbols |

■ **Table 2.** *A comparison of multiple-access methods.*

ing the symbol duration and reducing the symbol rate after serial-to-parallel conversion, equalizers for OFDM solutions require less computational effort than do SC systems.

Computational cost in OFDM systems is dominated by the multicarrier filter bank implemented by means of fast Fourier transform (FFT). A simple one-tap linear equalizer per subcarrier can be used to cope with channel impairments. Moreover, as the UL channel becomes quasi-stationary, these frequency domain equalizers can be properly adjusted according to the MMSE criterion and adapted by means of the LMS algorithm.

Intercarrier interference (ICI) and ISI can be eliminated by introducing a guard time interval and cyclic symbol extension between successive symbols.

Multicarrier systems are more immune to channel dispersion than SC systems. However, multicarrier systems have the disadvantage of more sensitivity to local oscillator phase noise and carrier frequency offsets. Phase noise originates from local oscillator instabilities and affects the signal in up-down frequency conversion operations. It is difficult to design oscillators with moderate instabilities in the frequency range of some tens of gigahertz. Carrier frequency offsets result in the rotation and attenuation of the useful signal component for both SC and OFDM systems. For SC systems, the loss in useful signal power is the main contribution to bit error rate (BER) degradation.

Table 2 summarizes the key points of the comparison between SC and OFDM-based multiple access for quadrature phase shift keying (QPSK) modulation and an aggregated bit rate of tens of megabits per second. Also, a comparison of different OFDM schemes is reported: multiple access by time division (OFDM-TDMA), by code division (OFDM-CDMA), and by sharing sets of subcarriers among users (OFDMA) [11].

In OFDM-TDMA systems, phase noise causes a common phase error of received symbols at the decision point and loss of orthogonality of the subcarriers, which gives rise to ICI. The former is easy to estimate and compensate for, since it identically affects all subcarriers. In OFDMA, phase noise additionally gives rise to multi-user interference. It provokes multi-user interference and rotates the symbols at the decision point in OFDM-CDMA systems.

One of the main drawbacks of conventional OFDM is that the envelope power of the transmitted signal fluctuates widely. A $K$-carrier OFDM system has a peak-average power ratio (PAPR) of $K$. Normally, high amplifier backoffs are needed to avoid the signal distortion due to saturation of amplifier nonlinearities. Therefore, the average power must normally be reduced, resulting in inefficient amplification. For SC systems, data predistortion before the modulator, nonlinear equalization of the received signal, or predistortion of the modulated signal before the power amplifier can be used [12].

Several PAPR reduction techniques for

*Several PAPR reduction techniques for OFDM-TDMA systems have been investigated in the literature, which rely mainly on introducing redundancy or on processing the time domain signal before the amplifier.*

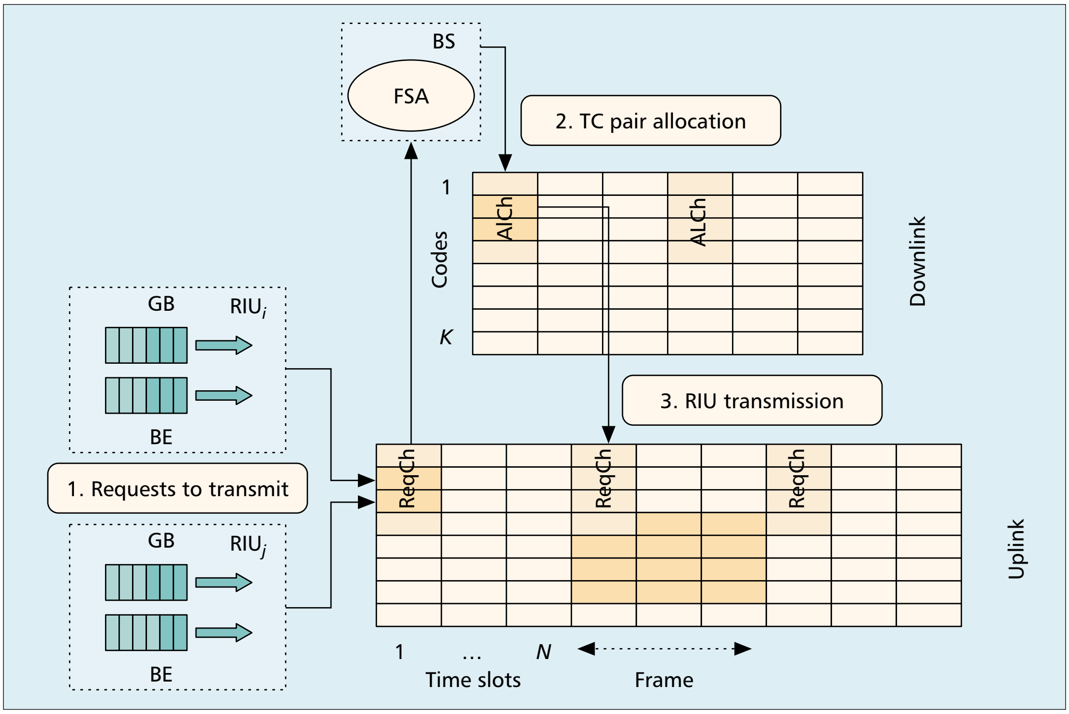

**Figure 2.** *The structure of the radio capacity and dynamic MAC operation scheme.*

OFDM-TDMA systems have been investigated in the literature, which rely mainly on introducing redundancy or processing the time domain signal before the amplifier. In the OFDMA case, where a variable number of subcarriers is dynamically assigned to users, the implementation of reduction techniques based on redundancy seems rather cumbersome.

Since OFDM-CDMA systems spread the data symbols across the frequency domain and employ OFDM modulation for conveying each spread data symbol, its transmitted signal exhibits a high PAPR. However, this impairment can be mitigated by appropriate selection of the spreading codes and moderate amplifier backoff [13].

The suitability of a given multiple access scheme for B-WLAN applications also depends on its flexibility to assign variable bit rates to users.

In an OFDM-TDMA scheme made up of $K$ useful subcarriers, each symbol interval is used for the transmission of $K$ data symbols of the same user. This implies that a delay, required to collect $K$ data symbols from a user (a sort of packetization delay), is introduced; this delay could impact performance significantly for values of $K$ commonly used (e.g., 512).

In the OFDM-CDMA, one symbol interval can be used for the transmission of data symbols belonging to up to $K$ different users. OFDMA allows an intermediate type of multiplexing by permitting each user to transmit $x$ data symbols on a set of $x$ subcarriers in each symbol interval ($x < K$).

Concerning bandwidth granularity, OFDM-CDMA and OFDMA offer the most flexibility. In these cases, to obtain a rate of $h$ data symbols per symbol time (with $h < K$), $h$ codes ($h$ subcarriers) in the same symbol interval are used. Such a rate value cannot be obtained in a single symbol time in OFDM-TDMA (it is necessary to average over a certain number of symbol intervals).

## A PROPOSAL FOR A MAC PROTOCOL BASED ON OFDM-CDMA

OFDM-CDMA has elegant waveform properties that make it useful for a variety of applications. In particular, we can mention fixed wireless access and WLANs. Here we follow the considerations presented above and describe a proposal of a multiple access technique, based on the OFDM-CDMA, which can be used in B-WLAN systems.

The basic B-WLAN system here considered includes a centralized BS and a group of terminals (around 50). The BS provides radio resource management. The considered case study is made up of one single cell working at a carrier frequency of 28 GHz. Frequency-division duplex is assumed; hence, nonoverlapping bandwidth portions are assigned to the UL and DL.

The number of OFDM subcarriers has been chosen to be 512. This number comes from a compromise of several factors: increasing the number of subcarriers improves multipath robustness and reduces the guard interval overhead; on the other hand, it increases phase noise sensitivity and flexibility in bandwidth assignment. Moreover, an FFT of 512 points can be implemented with today's technology at a symbol rate on the order of millions of symbols per second.

If we assume a channel bandwidth of 110 MHz, the resulting intercarrier spacing is 212 kHz. Thus, the Fourier period of the OFDM-CDMA symbol is equal to 4.71 µs. In addition, by selecting a guard interval of 442 ns, ISI is prevented in typical B-WLAN channels at millimeter-wave frequencies. Hence, symbol duration results equal to 5.16 µs, where an overhead of 8.5 percent is used to provide protection against multipath.

Typical OFDM implementations sacrifice some of the carriers to create a guard band between adjacent channels. Accordingly, we decided to use 400 out of 512 subcarriers, corresponding to a guard band of 11.8 MHz at each side. Therefore, if one adopts robust QPSK modulation, an aggregated bit rate of 155 Mb/s is obtained.

For a system designed with the above described parameters and adopting an MMSE equalization criterion, a BER of less than $10^{-3}$ can be obtained for an $E_b/N_0$ of 8 dB, and a spectral efficiency of about 1.4 b/s/Hz.

## QOS FEATURES

At the SL, we assume that IP is evolving toward a perspective where QoS handling is included. This might be the dominating scenario for B-WLANs, also in view of the development of powerful IP-based intranets. However, the proposed system is flexible enough to be used in a different context (e.g., ATM-based WLANs).

Basic guidelines considered for the quality-oriented WLAN definition are:

- To support a minimum set of traffic classes in which higher-layer classes can be mapped
- To dynamically allocate link capacity on demand
- To let the BS centrally control access by periodically collecting requests from the RIUs, since shifting complexity to the BS leads to more economical systems

Two traffic classes are specified:

- Guaranteed bandwidth (GB)
- Best effort (BE)

The GB class is for services with stringent requirements on delay and delay jitter (i.e., real-time services). Video and audio are typical GB information. This traffic class is handled in the system in order to satisfy QoS targets within a deterministic traffic control framework.

A case study of QoS support is developed, based on integrated services (IntServ) defined by the Internet Engineering Task Force (IETF), where the Resource Reservation Protocol, (RSVP) is adopted [14]. To apply the IntServ approach to deliver QoS to the GB class, flow traffic descriptors are required (e.g., peak bit rate); relevant admission control rules and flow parameter compliance checks must be defined and introduced. In this B-WLAN, we define the above operations by assuming that GB traffic is regulated by means of dual leaky buckets (DLB). DLB ensures that traffic entering the system can be characterized by a few traffic parameters [14].

Admission control is performed on the basis of the DLB parameters by adapting generic schemes holding for the IntServ approach. Once admission control is performed, the QoS guarantees are obtained by scheduling the packets in accordance to a fair sharing algorithm (FSA).

The BE class has a twofold purpose: to provide a simple (and also economic) means of satisfying service demands that are not critical but are interesting to users, and to accommodate the existing Internet/LAN application traffic as currently dealt with. The B-WLAN shall support this class by using the bandwidth not used by GB. It must be considered that high utilization of the air interface capacity can be achieved only if the capacity left by more demanding traffic can be filled by traffic with very loose requirements.

## A MAC PROTOCOL DESCRIPTION

A key point of the proposal here presented lies in the definition of a MAC protocol exploiting OFDM-CDMA and allowing for:

- Differentiated QoS support with fair resource sharing within each QoS class
- Efficient use of the radio resource under VBR and bursty traffic

This MAC concept can also be applied in a wireless local loop system [15].

The proposed MAC is based on the access structure corresponding to the OFDM-CDMA scheme where $K$ codes are available to be used to transmit data symbols of up to $K$ different users in a symbol interval. We further adopt a slotted time axis where the slot duration is the time to transmit a MAC_PDU. $N$ slots are grouped into a frame that carries $N * K$ time slot-code (TC) pairs.

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Figure 2 depicts the UL and DL logical structure of the proposed multiple access, hereinafter referred to as the *TC matrix*. The main innovation considered at the MAC level is the exploitation of the matrix structure of the radio interface. This structure is quite different from pure TDMA since it offers a grade of parallelism useful to allocate the same time slot to multiple users. The MAC functions (signaling, scheduling, etc.) are strictly related to this structure.

The UL capacity assignment is performed frame by frame. Each RIU can transmit on several time slots in the frame, distributing the MAC_PDUs on a given number of codes.

Basic MAC signaling consists of a UL logical channel to make dynamic capacity requests, the request channel (ReqCh), and a DL logical channel to answer the requests, the allocation channel (AlCh). Each terminal has a dedicated couple of ReqCh-AlCh in the TC matrix. The detailed format and dimensioning of the ReqCh and AlCh, for a system supporting 64 RIUs, are reported in [15].

The ReqCh is structured in minislots: each minislot transports the bandwidth request for the GB and BE classes of an RIU; the minislots are accommodated in TC pairs in the same time slots. Two queues are provided in each RIU, to store MAC_PDUs belonging to the GB and BE traffic classes. Bandwidth requests are expressed as the number of GB and BE MAC_PDUs waiting in the RIU queues; hence, they are $\geq 0$ and $\leq N * K$).

The DL AlCh is used by the BS to signal to the RIUs the number of TC pairs assigned to them in the frame.

Once the requests are collected, the overall available capacity in each frame is assigned to RIUs by the BS in accordance to the FSA.

The FSA is the key element to support different QoS at the MAC layer. It implements hierarchical link sharing, meaning that radio link capacity is shared hierarchically by groups of users with decreasing QoS targets. Specifically, GB traffic has priority over BE.

The major points of the QoS delivery mechanism of the defined B-WLAN system can be summarized as follows:

- GB flows negotiate the capacity required to guarantee the target QoS parameters; this is achieved by means of admission control that results in assigning, to the $j$th RIU, a weight $W_{j,GB}$ (expressed as number of TC

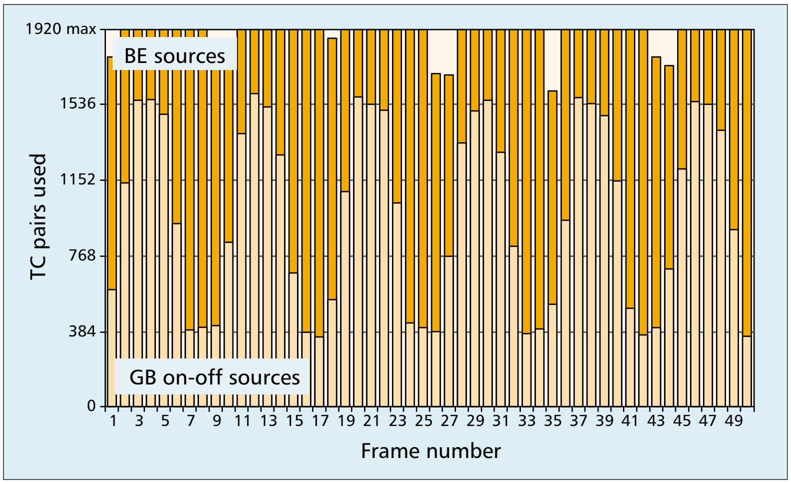

**Figure 3.** *Time slot-code matrix occupation.*

pairs per frame); $W_{j,GB}$ is the only information needed by the MAC from upper layers to handle the GB traffic.

- Also, the BE aggregated flow relevant to the $j$th RIU has an associated weight $W_{j,BE}$; this weight is used to create different priorities among the RIUs, even for their BE traffic.
- Both GB and BE traffic are handled dynamically (frame by frame): the BS is informed by the RIUs about the pending packets of the two types of flows; the $j$th RIU signals the TC pairs requested for the GB class ($Rq_{j,GB}$) and those requested for the BE class ($Rq_{j,BE}$).
- The BS assigns capacity to the RIUs according to the RIUs' requests and relevant weights (FSA); each RIU is in charge of splitting the assigned capacity among the GB flows multiplexed in the RIU itself. If the GB packet transmission in the frame does not require the whole negotiated capacity, the remaining part can be used by BE traffic.
- To avoid possible choking of BE traffic, a portion of the capacity ($S_{BE}$) can be reserved for BE traffic.

The logical steps performed by the FSA algorithm are the following:

- *Initial assignment*: Assign what is guaranteed, that is, $\min\{Rq_{j,GB}, W_{j,GB}\}$ to each RIU, $j = 1, \ldots,$ number of terminals in the B-WLAN.
- *Assignment of residual capacity*: If there are some GB class requests still pending (i.e., RIUs requesting more than their guaranteed capacity), redistribute residual bandwidth to these RIUs, proportionate to their respective weights.
- Run the steps above for the BE traffic by using the set $\{Rq_{j,BE}, W_{j,BE}\}$ and letting the overall capacity to be shared be $S' = S - \sum_i A_{j,GB}$, where $A_{j,GB}$ is the amount of bandwidth that the $j$th RIU got in the previous steps of the FSA and $S$ is the number of available traffic TC pairs in a frame.

It is to be noted that it is a task of admission control for GB flows to ensure that $\sum_j W_{j,GB} \leq S - S_{BE}$.

Given the way the requests are computed, it is clear that each RIU does not get less than the guaranteed capacity. It can get more if some RIU does not use all its guaranteed capacity. In this respect the FSA is work conserving: it does not waste a TC pair if there is at least one MAC_PDU waiting in the RIUs (no matter to which class it belongs).

Figure 2 explains the main steps performed in the dynamic assignment procedures. Requests based on the RIUs' queue status are sent to the BS by means of the dedicated ReqCh. All the requests are elaborated at the BS in accordance to the FSA algorithm. The complete pattern of matrix occupation in the next frame is signaled to the RIUs by means of the AlCh. Each RIU fills the assigned TC pairs with the MAC_PDUs in the two queues by first serving the GB queue and then the BE one.

This MAC mechanism has been investigated via an exhaustive performance analysis based on simulations in accordance to the scheme of Fig. 2. Several kinds of traffic sources have been considered in both homogeneous and heterogeneous mixes:

- Measured MPEG coded traces, used to model real-time multimedia GB traffic
- Measured LAN IP packet traces, used to model BE traffic
- Artificial sources with ad hoc emission profiles (e.g., constant data rate, Poisson, and on-off sources)

Figure 3 shows one of the observed results in the performance analysis: a sample path of the TC matrix occupation by both GB and BE traffic flows. Four RIUs have been considered, each handling two types of traffic flow: a GB flow conforming to a worst case on-off DLB-compliant mask and a BE traffic modeled as a Poisson flow.

The GB traffic always gets the required bandwidth. As can be noticed, the matrix occupation presents periodic peaks caused by the GB traffic characteristics (deterministic on-off). The BE traffic, although it has negative exponentially distributed interarrival times, is "shaped" by the GB traffic, which has higher priority, and assumes a peaked profile. BE traffic is allowed transmission only in the intervals between two successive GB traffic peaks.

In heterogeneous conditions we evaluated the system with different mixes of traffic at the RIUs. Each GB flow at an RIU has a negotiated maximum delay that is reflected in an assigned weight in the admission control phase. Figure 4 depicts the minimum, average, and maximum delays perceived by GB and BE traffic in heterogeneous conditions. We simulated the system behavior by considering six active terminals, each with a mix of BE and GB traffic; the capacity utilization is close to saturation. The minimum value of the perceived delay does not depend on the negotiated one and is just equal to the minimum delay resulting from the request/assignment mechanism in the frame. The maximum delay for GB traffic is always less than or equal to the negotiated one.

## CONCLUSIONS

In this article we present a B-WLAN able to offer a range of QoS profiles in an IP environment.

A key point of the proposed system is analysis of the adoption of OFDM-CDMA as the access technique since it offers robustness to channel impairments, relatively low complexity, and high

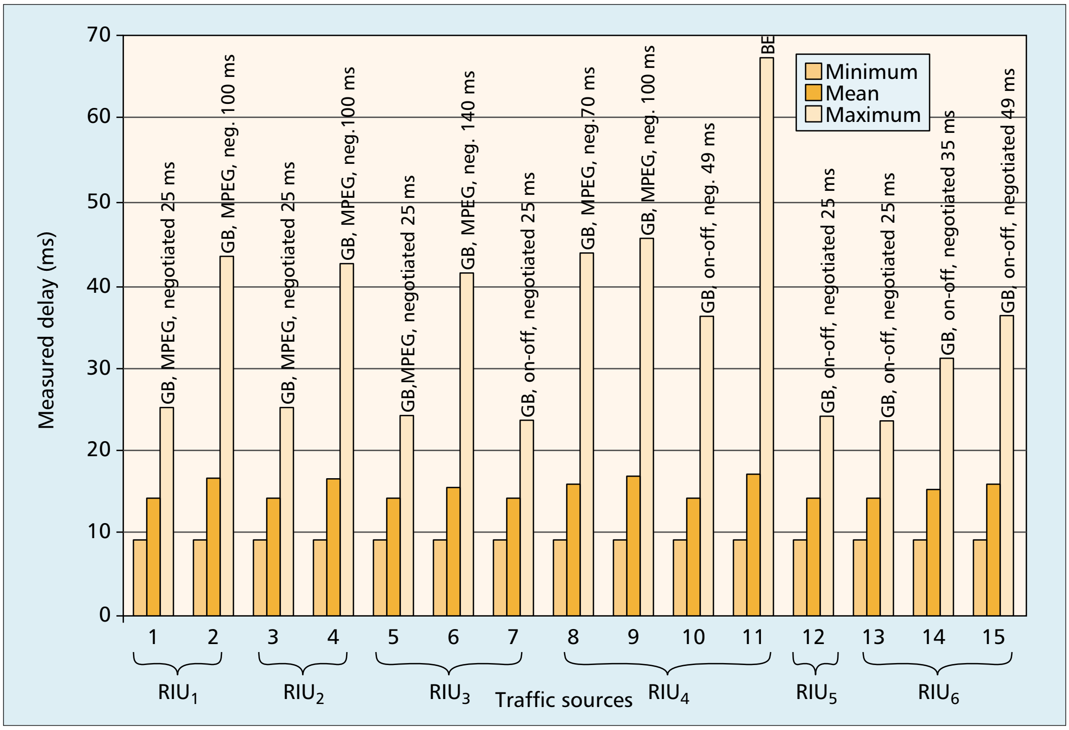

**Figure 4.** *Minimum, mean, and maximum measured delays.*

*In heterogeneous conditions, we evaluated the system with different mix of traffic at the RIUs. Each GB flows at a RIU has a negotiated maximum delay that is reflected in an assigned "weight" in the admission control phase.*

flexibility in bandwidth assignment. Reasons are discussed why CDMA combined with OFDM appears to be an appealing solution for a system with characteristics like those of B-WLANs.

The definition of a MAC protocol sitting on top of OFDM-CDMA is investigated, and the functionality to allow differentiated QoS support with fair resource sharing and efficient use of radio resource has been defined and evaluated.

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