The Magic WAND—Functional Overview

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***Abstract*—The Magic WAND project (Wireless ATM Network Demonstrator) is one of the largest projects within the European Union ACTS (Advanced Communications Technologies and Services) initiative. The project aims to design, verify, implement, and demonstrate a wireless access network for ATM LAN's. The complete range of functionality, from physical data transmission to shared multimedia application, is addressed. The WAND system is designed for indoor environments with user mobility limited to walking speed. The system's functional specification has been designed and verified using SDL (specification and description language). In this paper, the WAND system functional model is given and SDL simulation results are presented, to illustrate how the protocols support some of the key operations of a wireless access network. These include initial registration, call setup, and handover.**

***Index Terms*—Asynchronous transfer mode, functional model, mobile multimedia communication, wireless LAN.**

I. Introduction

The Magic WAND (Wireless ATM Network Demonstrator) is a three-year (9/95–9/98) European-Union-funded ACTS (Advanced Communications Technologies and Services) project. The Magic WAND project is a collaboration project among six industrial, two research institutes, and five university partners. Due to the large project size, there is a unique possibility to cover the whole range of functionality from basic (wireless) data transmission to shared multimedia applications for an ATM transparent wireless access network for business and professional use. More precisely, the Magic WAND project focuses on developing an ATM-oriented high-speed radio subsystem, network protocol with mobility support, and QoS (quality of service)-aware applications for end users.

The high-speed radio subsystem work focuses on developing radio and medium-access control layers that are adapted to the 5.2-GHz frequency band and a 20+ Mbit/s data rate. The radio subsystem is required to support mobile operation with seamless ATM interworking. In addition, studies and component development have been performed for very high-speed operation in the 17-GHz frequency band, with a 50+ Mbit/s data rate. The 17-GHz work is aimed at point-to-point and point-to-multipoint operation.

Manuscript received August 31, 1997; revised February 15, 1998. This work was performed in the framework of Project ACTS AC085 The Magic WAND, which is supported in part by the European Community and the Swiss BBW (Bundesamt für Bildung und Wissenschaft).

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Publisher Item Identifier S 0733-8716(98)04799-4.

Network protocols defined for QoS-based communication, such as ATM/B-ISDN signaling, do not include mobility support. The Magic WAND project will define required mobility extensions, including handovers and location management, for indoor cellular access network operation within one ATM switch, taking into account both the high data rate and the stringent requirements set by the relatively small radio cell size.

QoS-aware applications are needed to verify the technology platform and to demonstrate the benefits of new multimedia services to mobile users. For this purpose, two separate user trials are to be arranged, with "real" end users. These user trials are called *mobile computing* and *medical consultation* [17]. The mobile computing trial will demonstrate student users using legacy applications such as Internet Web browsers built on top of the TCP/IP protocol stack running over the wireless ATM link. The medical consultation trial will show a more advanced scenario, fully exploiting the wireless ATM service capabilities, in a hospital environment with applications such as video conferencing and X-ray retrieval. Note that the applications will be QoS but *not* wireless aware, even when they have been developed within the WAND project. Unlike in the cellular telephony environment, where specific mechanisms and applications are needed to overcome the low bandwidth and high error rate, WAND is aiming to provide a service adequate for standard user applications.

This paper will start out by outlining the rationale for the development of yet another new wireless system, followed by the system partitioning and the key design aspects. The WAND system has been specified and simulated with the SDL (system description language) of which examples will be shown where appropriate. Furthermore, the paper focuses on explaining the WAND (5 GHz and 20+ Mbit/s) demonstrator system functional design, concentrating on the technology development, i.e., the radio physical layer, the medium-access control layer, and the ATM signaling extensions needed to support wireless ATM network users operating within one ATM switch.

Further work expanding WAND local-area handover and general location management schemes, to also cover the interswitch handover case and wide-area mobility management, may be found in [24] and [16]. Application-related QoS work is also outside the scope of this paper. More information on application-level QoS may be found in [18] and [13]. In the demonstration design work, some choices have been guided by the implementation restrictions. Envisaged deviations from the final system are explained where appropriate.

II. Rationale

The rationale for wireless ATM is based on the emerging need for higher bandwidth, QoS provision to the end user

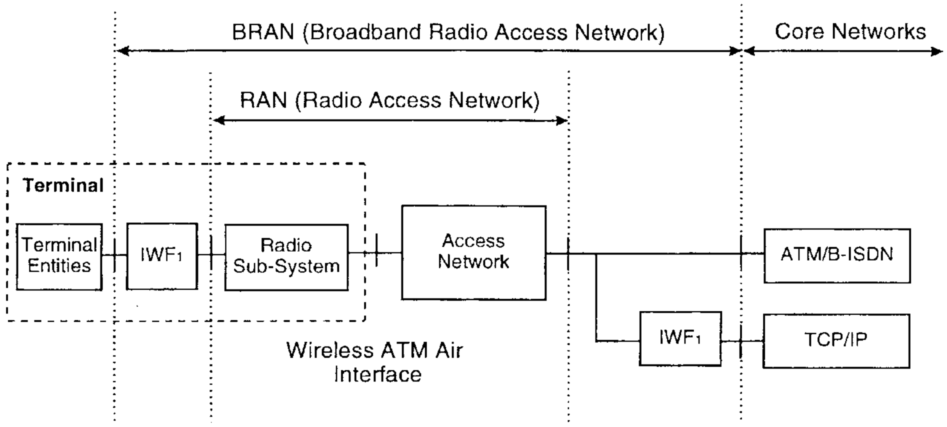

Fig. 1. WAND reference model.

applications, and on the technology harmonization over wired and wireless media. The recent developments in user terminal platforms such as PC's have enabled true multimedia-oriented applications. The implication is that today's PC's may simultaneously function, e.g., as a telephone, video-conference terminal, and text processor.

In one of the WAND user trial scenarios, doctors will retrieve X-ray pictures from the network, share applications, and be engaged in video-conferencing connections. The bandwidth that is required cannot be met with existing narrow-band or wide-band systems, which are able to support instantaneous bandwidths up to 2 Mbit/s. The peak bandwidth requirement for one X-ray retrieval may be up to 6 Mbit/s [17]. Furthermore, the gross bandwidth required for voice, data, and multimedia applications combined will create the need for the WAND type of broadband channel.

Service guarantees, some requiring high bandwidth on demand and others constant bandwidth reservation, can, in fixed networks, be serviced by providing excessive, cheap bandwidth. The same is not economically possible in a wireless environment, where bandwidth is scarce and expensive. In wireless, a relatively high bandwidth is required, but specific emphasis must be put on the QoS provision. A WAND example that will test the QoS provision in the system is a simultaneous video-conferencing connection and X-ray retrieval in the medical user trial scenario.

To summarize, the driving forces behind wireless ATM's are similar to those for fixed network ATM evolution. Radio is a shared resource, as are the ATM backbones, the area where ATM has been exploited first. Multiple users running services with varying traffic and QoS characteristics must be cost-effectively multiplexed into one medium while making efficient use of the scarce radio spectrum. For this purpose, a common ATM-based radio subsystem is needed. Multiplexing of services with one unique technology into both wired and wireless media will enable true integrated services broadband communications. In the wireless environment, there is a good chance for a wireless ATM-based approach to become the driver for the future QoS-based communication.

III. Reference Model

The Magic WAND project aims to provide input for standardization. Therefore, the key issues in the early stages of the system design are the identification of the functional groupings and respective reference points within the system and their correspondence with existing systems. While defining the WAND network reference model, the main objectives were:

- to clearly separate radio-dependent and radio-independent parts, and
- to allow modular usage of newly designed radio technology with a variety of core networks.

Work done within the European UMTS generic radio access network specification has been used as a starting point for the model applied for WAND (presented in Fig. 1) [11].

According to this model, the WAND reference model consists of three key elements: RAN (radio access network), BRAN (broadband radio access network), and two different core networks. The RAN consists of radio-dependent functionalities such as radio physical layer and MAC (medium-access control) layer, whereas the core network comprises fixed network physical transport and network signaling layers. RAN will provide support for handovers within its service area that are controlled by the core network. The rationale is to separate radio-dependent and radio-independent parts, defining interchangeable modular blocks. The same radio access network can be exploited with different core network technologies and vice versa by defining the required interworking functions. The interworking and RAN specifications together form the BRAN concept.

The scope of the Magic WAND project includes wireless ATM-based BRAN, with ATM/B-ISDN- and TCP/IP-based core networks. The reference model states that a core network and the terminal are the endpoints of the ATM signaling (UNI). In WAND mobility signaling, (M) is similarly defined between the core network and terminal, including messages, e.g., for registration, authentication, and handovers. Since ATM cells are transmitted in the radio subsystem, no interworking functions are needed for ATM/B-ISDN-based core networks. Thus, processing per packet and frame is minimized in native ATM networks. In addition, IWF_1 (interworking functionality)

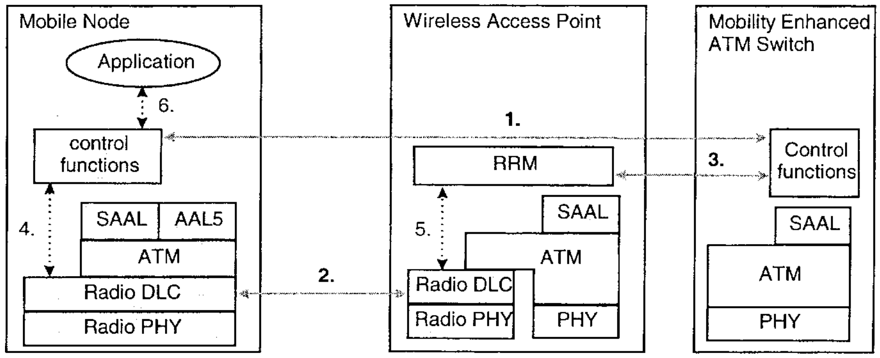

Fig. 2. Wireless ATM access system layer architecture.

for TCP/IP adaptation has been designed and implemented in the form of ATM LANE (local network area emulation).

IV. Functional Model

The reference model presents a general framework that could be implemented with various physical configurations. In the WAND proof-of-concept setup, the radio access network is seen to be composed of a mobile terminal radio subsystem and a wireless ATM AP (access point). An ATM switch enhanced with mobility support functions forms a simplified core network. Functionalities are distributed into network elements according to the reference model and based on the following practical guidelines.

- It should be possible to upgrade a legacy ATM switch with specific software to support wireless users.
- The same switch should also support standard ATM users employing wired connections.
- The system should be scalable from point-to-point wireless connections to larger (pico) cellular networks.
- The focus is in the customer premises network, trying to maintain local location management, i.e., supporting handovers, registration, authentication, etc.
- No provision will be made for wide-area mobility management,[1] i.e., mobility within an area covered by multiple switches.

The functional division between the radio access network (access point and mobile terminal) and the core network (ATM switch) is one of the key system design issues for the wireless ATM access networks. The aim here is to keep the ATM switch complexity at a manageable level, and to move all of the radio-specific network functions into the radio access network, and more specifically into the AP RRM (radio resource manager). The RRM provides interface functions for both the ATM switch and the AP transceiver.

In most wireless ATM system proposals, the wireless CAC (connection admission control) function has been included in the ATM switch, which has the benefit of centralized decision and simpler implementation of the AP [33], [6]. The alternative presented here, as shown in Fig. 2, moves the computation-intensive wireless CAC calculation into the AP, where the most accurate radio interface information is known. In each AP, the wireless CAC can be tuned to match the specific way that different radio subsystems operate. In addition, the localized decision making gives a short response time and distributes the processing load. Many AP's can be consulted simultaneously, which is beneficial, e.g., in the handover situation, where multiple AP's have to be considered before the target AP can be decided. The switch will issue inquiries about the wireless CAC status after having completed the switch CAC. Note that if the wireless CAC is not done in the AP, the wireless-specific information would have to be transferred into the switch, reducing the scalability of the wireless subsystem and adding significantly to the ATM switch implementation complexity.

In Fig. 2, ATM, SAAL (signaling ATM adaptation layer), AAL5 (ATM adaptation layer 5), and PHY (ATM physical) layer are assumed to be used as in existing ATM standards. Control functions radio DLC (data link control), radio PHY, and RRM are the WAND focus areas. Table I presents the main interfaces between the system functional entities. Interfaces 1–3 in Fig. 2 are protocols between peer layers, while numbers 4–6 refer to control interfaces between different protocol layers.

To summarize, the main protocols such as network signaling flow transparently over the WAND radio access network. The ATM switch and mobile terminals are the endpoints of network signaling. Standard signaling is enhanced with mobility-specific features which are grouped into two separate functional entities (UNI+M). Radio-specific functions are grouped under RRM, and a new protocol called APCP (access point control protocol) is introduced between the radio access network and the mobility-enhanced ATM switch for radio connection admission control and radio access network management.

V. System Design—SDL

A key factor in successful software development and maintenance is a thorough system specification. This requires a formal specification language that makes it possible to create, maintain, analyze, simulate, and translate system descriptions [34]. Natural language is generally ineffective to communicate and reason on such items. Hence, the Magic WAND consortium has chosen to use SDL (specification and description

[1] Wide-area mobility management is seen to be complementary to local mobility management (taken care of by handovers) which covers an area of a single switch. In a full core network model, the wide-area mobility management should also be included.

TABLE I
PROTOCOLS AND LAYER INTERFACES

Ref n:o	Interface	Comments
1	ATM UNI + "M"	The "M" protocol is used for mobility specific messages, while UNI is the standard ATM connection control.
2	Radio Link Control protocol	The Radio sub-system control protocol between MT and AP.
3	Access Point Control Protocol	Protocol used for managing connections and radio access network.
4	MT radio sub-system control	Layer management interface.
5	AP radio sub-system control	Layer management interface.
6	Application Programming Interface	Various environments have different implementations of this API (e.g. Winsock2.0 for Windows.

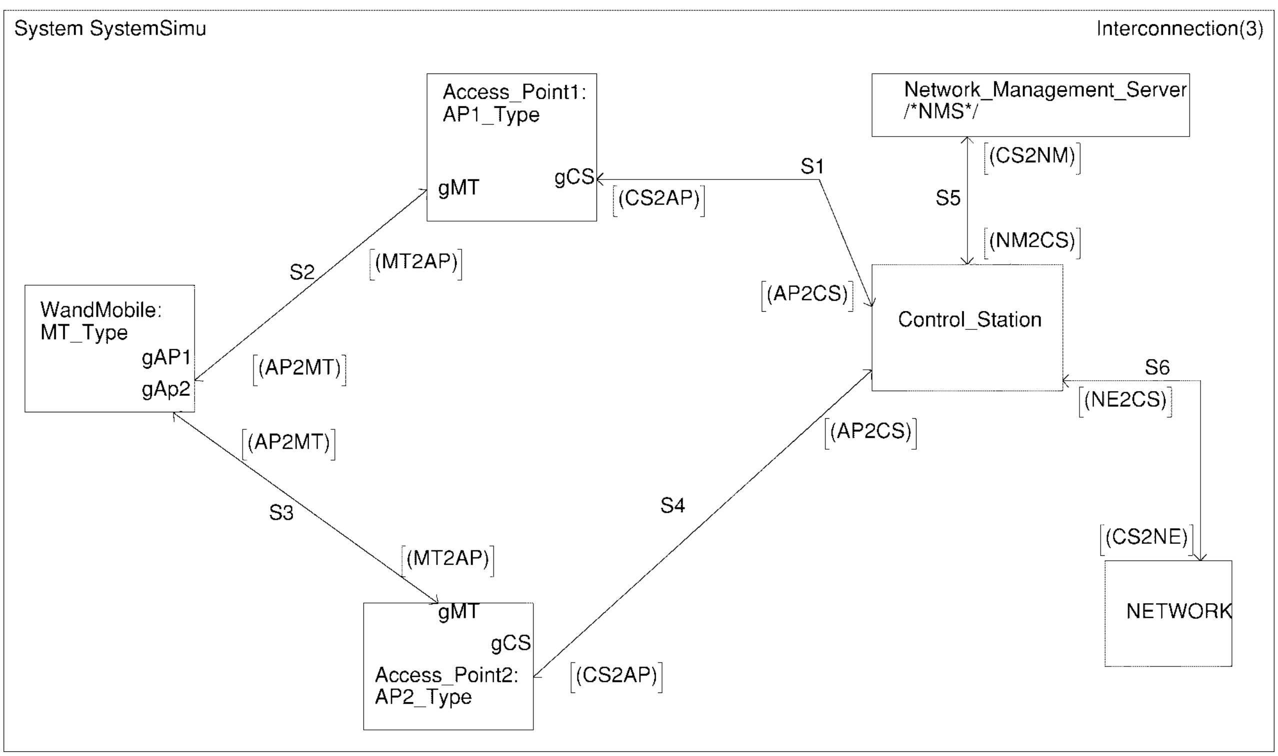

Fig. 3. SDL simulation model of WAND.

language) for system specification and medium-access control layer implementation. SDL is a formal language that has all of the benefits of the above. More precisely, SDL is an object-oriented language with concepts for describing the logical structure, data structures, and behavioral aspects of the wireless ATM access network [27].

Besides SDL, additional information is needed to gain initial understanding and information on the logical system operation. In WAND, MSC's (message sequence charts) were used to help understand the information that is required to be passed between various entities of the system (and to/from the environment). Initial MSC's were drawn at the same time as the system was divided into separate communicating parts. The entities represented were SDL blocks and processes. Fig. 3 presents the top-level SDL block diagram of WAND with corresponding communication channels.

The entities correspond to the physical entities found in the WAND wireless ATM access network (see also Fig. 2). The entity referred to as *control station* is a control part of the ATM switch. For ease of demonstrator implementation, the control station is a separate workstation with a control interface to the ATM switching fabric.

The benefit of using MSC's is that these may be used as a design base for the functional entity behavior and later testing of different entities. Furthermore, the SDL simulator tool produces the same format of MSC as those produced in the design phase with the MSC tool, so the implemented design can be verified. The next sections explain in more detail the structure and functional behavior of the WAND system. At the end simulator, MSC traces are used as examples to present the system operation.

VI. Network Software for the WAND System

The networking software is the layer in the protocol hierarchy which provides applications the facilities to transfer data between two end systems. Networking software encompasses a large number of facilities ranging, e.g., from signaling for setting up end-to-end connections, to name service providers, to translate human readable names into ATM addresses, LAN emulation for legacy networks, and to performance-monitoring software.

First, this section of the paper concentrates on the key areas of the network software which we consider important for a wireless ATM network: standardization, QoS of ATM, and mobility. Second, a description of the system is given in terms of the software components in the mobile terminal and the control station of the ATM switch. A description of the important mobility and radio resource messages is then given. The actual interaction in terms of message exchanges between the functional modules described here is presented in Section IX.

A. Important Networking Features

Standards compliance and contributions toward interoperable wireless ATM products are some of the main aims of the WAND work. To achieve this aim, modifications to the standard ATM signaling plane have been minimized. All of the new features that are required for wireless ATM have been implemented as protocol layers parallel to the standard protocols. For example, handover has been implemented separately from ATM signaling, even though they share some common operations, i.e., setting up and removing ATM links between a switch and the end system. Not modifying standardized protocols maximizes the interoperability of fixed and wireless ATM systems since the mobility of a terminal is completely transparent to a fixed terminal and the core network.

The QoS provision of ATM is one of its main strengths. While in the network level this is seen as guarantees on bandwidth, delay, and jitter for connections, the user perception of QoS in wireless ATM should contain this and more. An application that is QoS and mobility aware may try to adapt to changes in the wireless environment. Mechanisms can be provided to allow an application to be informed of the current situation, and the application can then adapt to these situations. Knowing that a handover is being performed and that there will be a temporary loss of connectivity, an application can stop sending data until the handover is complete. If the radio link has degraded so that less bandwidth is available, the application can, for example, reduce the size of the image it is transferring or reduce the quality of speech transferred, etc. Some existing application programming interfaces provide a limited way of informing the application of these events, and WAND is utilizing and extending them. For further information on this, see [21].

Mobility is the most important property of a wireless system. The lowest level of mobility is a system with a single base station. Mobility is minimal, limited to within the radio range of the base station, and logically, all mobility is limited to within the domain of the base station and end system. The next level is to have a number of base stations connected to one ATM switch. Here, the domain of the mobility is extended to encompass the switch, and its software must be extended to allow a mobile terminal to move from port to port. Retaining interoperability with wired networks is easy to achieve since only one switch is involved. The next level allows multiple ATM switches with base stations. Here, the interoperability problem becomes harder if performance and utilization are to be maintained. WAND tackles the second level of mobility, and aims to keep the mobility transparent from the mobile terminal and the core network. In keeping with the idea of separating standard and new functionality, mobility management is implemented as a protocol alongside the standard signaling protocols in the mobile terminal and the ATM switch.

Below, a functional description of the modules that implement the WAND demonstrator handover algorithm is given. WAND defines both lossy backward and forward handover schemes [14]. Furthermore, WAND has also specified a lossless handover for wireless ATM that is fully compatible with the lossy schemes. In [23], various design tradeoffs for lossless wireless ATM handover such as cell duplication and cell misordering are discussed. Furthermore, [23] addresses the overall relation of WAND handover schemes with other work in this area [6], [19], [38], [39], and [42] and [24] extend the basic model into the interswitch domain.

B. Description of WAND Modules

The networking software in the mobile terminal and control station has been designed as a number of protocols or modules. The mobile terminal design is based on commercial software for Windows NT4 and a commercial ATM stack. These form a framework which has been extended with new modules to work in a wireless environment. These extensions are MMC (mobility management and control), CC (call control), and an LCP (layer control protocol). In addition to these extensions, an interface between the AAL5 layer and the Winsock 2 API [41] has been implemented so that applications can use native ATM protocols with QoS support, as well as legacy protocols such as TCP/UDP/IP which are best effort. Fig. 4 shows the protocol stack of the mobile terminal.

As with the mobile terminal, the control station is based around commercial software which has been extended. The

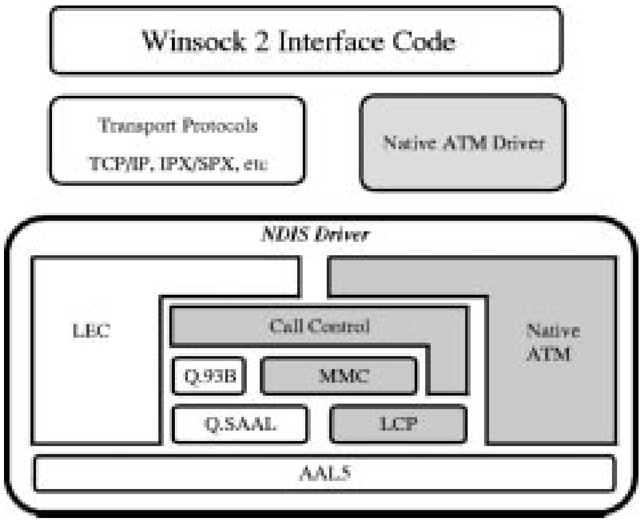

Fig. 4. Mobile terminal modules.

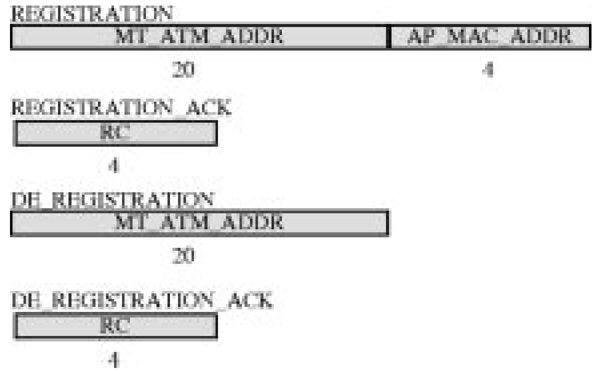

Fig. 5. Registration PDU's.

extensions add the MMC functionality and RRM (radio resource management), as well as the ability to reconfigure the ATM switch during a handover.

The MMC protocol is responsible for implementing mobility above the MAC layer [15]. The MMC protocol performs registration when the MT first joins the network and performs handovers when the MAC layer indicates that a handover should occur. MMC supports both forward and backward handover, and will decide which one to perform depending on the radio conditions when the handover is started. During handover, the CS MMC performs the reconfiguration of the connections from the old AP to the new AP, and informs the network management system of these network events. Communication between the MMC in the mobile terminal and the control station has to be reliable so Q.SAAL is used.

To perform these MMC operations, a number of PDU's (protocol data units) have been defined. Fig. 5 shows the REGISTRATION and REGISTRATION_ACK PDU's, as well as the DE_REGISTRATION and DE_REGISTRATION_ACK PDU's. The ATM address is used to identify a mobile terminal at the network level. The AP_MAC parameter indicates which AP the mobile terminal is using. RC is the return code which indicates the result of the operation.

Moving from one access point to another can take two forms, either a location update or a handover, depending on whether the mobile terminal has any connections. The PDU's for the handover signals are shown in Fig. 6. As with registration, the ATM address parameter identifies the mobile terminal, while the AP_MAC parameter indicates the new AP the mobile terminal is moving to. For a handover, a list of connection priorities can be included so that, if the new AP does not have sufficient resources for all of the connections, the more important connections can be preserved and less important connections either given a reduced level of service or dropped. The RLQ (radio link quality) is passed on from MMC to RRM so that RRM can make a better estimate at the bandwidth required for ARQ to give the desired QoS.

In the mobile terminal, the existing ATM framework does not provide a CC layer implementation with the required mobility interfaces to functional entities. For both MAC and MMC operations such as handover, information about the current calls is required. A simple CC layer has been implemented which builds a database of calls as they are made and released, and configures the MAC layer with information about the calls as they are set up and released.

The MAC protocol for the mobile terminal has been implemented on a separate processor from the host, and the access point is separated from the control station. To allow communication between the MT/CS and the MAC, a simple protocol is required to support this communication. LCP provides a reliable way of transporting messages between a number of ports on the MT to the MAC.

The RRM controls the radio resources of each AP, in order to maintain the QoS of the guaranteed connections. Wired ATM systems contain resource managers to ensure that resources such as input and output buffer, switching bandwidth, and link bandwidth are not exhausted. If any one of these resources is exhausted, it affects the traffic, and guarantees are broken. In WAND, as a new connection is requested, the target AP is queried if it has sufficient resources available to support the connection. These resources could include radio bandwidth, buffer space, and processor bandwidth to perform the data processing operations required for the requested level of QoS.

The model of the WAND system in Fig. 2 shows that RRM is located in each AP, which keeps the design philosophy of not modifying existing systems unless required. RRM is external to the signaling software, and is consulted only when required. To ease demonstrator implementation, this model has been changed slightly in that the RRM process for each AP is actually run in the CS as shown in Fig. 7.

To allow the control station to query the AP about radio resources, a number of PDU's have been defined as shown in Fig. 8. As in the MMC PDU's, the ATM address and AP_MAC address identify the mobile terminal and access point, respectively. The connection identifier indicates the VPI : VCI for the new connection. The ATM parameters give the bandwidth requirements of the new connection in terms of PCR (peak cell rate), SCR (sustainable cell rate), and MBS (maximum burst size) [35]. The broadband bearer capability and QoS parameters indicate what level of quality of service is required. Finally, the radio link quality as observed by the

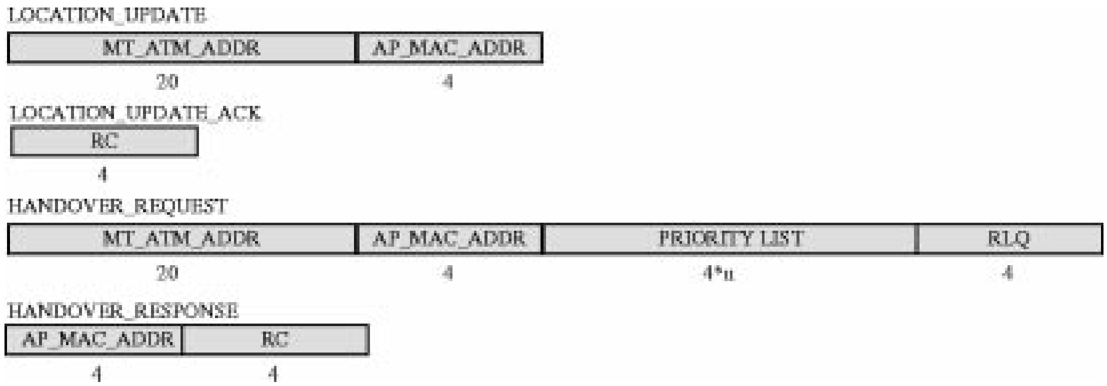

Fig. 6. Handover PDU's.

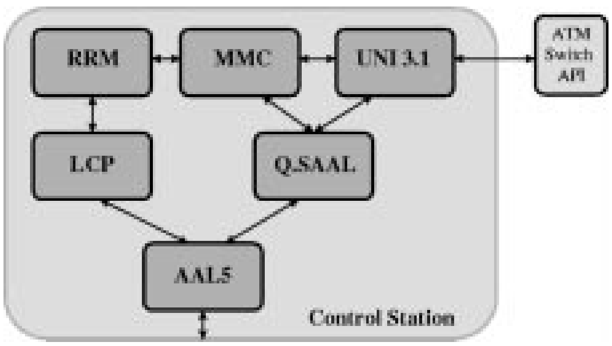

Fig. 7. Control station software.

MT is passed so that an estimation of the amount of bandwidth required for ARQ can be made. The release messages are used once the connection has been finished and the radio resources are no longer required.

VII. MASCARA

The MAC (medium-access control) and DLC (data link control) layers have been combined in one layer, bearing the name MASCARA (mobile access scheme based on contention and reservation for ATM). The underlying concept is based on the following set of ideas and requirements which are elaborated on in the subsequent paragraphs:

- QoS-aware, reservation-based demand assigned protocol;
- multiple virtual connections per terminal;
- power efficiency;
- cell transfer service for optimal interworking with ATM;
- amortization of PHY overhead over multiple cells;
- contention-mode request and control channel;
- ARQ (automatic repeat request)-based cell loss recovery.

ATM is designed to offer service to wire-line users with a guaranteed quality of service. To extend ATM service to mobile terminals, the wireless access network needs to be QoS aware as well. A centralized algorithm allotting transmission time to users on the basis of their explicit demands seems to be an obvious way to provide QoS and isolation between the users' traffic streams. This is supported by simulation results presented in [25]. Indeed, many other wireless ATM projects [5], [32], [36], [33] have adopted a demand-assigned MAC. We note that the disadvantage over contention-based algorithms as used in wireless LAN's [10] and wireless PBX's [7] is that they do not inherently support multicellular operation. To function correctly, they require a cellular frequency reuse topology, with perfect separation between radio cells with identical frequencies. As usual, for wireless LAN's, time-division duplex between uplink and downlink is chosen, primarily to support traffic asymmetry.

As a multimedia terminal may have many simultaneous connections, most probably with different QoS requirements, the network must be able—besides addressing individual terminals—to distinguish separate connections of those terminals. Given the smaller number of users and the scarcity of bandwidth, the relatively large addressing overhead of ATM, being designed for large wire-line networks, must be avoided.

Mobile terminals draw power from batteries, and to extend battery life, the protocols need to be energy aware. A frame-based MAC, in which the access point notifies all associated terminals about their expected transmissions and receptions in the entire frame, helps to conserve power. Terminals switch on their radios only when it is necessary. From the energy perspective, the frame duration should be made as long as possible. QoS considerations, on the other hand, put a bound on the maximal frame length. For this scheme to work, a frame structure by itself is not sufficient. A common time base among terminals and access points is required as well. For practical reasons, the granularity of time must be bounded. The unit of time in MASCARA is a time slot, and all packet transmissions commence on a time slot boundary.

To provide seamless interworking with the ATM backbone and transparency to the user, packets must carry ATM cells. It makes sense to choose the slot duration equal to a cell's transmission time. The same length of time is imposed on the packet header (radio preamble and MAC header) as well. In the WAND system, the first half of the overhead slot is used for the preamble, and the other half is used for the MAC header.

If each packet were to contain just one cell, the protocol efficiency would be merely 50%. To increase efficiency, a longer packet size can be adopted. On the other hand, QoS-driven restrictions on cellization delay put an upper bound on packet length. In the case of 64-kbit/s speech traffic, for instance, the cellization delay is 6 ms per cell, which restricts the packet length to one or two cells. The logical decision is to allow packets of variable length, depending on the

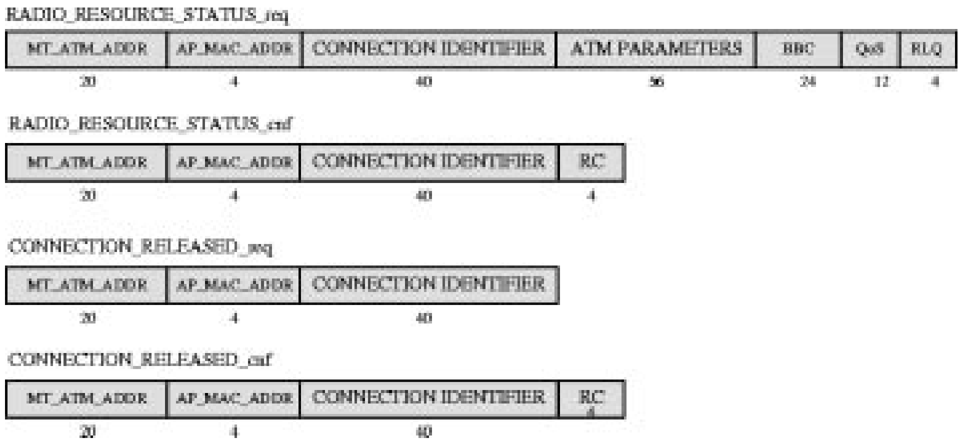

Fig. 8. Radio resource management PDU's.

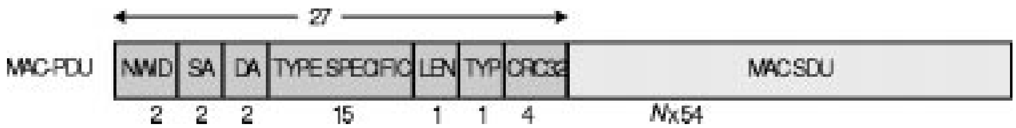

Fig. 9. MAC PDU.

connection's delay requirements, with a payload of an integer number of cells.

Demand-assigned algorithms assign time slots to terminals, based on terminal demand. Uplink packets contain fields in which a terminal can put its request. If a terminal cannot piggyback its request because no time slots were assigned to it (a deadlock situation) or because it cannot afford to wait for the next packet, the terminal can transmit its request in an unreserved time slot. A contention period is scheduled at the end of every frame. Contention slots can be used for incidental control packets as well.

Adverse radio propagation conditions affect the CLR (cell loss ratio) QoS. By its nature, a radio network cannot provide the same QoS consistently. To sustain a negotiated CLR QoS as long as possible, the DLC layer adds ARQ capability to the system. ARQ can help to retain the agreed-on cell loss rate, at the cost of an increase in delay and data overhead.

A. MASCARA Protocol Data Unit Layout

The MAC-PDU is shown in Fig. 9. The first half slot is used for the MAC-PDU header. Its first field is the network ID. This number identifies the network, consisting of a collection of AP's and their associated MT's, using a 16-bit number, which is derived from the network's ASCII name through a hashing function. The second and third fields contain source and destination MAC addresses. Both AP's and MT's have MAC addresses. AP addresses are unique throughout the network, while MT addresses are unique within a radio cell. MT's send packets and receive packets to and from their own base station only. It might, therefore, seem redundant to include a destination address in uplink packets or a source address in downlink packets. Yet, this is done to protect a cell against cochannel interference, i.e., transmissions from AP's and MT's in remote cells, using the same radio frequency. A 15-byte-long type-dependent field has multiple uses, depending on the type of the MAC-PDU. The length field specifies the number of MAC-PDU payload cells which follow the MAC-PDU header. A void payload MAC-PDU is possible, and is used by MT's, for instance, to transmit slot allocation request to the AP. The type field determines the type of the packet, and controls the interpretation of the type-dependent field. The following types are defined.

1) Downlink MAC-PDU: This type is used for packets transmitted by the AP to the MT. The type-dependent field for downlink MAC-PDU's is not used.
2) Uplink MAC-PDU: This type is used for packets transmitted by MT's to the AP. The type-dependent field contains two resource requests. Here, MT's can piggyback allocation requests, each of which consists of an MVC (MASCARA virtual connection) identifier (defined below), and a byte which quantifies the number of ATM cells that the MT has queued for the specified connection.
3) FH (Frame Header): This is the first packet in each frame, which is sent by the AP. The payload contains a slot map, which describes the transmission schedule in the current frame. FH's have a longer preamble which is one slot longer than the preamble of regular packets, facilitating frame synchronization for mobiles. The type-dependent field contains the length of the frame (in slots) and the length of the slot map itself. The FH will have its destination address field set to a special value, denoting the broadcast address.

The entire MAC-PDU header is protected against bit errors by a 32-bit cyclic redundancy check code.

Fig. 10 shows a 54-byte-long DLC-PDU. The MVC field is an 8-bit connection identifier. The DLC layer translates ATM's (VPI, VCI) pairs to MVC's and vice versa. The request

Fig. 10. DLC-PDU.

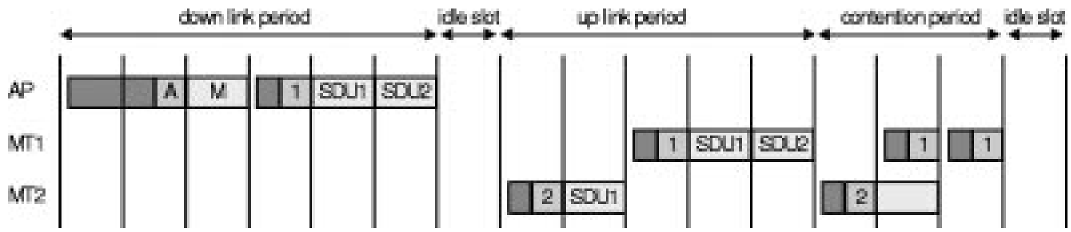

Fig. 11. Example of a frame.

fields are used only in uplink DLC-PDU's. This implies a redundancy if more than one DLC-PDU is carried in the MAC-SDU. In the downlink MAC_PDU's, the REQ field remains empty. MT's use it to piggyback requests for the current MVC. The 4-bit SN and RN fields form the sequence number/request number field used by the go-back-N ARQ algorithm employed by the DLC layer. See [3] for additional specification and analysis of the DLC's ARQ protocol. The RES field is reserved for future use, possibly to extend the range of SN and RN, to allow larger retransmission windows. The PTI/CLP field holds the payload-type indicator field and the cell loss priority bit which are simply copied from and to the ATM cell header. In the trailer, a 2-byte CRC code protects the DLC PDU, header, and payload against bit errors. It is possible to bundle DLC-PDU's with different MVC's in a single MAC-PDU.

Fig. 11 depicts an example frame. Two MT's and one AP are engaged in the exchange of packets. For instructive purposes, the frame duration is shorter than typically encountered in practice. The AP initiates every frame by broadcasting a frame header, containing the slot map, to all associated MT's. The FH has a long preamble, allowing MT's to synchronize to the AP. Subsequently, the AP sends its downlink data, one packet in this example. The channel remains idle for one slot to allow the AP to turn around its radio from transmitting to receiving. Then the MT's are allowed to transmit their MAC-PDU's. In this example, each MT transmits one. After the uplink period, a contention period is scheduled, which in this example is used by both terminals. Terminal 1 is transmitting two request packets, and terminal 2 is transmitting a two-slot control packet. In the example, two packets collide, resulting in the loss of the control packet and one of the request packets. The second request packet is transmitted successfully in the third slot. After the contention period, and before the next frame, an idle slot is inserted to allow the MT radios to turn around.

B. MASCARA Architecture

A functional block diagram of MASCARA is shown in Fig. 12. There are differences between AP and MT, but they are hardly reflected on the architectural level. Both AP and MT can be seen as an interworking function between an ATM link and a radio link. The ATM link's capacity has to be equal to or exceed that of the wireless link.

The ATM layer delivers receives and transmits 52-byte ATM cells. The 1-byte header error check belongs at the ATM physical layer, and remains invisible to the ATM service user. The AAL0 block provides transparent access to those cells. This means that the AAL0 service user has access to the cell's 48-byte payload, and also to its 4-byte header. The AAL5 layer provides a variable-length payload transfer service. It contains segmentation and reassembly functions to map its SDU's onto 48-byte cell payloads and vice versa. AAL5 connections are used for control traffic between the AP and the control station in the ATM network. AAL0 connections are used solely for user data. This does not preclude the existence of terminal-to-terminal AAL5 connections. It just means that nonintermediate reassembly and segmentation of AAL5 frames is performed. In fact, by operating on cells only, MASCARA supports all AAL's, existing and future ones. The separation between user and control plane is indicated by the vertical, dotted line in Fig. 12.

The DLC block translates between ATM cells and WDLC payloads. This involves (VPI,VCI) $\leftrightarrow$ MVC translation, and executing the ARQ protocol on delay-insensitive data. Delay-sensitive data are passed through directly. Besides user connections, the DLC also maintains a number of wireless control channels between the AP and the MT. Since the DLC block is essentially a cell transfer service, an additional segmentation and reassembly block is required to map control packets onto 48 DLC payloads and vice versa. The DLC exchanges DLC-SDU's with the MAC-PDU handler.

At the start of each frame, the master scheduler in the AP passes its schedule, the slot map, to the MAC-PDU handler. The slot map describes precisely how the MAC-PDU headers should be constructed, and which DLC-PDU's should be used for payload. The MAC-PDU handler first builds a frame header MAC-PDU. It then constructs a series of downlink MAC-PDU's. Finally, it sets up buffers to accommodate incoming MAC-PDU's in the uplink and contention periods of the frame.

The real-time transmit and receive functions are taken care of by a frame handler (in the WAND implementation, the frame handler functions are performed by hardware, while the MAC-PDU handler is implemented in software). It obtains timing information, as slot numbers, and buffer addresses from the MAC-PDU handler. The frame handler uses this

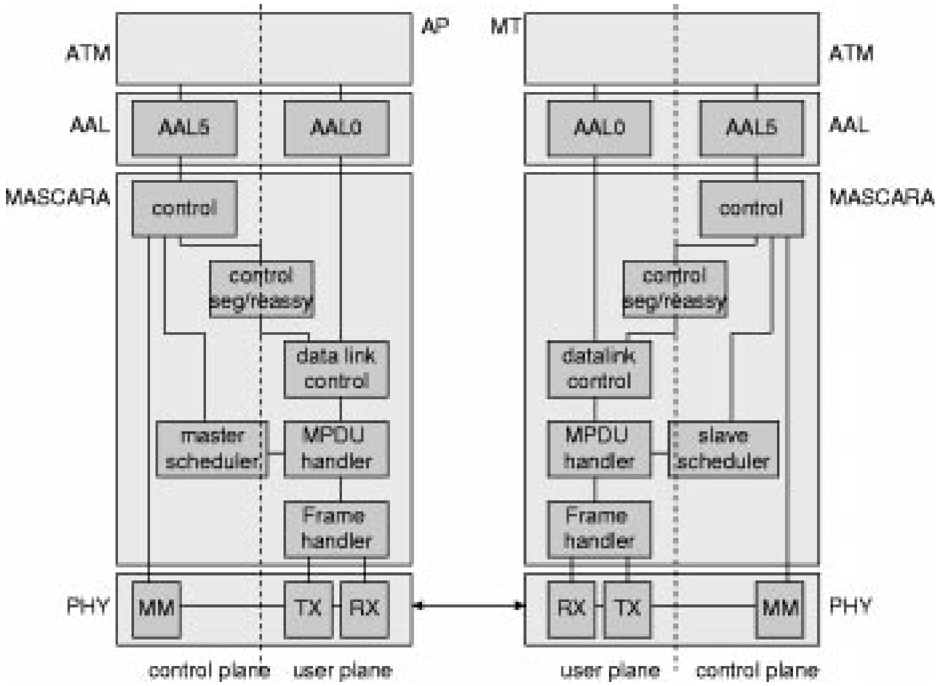

Fig. 12. MASCARA architecture.

information to control the transmit and receive modems in the PHY layer, and to set up DMA (direct memory access) channels to transfer data from MASCARA's memory to PHY and vice versa.

The master scheduler, which must be able to schedule the transmissions of any mix of ATM traffic classes (CBR, VBR-RT, VBR-NRT, ABR, and UBR), employs a leaky-bucket-based scheme where the highest priority is given to CBR, the second priority to VBR-RT, and so on. Tokens, which are generated at a constant rate, fill a bucket. The scheduler takes tokens from the bucket, and translates them in the allocation of slots in the slot map according to the connections' delay requirements. A traffic source can request slots (AP's directly, MT's use piggybacked and contention requests) in excess of the mean rate. Depending on the negotiated burstiness of the source, which is reflected in a commensurate bucket depth, the scheduler will grant the request. Effectively, the scheduler polices and shapes the traffic on the wireless link, to guarantee delay QoS compliance for all connections.

The second important measure of QoS, besides delay and delay jitter, is the connection's error performance over the wireless ATM link. In WAND, the radio physical layer provides a constant service that can meet typical real-time service requirements, e.g., for a voice service. TCP/IP-based data connections cannot tolerate high cell loss (10^{-2}), and these are protected by ARQ. Third, there are services such as video requiring real-time service with low error rate. The solution applied in WAND is to apply ARQ with a limited number of retransmissions.

The master scheduler is controlled by the control block, which can request creation/deletion of token generators and buckets when connections are established or released. Besides connection setup and release, the control block is responsible for mobility support. This involves handoff of active connections to adjacent AP's, and association/dissociation management. MAC addresses must be issued to terminals that join the cell (without being handed over), and withdrawn from stale terminals which have probably wandered out of the radio cell (without requesting a handover). To indicate the need for a handover, the MT's control block measures the received signal strength on the current and the other radio channels. To effectuate the handover, the MT based control block switches the radio channel. For this reason, the control block has access to the MM (modem management) block in PHY, which controls the frequency selection of the PHY's RF stages and collects received signal strength measurements.

C. MASCARA Performance

We performed Monte Carlo simulations to assess the throughput and delay performance of the MASCARA MAC. A single access point, serving 25 mobile terminals, was modeled. The AP has 25 cell queues for downlink cells, one for each MT. Each MT has a single queue for uplink cells destined to the AP. All queues have a length of ten cells.

At each of the queues, cells arrive according to a Bernoulli process. All MT queues handle an equal traffic load. The AP has one queue for each MT, and the stream of cells for these queues is also modeled with a Bernoulli process, all with equal arrival rates. The fraction of downlink traffic of the total traffic load r can be set. We present results for $r = 0.25$, $r = 0.5$, and $r = 0.75$. From the MAC's point of view, Bernoulli traffic represents a worst case choice. Piggyback requests exploit burstiness since the MT sends a request for the entire burst. Requests for cells arriving later can piggyback on uplink transmissions. Hence, the less burstier the traffic, the more request traffic is needed. Bernoulli traffic is the least bursty kind of random traffic.

Having a single queue—i.e., one virtual connection—per MT is also a worst case assumption. First, in a multiple-connection situation, requests for a connection can be piggybacked on uplink transmissions of the other connections. Second, cells of multiple connections can be multiplexed in a single MPDU, reducing the relative overhead due to the single slot of PHY training and MASCARA header. These advantages were not available to MASCARA in our simulations.

Being primarily interested in MAC capacity, we chose the simplest scheduling algorithm possible. The MT's and AP request a number of slots equal to the number of cells in their queues. The scheduler simply allocates all requested slots, without regard to any QoS requirements that there may be for each connection. In this way, we are able to stress the MAC, and determine its maximal capacity and delay under heavy load. A detailed study of a much more advanced scheduling algorithm for MASCARA can be found in [30]. In order to satisfy QoS demands of individual connections, this scheduler has to trade off the high utilization against low-loss probability, bounded delay, etc.

The simulated scheduler makes packets as long as possible, i.e., equal to the number of slots requested, while respecting the maximum packet length of 64 cells imposed by the MASCARA protocol. Since the queues have a capacity of just ten cells, packets longer than ten cells were never encountered in our simulations. For instance, in the 50% downlink traffic scenario, the average number of cells per packet was 5.4. Real-life traffic will be burstier, which leads to larger packets and, as a result, improved protocol efficiency. Note that the exhaustive scheduling policy is again a worst case assumption for the request mechanism. When an MT's request is granted, it is allowed to drain its queue, preventing the use of a piggybacked request for the next burst of cells.

The frame header length was obtained by rounding up the frame map size to the nearest multiple of 54 bytes. Idle slots were inserted as in Fig. 11. Neither random access control traffic nor ARQ was modeled.

For the contention period, the following simple algorithm was employed. The AP announces the contention period duration in the frame header. Call this value n. Each MT which intends to send a packet randomly selects one of the slots, i.e., any slot is chosen with probability $1/n$. If we denote the number of requesters by k, the probability that an MT's request does not share its slot with another request packets equals $(1-1/n)^{k-1}$. Assuming that transmission of two or more requests in a slot causes all requests to be lost, the throughput of request packets in the contention period is equal to $(k/n)(1-1/n)^{k-1}$. This value is maximized when n is chosen equal to k. Note that the optimal throughput reduces to e^{-1} as $k \rightarrow \infty$. Although the AP does not now the value of k in advance, it does know an upper bound $k_{\max}$, which is the number of MT's which do not have a pending request. The simplest rule, then, which has been used in simulations presented, is that the AP announces an contention period of duration $k_{\max}$. Note that this algorithm is particularly wasteful if the uplink traffic load is light: $k_{\max}$ will be large while there are only a few users of the contention period. Hence, the contention window length will be too long.

It is possible to prove that, if the AP has *a priori* knowledge that any MT has a packet queued with probability q, the optimal choice of n equals $q \times k_{\max}$. The request period throughput is then equal to $q^{-1}(1-1/k_{\max})_{\max}^{k-1}$ which is always higher than if n were chosen to be $k_{\max}$. However, the AP now has to estimate q. In the simulation, this is quite possible because perfect Poisson traffic is used. Hence, the AP can calculate, for every MT, the probability that new cells have arrived since the last time the MT has requested slots. It can then set q to the maximum of the estimated probabilities. In the real system, the statistics of the packet arrival process are not known, so the AP must somehow make a more conservative estimate of q, and the throughput gain will be more modest. Simulations (not presented here) to determine an upper bound on the delay reduction achievable with window sizing (we allowed the AP to peek in the MT buffers) showed that a 50% reduction of the average delay compared to the simplistic $(n \leftarrow k_{\max})$ algorithm can be achieved at light loads. At loads >0.5, a negligible reduction was observed, which is understandable, as the simple algorithm chooses a small contention window under heavy traffic as well, and hence its contribution to the system delay is minor.

The graph in Fig. 13 shows the throughput versus delay curves for various ratios of uplink and downlink traffic. It can be observed that throughput increases linearly up to a load of 0.6 cell/slot (corresponding to 10.67 Mbits/s of ATM-SDU throughput). At that point, the finite cell queues start to overflow. The system throughput starts to level off at about 0.8 cells/slot (14.2 Mbits/s). Note that in the 50% downlink traffic scenario, the uplink (MT) throughput reaches its optimum at lighter load than does the downlink throughput. In case of 25 and 75% downlink traffic, the majority traffic throughput (uplink and downlink, respectively) reaches its maximum first. It should be noted that, had queues of infinite length be used, throughput would increase linearly for all loads, although the delay would have been extremely large.

The graph of Fig. 14 shows how delay increases with load. Consistently, uplink traffic is delayed more than downlink traffic. At 60% load, the average downlink delay is less than 100 slots (or 2.16 ms). At the same load, the average uplink delay is less than 300 slots (6.48 ms) As can be expected, both uplink and downlink delay increase when the fraction of downlink traffic decreases. Note that when 75% of the traffic is in the downlink direction, both AP and MT delay are *larger* than if the majority of traffic flows in the uplink direction. This occurs since the contention window size selection algorithm does not take traffic load into account. Under light uplink traffic, it will overestimate the required contention window length, causing a larger delay to both uplink and downlink traffic.

In Fig. 15, which depicts the average duration of the periods which make up a frame, it can be seen that as the traffic load increases, the contention period shrinks since MT's can increasingly rely on request piggybacking. It follows that smarter contention period algorithms will contribute little to delay reduction for loads larger than 60%. All other periods increase with increasing load, except for the IDLE period, of course. The frame header duration increases since the

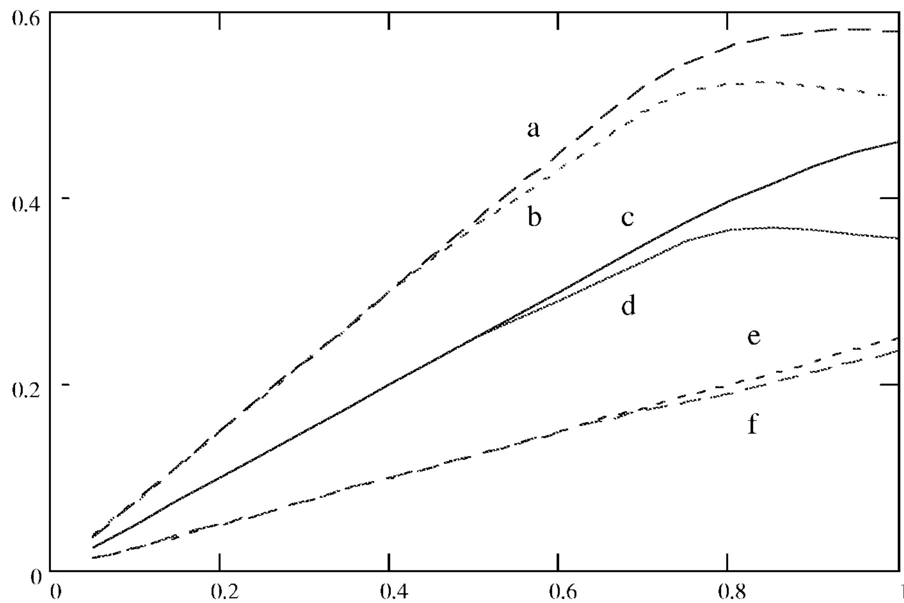

Fig. 13. Throughput [cells/slot] versus load [cells/slot] for 75% downlink, AP (a) and MT (f), for 50% downlink traffic, AP (c) and MT (d), for 25% downlink traffic, AP (b) and MT (e).

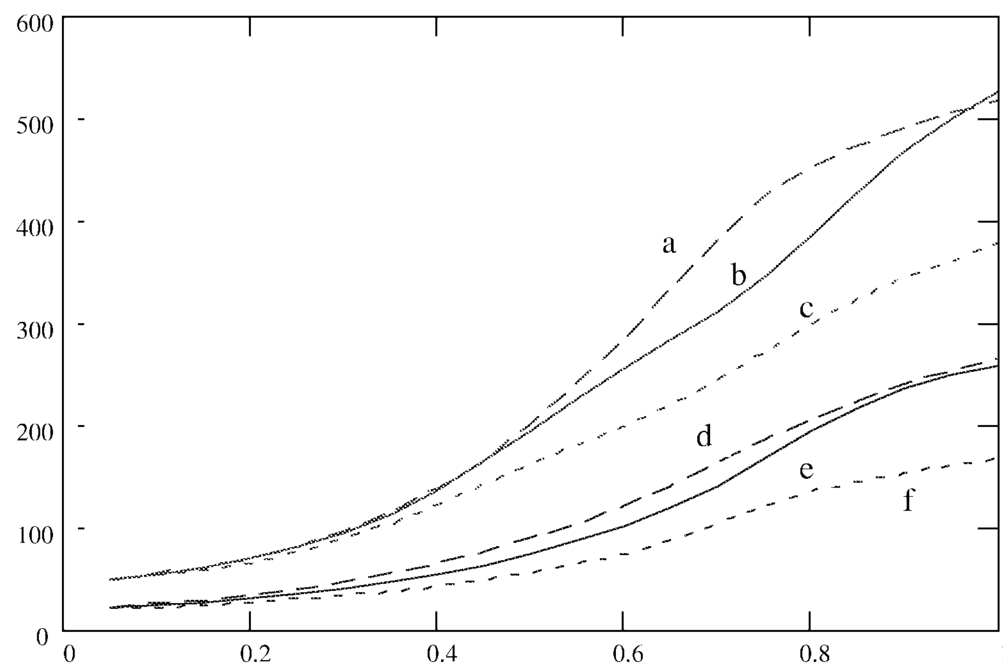

Fig. 14. Delay [slots] versus load [cells/slot] for 75% downlink, AP (d) and MT (a), for 50% downlink traffic, AP (e) and MT (b), for 25% downlink traffic, AP (f) and MT (c).

frame map size increases as the frame duration grows; the UP and DOWN periods increase since there is more traffic to handle.

Detailed performance simulations including ARQ for the WAND demonstrator system are presented for the selected go-back-N ARQ approach in [4], and a detailed description of the scheduling algorithm and its performance analysis can be found in [30] and [31]. Furthermore, it is assumed that the concept of slave scheduling may improve the system performance from the given results for WAND target system. In this concept, the slave scheduler can fine tune the AP's master scheduler. It can occur, for instance, that an MT is granted a few time slots to a particular MVC for which it has no cells queued. The slave scheduler can then decide to transmit data pertaining to a different MVC instead.

VIII. Radio Physical Layer

A. Use of 5-GHz Radio Technology

At the very bottom of the protocol stack in any communications system lies the physical layer. The mechanism for moving information from one network entity to another is a

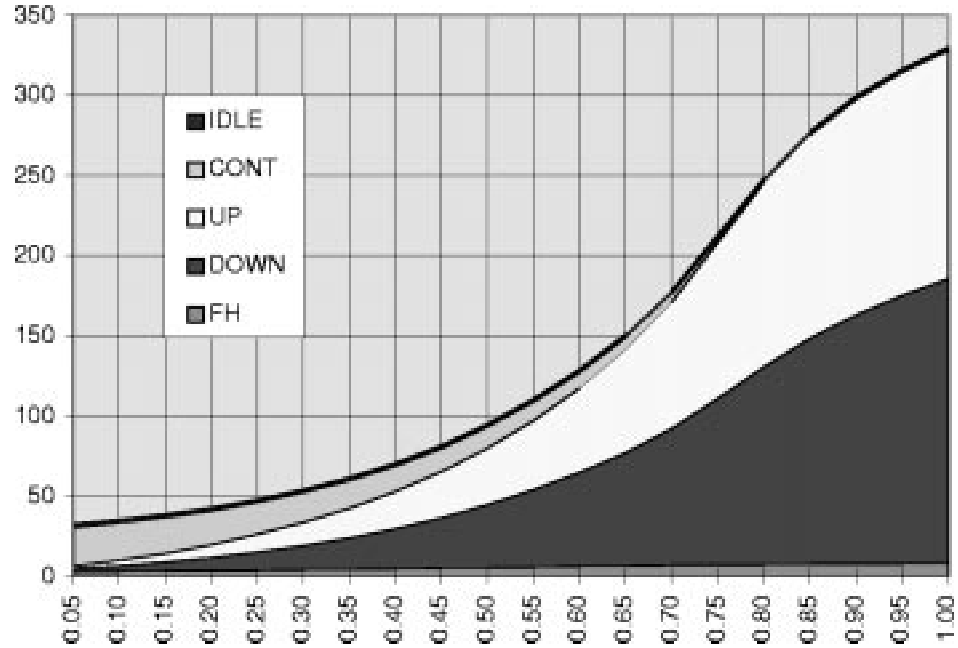

Fig. 15. Mean frame period durations for 50% downlink traffic.

fundamental system building block, and consequently dictates much of the system design. It is the potential (stemming from continuing developments in digital and analog component technology) to implement a 20-Mbit/s radio modem at reasonable cost, which has provided the primary impetus for WAND and many similar projects.

The WAND modem uses a radio spectrum between 5.15 and 5.30 GHz. This spectrum is allocated in Europe for license-exempt use by HIPERLAN's (high-performance radio local area networks), a family of wireless networking systems being standardized by ETSI (the European Telecommunications Standards Institute). The same spectrum (with slightly different access rules) is available in North America for license-exempt use, as part of the NII (National Information Infrastructure) band. The spectrum has been made available precisely for systems such as WAND [12], [28]: privately owned, low power, short range, primarily for indoor use, supporting multimedia and local-area network traffic. This common allocation across the Atlantic is very valuable, allowing the same products to be sold both in Europe and America.

Furthermore, 5.15–5.30-GHz spectrum allocation is also a good compromise between bandwidth availability and propagation limitations. At 5 GHz, radio propagation is adequate to provide reasonable in-building range. However, reducing the carrier frequency would certainly improve the range/transmit power tradeoff. Radio waves at these frequencies do, however, penetrate walls, especially the nonload-bearing walls typically found inside modern office buildings. They also reflect and refract significantly in a cluttered indoor environment. This is important because it allows nonline-of-sight communication. As frequency increases, wall blockage becomes stronger, and free space path loss also increases. At 60 GHz, communications are effectively limited to a single room [22], and when using infrared communications, probably even less than this.

B. Orthogonal Frequency-Division Multiplex Modulation

The use of omnidirectional antennas, and the reflection/refraction processes, jointly cause the fundamental problem of mobile radio communication: multipath. Multiple propagation paths from transmitter to receiver, with nonequal propagation delays and path losses, create a distorted signal at the receiver. If the *delay spread* of the radio channel is small compared with the bandwidth of the signal, then the multipath causes rapid fluctuations in the power of the received signal (*frequency-nonselective fading*). If the delay spread is large, then the power of the received signal fluctuates less, but the signal suffers distortion—the time dispersion causing *frequency-selective fading*.

In the WAND system, both frequency-nonselective and frequency-selective fading may be present. The system design (physical and data link layers) must therefore be designed to cope with both. The possible ways to correct for the frequency-nonselective fading are by providing a power margin, by using FEC (forward error control) coding, or by using an ARQ scheme. The transmit power in the WAND system is limited, so whether a power margin exists depends on the communication range. FEC is only effective in countering frequency-nonselective fading if it introduces a delay larger than the fading rate, and this cannot be guaranteed in the WAND system. Therefore, an ARQ scheme is used in the DLC layer.

The frequency-selective fading, on the other hand, must be dealt with in the physical layer. Uncorrected, it will cause a total loss of data. The options are: to remove the multipath through the use of directional antennas, to equalize the channel in the receiver, or to use a modulation scheme which is intrinsically resistant to the problem. Directional antennas are not compatible with mobility and small-sized equipment, and so this option was rejected for the WAND system. Channel equalization has two major disadvantages: it is an extremely computationally intensive operation, requiring a large amount of cost- and power-hungry signal processing in the receiver; and a significant overhead is required because the equalizer must be trained (or the radio channel measured and the optimum equalizer setting calculated) before data can be demodulated.

Modulation schemes with an inherent resistance to multipath distortion are therefore valuable. The WAND system uses an OFDM (orthogonal frequency-division multiplex) modulation. In an OFDM scheme, the transmit data are multiplexed into a large number of parallel streams, which are transmitted simultaneously [8]. Because every stream has a low data rate, they are not (individually) subject to frequency-selective fading. These substreams are modulated onto a set of evenly spaced carrier frequencies. In the receiver, these are jointly demodulated using an FFT process. The subcarriers remain orthogonal to each other, provided that the receiver discards those parts of the received signal which contain data transitions. This is possible if the transmit symbols are extended by a "guard time" which is longer than the maximum excess delay of the radio channel.

OFDM modulation also has some disadvantages. The DSP (digital signal processing) complexity of an OFDM modem is also high, although for the WAND system, it should be lower than that of an equalizer. In general, the complexity of a channel equalizer increases linearly with the data rate, but the complexity of an OFDM modem increases logarithmically. Error control coding is essential for OFDM-based systems because every subcarrier is subject to frequency-nonselective fading. The biggest disadvantage of OFDM is that the transmit signals have a nonconstant power envelope. This means that any nonlinearity in the transmitter will cause in-band noise and spectral splatter—causing degraded performance and adjacent channel interference. The peak power of an OFDM signal is in theory N times higher than the average power, where N is the number of subcarriers. It is necessary to back off the transmit power amplifier in an OFDM system by a large factor, and this has a major impact on battery life in a mobile system.

C. Details of Modulation and Coding

The WAND modulation scheme is described in detail in [1]. It is based on 16 subcarriers, with 8-PSK modulation on each one. A special coding scheme is employed, which provides error control *and* peak power control [37]. This code, known as a *complementary code*, reduces the peak power of the transmit signal to just four times the average power. It has a minimum distance of four symbols, and there are two codewords in each OFDM symbol. It is possible for the receiver to erase six of the 16 subcarriers if these are subject to fading.

Fig. 16 shows the structure of a single OFDM symbol in both time and frequency. We see that the symbol period is 1.2 μs. There are 16 subcarriers, so the total 8-PSK symbol rate is 13.3 Msymbols/s. The raw bit rate is thus 40 Mbits/s, and this is reduced by coding to 20 Mbits/s. The spacing of the subcarriers is 1.25 MHz, the reciprocal of the FFT period.

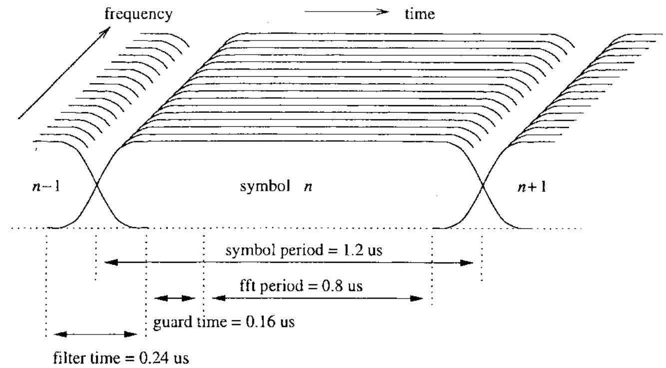

Fig. 16. Structure of WAND OFDM symbol in time and frequency.

This is essential for the subcarriers to be orthogonal. Thus, the total bandwidth is 20 MHz.

Each symbol is composed of some ramp-up and ramp-down (filter) time, some guard time, and some "useful signal" time. The filter time is necessary to reduce the sidelobes of the power spectrum, so that adjacent channel interference is not a problem. The guard time is for protection against time-dispersive propagation.

Fig. 17 shows the power spectrum of the transmit signal in the WAND system. Also shown is the spectrum of the signal if it is amplified by a nonlinear power amplifier without back-off. A frequency slot in the WAND system is 23.5 MHz wide, so it is clear to see that the distorted signal would cause severe adjacent channel interference.

D. Burst Structure

In order to support packet-based communication effectively, each data unit must be transferred independently of other data units. The implication is that a physical layer data unit (a transmission burst) must be self-contained. All overheads for channel estimation, automatic gain control, timing recovery, and so on must be included in every burst.

Radio packets or, more formally, PHY-PDU's (protocol data units) are preceded by of a guard time that is required to absorb propagation delay differences in the TDMA air interface (see "MASCARA" section), and to allow the RF (radio frequency) amplifier to ramp up (or down) transmit power. Figs. 18 and 19 show two different PHY PDU's. One has a long preamble of 1.5 slots, including guard time, and the other one has a half-slot preamble. The long PDU is used by the access point as the first packet it transmits in every frame.

Upon reception of the long PHY-PDU, terminals synchronize their local slot clock to that of the AP. The shorter format is used for all other packets in a frame. Synchronized terminals expect packets to begin on a slot clock, and this allowed for a reduction of the preamble length for in-frame packets. This preamble is a system constant. It is 8.4 μs in duration, and consists of one OFDM symbol, repeated seven times. This preamble is used for:

- burst detection and automatic gain control;
- transmitter–receiver frequency offset estimation;
- optimum symbol timing recovery;
- coherent channel estimation.

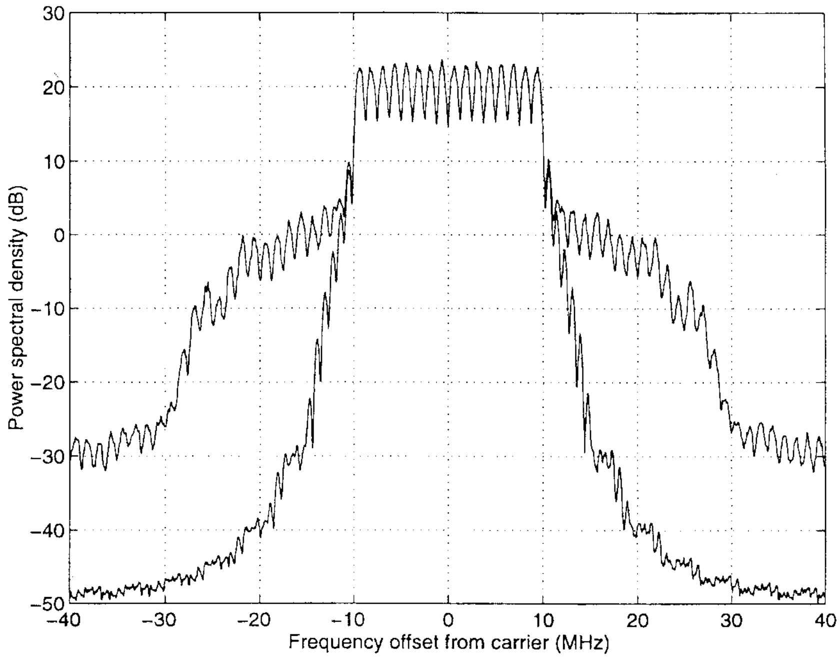

Fig. 17. Power spectrum of WAND signal before and after a nonlinear amplifier.

Fig. 18. Short PHY-PDU.

Fig. 19. Long PHY-PDU.

The PHY payload holds an odd number of half slots. Each half slot consists of 27 bytes. This number was chosen so that a full slot, of 54 bytes, can hold an ATM cell (which is 52 bytes long), and is also a multiple of 3 bytes, which is imposed by the PHY's modulation scheme. To translate the field length in bytes, as shown in the figures to time, divide by the PHY's Byte rate of 2.5 Mbytes/s. For instance, this yields a guard time of 6/2.5 $=$ 2.4 μs long, while a slot lasts 54/2.5 $=$ 21.6 μs.

E. Errors and Range

The WAND physical layer has been simulated to determine the expected performance. Multipath propagation was simulated using the standard WSSUS (wide-sense stationary, uncorrelated scattering) channel model. A negative exponential power delay profile was used. This channel model has just one parameter, the *rms delay spread* of the channel. This parameter determines the amount of time dispersion in the radio propagation. Measurements show that delay spreads of real channels at 5 GHz vary between 0 and 50 ns for typical office environments. In large buildings with big rooms, the delay spread can increase to 100 ns or more [29].

Fig. 20 shows the loss rate for DLC-PDU's in the WAND system. Each DLC-PDU contains one ATM cell, but this loss rate is not the same as the cell loss rate because the DLC layer includes an ARQ loop to retransmit errored PDU's [4]. Four curves are shown for four different rms delay spreads.

It can be seen that the system works best for channels with a delay spread around 50 ns. If the delay spread is lower, then a higher signal-to-noise ratio is required for the same error rate. This is because the errors become dominated by the nonfrequency-selective fading. For higher delay spreads, an irreducible error ratio is visible. As the signal-to-noise ratio tends to infinity, the error ratio does not tend to zero. This occurs because the guard time in the OFDM modulation is limited. If it were considered necessary, the guard time could be increased without reducing bandwidth efficiency by increasing the number of subcarriers [2].

The signal-to-noise ratio figures (strictly energy-per-bit-to-noise-power-spectral-density (Eb/No) ratio) may be used to predict the possible range of the radio physical layer. We assume propagation losses to be composed of an unknown part caused by self-interference and wall/furniture/etc, blocking, and a predictable part, dependent only on transmitter-to-

TABLE II
PROBABILITY THAT COMMUNICATION IS POSSIBLE WITH DIFFERENT RANGE AND TRANSMIT POWER COMBINATIONS

Range (metres)	Transmit Power	Probability that communication is possible
20	250 mW	99.6 %
20	25 mW	91.5 %
50	250 mW	73.4 %
50	25 mW	26.6 %

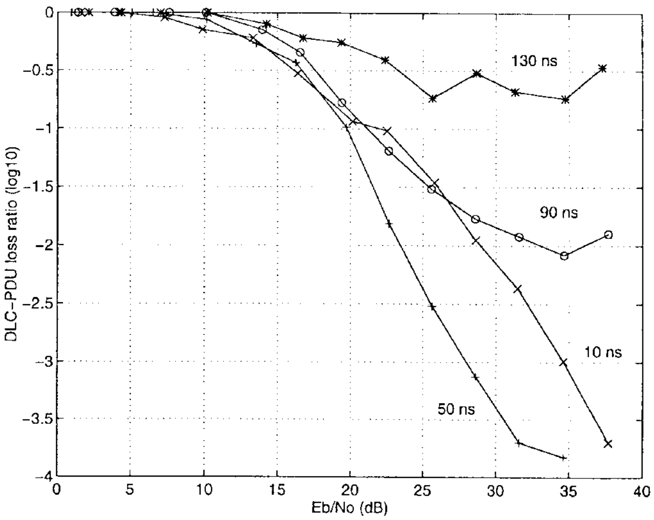

Fig. 20. DLC-PDU error ratio against signal-to-noise ratio for a range of channels.

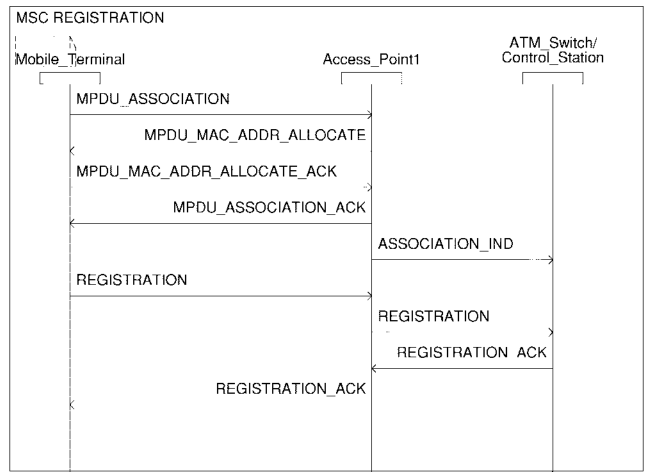

Fig. 21. Simulation trace on association and registration.

receiver distance. The distance losses are modeled as inversely proportional to the fourth power of distance. The unknown part is modeled as a random loss, Gaussian-in-dB, with a standard deviation of 8 dB. The model is calibrated from actual measurements, e.g., [29]. For a given range and a given transmit power, it is possible to calculate the probability that the receiver Eb/No is above some level. Table II gives these results.

It has been assumed that a DLC-PDU loss ratio of 1% is tolerable, and that the delay spread is 50 ns. These results should be treated with caution. Real propagation losses vary greatly, depending on the nature of the building. A building with many concrete interior walls will have much higher losses than those assumed here, and the range will be much more limited. However, we can be confident that, in many cases, a range of 50 m will be possible. Two transmit power levels are compared in the table. The higher (250 mW) represents the transmit power in the WAND demonstration system. A 1-W linear power amplifier is required to obtain this power level for the OFDM modulation scheme without distortion. This may not be credible in a mobile terminal, so results are also displayed for a 25-mW transmit power level. Even with only 25 mW, a 50-m range is sometimes possible, and a 20-m range is no problem. This is borne out by practical experiments [40].

IX. Overview of WAND System Level Operation

The WAND functional system, including network software and MASCARA as described in this paper, has been designed in SDL. This has allowed a good understanding of the system to be gained before implementation is started and simulations to be carried out to ensure that our designs are correct. SDL also produces very good specifications which can be implemented very easily, or automatically turned into executable code [20]. Three key scenarios of the networking software are described below using the MSC's produced during SDL simulation runs.

A. Association and Registration

Before an MT can establish connections to transfer data, it must first associate and register with the network. MSC's for these procedures are shown in Fig. 21. Association establishes a MAC-level communication between the MT and the AP. Registration allows access to the network via any of the access points. Association has to be performed each time the MT moves from one AP to another, and can be seen as part of the handover procedure shown in the "Backward Handover" section. Registration only has to be performed when joining the network.

Association starts with the MAC layer determining which is the best AP to use, and sending an association request to the AP. The AP allocates a MAC address for the new MT, and this is sent to the MT. The MT acknowledges the MAC address, and the AP completes its association procedure by acknowledging the completion of the association and by informing the control station of the newly associated MT.

Registration is then started by the MMC protocol. A registration request is sent via the access point to the control station. The control station validates the new MT, checking that the MT is allowed to access the network, and then acknowledges the registration.

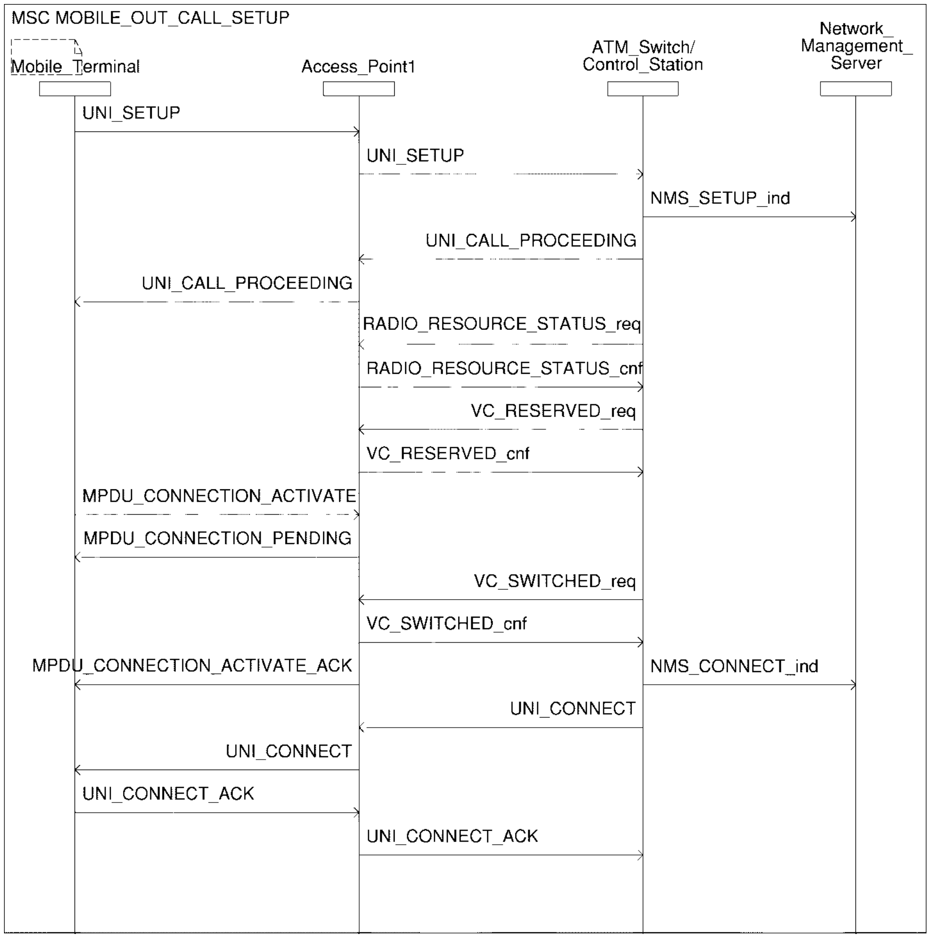

Fig. 22. Simulation trace on mobile-initiated call setup.

B. Call Setup

The call setup MSC initiated by a mobile terminal is shown in Fig. 22. A very high-level view of the system has been taken, with just four high-level blocks being shown. These blocks are the mobile terminal (MT), an access point (AP), the control station (CS) which controls the ATM switch, and the network management system (NMS).

The MSC starts with the signaling software on the MT sending a UNI SETUP message to the network via the access point. The CS is the first switch in the network, and the first to process the SETUP message. The NMS is informed of the SETUP message, and a UNI CALL PROCEEDING message is sent back to the MT via the AP. All of the UNI signaling messages are passed transparently through the AP as a sequence of ATM cells; the AP is not involved in processing any of these signaling messages. The CS then starts the call admission control processes. Resources internal to the control station and switch are checked and reserved, and then the radio resources are checked. The CS checks the radio resources by sending a RADIO_RESOURCE_STATUS_req to the radio resource manager in the access point with ATM user cell rate information. The RRM evaluates the new connection, and returns a yes or no decision as to whether the new connection can be supported without affecting existing connections. The decision is returned in the RADIO_RESOURCE_STATUS_cnf message. Assuming that sufficient resources are available to support the new connection, the resources for this new virtual connection are reserved in the access point.

When the MT receives the call proceeding message, it internally configures its MAC layer for the new connection. The MAC layer on the MT then uses MAC-level messages to inform the AP that it is ready to process cells for the new connection. This is the MPDU_CONNECTION_ACTIVATE message. Although, at this point, the resources of the new connection have been reserved, the connection is not active, so a pending message is sent back to the MT MAC layer. Once the control station has completed configuration of the ATM switch and the rest of the wired network for the new connection, the CS informs the AP that the new connection should be activated using the VC_SWITCHED_req message. On reception of this message, the AP starts scheduling transmission of ATM cells for the new connection, confirms back to the CS, and informs the MT that the connection is now active. Once the CS has received the confirmation, the NMS is informed of the newly connected connection, and standard UNI signaling is used to inform the signaling entity in the MT that the connection has been connected. The MT signaling then finally acknowledges the connect message.

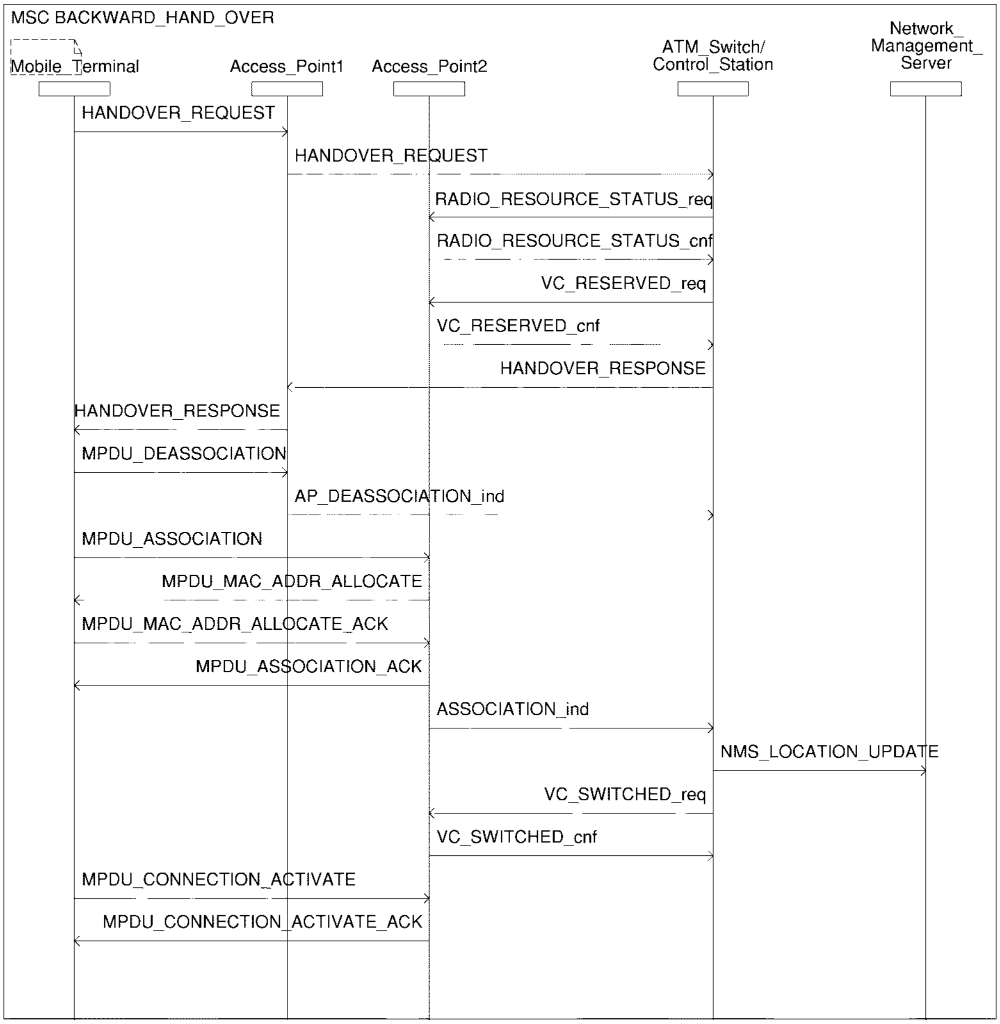

Fig. 23. Simulation trace on backward handover.

C. Backward Handover

There are two major forms of handover when a terminal moves from one cell to another. If the move is graceful, implying that the new AP can be located before the old one is lost, a backward handover can occur. If the new AP is not known before access to the old access point is lost, a forward handover occurs. The MSC in Fig. 23 shows a simulation run of a backward handover.

The handover is started once the MT MAC layer decides that the radio link quality to another AP is better than the current link. The MAC layer informs the MMC that a handover should occur, and gives the address of the new AP, in this case AP2. MMC then passes a HANDOVER_REQUEST to the CS via the old AP. The CS then starts reconfiguring the connections to the new AP. Each connection must go through the call admission control procedure for both internal switch resources and radio resources. As with call setup, the Radio CAC is performed by the AP with RADIO_RESOURCE_STATUS_req and RADIO_RESOURCE_STATUS_cnf messages, and then resources are reserved with VC_RESERVED_req and VC_RESERVED_cnf messages. The MSC only shows the handover for a single connection, but when there are multiple connections, the CAC and resource reservation phase is repeated multiple times. If there are sufficient resources for all of the connections through the new AP, a HANDOVER_RESPONSE is passed to the MT via the old AP. The MT then dissociates from the old AP, and starts association with the new AP. The new AP allocates a free MAC address to the MT which the MT acknowledges, and the new association is acknowledged. The CS is informed that the MT has successfully associated to the new AP, and the CS informs the network management system of a location update of the mobile terminal. The CS then activates the connections in the new AP with a VC_SWITCHED message so that it starts scheduling traffic, and reconfigures the ATM switch to send the ATM traffic to the new AP. Once the MT has finished associating with the new access point, it reconfigures its MAC layer with the new connections, and the MAC uses MAC-level messages to inform the new AP that it is ready to accept traffic for the connections.

X. Discussion

The functional design presented in this paper permits a flexible and modular architecture for future wireless ATM access networks that allows them to be connected seamlessly into ATM/B-ISDN networks. The radio subsystem is based on OFDM modulation and a TDMA/TDD frame structure, capable of supporting QoS requests. The core network is based on ATM/B-ISDN signaling enhanced with the mobility-specific features. Furthermore, the WAND system functional design has been specified and verified using formal SDL modeling.

Currently, two standardization bodies are jointly working on an ATM-based system matching the work carried out in the Magic WAND. The standardization work within ETSI Project BRAN (broadband radio access networks) is concentrating on the radio-access-related areas [9]. ATM Forum, on the other hand, focuses on providing required modifications in the ATM standards for mobility support.

Work in the Magic WAND is continuing toward demonstrator implementation, which is expected to be ready by spring 1998. The demonstrator will be used to verify the presented concepts, and to support WAND contributions in the standardization forums.

ACKNOWLEDGMENT

The authors would like to acknowledge the contributions of their colleagues from Nokia Mobile Phones, Tampere University of Technology, Technical Research Centre of Finland, Ascom Systec AG, Lucent Technologies WCND, University of Lancaster, Robert BOSCH GmbH, University of Ulm, Compagnie IBM France, IBM Zürich Research Laboratory, Eurecom Institute, ETH Zürich, INTRACOM Hellenic Telecommunications, and the University of Athens.

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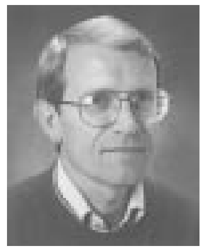

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