IP over Wireless Mobile ATM—Guaranteed Wireless QoS by HiperLAN/2

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Invited Paper

Wireless local area networks (WLANs) designed as wireless ATM systems to extend the services of fixed ATM networks to mobile users appear best suited to provide a guaranteed quality of service (QoS) for wireless IP networks. HiperLAN/2 is an ETSI/BRAN standard providing convergence layers for both IP and ATM classes of service. Besides a description of HiperLAN/2 and its Home Environment Extension, the performance for IP traffic flows is presented from analysis and from simulating a prototype implementation. Coexistence with the IEEE 802.11a WLAN is discussed and the ability of HiperLAN/2 to guarantee QoS even when coexisting is analyzed. Ad hoc networking of HiperLAN/2 is analyzed and two possible extensions of the system are introduced and their performance evaluated, namely, adaptive antennas and wireless base stations.

Keywords—*Ad hoc, coexistence, HiperLAN/2, IEEE 802.11, IP QoS, SDMA, W-ATM, wireless base station, WLAN.*

NOMENCLATURE

ACF	Association Control Functions.
ACH	Access feedback CHannel.
ADT	Abstract Data Types.
AP	Access Point.
APC	Access Point Controller.
APT	Access Point Transceiver.
ARQ	Automatic Repeat reQuest.
ATM	Asynchronous Transfer Mode.
BC	Broadcast.
BCCH	Broadcast Control CHannel.
BCH	Broadcast CHannel.
BMB	BitMap Block.
BRAN	Broadband Radio Access Networks.
C/I	Carrier to Interference ratio.
CC	Central Controller.
CDF	Complementary Distribution Function.
CL	Convergence Layer.
CRC	Cyclic Redundancy Check.
CTS	Clear to Send.
DCC	DLC Connection Control.
DF	Distribution Function.
DFS	Dynamic Frequency Selection.
DLC	Data Link Control.
DUC	DLC User Connection.
EC	Error Control.
F-BC Phase	Forwarding BroadCast Phase.
FCCH	Frame Control CHannel.
FCH	Frame CHannel.
F-DL	Forwarding DownLink.
FEC	Forward Error Correction.
FMT	Forwarding Mobile Terminal.
F-RCH	Forwarding Random Access CHannel.
FSM	Finite State Machine.
FSR	Frequency Sharing Rule.
F-UL	Forwarding UpLink.
H/1	HiperLAN/1.
H/2	HiperLAN/2.
HEE	Home Environment Extension.
HiSWAN	High Speed Wireless Access Network
IE	Information Element.
IP	Internet Protocol.
LA	Link Adaptation.
LAN	Local Area Network
LBT	Listen-Before-Talk.
LCH PDU	Long transport CHannel PDU.
MAC	Medium Access Control.
MCS	Modulation and Coding Scheme.
MF	MAC Frame.
MSC	Message Sequence Chart.

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MT	Mobile Terminal.
NAK	Negative AcKnowledgment.
OFDM	Orthogonal Frequency Division Multiplexing.
PCF	Point Coordination Function.
PDU	Protocol Data Unit.
PER	Packet Error Rate.
PHY	PHYsical layer.
PHY mode	PHYsical layer mode.
PPP	Point-to-Point Protocol.
QoS	Quality of Service.
RBCH	RLC Broadcast CHannel.
RCH	Random CHannel.
RFCH	Random access Feedback CHannel.
RG	Resource Grant.
RLC	Radio Link Control.
RMT	Remote Mobile Terminal.
RR	Resource Request.
RRC	Radio Resource Control.
RSVP	Resource Reservation Protocol.
RTS	Ready To Send.
SAR	Segmentation And Reassembly.
SCH PDU	Short transport CHannel PDU.
SCM	Spatial Covariance Matrix.
SDL	Specification and Description Language.
SDMA	Space Division Multiple Access.
SF	MAC SubFrame.
SN	Sequence Number.
SNR	Signal to Noise Ratio.
TDD	Time Division Duplexing.
TDMA	Time Division Multiple Access.
TPC	Transmitter Power Control.
ULA	Uniform Linear Array.
UNI	User Network Interface.
U-SAP	User Service Access Point.
W-ATM	Wireless Asynchronous Transfer Mode.
WLAN	Wireless LAN.

I. Introduction

To meet the networking requirements for multimedia services of tomorrow, new generations of both WLANs and cellular networks are under development [1]–[3]. These requirements include QoS support for multiservice networks, security, handover when roaming between local and wide area as well as between corporate and public networks, and, of course, increased throughput and small transmission delay for the ever-increasing demand of datacom as well as video streaming applications.

Wireless and cellular today are seen as access and extension technologies of IP networks and, therefore, must be able to support guaranteed IP QoS parameters.

The demand for mobile broad-band communication caused the European Telecommunications Standards Institute (ETSI) to create the Broadband Radio Access Networks (BRAN) Project. The project makes available various technologies for the access to wired networks in private as well as in public environments until the year 2000 and offers bit rates up to 155 Mb/s.

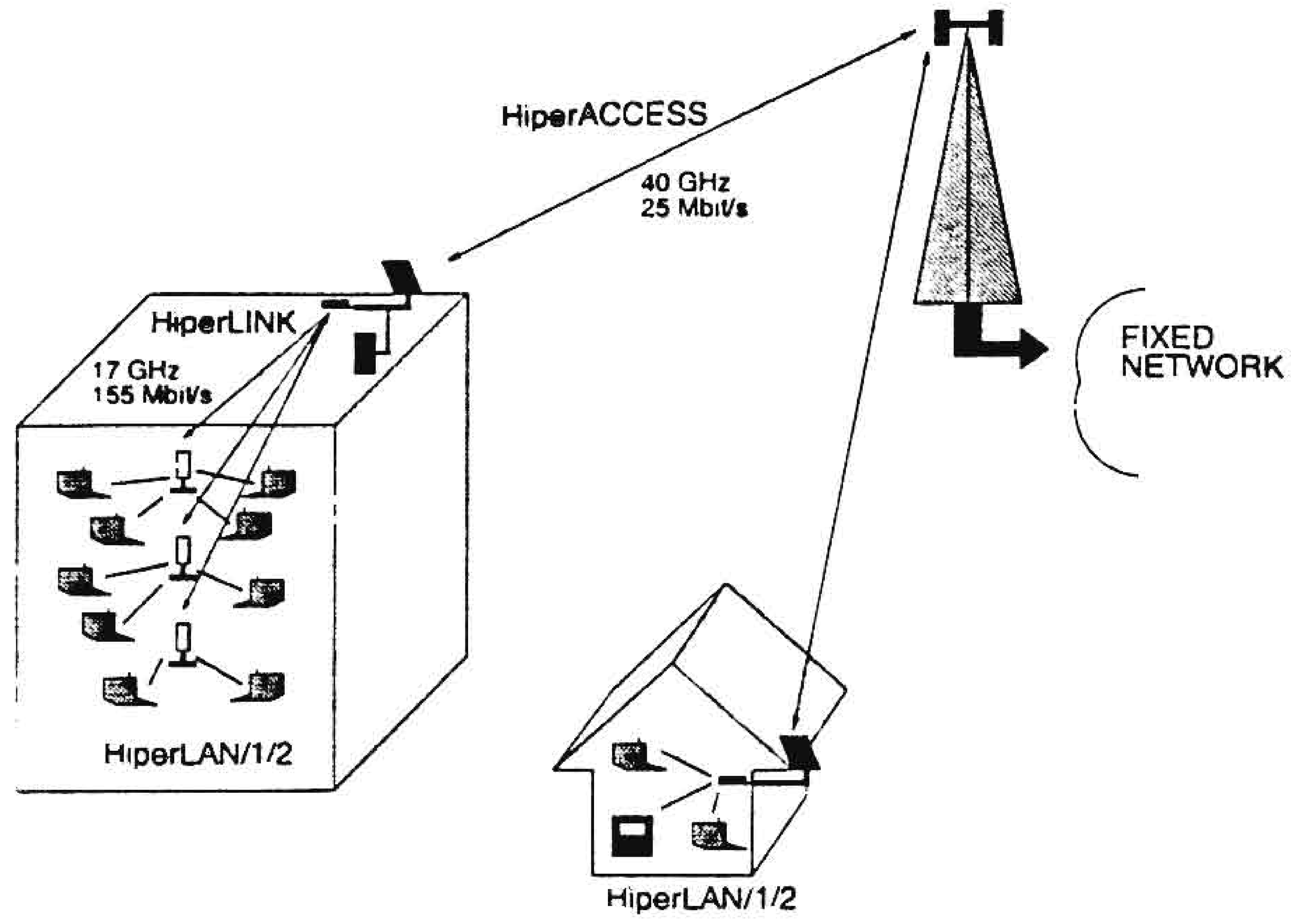

Fig. 1. ETSI BRAN

The project started with the goal of specifying a W-ATM-based air interface for applications, as shown in Fig. 1, and started close cooperation with the ATM Forum's WLAN group in June 1996. The W-ATM idea has been strictly followed when specifying the DLC layer of H/2 based on [4] where a user data packet handled in the MAC layer is one ATM cell. It was planned from the start that an ATM-based WLAN should be able to support any broad-band network-based service up to a WLAN's bandwidth limitations according to the service classes known from ATM networks [5]. To be able to establish a wireless system to support any type of transport network, both connection- and packet-oriented data transmission are taken into account.

An earlier initiative of the ETSI/BRAN project was ETSI/RES10, which produced H/1, a connectionless packet-based broad-band WLAN standard at 5 GHz in 1996 [6] that has not found acceptance to date owing to the lack of products.

H/2 is a connection-oriented high-performance radio technology, specifically suited for operating in LAN environments. The final specifications were issued in April 2000 [7]–[11].

This system operates in the unlicensed 5-GHz frequency band that has been specifically allocated to WLANs. In contrast to the IEEE 802.11 wireless Ethernet technology [12], H/2 is connection oriented with a connection duration of 2 ms or multiples of that. Connections over the air are time-division multiplexed. There are also specific connections for unicast, multicast, and broadcast transmission. H/2 allows for interconnection into virtually any type of fixed network technology and can carry, for example, Ethernet frames, ATM cells, and IP packets.

HiperACCESS, a fixed wireless access system, is meant for point-to-multipoint high-speed access with a typical data rate of 25 Mb/s for residential and small-business users to a wide variety of networks, e.g., ATM and IP-based networks, and as a distribution system within premises. Spectrum allocations are being discussed in CEPT FM29 and CITEL [13],

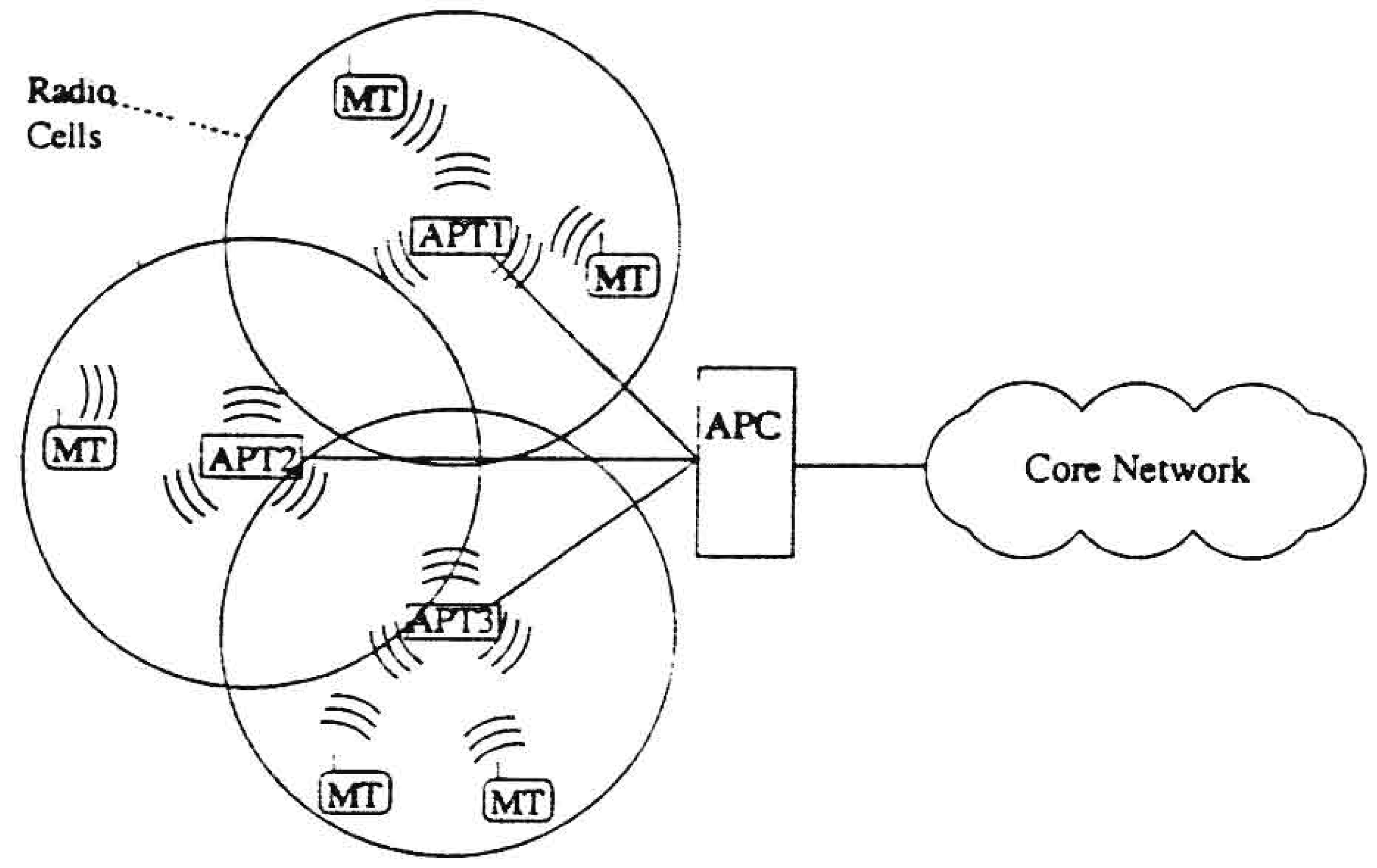

Fig. 2. Structure of a cellular H/2 system

e.g., 26 and 40 GHz. A similar standardization activity is going on with IEEE 802.16.

HiperLINK provides short-range very high-speed interconnection of HiperLANs and HiperACCESS, e.g., up to 155 Mb/s over distances up to 150 m. Spectrum for HiperLINK is available in the 17-GHz range.

II. H/2 System Overview

A. System Architecture

H/2 provides wireless access to wired networks for users by an MT inside buildings, outside in free terrain, or in the proximity of buildings.

Fig. 2 illustrates the schematic structure of a cellular H/2 system. An AP that is typically connected to a core network or a distribution system consists of an APC and one or more APTs. An APT operates one frequency carrier and covers a certain area, called the *radio cell*. The APC is responsible for the management of its APTs.

Two operation modes are defined for the H/2 DLC (see Fig. 3): *centralized mode* and *direct mode*.

In the centralized mode, MTs communicate via the AP with other MTs or networked terminals. In the direct mode, MTs can communicate directly over *direct links* with each other. In both modes, the AP assigns the radio resources and controls the communication in the radio cell.

B. H/2 Radio

The most important properties of H/2 are summarized as follows [14].

1) High-Speed Transmission: H/2 has a transmission rate that extends up to 54 Mb/s at the PHY and provides a user bit rate of up to 45 Mb/s. To achieve this, H/2 makes use of a modulation method called OFDM for transmission harmonized with IEEE 802.11a.

2) Connection Oriented: Data are transmitted on connections between the MT and the AP (with the direct mode between MTs) that have been established prior to the transmission, using signaling functions of the H/2 control plane. Point-to-point connections are bidirectional, point-to-multipoint and broadcast connections are unidirectional from

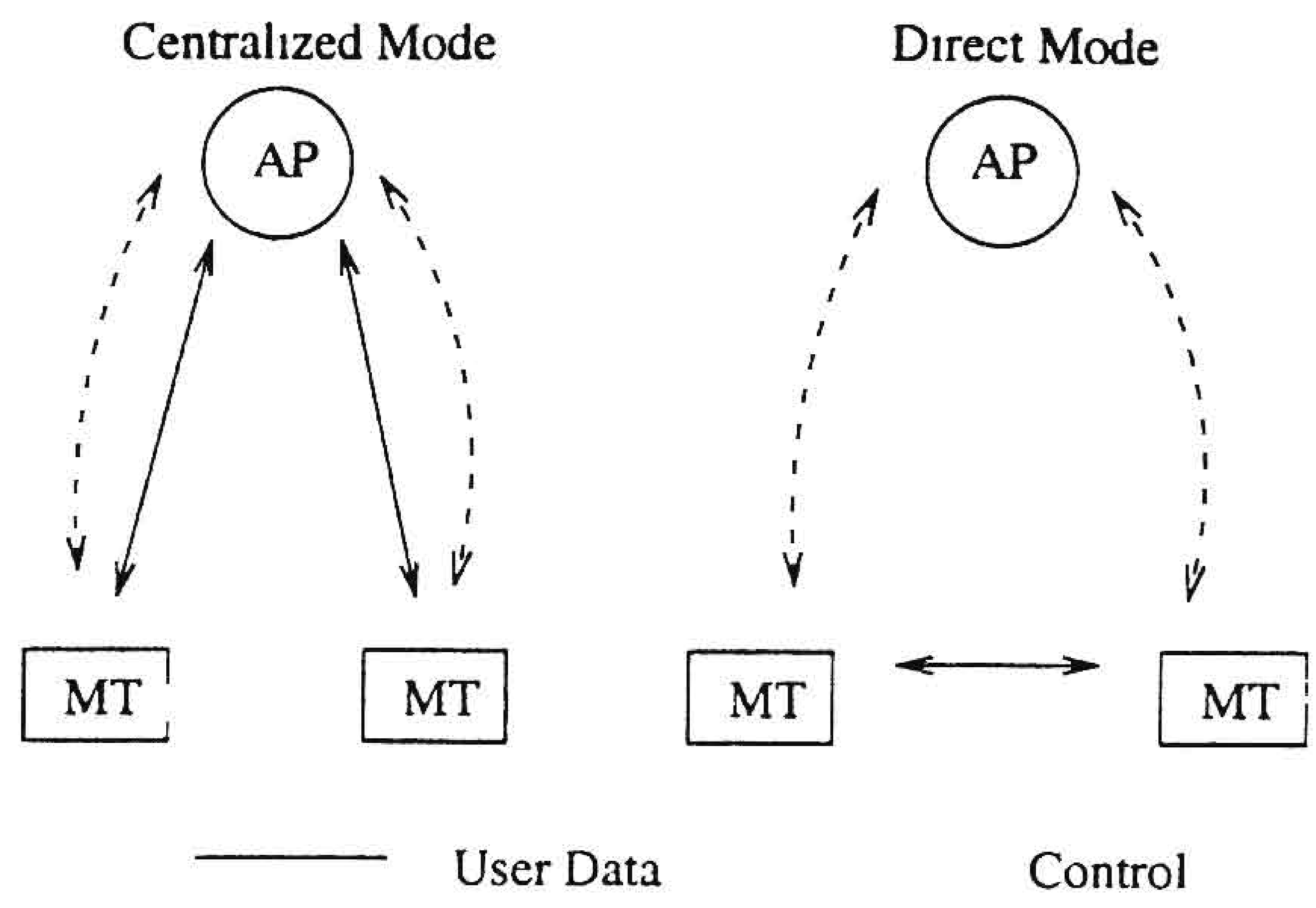

Fig. 3. Operation modes of H/2

the AP toward the MTs in the radio cell. Connections are realized by means of logical channels.

3) QoS Support: The connection orientation of H/2 is a prerequisite for the support of QoS. Each connection can be assigned a specific QoS parameter set, in terms of throughput, delay, delay variation, bit error rate, etc. In an environment where the connection characteristics are not available, QoS is supported by assigning a priority level relative to other connections.

4) Automatic Frequency Allocation: H/2 does not need a manual frequency planning like conventional cellular networks. The APs in H/2 automatically select an appropriate radio channel for transmission within each AP's coverage area by DFS. An AP listens to neighbor APs as well as to other radio sources in the environment and selects a radio channel based on its current load and SNR aiming to minimize interference with other radio cells.

5) Security Support: H/2 supports authentication and encryption. The AP and the MT may mutually authenticate each other to ensure authorized access. Authentication relies on a supporting function, such as directory service that is outside the scope of H/2. The user traffic on established connections may be encrypted to protect against eavesdropping and man-in-middle attacks.

6) Mobility Support: The MT uses the AP with the best radio signal performance as measured by the SNR and the PER. Thus, as the MT moves it may detect an alternative AP with better radio performance than the current AP. The MT will then initiate a handover to this AP and all its connections will be moved to the new AP. The MT stays associated to the H/2 network and can continue its communication. During a handover, some packet loss may occur. If an MT moves out of radio coverage for a certain time, the MT may lose its association to the H/2 network resulting in the release of all its connections.

7) Sleep Period: To allow MTs to save power, an MT may at any time request the AP to enter a low power state (specific per MT), and may request a specific sleep period. At the expiration of the negotiated sleep period, the MT searches for the presence of any wake-up indication from the AP. If no wake-up indication is received, the MT returns to its low power state for the next sleep period. An AP will delay any pending data to an MT until the corresponding sleep period has expired.

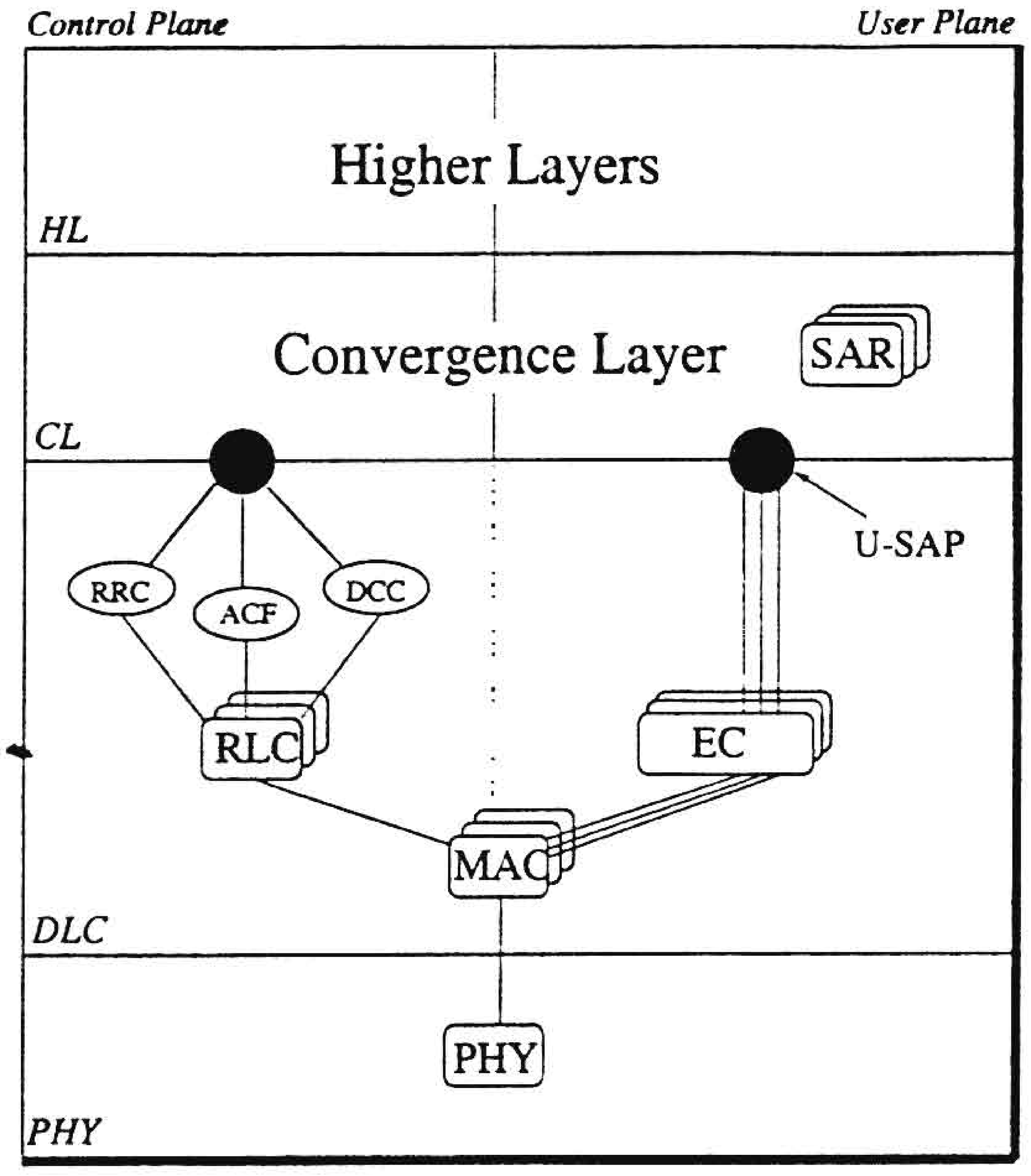

Fig. 4. Service model of H/2.

C. *H/2 Service Model*

The service model of H/2 is shown in Fig. 4. It comprises the PHY and the DLC layer for both MT and AP. Various network types like IP, Ethernet, IEEE1394, and ATM can be connected to the DLC layer by the CL that performs the adaptation of the packet formats to the requirements of the DLC layer. For higher layers other than ATM, the CL contains a SAR function. The PHY provides the basic transport functions for the DLC PDU (see [7]). The DLC layer is vertically subdivided into two parts, the *control plane* and the *user plane* [8]. In the user plane, the data transport function is fed with user data packets from the higher layers via the U-SAP. This part contains the EC that applies an ARQ protocol. The DLC protocol is connection oriented and provides multiple connection endpoints in the U-SAP. The control plane consists of the RLC protocol that includes the DCC, the RRC, and the ACF. Both planes access the physical medium via the MAC protocol.

1) Physical Layer: H/2 systems are meant to operate as private or public systems in the license-exempt spectrum in the 5–6 GHz band. Fig. 5 shows the frequency bands and power limits defined for H/2 in Europe, the Unlicensed Information Infrastructure (U-NII) in the United States, and the Mobile Multimedia Access Communication (MMAC) in Japan.

The frequency bands in its region are not attributed exclusively, but in Europe H/2 systems have to coexist with H/1 and radar systems, some of which might be mobile. In the United States and Japan, H/2, IEEE 802.11a, and HomeRF Systems will have to coexist. The channel grid is 20 MHz.

The H/2 sampling frequency is chosen equal to 20 MHz at the output of a typically used 64-point *Inverse Fast Fourier Transformation*. The obtained subcarrier spacing is 312.5 kHz. To facilitate implementation of filters and to achieve sufficient adjacent channel suppression, 52 subcarriers are used per channel; 48 subcarriers carry the actual

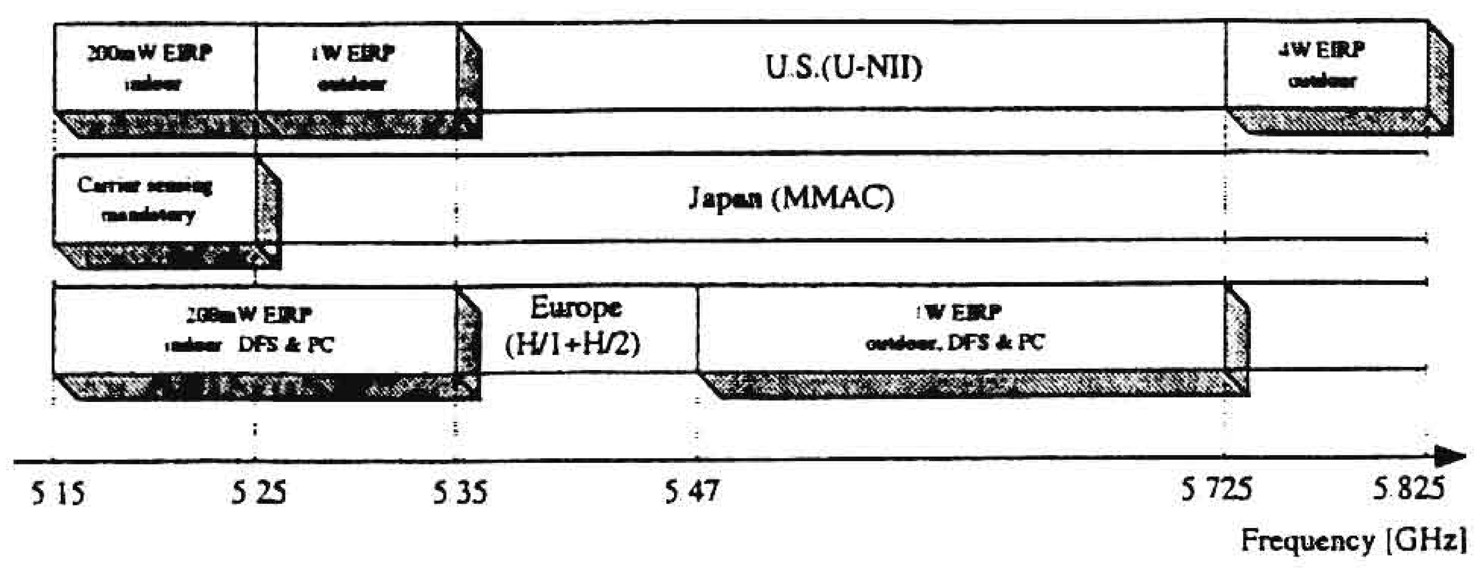

Fig. 5. Frequency allocation for WLANs

Table 1
Modulation- and Coding-Dependent Transmission Rates

Modulation	Code rate	Capacity of an OFDM-Symbol	Transm. rate
BPSK	1/2	3 byte	6 Mbit/s
BPSK	3/4	4.5 byte	9 Mbit/s
QPSK	1/2	6 byte	12 Mbit/s
QPSK	3/4	9 byte	18 Mbit/s
16QAM	9/16	13.5 byte	27 Mbit/s
16QAM	3/4	18 byte	36 Mbit/s
optional:			
64QAM	3/4	27 byte	54 Mbit/s

data and four subcarriers are pilots that facilitate phase tracking for coherent demodulation (for further details see [15]). The shortest transmitted unit is an OFDM symbol that has a duration of 3.2 μs with a cyclic prefix of 800 ns, altogether 4 μs [7], [14].

A key feature of the PHY is to provide several PHY modes with different coding and modulation schemes that are selected by a link adaptation mechanism. BPSK, QPSK, and 16QAM are mandatory subcarrier modulation schemes, whereas 64QAM is an optional mode. FEC is performed by a convolutional code of rate 1/2 and constraint length seven. Other code rates like 9/16 and 3/4 are obtained by puncturing. Accordingly, different transmission rates result, as shown in Table 1.

The PHY of H/2 is well harmonized with those being developed for the U.S. and Japanese markets. In the U.S., the high-speed PHY will be an extension of IEEE 802.11, called IEEE 802.11a [16], that will reuse the existing MAC layer. The corresponding system in Japan called HiSWAN will be based on the same PHY. The frequency allocation of these two systems partially overlaps that of H/2 (Fig. 5).

2) MAC: MAC protocol functions are used for organizing access to and transmission of data on the radio link. The control is centralized to the AP that informs the MTs at what point in time in the MF they are allowed to transmit their so-called *PDU trains*. The lengths of the PDU trains vary depending on the RRs received at the AP from the MTs.

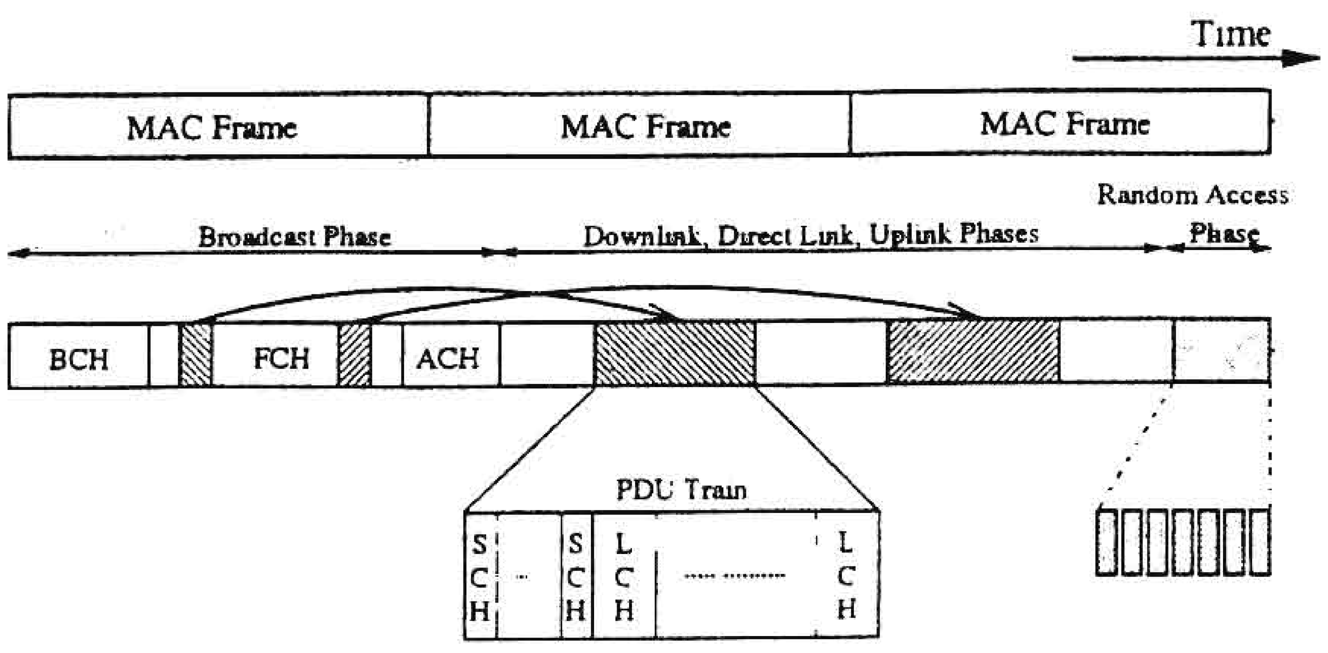

Fig. 6. Transmission phases in a MAC frame

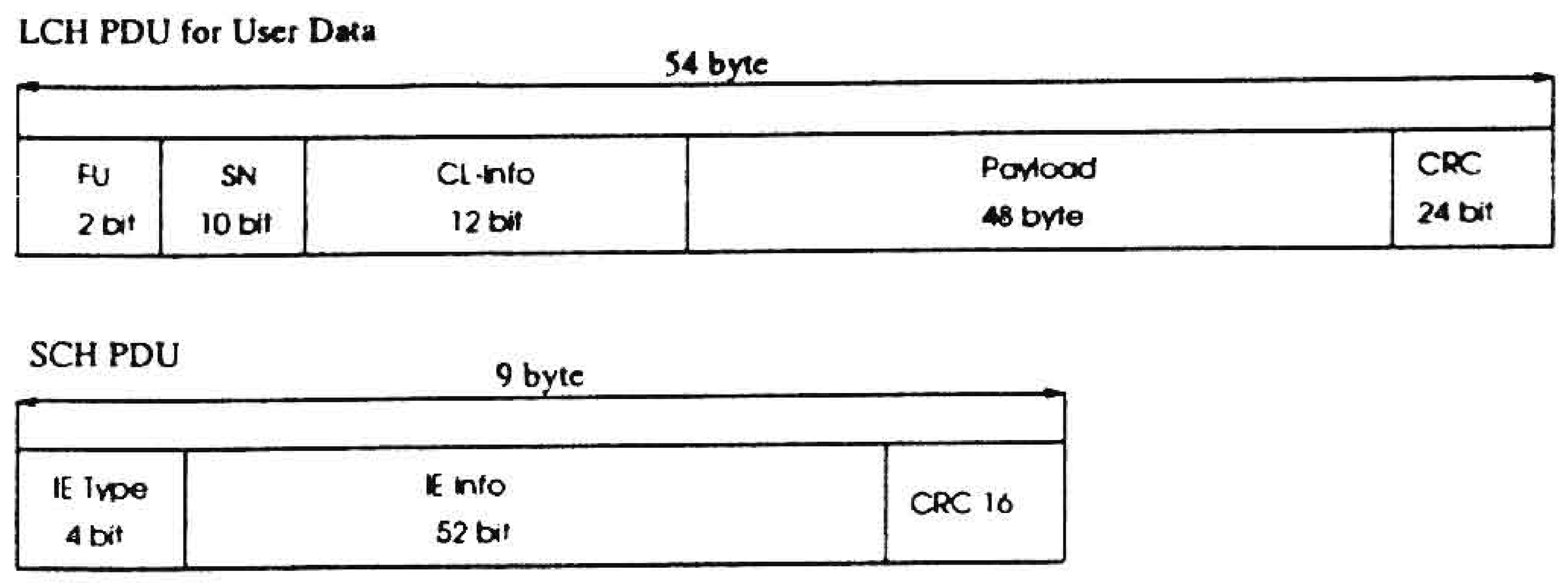

Fig. 7. LCH PDU and SCH PDU

The radio interface is based on TDD. The dynamic TDMA structure used in the MF allows simultaneous communication via a number of DLC connections in both directions downlink and uplink. The time slots are grouped to MFs of constant length of 2 ms. Thus, a MF carries 500 OFDM symbols. The assignment of resources for the individual MTs and their connections is not static but may change dynamically from one MF to the other. Each MF consists of different phases as shown in Fig. 6. These phases contain logical channels named with four letters that are mapped to physical transport channels named with three letters.

The *broadcast phase* carries the BCCH, the FCCH, and the RFCH.

The BCCH (downlink only) transmits control information through the BCH PDU in each MF and to all MTs. It provides information about transmission power levels, starting point and length of the FCH and the RCH, the wake-up indicator, and the AP identifier. The BCCH is 15 bytes long and is transmitted using the most robust modulation scheme available, i.e., BPSK 1/2.

The FCCH (downlink only) transmitted in the FCH contains an exact description of how the resources of the current MF have been allocated (and thus granted) in the downlink, the uplink, and the direct-link phases.

The RFCH (downlink only) provides information through the ACH on access attempts made by MTs in the RCH of the previous MF.

The downlink phase carries user-specific control information and the user data, transmitted from an AP to one or more MTs.

The uplink phase carries control and user data from the MTs to the AP.

The direct-link phase carries user data between MTs.

In the random access phase MTs that do not have capacity allocated in the current uplink phase may use the RCH to transmit an RR. Nonassociated MTs first get in contact with an AP via the RCH that is also used by MTs during handover to have access to a new AP. For the RCH, a *slotted ALOHA* protocol with a binary-exponential back-off collision resolution algorithm is used.

Two kinds of PDUs, the LCH PDU and the SCH PDU, are specified. An LCH PDU is 54 bytes long and contains a 48-byte *payload*, a 24-bit CRC24 for error detection, 12 bits for CL information, and a 10-bit sequence number for the ARQ protocol (Fig. 7). An SCH PDU is 9 bytes long and contains 52 bits for signaling data, a 16-bit CRC16 for error detection, and an IE of 4 bits to differentiate the types of signaling data, i.e., RR, EC, and RLC.

In order to reduce overhead, all LCH and SCH PDUs in an MF belonging to connections of the same MT are combined to a PDU train (Fig. 6). A detailed description of the MAC layer can be found in [8].

3) RLC: The RLC protocol provides three groups of functions for the higher layers [9] (see Fig. 4), namely ACF, RRC, and DCC.

a) ACF: ACF include the protocols for association, authentication, encryption setup and disassociation.

The MT has to scan for the *Beacon* signal sent in the BCCH of every MF containing among others the AP-ID and the NET-ID of the APT. The MT waits for the NETWORK-OPERATOR-ID broadcast periodically in the RBCH to check whether access to this particular network is feasible or not and then continues the association procedure by transmitting a request for a MAC ID. A MAC ID is assigned by the AP used for addressing the MT during the whole session at this AP and is valid only in the radio cell of one APT.

During the *Link Capability* procedure, the MT sends its own parameters to the AP containing:

- the DLC version running in the MT;
- a flag set, if the MT supports the direct mode;
- the CL services supported;
- authentication and encryption procedures supported.

The AP will respond with its own parameters and will select the CL services and the encryption and authentication procedure for the session.

The disassociation procedure may be initiated by either the MT or the AP. During explicit disassociation, MT and AP negotiate about disassociation shortly. Implicit disassociation occurs when MT and AP lose their radio link completely.

b) RRC: RRC functions provide procedures for radio link measurements, handover, power saving mode, power control, and dynamic frequency selection (see Section II-B).

c) DDC: DCC functions are responsible for setting up, maintaining, renegotiating, and closing a DUC at the DLC layer and may be initiated by either MT or AP. An MT requesting the establishment of a DUC, will propose the connection characteristics but the AP will decide on the DUCs characteristics and attribute a unique ID that together with the MAC ID uniquely identifies a connection in a radio cell. The AP is exercising its connection admission control algorithm to decide whether a connection can be accepted or not.

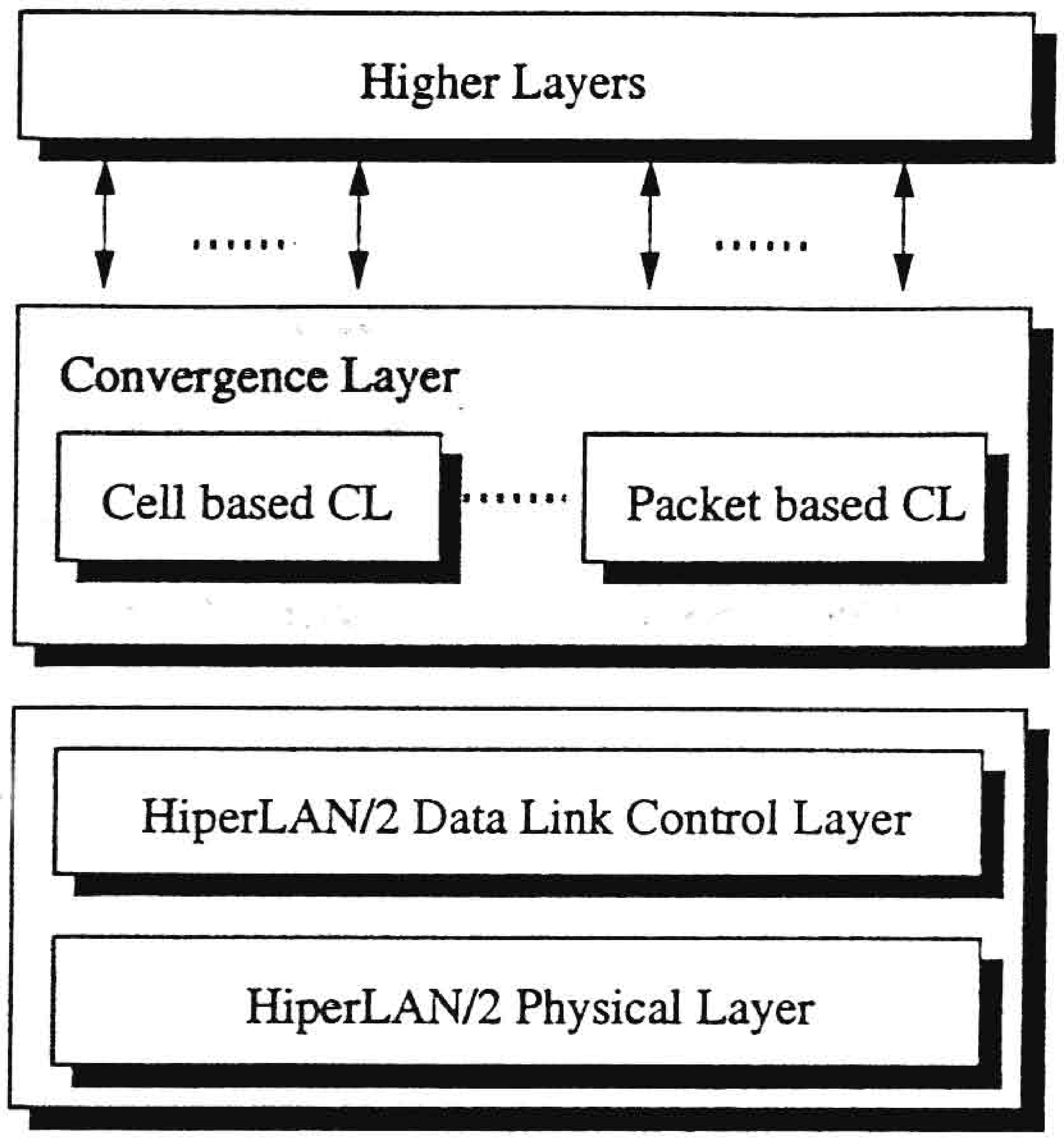

Fig. 8. HiperLAN/2 convergence layer.

4) EC Functions: EC functions are responsible for detection and recovery of transmission errors on the radio link and ensure that all frames are delivered to the CL in the proper order.

EC in the H/2 standard is based on Selective Repeat ARQ with CRC checksum and takes into account the QoS parameters agreed upon during setup of each DUC.

Partial Bitmap Acknowledgment is used where the ARQ feedback message contains three BMBs of a constant length of eight. The SN space, starting from SN = 0, is partitioned into consecutive intervals of SNs. A bit set to 1 in the BMB represents a packet received error free with the SN associated to the bit and a bit set to 0 indicates that this PDU has not been received [8]. This way error bursts can be recovered efficiently.

5) CL: The CL adapts the core network to the H/2 DLC layer. For each network supported a specific CL has been defined. The CL provides all functions needed for connection setup and mobility support.

There are two different types of CLs defined: *cell based* and *packet based* (see Fig. 8).

The packet-based CL is used to integrate H/2 into existing packet-based networks and support IP, IEEE 802.3, and PPP. It provides among others, an SAR function to fit, e.g., IP packets into the fixed-length payload of H/2 LCH PDUs.

The cell-based CL provides the mapping between ATM connection setup procedures and the corresponding H/2 functions. An SAR is not necessary, as the ATM cell payload and all necessary fields of the ATM cell header fit into the 54-byte H/2 packet. Nevertheless, a compression of the ATM cell header is necessary.

III. Serving IP QoS

QoS is becoming an important factor in data networks. The ability to differentiate traffic is attractive so that mission-critical traffic can be given higher priority in the network than other types of casual, nonmission-critical traffic.

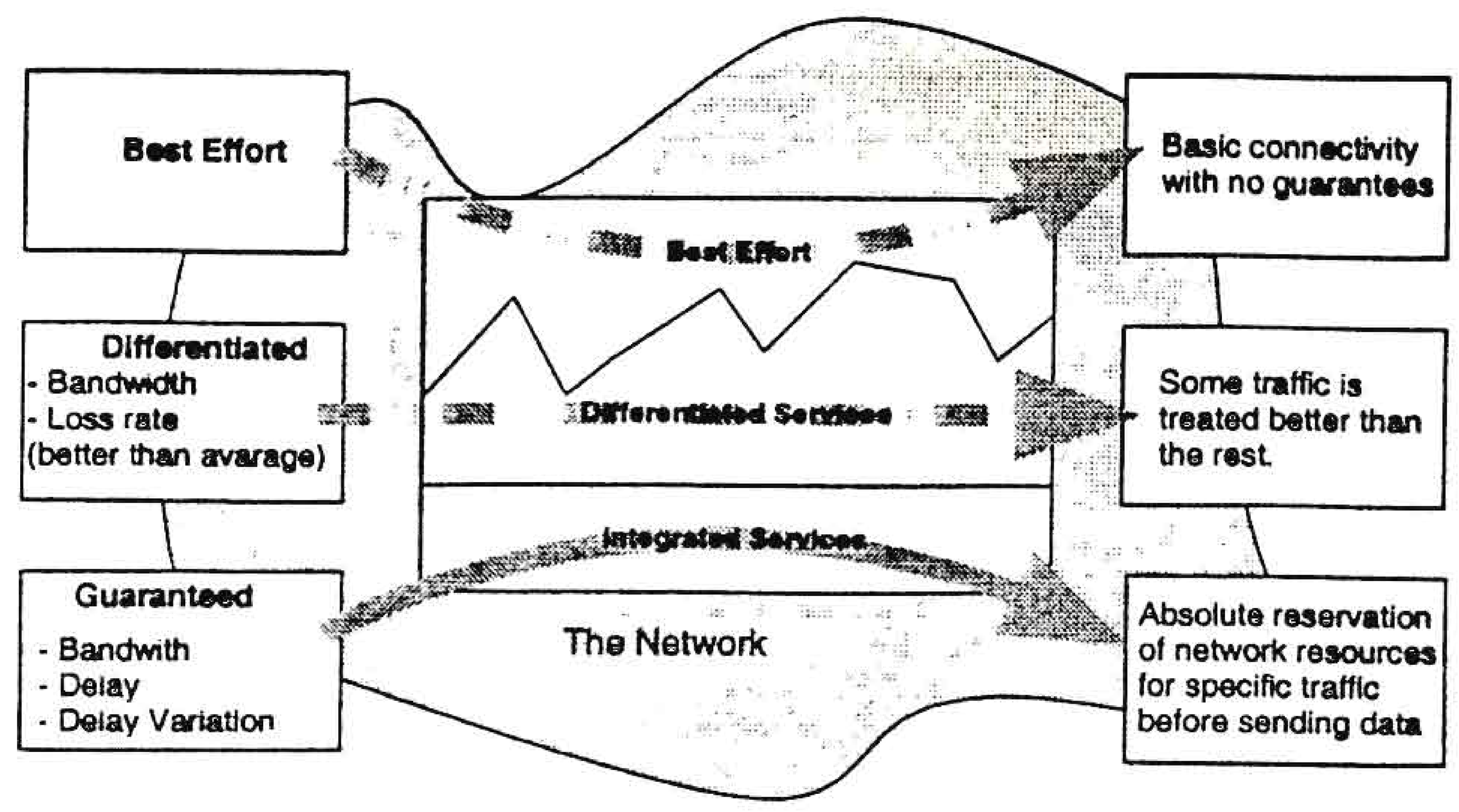

Fig. 9. QoS models

A. QoS in IP Networks

QoS refers to the ability of a network to provide better service to specific network traffic over various underlying wireline or wireless technologies. Internet QoS can be expressed as the combination of network-imposed *delay*, *delay variation*, *bandwidth*, and *reliability* [17]. Reliability is a property of the transmission system and is affected by the average loss ratio of the medium and by the routing/switching design of the network. In the fixed Internet, packet loss is caused mainly by congestion. In wireless networks, both congestion and the burstiness of errors on the radio link and the delay introduced then by ARQ protocols impact the QoS and have to be taken into account.

B. End-to-End QoS Models

A service model describes a set of end-to-end QoS capabilities defining the ability of the network to deliver data packets according to the service required by the specific traffic from one end of the network to another. For IP traffic, the following service models have been defined (see Fig. 9): *Best Effort Service*, *Differentiated Services*, and *Integrated Services*.

1) Best Effort Service: Best Effort Service is basic connectivity with no guarantees, so it is also known as lack of QoS. Best Effort is a single-service model where an application sends data whenever it has to and in any quantity. This is done without requesting permission or informing the network. For Best Effort Service, the network delivers the data as best as it can without any assurance of delay bounds, throughput, and reliability.

2) Differentiated Services: In this service model, traffic is grouped in service classes that are served differently by the network, whereby one class may be treated better than another, i.e., with higher bandwidth or lower loss rate. This results in a statistical preference and not in a hard guarantee, so that Differentiated Services are also called *Soft QoS*. For the Differentiated Services, the network tries to deliver the IP packets according to the QoS assigned to a specific service class indicated by each individual packet. This indication can occur in different ways; for example, using specific bit settings in the IP packet header [18]. This could be the *Type of Service* field in the IPv4 header and the *Traffic Class* field in the IPv6 header, respectively. Unlike the Integrated Services model, an application using Differentiated Services does not explicitly signal the network before sending data. Instead the application addresses a specific service agreed upon between network operator and user.

3) Integrated Services: This model represents an absolute reservation of network resources for specific traffic. It is also called *Hard QoS*. Integrated Services is a multiple-service model that can accommodate multiple QoS requirements. In this model, the application requests a specific kind of service from the network before sending data. The request is made by explicit signaling, e.g., by using the RSVP as specified in [19] and [20]. This means that the application informs the network nodes of its traffic profile and requests a particular kind of service that can encompass its bandwidth and delay requirements.

Integrated Services support both *Controlled Load Service* and *Guaranteed Service*. The Controlled Load Service [21] guarantees to provide a level of service equivalent to best effort service in a lightly loaded network, regardless of the actual network load. This service class is designed for adaptive real-time applications (e.g., applications that can modify their play-out buffer as the end-to-end delay varies). These applications work well on low-loaded networks, but their performance degrades quickly under overloaded conditions. Guaranteed Service [22] guarantees a maximum end-to-end delay and bandwidth. It is intended for audio and video applications with strict delay requirements. An important aspect to note here is that the Guaranteed Service does not control the minimum or average delay of datagrams, merely the maximum queuing delay. It guarantees that datagrams will arrive within the requested delivery time and will not be discarded owing to queue overflows, provided the flow's traffic status is within its specific traffic parameters [23].

The application is expected to send data only after it gets a confirmation from the network. It is also expected to send data that lie within its described traffic profile. The network performs for the traffic an admission control, based on information from the application and available network resources. It also commits to meet the QoS requirements of the application as long as the traffic remains within the profile specifications. The network fulfills its commitment by maintaining per-flow state and then performing packet classification, policing and an intelligent queuing based on this state.

C. Serving IP QoS in Wireless Networks

As described above, IP QoS focuses on end-to-end QoS, whereby the network elements have to serve the respective requirements on a per-hop basis. Wireless networks may provide only one or two hops of an end-to-end traffic flow, i.e., in case of wireless access networks (see Section V) on one or both sides of the IP network, may build an entire wireless network, i.e., in case of *ad hoc* networks (see Section VII), or a mixture of these.

An H/2 WLAN is able to support all the QoS classes defined for ATM networks and therefore is ideally suited to also support the QoS requirements of IP networks that are less stringent than those of ATM networks. The IP CL of H/2 provides the functions needed for mapping IP QoS requirements to the QoS parameters available from H/2 for its DLC connections.

The IEEE 802.11a WLAN specification contains very limited capabilities to support QoS requirements, e.g., by means of the PCF a continuous bit rate can be supported if there are no MTs active that are hidden to the coordinating terminal. This is the reason for a recent decision in the IEEE 802.11 project to start an initiative to upgrade the standard to be able to support QoS better in the future.

Besides the impact of buffer loads on the delay and loss characteristics of a traffic flow in a wireless network, the unreliability of the radio link has to be considered.

Mechanisms like error control by means of an ARQ protocol and dynamic link adaptation aim to reduce the radio specifics on the packet loss rate but introduce additional overhead and delay to the radio access system decreasing the capacity. To realize the QoS requested by an IP application at the radio interface, algorithms in the DLC layer must decide how to schedule the related data. In the following, we discuss the impact of H/2 and IEEE 802.11 radio access systems on IP QoS parameters like *throughput* and *delay*, and provide an insight by means of examples on how IP QoS is served by H/2 a wireless mobile ATM system.

IV. Traffic Performance Analysis of H/2

This section describes the tools and methods we used for performance analysis of H/2 protocols.

Development and implementation of telecommunication protocols are eased when a formal specification language is used to describe the signaling sequences and the data exchange within a single system, between systems, and to their environment. The SDL specified by ITU-T [24] is based on a FSM model, that receives signals from its environment and responds to these signals by generating internal and external signals that are related to state changes in the model. SDL represents a protocol as an FSM with states, well-defined signals, and transitions between states.

SDL has been used at ETSI/BRAN to formally specify the H/2 protocols. In the following, we present our approach for performance evaluation by simulation on the basis of protocols formally specified in SDL.

A. H/2 Specification in SDL

Our H/2 simulator is entirely specified in SDL completely reflecting the H/2 specifications of ETSI/BRAN. These specifications have been extended by algorithms, e.g., DLC scheduler and handover algorithm that are out of the scope of the standard but vital to complete an H/2 system.

When simulating the traffic performance of an H/2 protocol stack, we in fact are executing the protocols in detail instead of studying a model of the protocols.

Fig. 10 shows the highest level of the SDL system specification. It contains the four main building blocks: MT, AP, Channel, and SimControl. The blocks MT and AP contain the SDL specification of the respective H/2 protocols. Every AP and every MT in the simulation is represented by one block

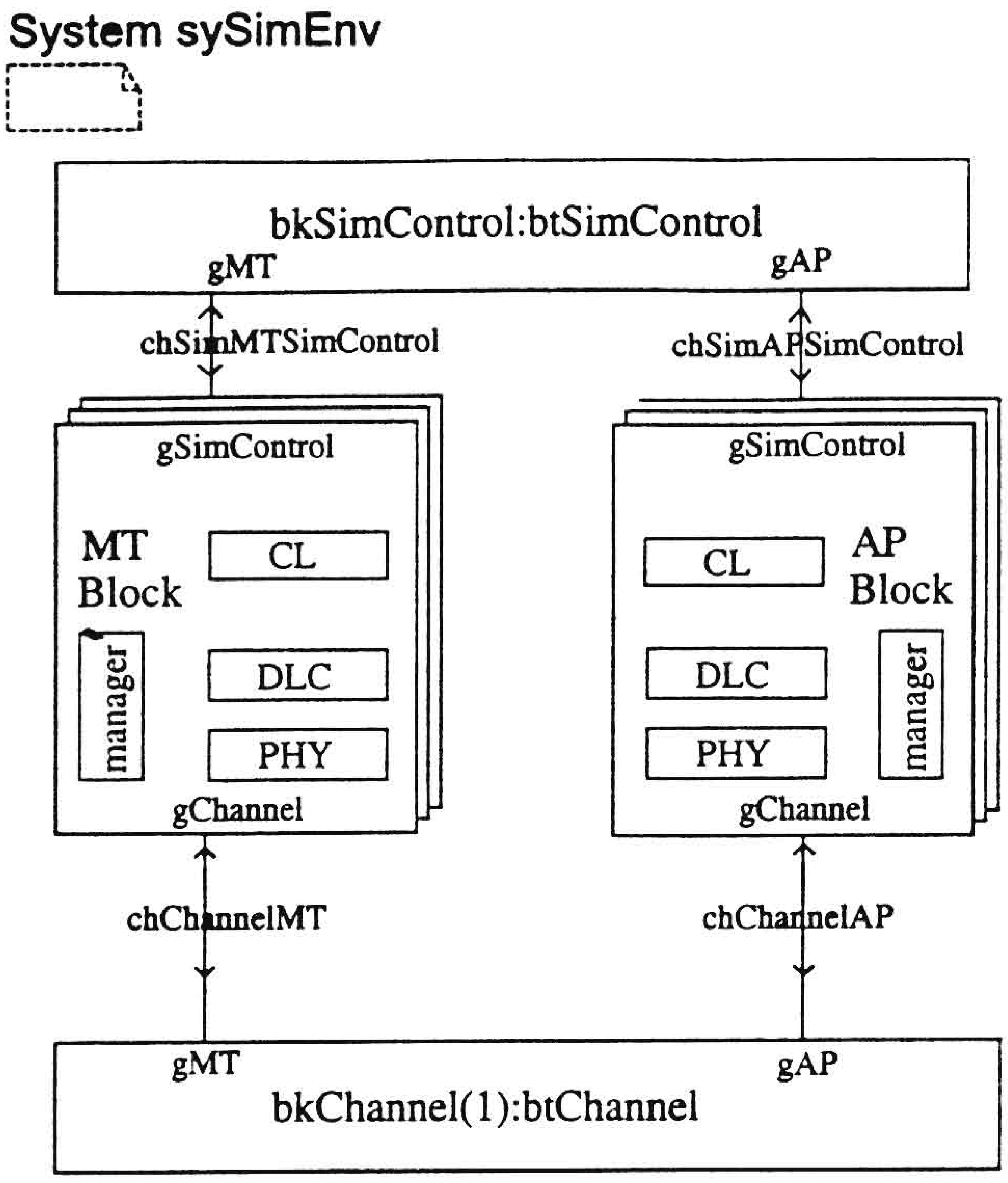

Fig. 10. H/2 system environment in SDL.

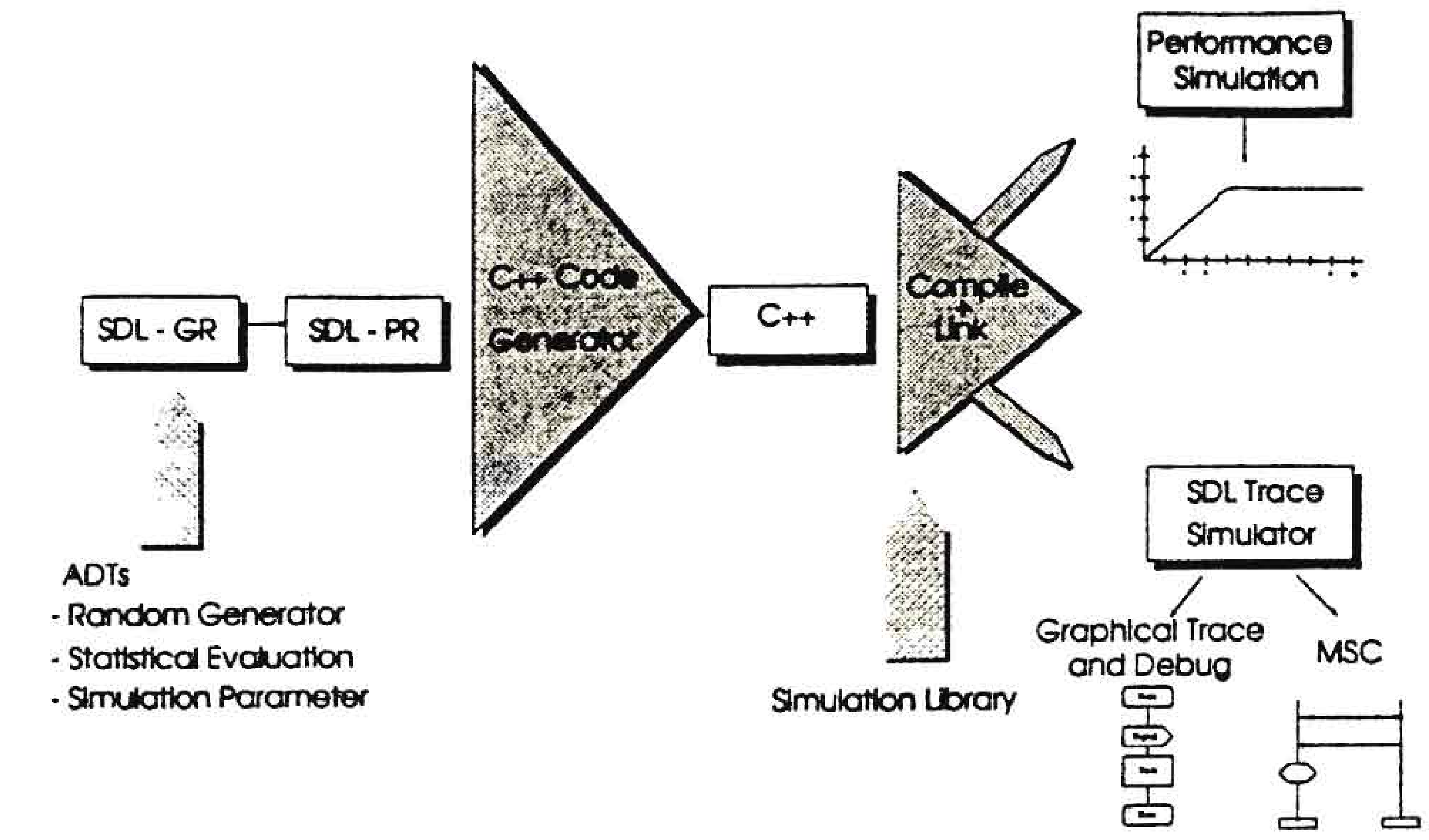

Fig. 11. Creation of a simulation.

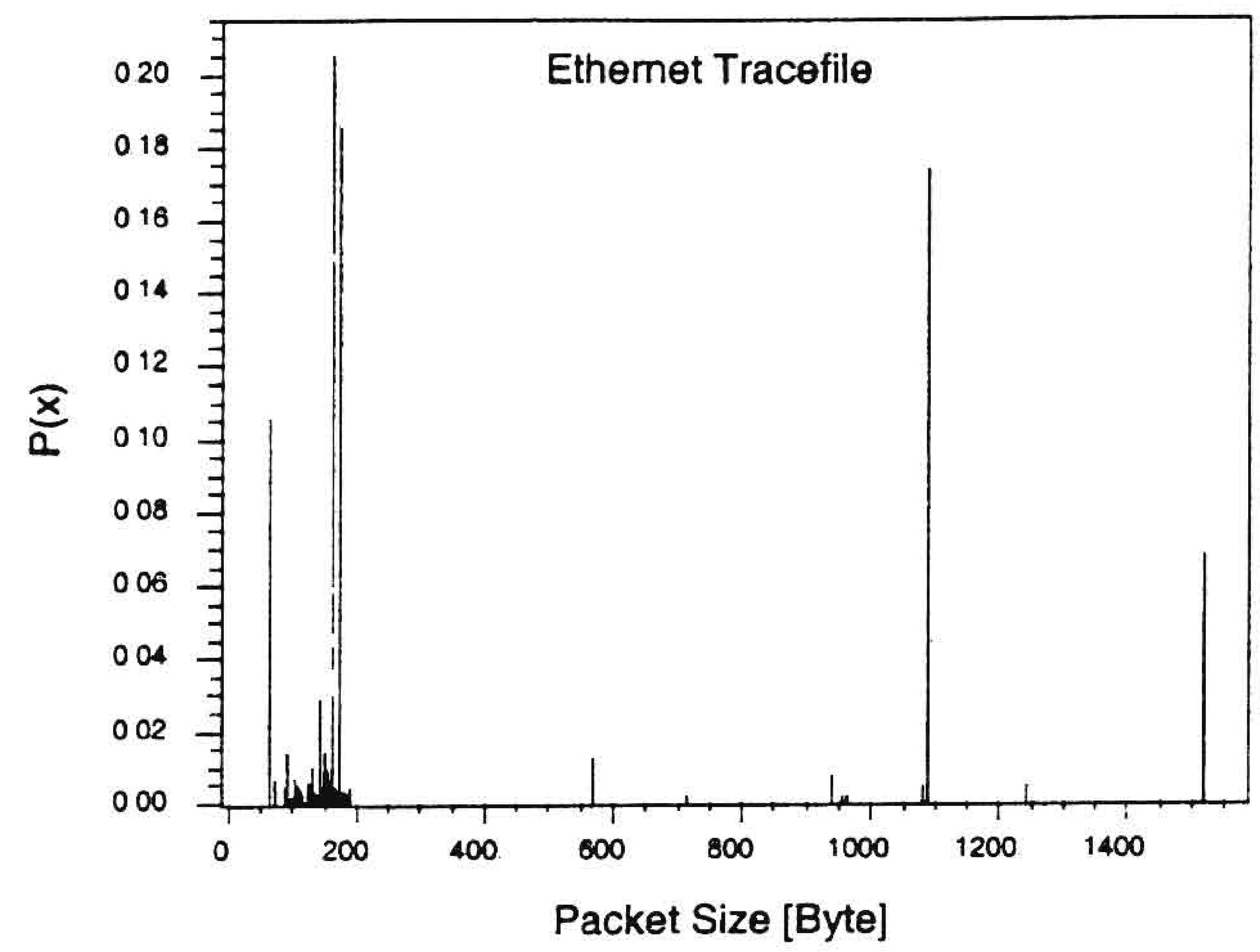

Fig. 12. Ethernet packet length distribution.

of the respective type. The blocks *Channel* and *SimControl* are introduced to complete the simulator and to place the H/2 system in a given operations and usage environment.

The main tasks of SimControl are the initialization, control, and execution of the simulation. At start-up, all AP and MT blocks log on to the SimControl, the latter distributing unique AP and Mobile IDs. Other parameters specific to a simulation to be executed are read from parameter files. SimControl also contains the traffic load generators.

The task of the Channel is to transfer and broadcast the signals from APs to MTs and vice versa. It incorporates a channel and a mobility model. Together with the PHY-layer model being part of the blocks MT and AP, the actual C/I and the resulting PER are calculated.

The blocks AP and MT are subdivided into subblocks that represent the H/2 protocol layers PHY, DLC, and CL. The DLC block combines the functionalities of the MAC, the RLC, and the EC sublayers (see Fig. 4). Besides, there are blocks for the *DLC scheduler* and a *DLC layer manager*.

B. The SDL-Based Performance Simulator

Based on SDL-specified protocols, an executable simulator for traffic performance analysis is generated using tools for automatic code generation plus a library for statistical analysis of protocol parameters [25]. Fig. 11 shows the steps to arrive at a simulation program.

Starting from an SDL system specified in the *graphical representation* (SDL-GR), as shown in Fig. 10, *SDL phrasal representation* (SDL-PR) will be generated. ADT are used to integrate specific tools for performance analysis into the block *SimControl*, e.g., traffic generators and statistical results analysis.

The SDL specification by means of a code generator is automatically translated into C++-code that is conventionally compiled and linked with a C++-based performance evaluation library to generate different types of simulators. Besides a stand-alone simulator program to be run on a UNIX or LINUX platform, an interactive simulator can be generated that allows the SDL specification to be graphically traced and debugged.

C. Parameterization of the Simulator

To be able to study an H/2 system under reproducible load and radio propagation conditions, a scenario has to be defined including traffic generators, number of MTs and APs, and a radio channel model.

1) Traffic Generators:

a) N-ISDN: A voice source with a constant bit rate of 64 kb/s has been modeled by generating a packet of 48 bytes every 6 ms.

b) LAN: Traffic has been modeled by using a trace file of Ethernet traffic [26]. Fig. 12 shows the distribution of the Ethernet packet length. The mean inter arrival time of packets has been varied in the simulator to create various traffic load conditions.

c) Video: A video traffic source has been derived from a trace file based on the coding of the "Star Wars" movie according to the MPEG-1 standard [27]. Fig. 13 shows the

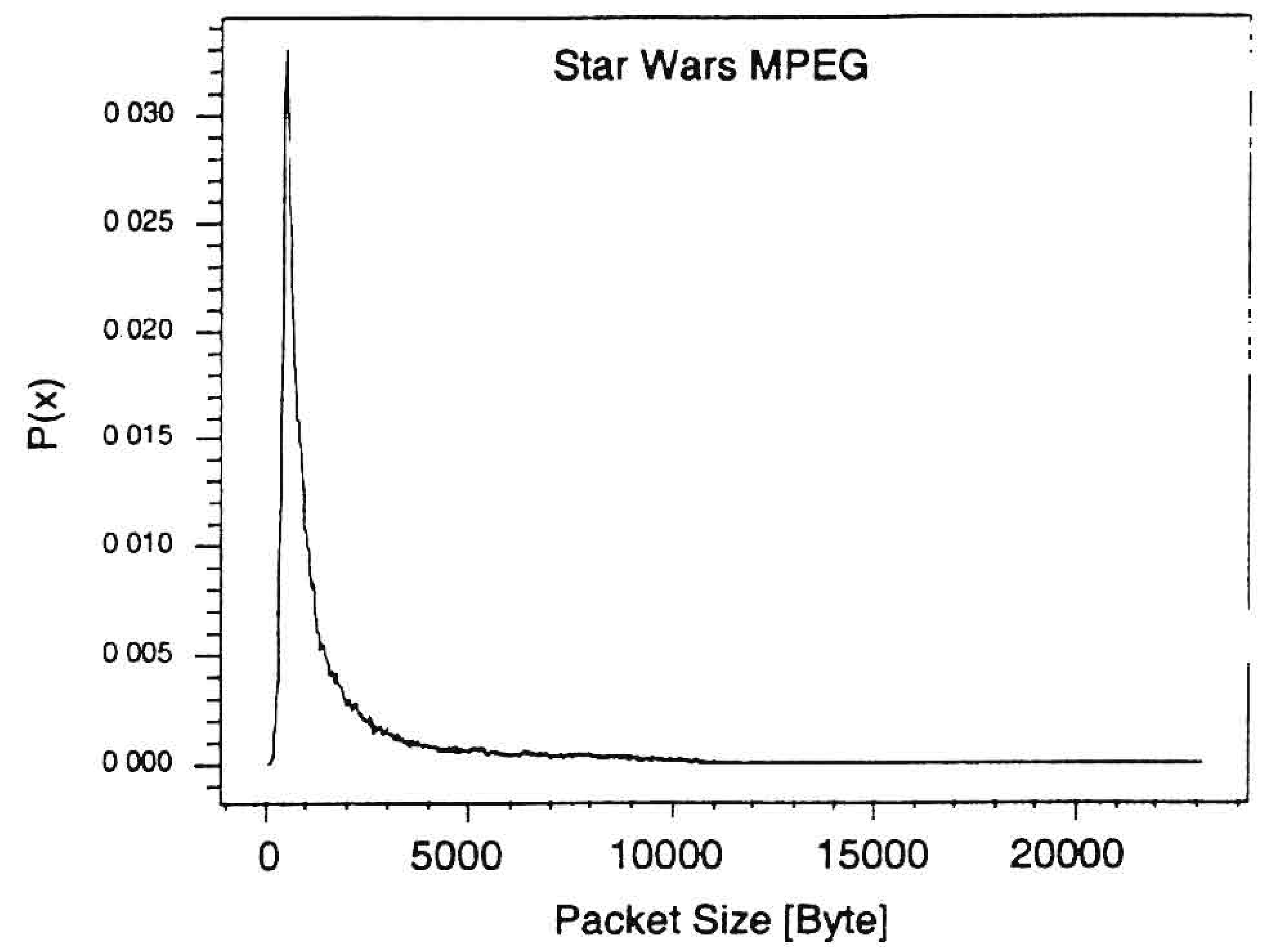

Fig. 13. MPEG packet length distribution

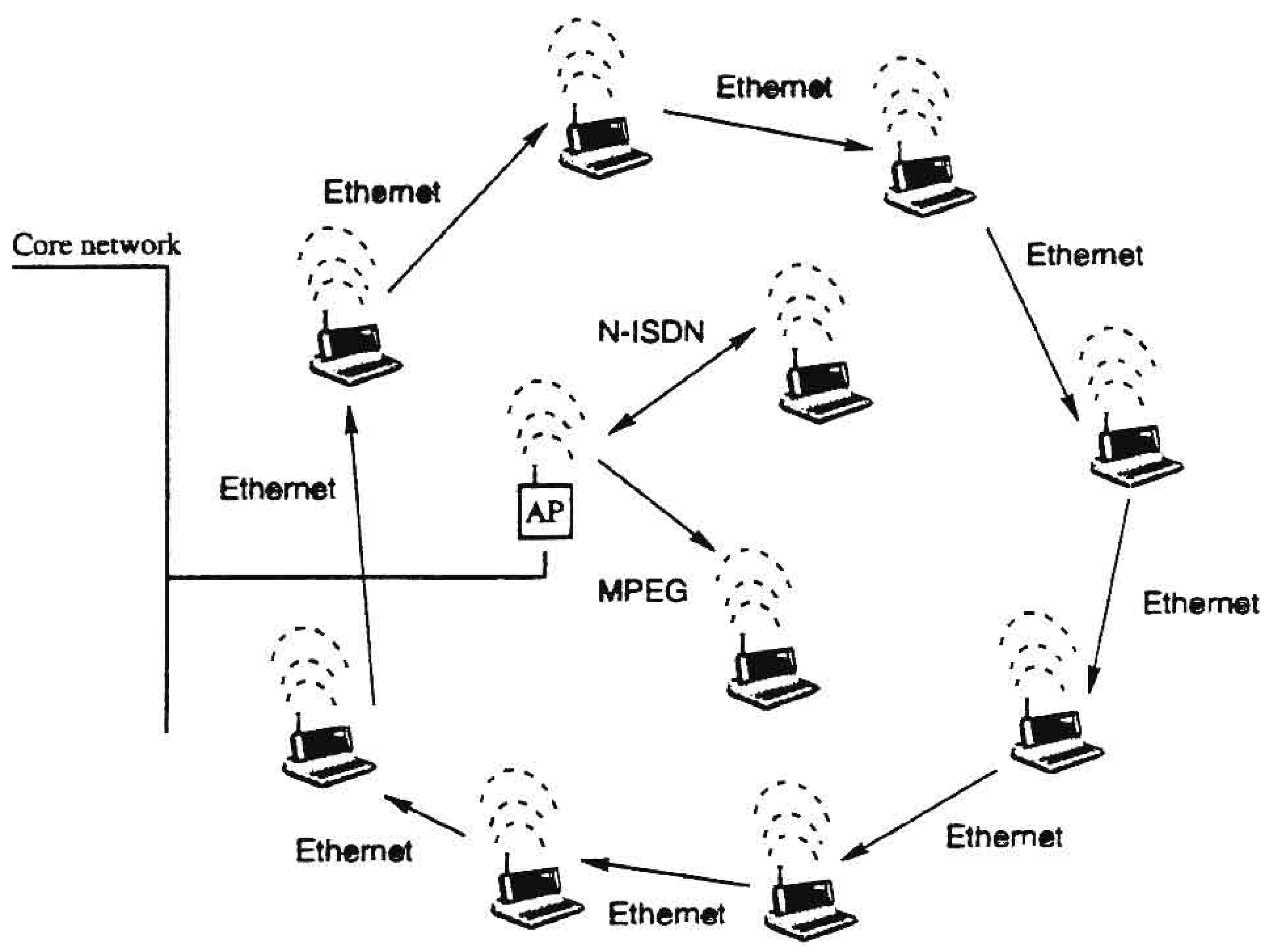

Fig. 14. Simulation scenario

distribution of the MPEG packet length, the inter arrival time of packets is constant and has been varied in the simulator to create various traffic load conditions.

2) Isolated H/2 System: Fig. 14 shows the reference scenario studied by simulation. It consists of an AP serving a video stream download (MPEG) and a duplex voice connection (N-ISDN), and eight terminals exchanging Ethernet packets with their direct neighbor MTs in a circular way. The data rate of the Video traffic has been set to 5 Mb/s whereas mean data rate of the LAN traffic has been varied in the simulation runs to model different loads.

3) Cellular H/2 System: We have also studied by simulation large cellular H/2 systems with 61 cells to evaluate the performance of the dynamic channel selection under heavy interference and found that H/2 systems are then still able to provide QoS guarantees as in an isolated system [28].

4) Channel Model: The propagation model taken for the H/2 simulations is realized as a distance-dependent model where the received power P_R at each receiver is expressed by

$$P_R = P_S g_S g_R \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{d^\gamma}. \qquad (1)$$

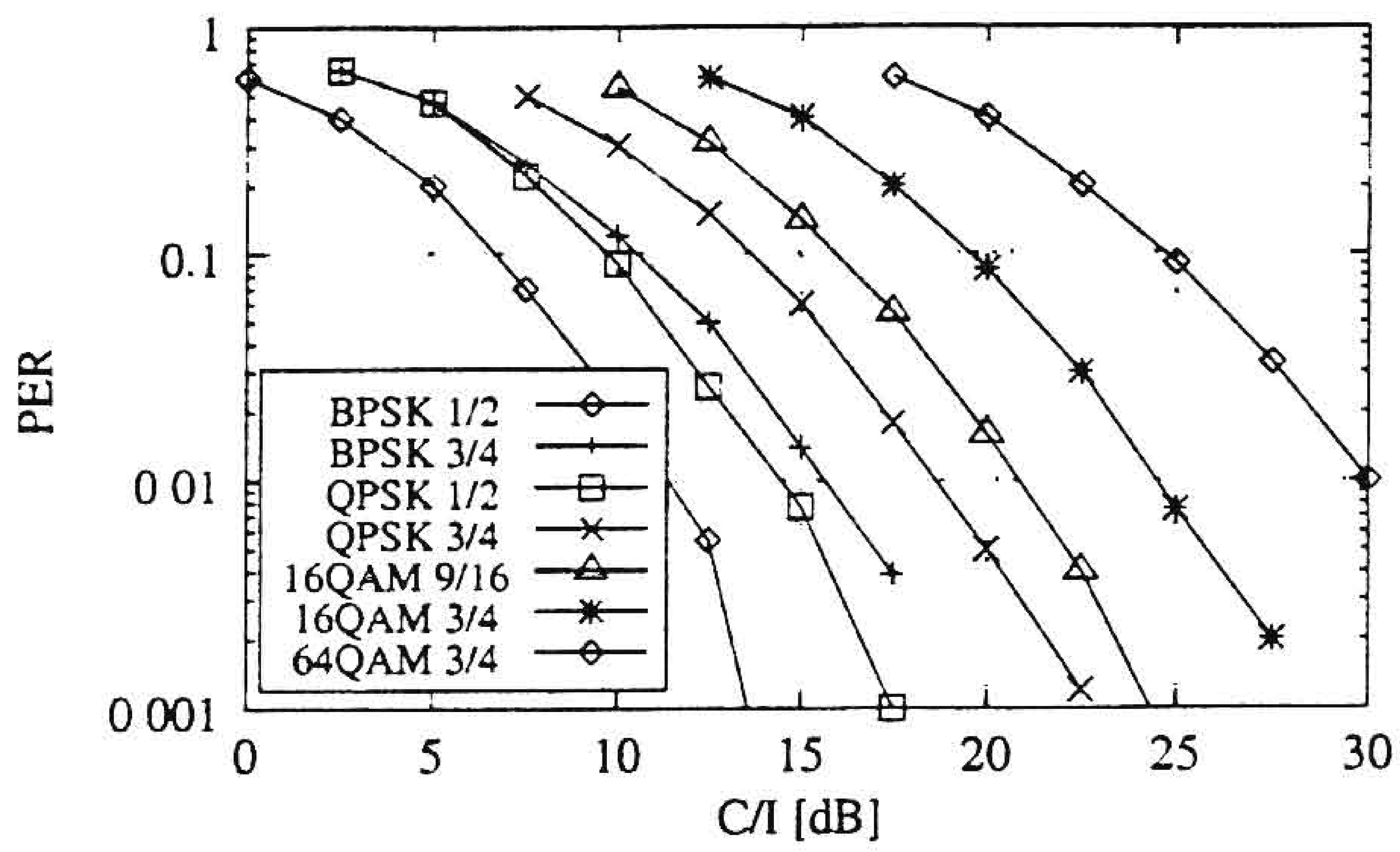

Fig. 15. PER versus C/I

λ is the used wavelength and d is the distance between sender S and receiver R. Antenna gains g_S for sender and g_R for receiver have been set to 1. The transmission power P_S was set to 200 mW and $\gamma = 4$. Based on the propagation model, the C/I per PDU transmitted is calculated also taking into account thermal receiver noise.

The PER has been evaluated for different PHY modes and C/I values in [29]. The results are shown in Fig. 15 and were used for the simulations to reflect C/I dependent errors.

V. Performance Characteristics of H/2

A. *Maximum Throughput Analysis of H/2*

The H/2 MAC protocol provides the flexibility to accommodate a large variety of MTs and connections on the one hand and different QoS requirements on the other. The actual data rate supported by the MAC protocol can be defined by an AP for each MT connection individually over time by defining the size of a PDU train and the PHY modes.

The MAC layer contains some protocol overhead that is considered in the following to calculate the throughput available on top of the MAC layer assuming a number n_{MT} of MTs active in a radio cell. In this calculation, the MTs use only one connection. The influence of a varying number of MTs and connections has been studied in [30].

By considering the static and dynamic lengths of the control channels and the PHY modes assigned (see Table 1), the length L of the MF phases (see Fig. 6) in a number of OFDM symbols can be calculated.

1) BCH: 15 bytes transmitted with the PHY mode BPSK 1/2 preceded by a preamble

$$L_{BCH} = 15/3 + \text{Preamble}_{BCH} = 9. \qquad (2)$$

2) FCH: variable in length built up from n_{MT} RGs transmitted in 27-byte blocks containing three RGs and a CRC-24 checksum with the PHY mode BPSK 1/2

$$L_{FCH} = 9 \cdot \lceil n_{MT}/3 \rceil . \qquad (3)$$

3) RCH: variable and determined by the number of RCH slots ($Slots_{RCH}$). Each RCH slot has the length of an SCH transmitted with the PHY mode BPSK 1/2 plus the uplink PHY Preamble

$$L_{RCH} = Slots_{RCH} \cdot 7. \qquad (4)$$

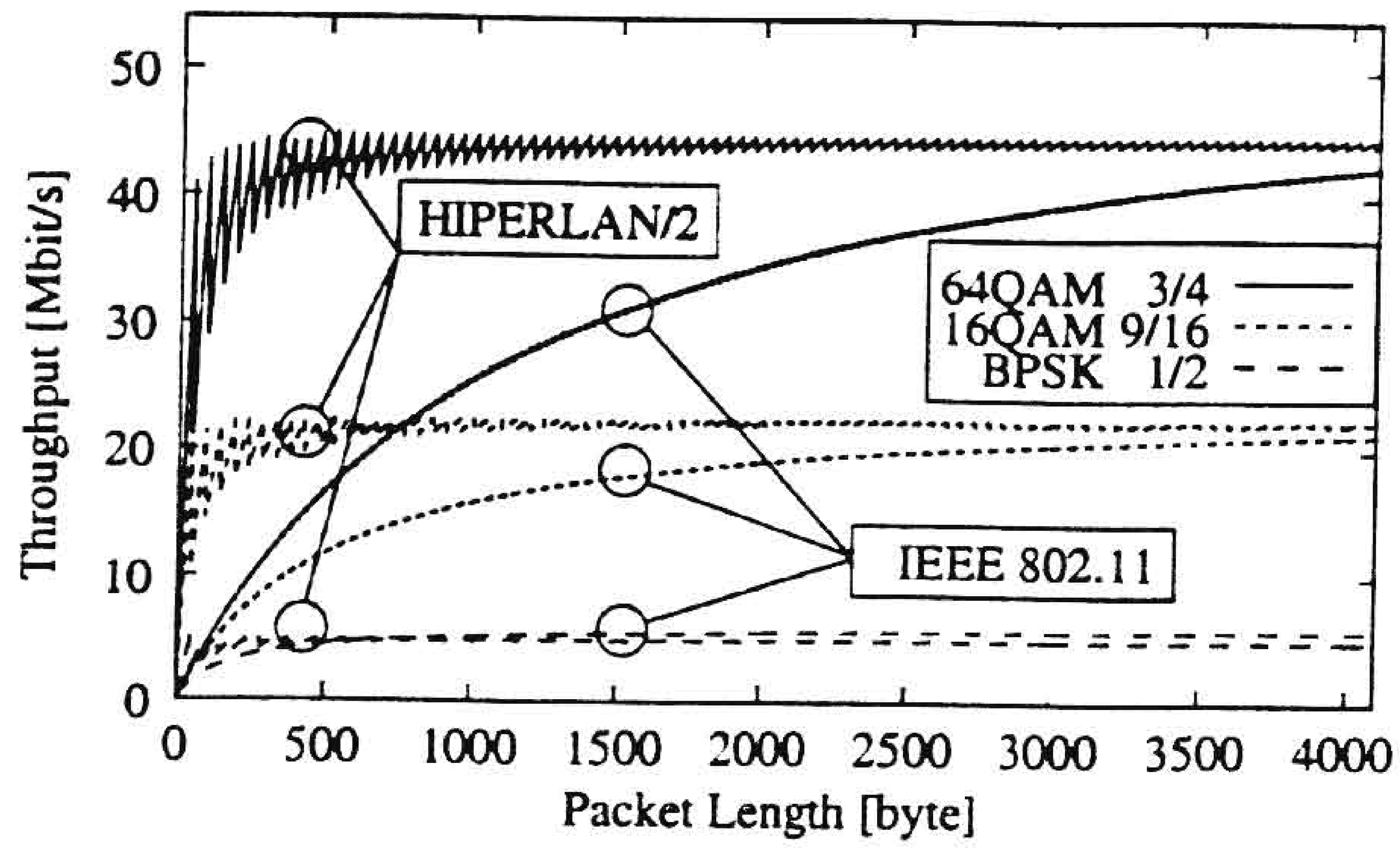

Fig. 16. Throughput over packet length.

4) ACH: fixed with a length of 9 bytes transmitted with the PHY mode BPSK 1/2

$$L_{ACH} = 3. \tag{5}$$

5) Uplink Phase: per connection served in an MF one SCH is granted in order to allow piggybacked resource requesting.

Assuming BPSK 1/2 for SCH symbol transmission and a PHY Preamble per PDU train

$$L_{UL} = n_{MT} \cdot (\text{Preamble}_{UL} + 3) = n_{MT} \cdot 7. \tag{6}$$

From (2)–(6) the number of OFDM symbols per MF to transmit user data via LCH PDUs can be calculated. With a length of 4 μs per OFDM symbol and a MF length of $t_{\text{frame}} = 2$ ms, 500 OFDM symbols are contained, in total giving

$$L_{LCH} = 500 - L_{BCH,FCH,ACH,UL,RCH}. \tag{7}$$

The total number of LCH PDUs (N_{PDU}) per MF is

$$N_{PDU} = \lfloor L_{LCH} \cdot BpS/54 \rfloor \tag{8}$$

with BpS giving the number of bytes coded per OFDM symbol. The maximum throughput is then given by

$$\text{Throughput} = N_{PDU} \cdot \frac{x}{\left\lceil \frac{x+4}{48} \right\rceil} \cdot \frac{8}{t_{\text{frame}}} \tag{9}$$

where x is the length of the user data packet in bytes. N_{PDU} depends on the PHY mode chosen and therefore on the available data rate. In (9), the overhead introduced owing to SAR to packets of 48 bytes in the CL is already included.

Fig. 16 compares the throughput over the packet length for H/2 and IEEE 802.11a for one MT [31]. The throughput of H/2 mainly depends on the SAR performance, whereas the throughput of IEEE 802.11a strongly depends on the packet length and the data rate.

B. Dynamic Performance of the H/2 DLC Layer

The results of Section V-A are derived for a quasi-static system, where a fixed number of MTs and connections are served per MF. Owing to the dynamic bandwidth requirements of broad-band applications, the amount of data to be transmitted for a specific MT may change from frame to frame. Furthermore, the scheduling strategy used in the AP determines the number of PDU trains granted per MAC frame. To analyze the H/2 performance under dynamic conditions, an event-driven computer simulation has been performed.

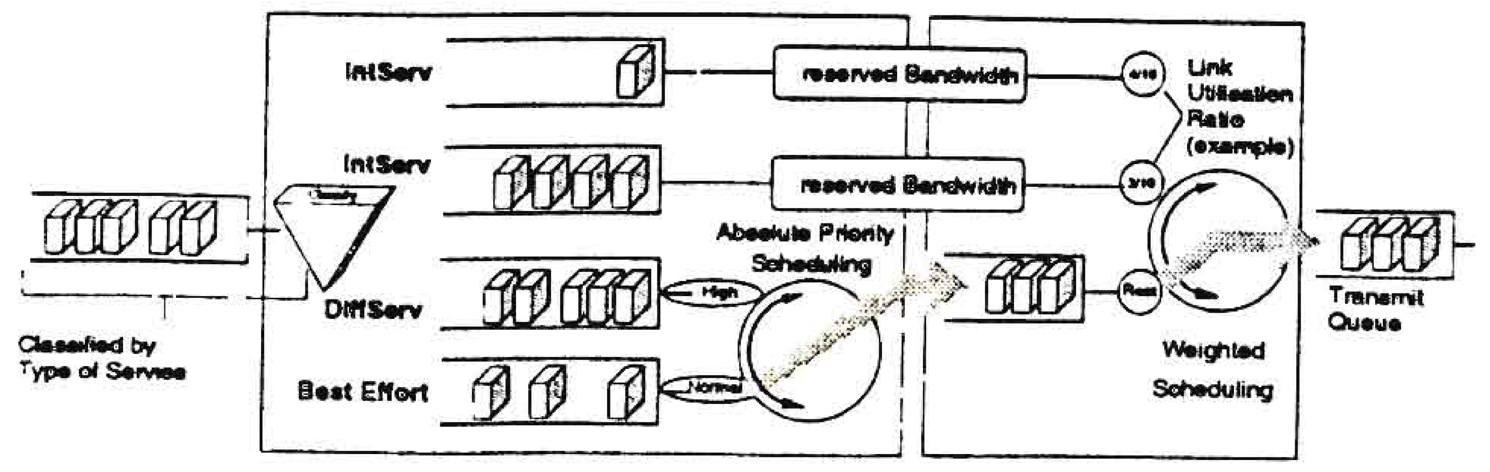

Fig. 17. Concept of IP QoS model scheduling

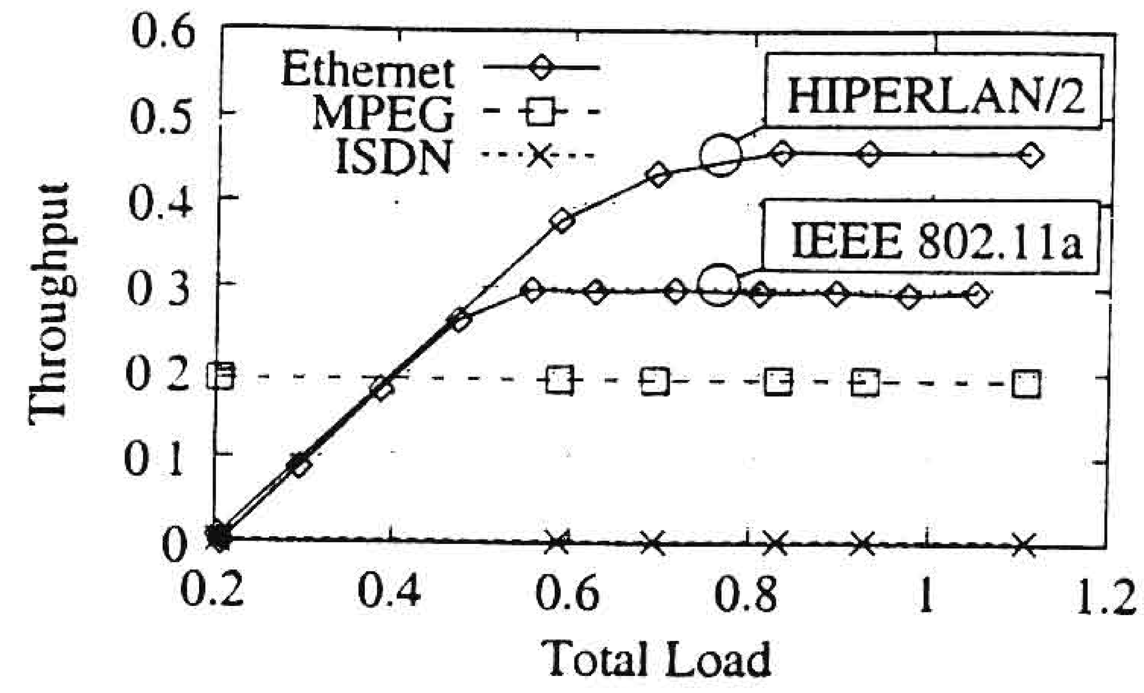

Fig. 18. Relative throughput of the traffic flows.

The scheduling algorithm considered here for dynamic performance analysis takes the different IP QoS service models into account (see Fig. 17): Best Effort, Differentiated and Integrated Services. To accommodate the various QoS requirements, a two-staged scheduling strategy is chosen. In the first stage, *Priority Scheduling* is performed for Best Effort and Differentiated Services classes with higher priority for the Differentiated Services classes. In the second stage, *Weighted Scheduling* is carried out where specific amounts of capacity are allocated for the Integrated Services traffic flows. The remaining capacity is used by the traffic resulting from the first stage. Call admission control takes care that sufficient resources are available for Differentiated Services traffic.

In the simulations, the scenario of the *Isolated H/2 System* described in Section IV-C has been used. H/2 MAC signaling PDUs, i.e., BCH, FCH, ACH, SCH, and RCH, use the PHY mode BPSK 1/2, whereas data PDUs, i.e., LCH, are coded with 16 QAM 9/16. The effort for ARQ and SAR is included in all the results for H/2.

First, the performance of H/2 is compared with that of IEEE 802.11a. The PCF of IEEE 802.11 with a *contention-free repetition interval* of 10 ms is used to serve the ISDN and MPEG services that are prioritized over the Ethernet service. The same prioritization has been applied for H/2. Fig. 18 shows the relative throughput of the different traffic flows where the load of the Ethernet service has been varied. In both systems, the prioritized services ISDN and MPEG are served comparably well under all load conditions, whereas the throughput for Ethernet traffic is significantly higher in H/2. This means that the effort to serve high-priority services in IEEE 802.11a is much higher than in H/2.

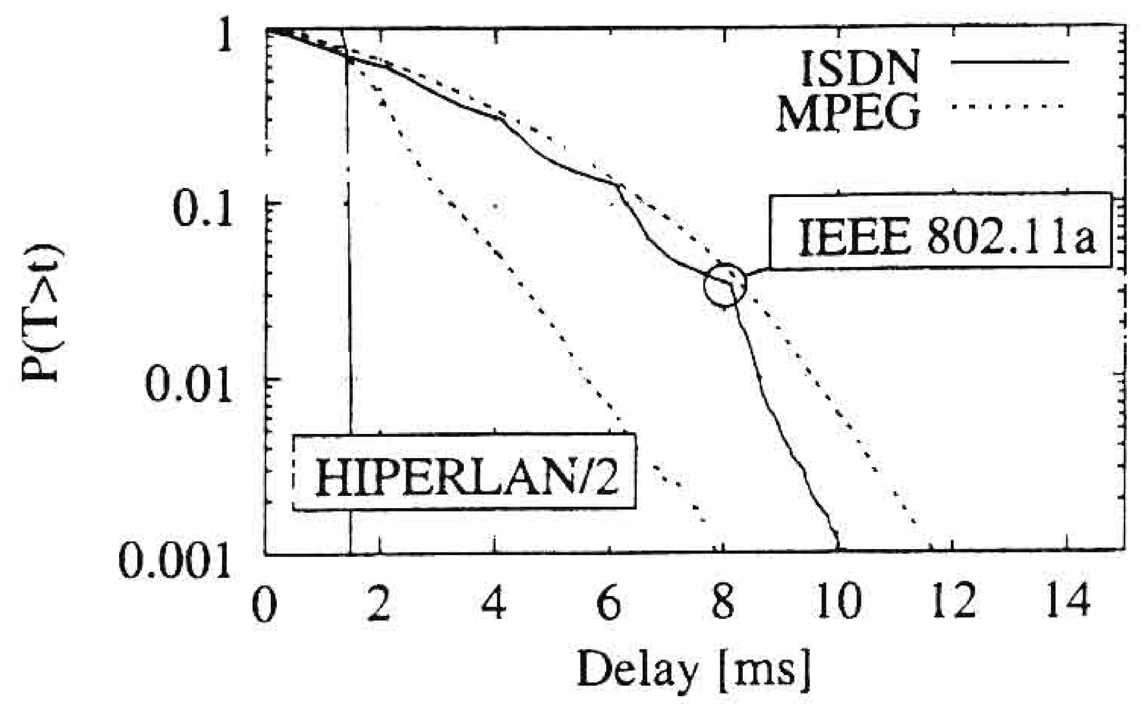

Fig. 19. CDF of the user packet delay

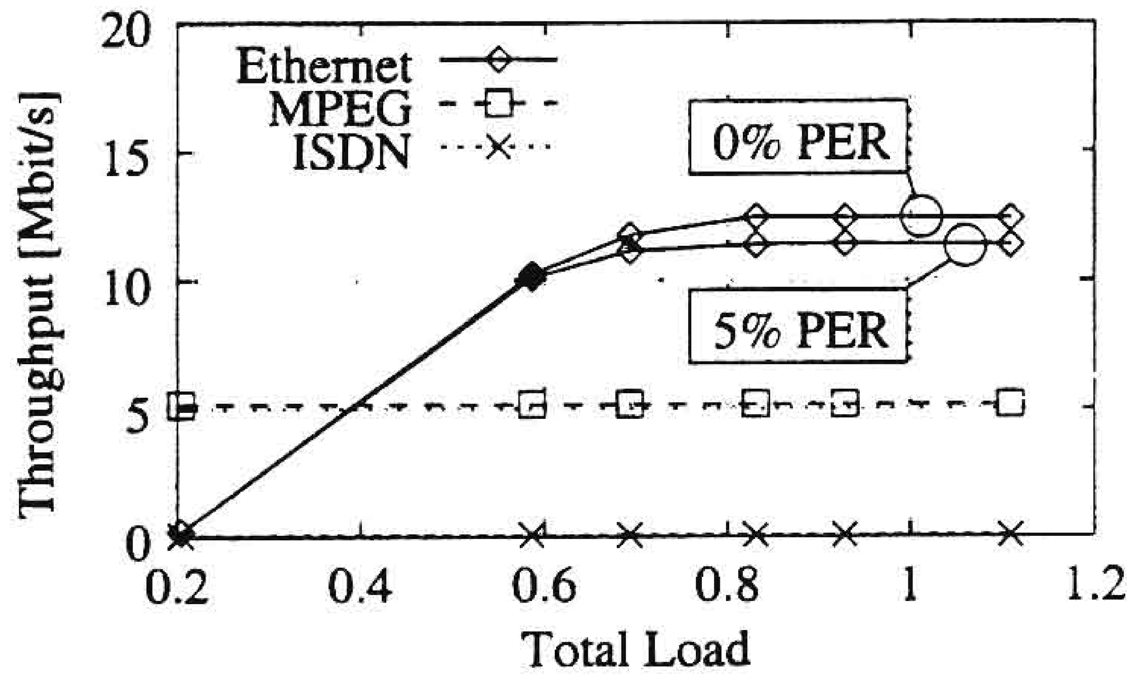

Fig. 20. Throughput of the traffic flows, with PER = 5%

To evaluate the grade of QoS support of the ISDN and MPEG services, the CDF of the packet delay at high-load conditions is shown in Fig. 19. Especially the packet delay of the ISDN service is bounded to 2 ms in H/2, whereas for 0.1% of the packets it goes up to 10 ms in IEEE 802.11a. The difference in packet delay for MPEG considering the 0.1% level is about 4 ms which underlines the superior QoS support of the H/2 system compared to IEEE 802.11a for an interference-free scenario. With co-channel interference, we have found that H/2 performs comparably well [28].

C. *Performance under Packet Errors*

The simulations have been repeated for H/2 with a C/I value of 17.5 dB that results in an average PER of 5% for LCH and no errors for the signaling PDUs (see Fig. 15). The throughput for the different traffic flows for a PER of 0% and 5% is shown in Fig. 20. It can be seen that the degradation in throughput is limited to the Ethernet service. It is on the order of the PER, i.e., 5%.

Fig. 21 shows the influence of packet errors on the packet delay; 5% of the ISDN packets need more than one transmission for a successful reception. This is comparable to the performance of an ideal *Selective Repeat* ARQ protocol as it is limited only by the loss of the data packets. The additional delay for the MPEG packets mainly results from the resequencing in the receive buffer and it is limited to 3 ms. Even under hostile conditions with a PER of 5%, H/2 enables a good QoS support. It has to be noted that for delay-sensitive services it may be better to choose a more robust PHY mode than that used in the simulations to meet the required QoS.

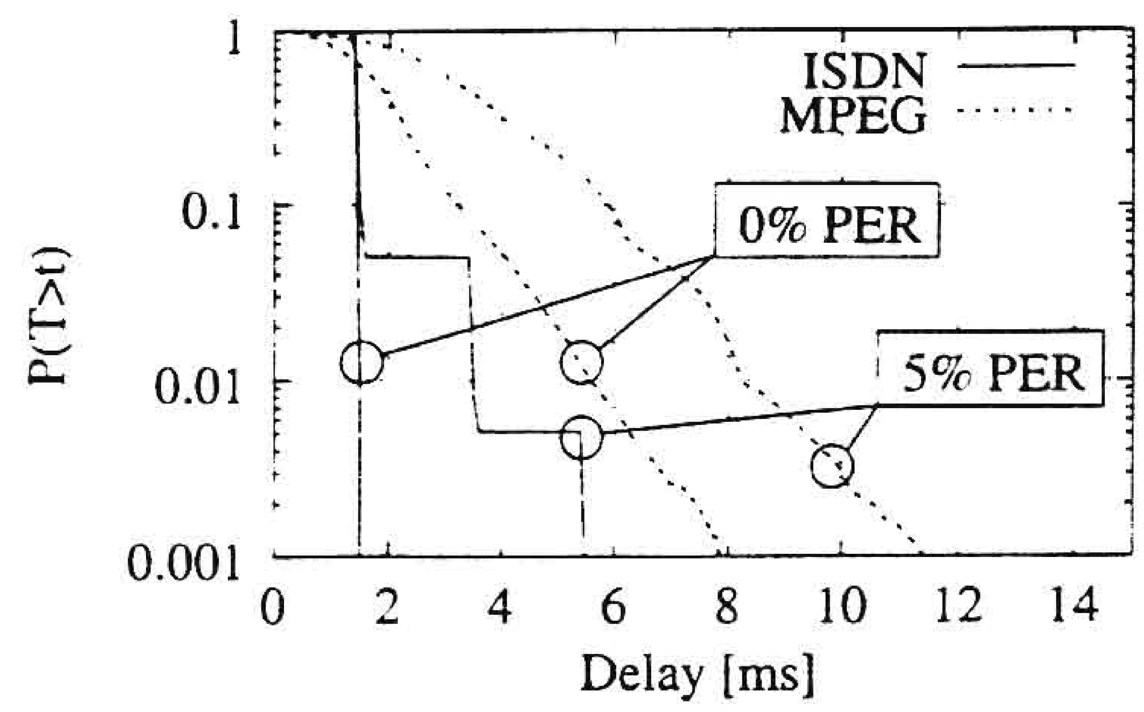

Fig. 21. CDF of the packet delay, with PER = 5%.

VI. Coexistence and Resource Sharing

A. *Frequency Sharing Rules for H/2 and IEEE 802.11a*

The guarantee of a certain QoS for wireless multimedia services is more complex if WLANs are sharing the spectrum rather than are operating in their own frequency bands [32]–[35]. As discussed in Section II-C, H/2 is likely to have to share the spectrum with other system types like IEEE 802.11a. H/2 specifies a centrally controlled air interface with a 2-ms MF (see Fig. 6). IEEE 802.11a, in contrast, applies CSMA/CA, an LBT scheme with variable packet lengths. For coexistence of the two standards, the following facts have to be noted. H/2 applies DFS and supports TPC. The IEEE 802.11a system keeps operating the same carrier once it has selected it and does not apply TPC nor DFS. Both systems use the same PHY protocols, carrier bandwidth, and apply LA, a flexible interference-dependent selection of a PHY mode. Based on these schemes, an FSR may allow operation in a common spectrum. An FSR defines techniques for radio channel management for the systems operating in a common spectrum and is not contained in the individual standards.

Results of a simple simulation scenario indicate the problems arising when H/2 and IEEE 802.11a operate simultaneously without applying any sharing rule. In Fig. 22, the throughput is shown of an IEEE 802.11a and an H/2 terminal when transmitting on the same carrier. The load to the terminals is varied between 0 and 20 Mb/s. Two configurations have been simulated for the IEEE 802.11a terminal, one where it is sending long packets of 2048 bytes without fragmentation and another one where it is sending short packets (48 bytes) only. No DFS, LA, or TPC has been simulated. For the long packets the H/2 CL applies SAR, while the short packets directly fit into the LCH PDUs.

It can be seen in the upper part of Fig. 22 for long packets with a small to medium load that the IEEE 802.11a scheme operates well and the H/2 does not. The reason for this is that the H/2 terminal is heavily interfered with by the long IEEE 802.11a packets that are sent after carrier sensing and after RTS and CTS since the packets are overlapping with the periodic BCH of H/2. Once the BCH of H/2 is corrupted, the related MF remains unused and no traffic can be carried there. If the traffic load to both systems is close to capacity, i.e., the H/2 frame is filled up well, the IEEE 802.11a system fails to operate and the H/2 system reaches nearly its optimum throughput. With short packets only (bottom part of

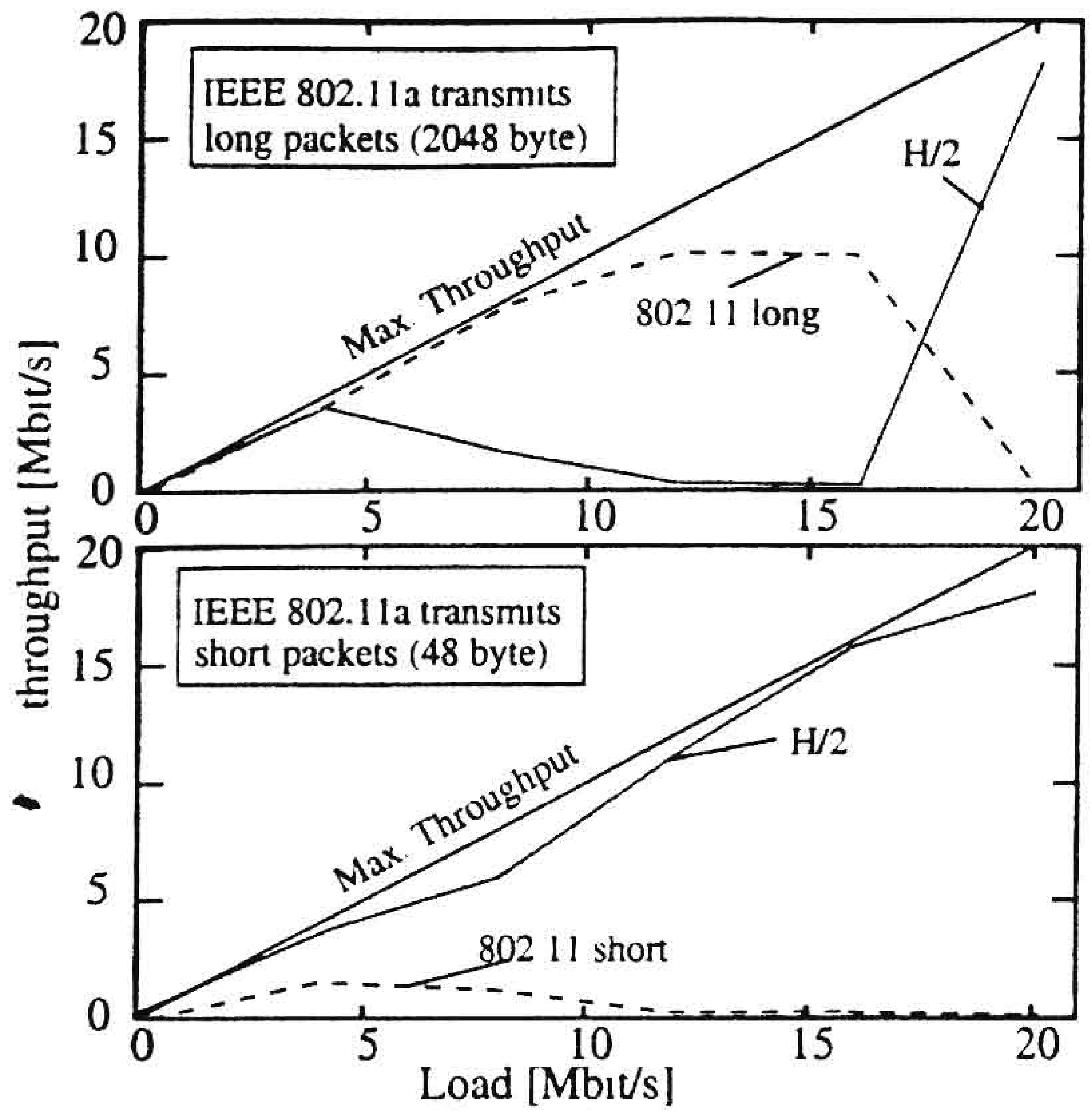

Fig. 22. Throughput of H/2 and IEEE 802 11a versus load

the figure), the H/2 system performs always close to its optimum, at the cost of the IEEE 802.11a throughput. This is owing to the fact that the BCH of H/2 is only rarely interfered with by IEEE 802.11a packets. The transmission period of a short IEEE 802.11a packet under low load fits into the parts of the H/2 MAC frame not used. From these preliminary results, it can be concluded that without appropriate sharing rules, the mutual interferences would lead to a poor QoS for both systems. A 5-GHz Industrial Advisory Group has been formed[1] that is developing coexistence supporting measures and respective improvements to the protocols of both H/2 and IEEE.11a.

Various coordination strategies across systems as well as QoS support strategies may be followed based on TPC, LA, and DFS. One possible way to protect H/2 against interference when sharing the spectrum with IEEE 802.11a is presented in the following.

B. *A Way to Guarantee QoS of an H/2 System Interfered with by an IEEE 802.11a System*

One method to allow real-time traffic in a spectrum-shared scenario with QoS guarantee is derived from Fig. 22 and is illustrated in Fig. 23.

In order to avoid the transmission of a competing IEEE 802.11a terminal on the same carrier in unused parts of the H/2 MF, LA is applied and an MCS is selected that fills up the MF as much as possible. If this measure does not suffice to fill the MF completely, the AP would broadcast system-related management information in unused parts of the MF to fill it completely and avoid an IEEE 802.11a terminal sensing the channel as free and starting its transmission.

Since some random access slots of the RCH might be unused in H/2 and could therefore motivate an IEEE 802.11a terminal to start transmission, the AP will transmit an NAK in an RCH slot as soon as it has detected it to be unused. No idle periods in the MF longer than the inter frame space of 34

[1]Send subscribe e-mail to listserv@list hwdev net to receive the actual discussion contributions

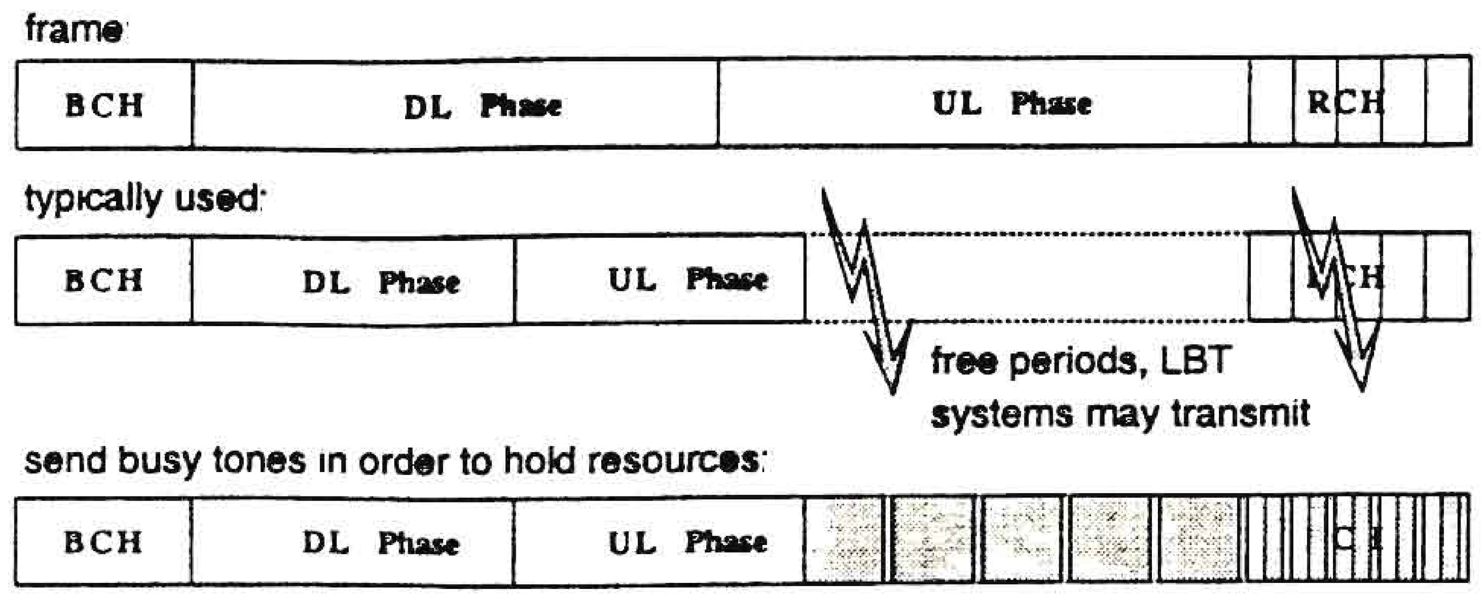

Fig. 23. Interference protection by filling up the H/2 MAC frame.

μs necessary for starting a transmission of an IEEE 802.11a terminal should occur (Distributed Coordination Function Inter Frame Space DIFS = 34 μs) to avoid an IEEE 802.11a system interfering with H/2 during intervals where H/2 is aiming to guarantee QoS for real-time traffic.

Apparently, a system that is contracting services to users with a QoS guarantee must be able to apply measures to keep a resource it had at the time it contracted the service. The only way to reach that goal is to occupy the resources for the duration of the service, e.g., to protect it against unpredictable interference by another system.

VII. *Ad Hoc* Networking Concepts with H/2

The communication between home devices including the support of IEEE 1394 is another purpose of H/2. The HEE specifies an *ad hoc* network configuration to allow plug-and-play operation [10]. The concept of central control of the air interface has been kept but is now performed by a CC, a terminal that has been assigned this role *ad hoc* in a decentral way. The direct mode is here the normal way to exchange data between mobile terminals in unicast, multicast, or broadcast mode.

A. *Ad Hoc Definition of CC*

An H/2 HEE network is controlled by a CC instead of an AP. *CC Selection* is a decentrally operating algorithm to select a terminal to coordinate transmission of terminals in its neighborhood (see Fig. 24). The CC function, in general, is available from so-called CC-capable terminals only.

The CC Selection algorithm ensures that within one subnet only one CC is established and is performed in a decentralized and autonomous way by each CC-capable terminal when powered on or when the CC has been lost. A CC-capable terminal, in general, aims to be an MT and to associate to an existing CC. Therefore, it scans the available carrier frequencies to find an operational CC to associate to it. If the association procedure fails, e.g., because the detected CC belongs to a foreign subnet, scanning is continued. If no CC has been found, the dynamic CC Selection algorithm is continued.

CC Selection of a terminal has a fixed duration T_{CC}. A CC probing terminal alternates probes and scans. These probing and scanning phases together form *Probing Periods* (see Fig. 25).

Each probing phase is subdivided into *Probing Frames* where a CC-capable terminal sends one so-called beacon signal per Probing Frame to inform other terminals about

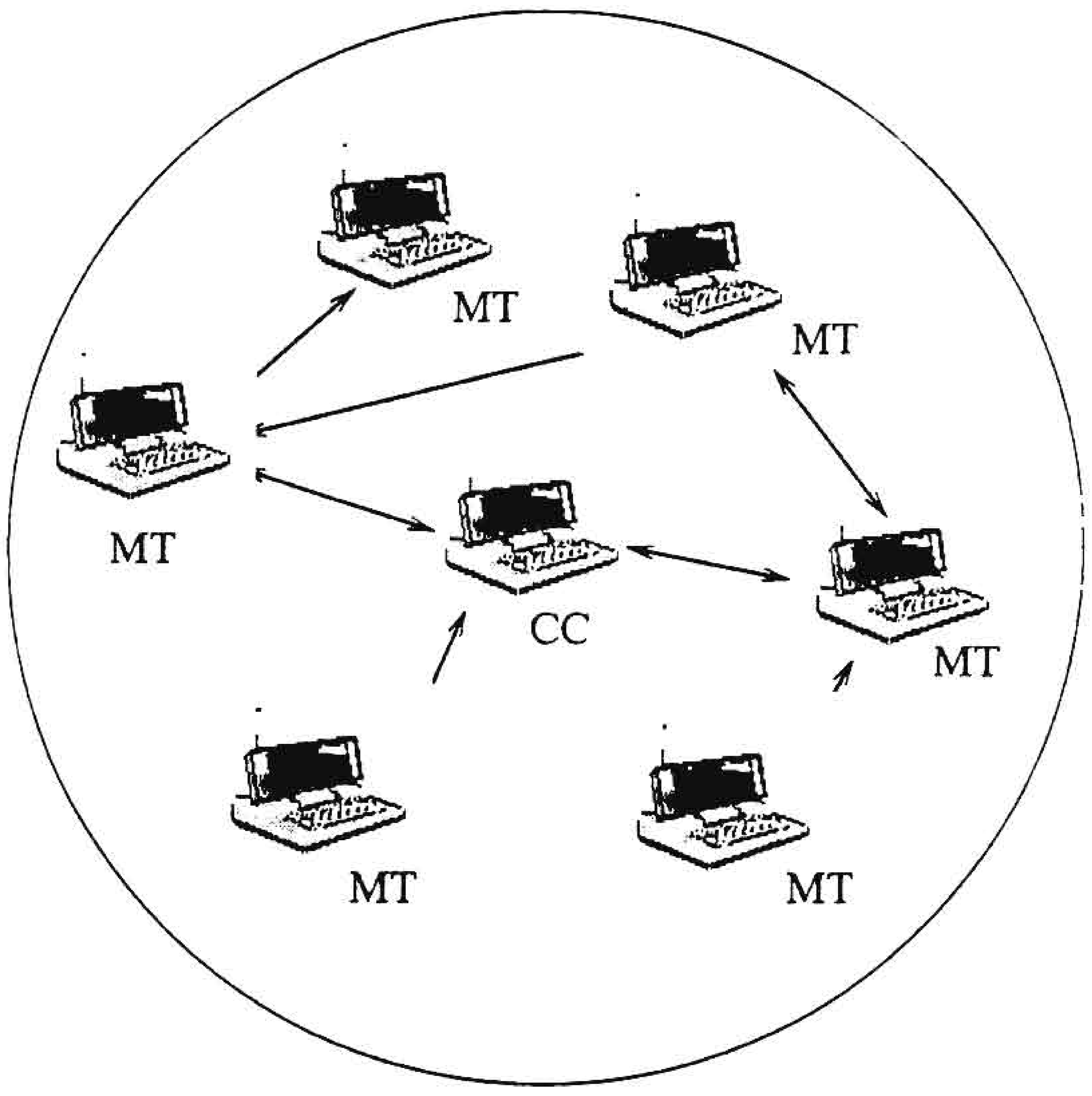

Fig. 24. *Ad hoc* subnetwork topology.

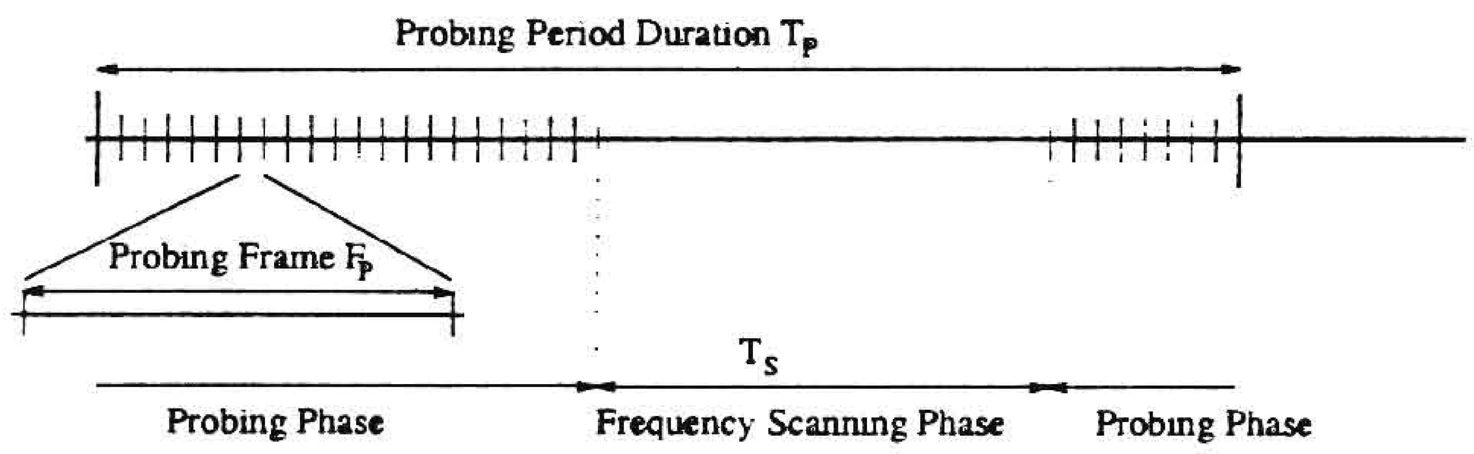

Fig. 25. CC probing period of a CC-capable terminal

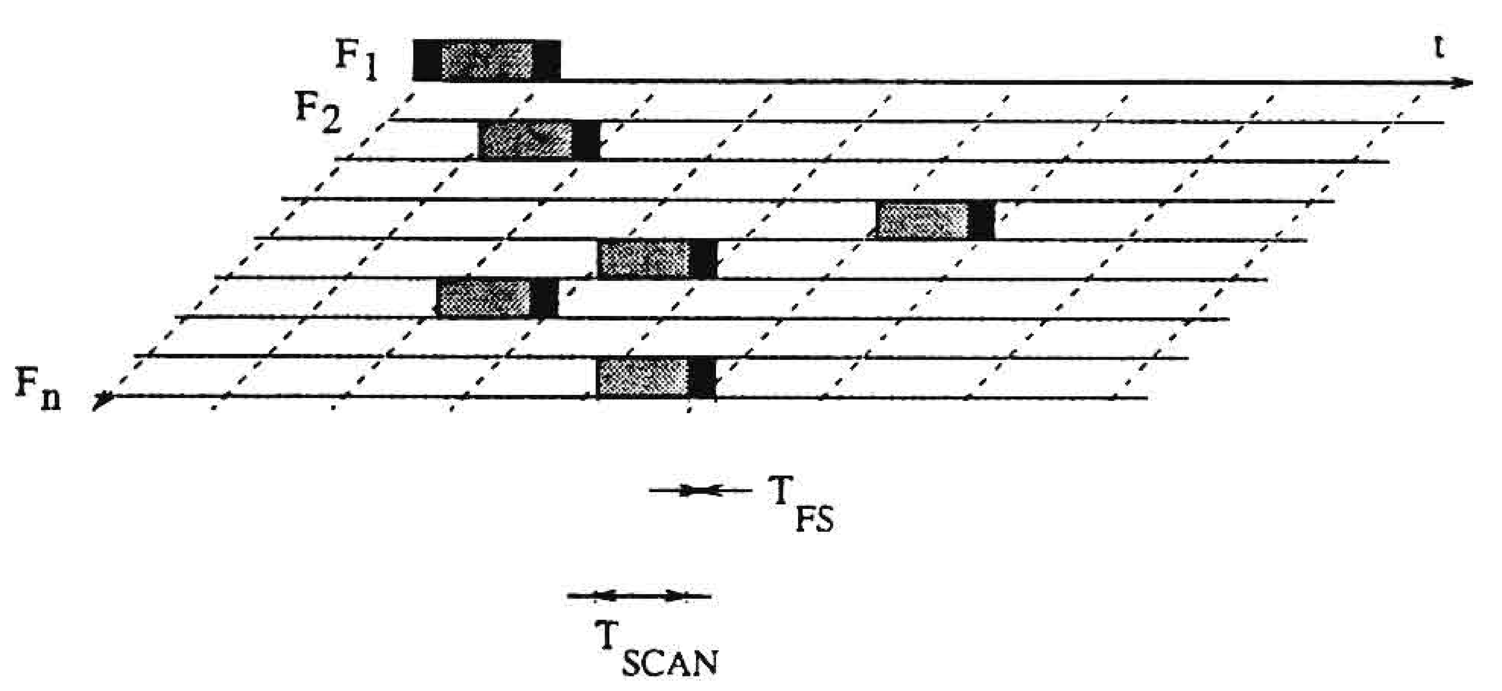

Fig. 26. Frequency scanning

its existence. In order to avoid collisions, the transmit time of the beacon is determined randomly. Since a probing terminal operates on one frequency channel for a whole probing phase, the probability of two terminals probing on the same frequency and not hearing each other is close to zero.

During frequency scanning, a terminal searches for further terminals probing on other frequency carriers. Fig. 26 shows the frequency scanning phase T_S (see also Fig. 25) performed within a Probing Period of length T_P. A CC-capable terminal scans all available frequencies for beacons. The *Frequency Switching Time* T_{FS} is the maximum time to change a frequency channel and is defined to be 1 ms [7]. The *Frequency Scanning Time* T_{SCAN} determines the duration a CC-capable terminal scans one frequency channel for a beacon. After having scanned a frequency, the CC-capable terminal switches to the next frequency in random order.

The performance of the CC Selection algorithm is characterized by the probability P_m that after a duration T_{CC} there are multiple CC-capable terminals deciding they have to be the CC. The probability P_m can be reduced significantly

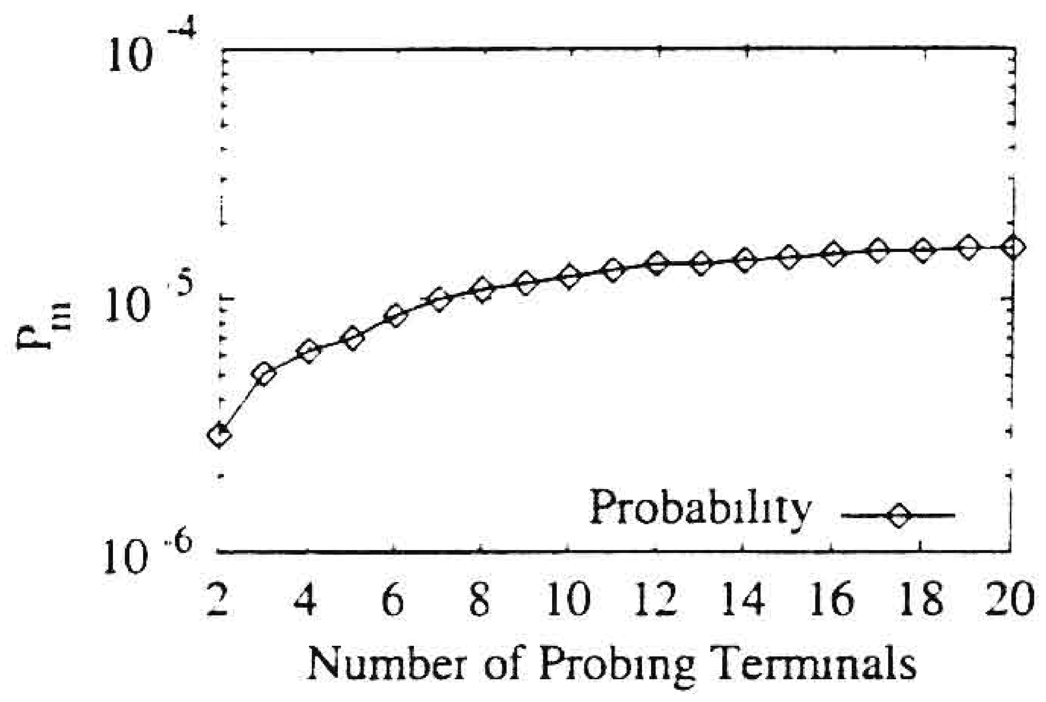

Fig. 27. Probability for more than one CC in the same subnet

if probing and frequency scanning phases are repeated N_P times within T_{CC}. To avoid synchronized and steadily overlapping scanning phases of different probing terminals, the start of a frequency scanning phase is determined randomly.

Each CC-capable terminal that senses a beacon immediately withdraws from CC Selection, starts a back-off to await the result of the CC Selection algorithm of the other terminals, and then starts its initial scan process again to find an operational CC.

1) Performance of CC Selection: The probability P_m has been calculated to evaluate an optimum set of parameters and the results have been validated by simulation [36]. For the parameters specified in H/2 ($T_P = 100$ ms, $T_S = 37$ ms, $N_P = 10$, $T_{CC} = 1$ s), a probability P_m of $\approx 10^{-5}$ is achieved as shown in Fig. 27. This probability has been found to be acceptable for home users.

B. CC Handover

Handover of a CC will become dynamically necessary during operation owing to:

- switch-off of a current CC;
- power constraints of a CC;
- bad connectivity of one or multiple terminals.

Instead of relying then on the CC Selection algorithm described in Section VII-A, which is time consuming, a handover procedure has been specified.

The *CC Handover* procedure as described is part of the H/2 HEE standard. It is transparent to the MTs in the network in the sense that the data transfer on the MAC layer goes on without interruption. The process only involves the control plane of H/2 in the RLC protocol. A CC Handover either is initiated by the current CC itself or proposed by any MT in the subnet. Then, the CC selects a terminal known to be CC capable and sends a request to it. Upon a positive reply from the CC candidate, all MTs are informed about the forthcoming CC Handover and all other RLC procedures are stopped to freeze the RLC data in the CC and not allow connections to be established with the old CC.

The data to be transmitted from old CC to new CC comprise data related to all associated MTs (like MAC ID, MT capabilities, etc.). To maintain ongoing Direct Link connections between MTs, all connection-specific RLC parameters have to be transmitted, too. A question arises whether MAC data of the different MTs supervised by a CC should be transmitted as well. These MAC data would mainly consist of information related to MT RRs of the past.

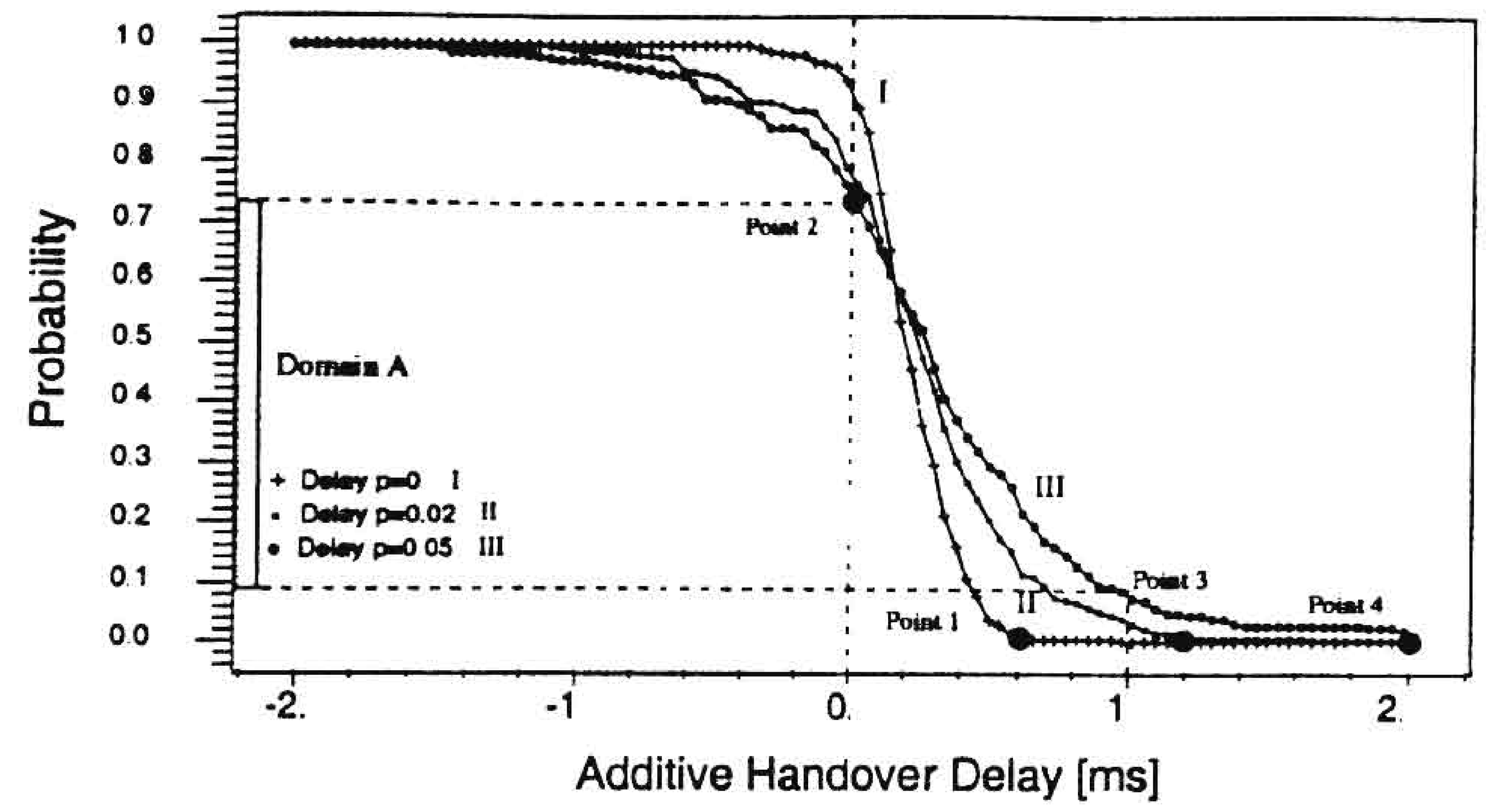

Fig. 28. DF of additive delays with polling of MTs compared to global database.

Alternative strategies to build the MAC database in the new CC may be applied. One possibility would be to permanently maintain a database in the CC-candidates. As a reference scenario, we assume that the database is available already in the new CC. To approach this situation as close as possible, a CC candidate should build its own database by listening to RRs of MTs transmitted in the frames before a CC Handover. As it is uncertain whether a CC candidate is able to receive all MTs owing to the applied power control in HEE, an alternate solution is analyzed here. We assume that the CC polls all MTs by granting them an SCH PDU (see Fig. 7) in the first frame after CC Handover to transmit their RRs and an LCH PDU for immediate data transmission. The DF of the resulting additive delay compared to the ideal solution with a global database (no delay) is shown in Fig. 28 for PERs of 0%, 2%, and 5% in a scenario with three MTs. It is obvious that for an error-free channel the cell delay with polling is always longer than with a global database (see curve I). The maximum additional delay is 0.6 ms (point 1). With a PER of 2% or 5%, negative additional delays can be found with some probability. For a PER of 5%, the probability of a shorter delay with the polling solution is 28% (point 2). This results from the fact that after CC Handover LCH PDUs are granted to MTs that did not yet send out an RR. These MTs save the time to send out an RR and to wait for the RG. The maximum additional cell delays for PERs of 2 and 5% amount to 1.2 ms (point 3) and 2 ms (point 4), respectively. For a PER of 5%, the additional delay lies in-between 0 and 1 ms with a probability of 70% (domain A).

These results show that the QoS degradation owing to CC Handover can be kept in small limits by polling all MTs in the next MF after CC Handover.

After successful transmission of the RLC data from the old CC to the CC candidate, the old CC indicates to the new CC the frame to take over BCH and FCH responsibility thereby providing a seamless CC Handover. The new CC in turn informs the MTs about the successful completion of the handover, thereafter other RLC procedures can be restarted.

VIII. H/2 and Adaptive Antennas

The H/2 infrastructure-based system as described in Section II also specifies sector antennas at an AP and specifies broadcast phases per sector in a common MAC frame as an option.

A. The Spatial Dimension

Cellular radio systems make use of the spatial dimension by reusing frequencies at geometric intervals determined by the propagation attenuation [5]. The use of a smart array antenna opens up the spatial dimension within the single radio cell and permits, together with advanced signal processing techniques, the use of true SDMA. This access technique allows different users on the same frequency at the same time. The ability to set up multiple antenna beams that can be directed to the MT locations adaptively, leads to an increase in capacity and reduces signal interference. In the following, we discuss the use of ULA antennas consisting of M identical antenna elements.

Mainly two spatial signal processing algorithms are required to enable SDMA: Spatial filtering separates the signals impinging on the antenna array during receptions, and beamforming algorithms control the radiating directions of the array during transmission. Subsequently, we describe and evaluate a proposed concept for a joint TDMA–SDMA approach that nicely fits into the H/2 system:

- 5-GHz frequency band: Permits compact construction of array antennas for AP deployment.
- TDD: Information gathered at the uplink channel soon after supports downlink beamforming on the same carrier.
- MF duration (2 ms) is typically shorter than the channel coherence time. Spatial parameter estimation is needed less frequently which reduces the computational load.
- Reservation-based MAC protocol: Permits a flexible transmit capacity allocation considering QoS requirements and the actual packets pending.
- ARQ error recovery at the radio interface: Provides fast retransmission in cases of transmission errors and inaccurate parameter estimation.

Owing to its flexible structure and its versatile signaling abilities, the H/2 MAC protocol can easily be extended to meet additional requirements imposed by space–time processing. Fig. 29 shows a possible MAC frame structure considering the spatial dimension, reflected by the parallel use of transport channels and a pilot tone phase introduced to support accurate uplink spatial parameter estimation [37]. The pilot tones might be omitted and parameter estimation might take place during concurrent uplink reception. This will reduce the probability of successful reception since estimation accuracy will degrade owing to increased interference power present during reception.

B. Space–Time Scheduling

For an SDMA system, the scheduling is a two-dimensional problem. The scheduler has to determine the temporal transmission sequence of MAC PDUs as well as the MTs that can simultaneously be addressed or can be allowed to concurrently transmit their bursts. The applied algorithm is called space–time scheduling. Based on temporal input parameters

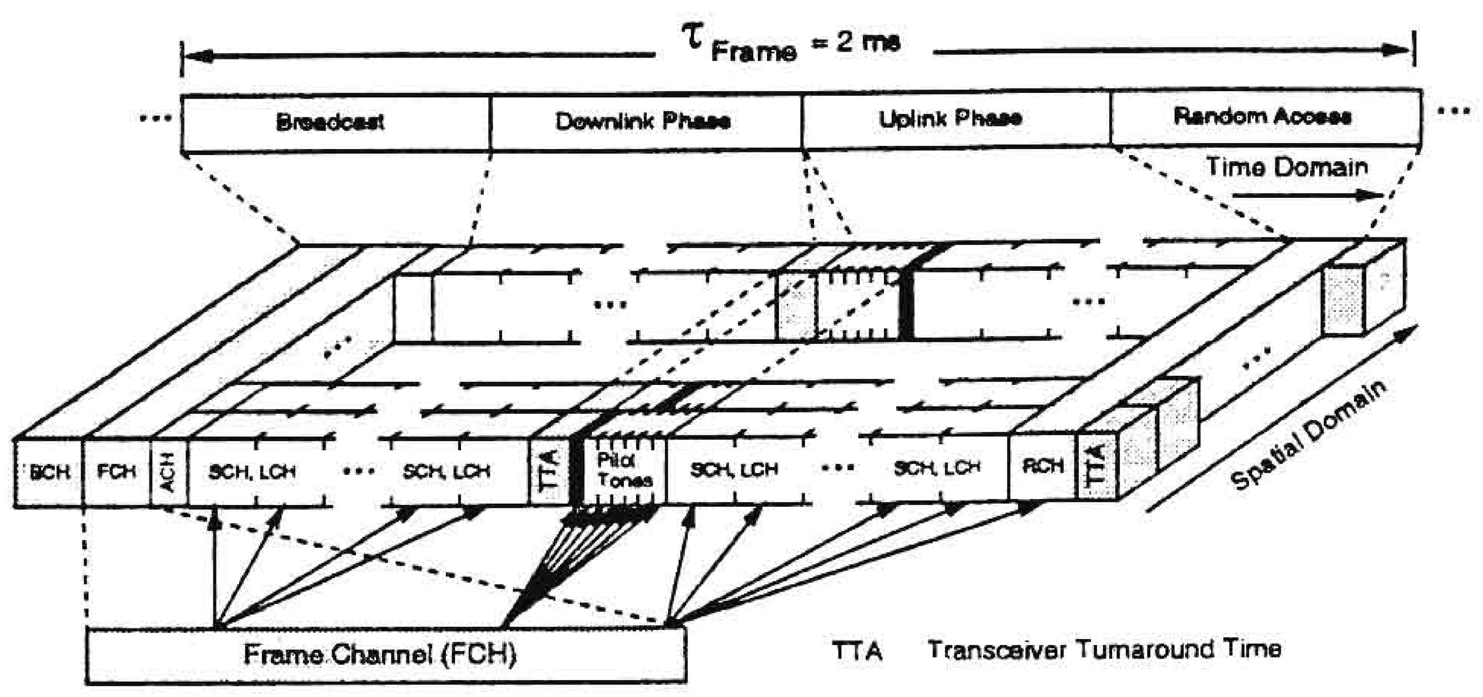

Fig. 29. Spatially extended H/2 MAC protocol frame

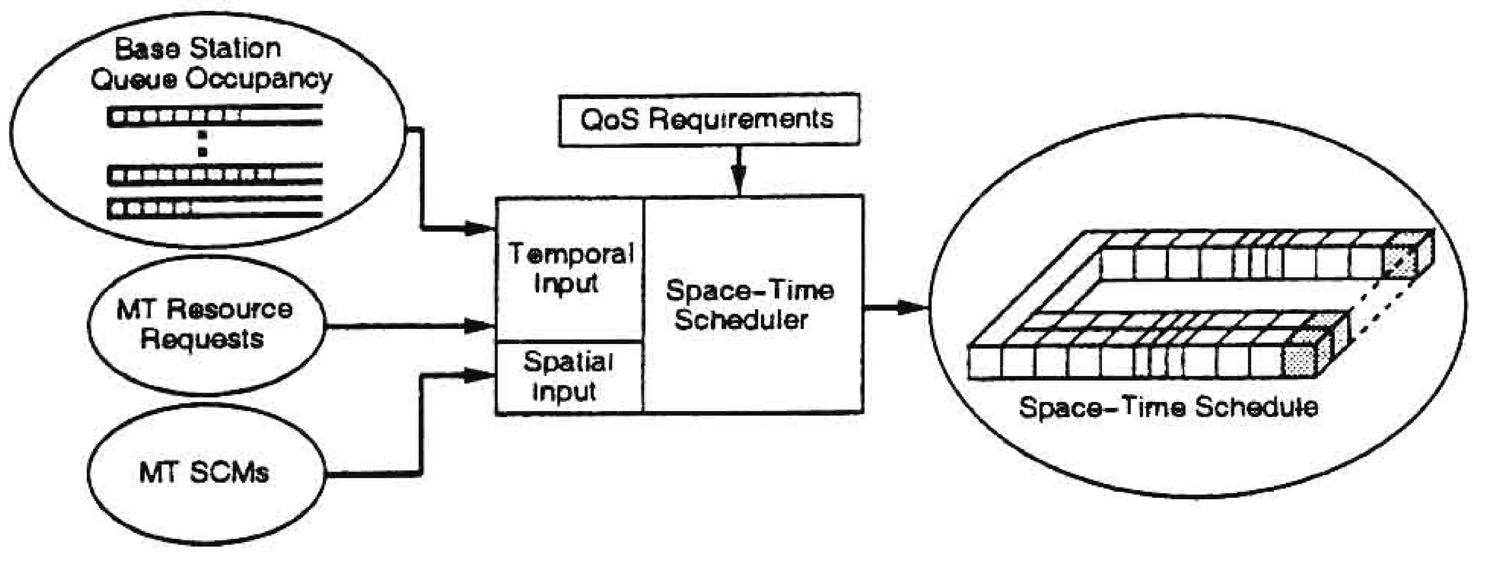

Fig. 30. Space–time scheduling meeting QoS requirements

like queue occupancy at AP and RRs received and on spatial input parameters, the algorithm determines the transmission and reception schedule obeying the agreed QoS requirements (Fig. 30).

1) Uplink Scheduling: The most intuitive space–time scheduling approach for the uplink is to fix an upper threshold number of concurrently transmittable MAC PDUs per time slot and to schedule the MAC PDUs with decreasing temporal priority. Then it is the task of the receiver signal processing algorithms to spatially separate the concurrent signals. The maximum number of concurrently transmittable MAC PDUs equals the number K of MTs operating in the system. The actual number of uplink MAC PDUs can be adjusted to meet the desired system dynamic obeying the downlink transmission needs and the MAC frame length of 2 ms.

A more sophisticated scheduling approach incorporates additional knowledge about the individual MT positions. By tracking these positions and monitoring the reception success, the scheduling algorithm can try to find spatially compatible groups of MTs that increase the mean number of successfully received bursts.

Both approaches are limited by the reception capabilities of the antenna system, i.e., it makes no sense to allow simultaneous transmission for more MTs than the spatial filtering algorithm is theoretically able to separate, while multipath propagation reduces the successful signal separation even further. Another limiting factor is the interference power. If the interference exceeds a certain threshold because too many MTs are transmitting simultaneously, it becomes impossible to separate any signal at all. Therefore, another objective of the scheduling algorithm is to split up transmission constellations on the time axis that cannot be separated in space.

2) Downlink Scheduling: Space–time scheduling on the downlink may be based on the due dates or other parameters of MAC PDUs in the MT-specific AP queues and on spatial information gathered on the uplink during the last MAC frame. Knowledge of the spatial channel characteristics offers the possibility to group MTs, which are suited for concurrent reception of MAC PDUs. Sets of concurrently transmittable MAC PDUs for the same time slot in the MAC frame transmitted into different directions have to be defined obeying the constraint that the interference power has to be kept below a level γ. Thus, all sets whose elements cause less than γ as interference power at each other set element, are considered to be spatially compatible.

C. Random Access and SDMA

The number of concurrently receivable signals is restricted by the antenna system and is interference limited. With an increasing number of simultaneously transmitting MTs, the C/I decreases and a correct reception of a burst becomes less likely. The present interference situation depends on the number of simultaneous transmissions, the MTs' positions, and the channel characteristics. Since no further restrictions can be imposed on the initial access to the RCH, i.e., the interference situation could not be taken into account, some MTs might not succeed in transmitting via the RCH. To control the retransmission attempts of these collided MTs, a collision resolution algorithm has to be applied that can make use of the enhanced reception capabilities. Thus, the transmission of RRs will benefit from an increased throughput and a reduced delay. In H/2, MTs may use the RCH to transmit their RRs to the AP. Especially for delay-sensitive services, this access should be carried out as fast as possible, i.e., the collision resolution algorithm has to be optimized for short delays, while throughput becomes a second-order optimization criterion. Collision resolution algorithms incorporating SDMA have been evaluated (e.g., Slotted ALOHA in [38] and splitting algorithms in [39]).

D. Performance Evaluation

Bit-level simulations were performed based on a stochastic directional scattering channel model parameterized for a picocellular indoor multipath propagation environment. In all simulations, a ULA with 12 antenna elements and interelement spacing of $\lambda/2$ was used. The unitary ESPRIT algorithm with Spatial Smoothing was used. Table 2 gives the mean E_k of the number of MAC PDUs successfully received by the AP on the uplink. A detailed description of the simulation scenario can be found in [37].

The number of MTs allowed to transmit their bursts simultaneously has been set to k and the MT positions have been chosen at random, equally distributed within the coverage area of the AP antenna. No further spatial evaluation of the MT constellation was considered.

The values clearly show the limitation of the signal resolution capabilities of the antenna system, since the number of successfully received bursts only slightly increases for more than $k = 4$ MTs. For more than six MTs, the values are decreasing despite the fact that the number of signals offered to detect has increased. The useful signal energy is corrupted by the additional intra cell interference. This effect shows the interference limitation. A performance evaluation of the

Table 2
Successfully Received MAC PDUs

k	E_k	k	E_k	k	E_k	k	E_k
1	0.994	3	2.605	5	3.193	7	3.079
2	1.926	4	3.000	6	3.194	8	2.973

downlink space–time scheduling algorithm was performed with $k = 6$ MTs under heavy traffic load. The probabilities of a successful reception and the exploitation of the available spatial channels have been evaluated as a function of the interference threshold γ. The logarithmic values of γ relate to the normalized transmission power $S = 1$.

Fig. 31 clearly underlines the tradeoff between a large probability of correct MAC PDU reception and efficient use of the $k = 6$ theoretically available spatial channels. These results encourage the idea of adapting the spatial exploitation of the available time slot to the QoS requirements of the service the PDUs to transmit belong to. On the uplink, a low threshold for the number of concurrently transmitting MTs could be applied for time-critical PDUs, while for nonreal-time services the schedule could be optimized for full spatial exploitation, i.e., throughput. The same applies for the downlink. In addition, here the parameter γ controls the interference situation. A small value for γ, which stands for a nearly perfect spatial compatibility, is suitable for real-time-oriented services, whereas a large γ leads to the desired high throughput especially of interest for nonreal-time-oriented services with the drawback of low reception probabilities. Aiming at very low delays, a very high probability of a successful transmission is achieved by scheduling a MAC PDU in an exclusive time slot, although the additional capacity of the spatial dimension is lost then. Together with position tracking of the MTs, more elaborate scheduling algorithms will permit a further increase in efficiency, while obeying the delay constraints of real-time services.

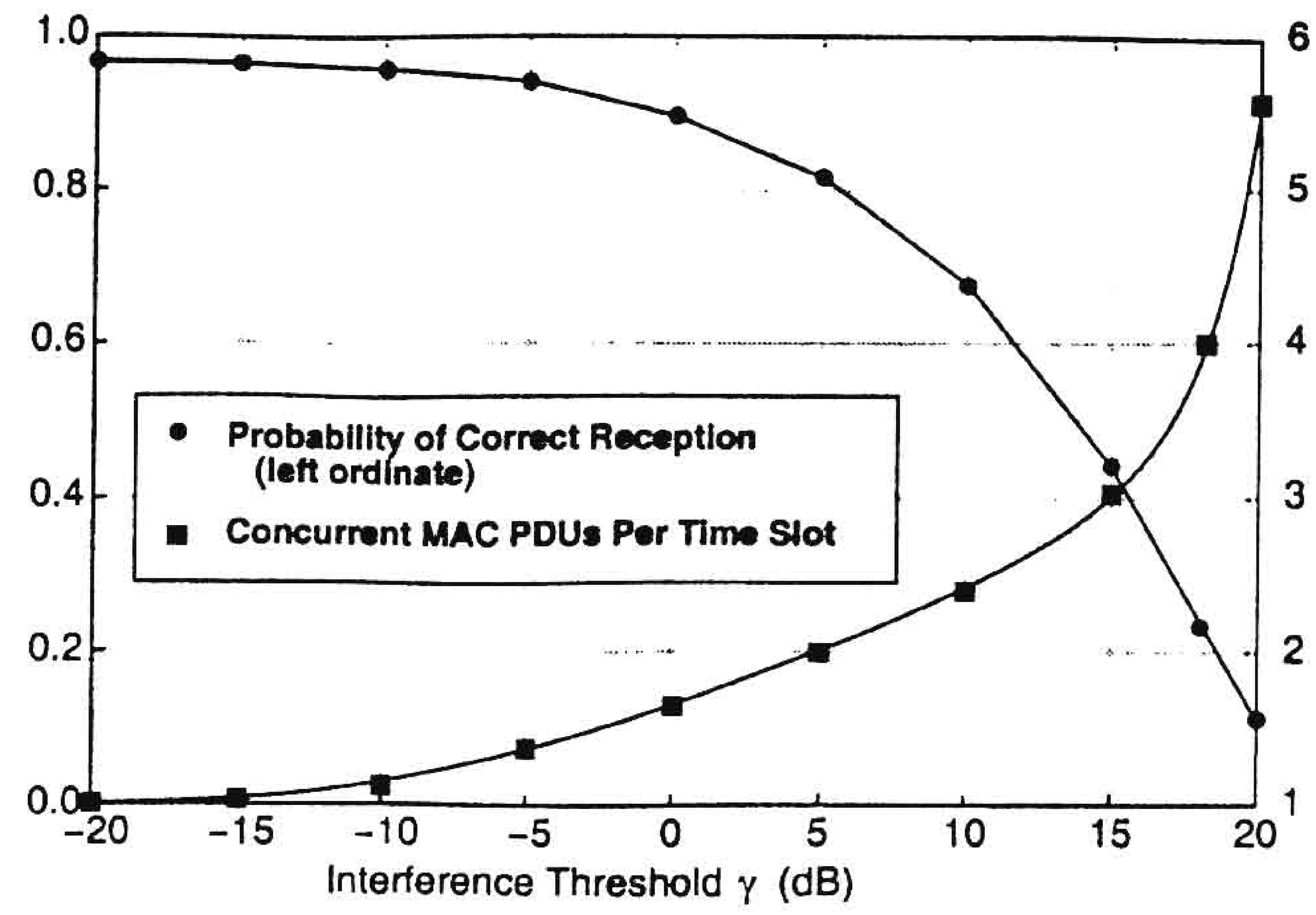

Fig. 31. Successful reception and spatial exploitation for $k = 6$ MTs.

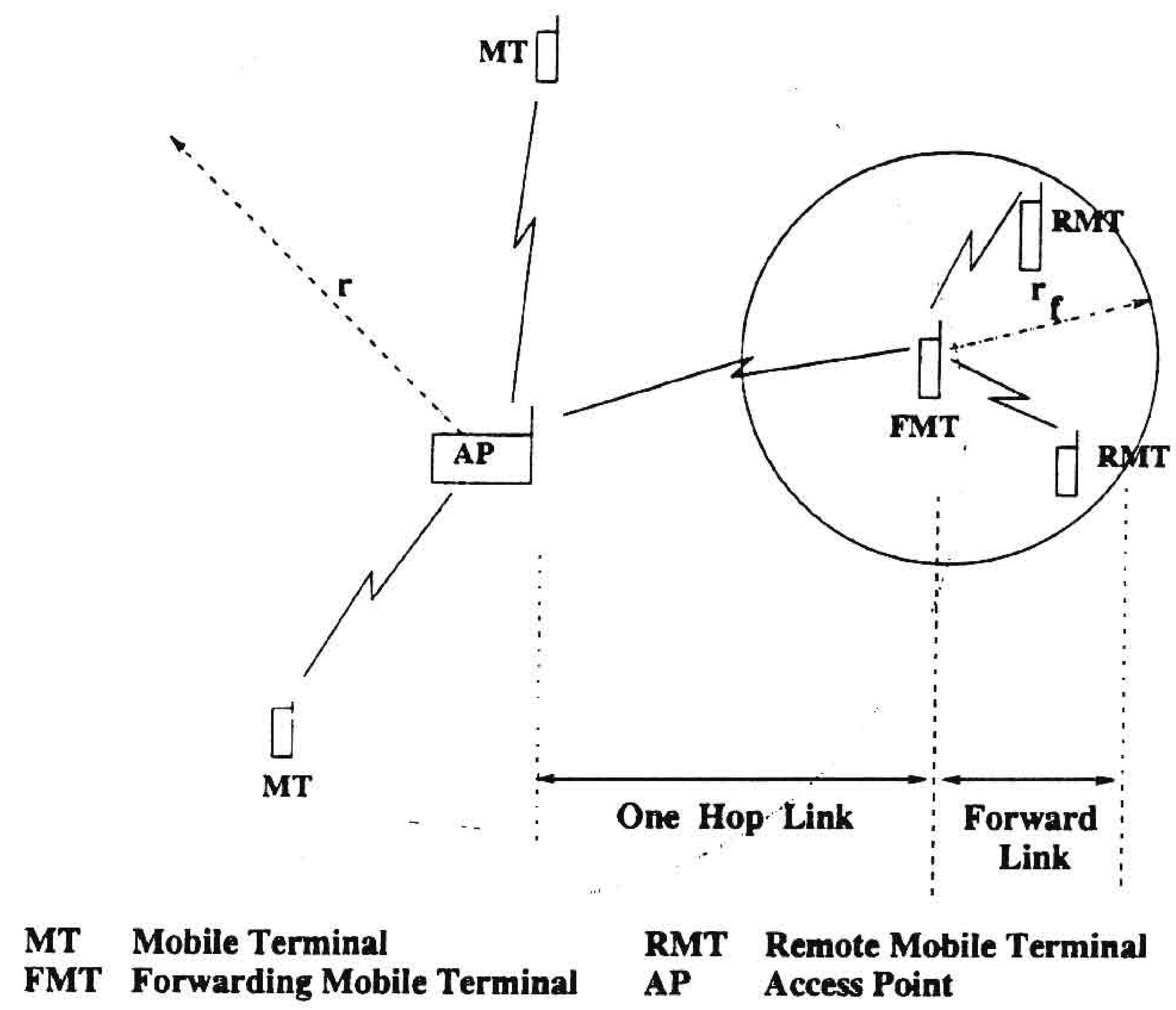

Fig. 32. Wireless base station scenario.

IX. H/2 Wireless Base Station Concept

In the following, we introduce a so-called FMT to enhance the communication range of an AP.

The typical forwarding scenario presented in Fig. 32 generally applies to outdoor and indoor/office environments. The RMT is an MT that cannot communicate directly with the AP on the *One-hop Link* but needs a forward link for two-hop communication. The term *Remote* differentiates it from a normal MT that is connected to the AP over the one-hop link. An MT associated to the AP via the one-hop link and located at the edge of the AP coverage area may perform the function of a forwarder and is thus named *Forward Mobile Terminal.* Since the edge of the AP coverage area depends on the PHY mode used, a new dimension is introduced into the H/2 world by the FMT to further improve spectrum efficiency and to complement the service coverage area. The FMT concept is applicable to the H/2 HEE standard, too.

A. Forwarding in H/2

There are a number of possibilities for forwarding within the H/2 system. The concepts are depicted in Fig. 33:

I) One-hop links and forward links operate on different frequencies.

II) The links are separated in time on a time-sharing basis.

III) A combination of I) and II). The FMT uses a frequency different from the AP, but also shares some parts of the frequency of the one-hop link on a time-sharing basis.

In the following, the time-based concept II) is further explained and investigated, as it enables the entire system to use synchronized subnets able to support well-defined QoS parameters. This concept needs only one transceiver per FMT keeping its cost quite low.

1) MAC SubFrame: A possible implementation of the time-shared forwarding concept with little change in the existing H/2 specifications of MT and AP is shown in

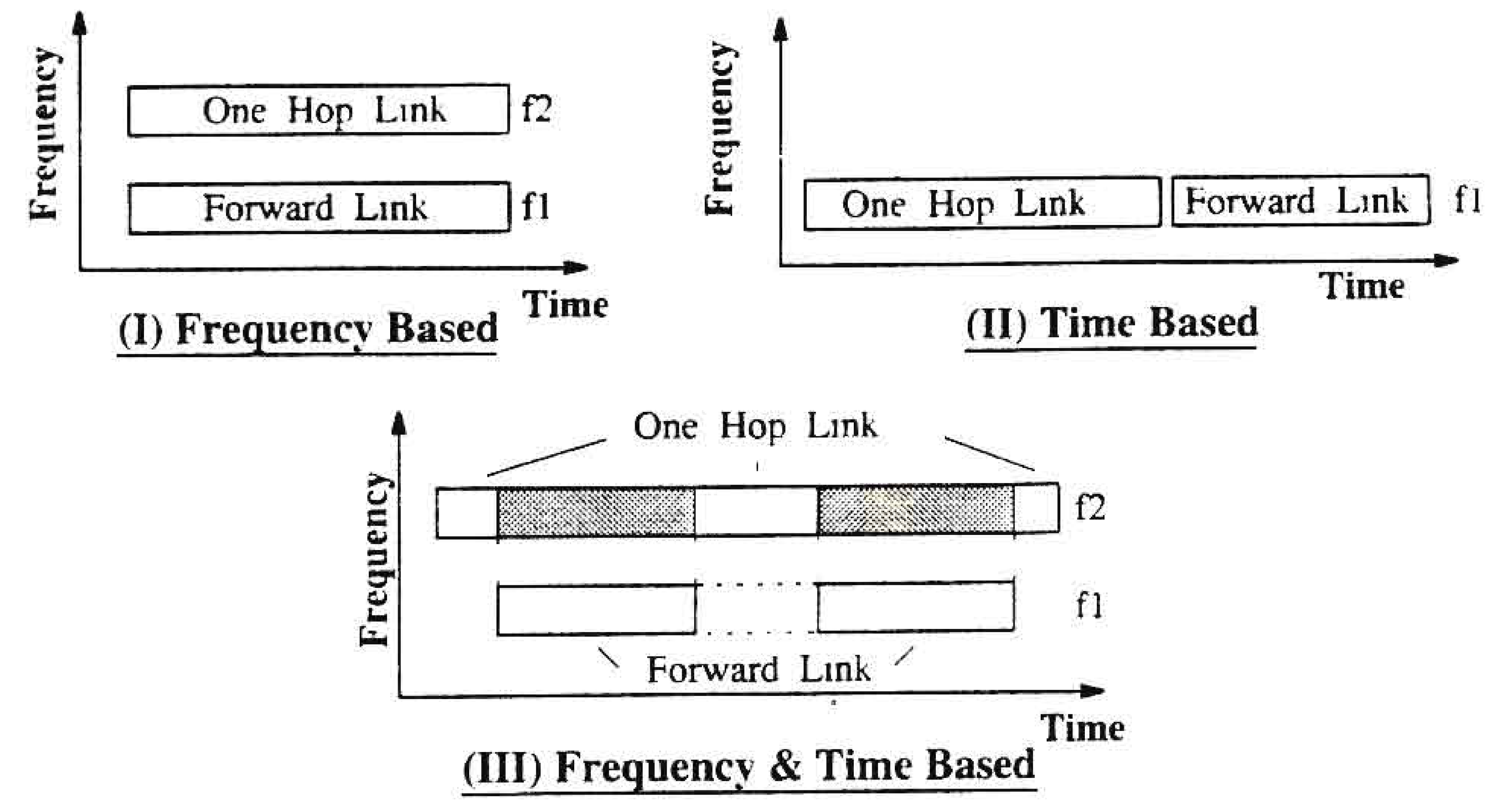

Fig. 33. Forwarding concepts in time and frequency domains

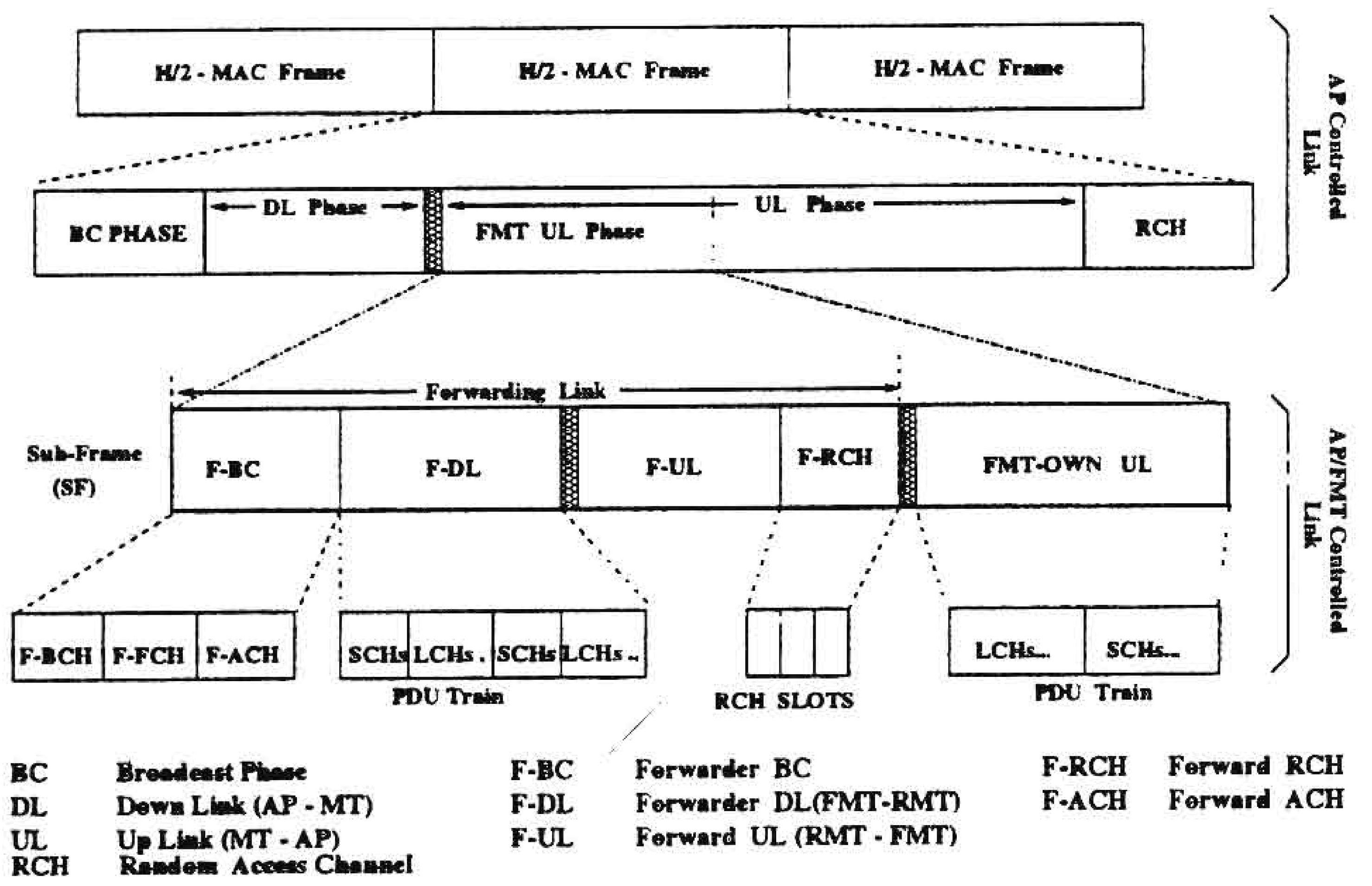

Fig. 34. Forwarding MAC SubFrame structure.

Fig. 34. A normal MT is modified to become an RMT but is still able to receive a H/2 MF.

The MAC SF in Fig. 34 is the key element of the new forwarding concept. The SF is being generated by the FMT to communicate with the RMTs associated to it. The UL phase capacity assigned to the FMT in the MF is exploited by the FMT to define an SF and to transmit its own UL traffic if any.

The structure of the SF is similar to that of the MF and the SF is nested into the MF so that an MT can operate on both frames when working as an FMT. Further, an MT that temporarily is served as an RMT needs little modification of its protocol software (see below). Since MTs synchronize to the AP via the BC phase, this phase has to be logically forwarded by the FMT to its associated RMTs. This phase is called F-BC Phase in the SF. Other phases of the SF appear to be exactly the same in structure as in the MF. Thus, during the F-DL phase, the FMT transmits the data packets to one or more RMTs and receives uplink data from RMTs during the F-UL phase.

The number of *Random Access Slots* in the F-RCH may be small compared to the standard MF, because of a smaller number of RMTs associated to an FMT than MTs to an AP.

The SF is supervised by a scheduler located in the FMT. An FMT transmitting the SF will be received by the AP but only the uplink of the SF is accepted by the AP while the other parts are ignored.

The data flow in the FMT is handled in queues that decouple the data flow between conventional and forwarding links.

2) *Design Aspects:* The forwarding concept is aimed at offering an acceptable performance for throughput, delay, and other QoS parameters.

The radio resources requested by an FMT will naturally be more than that of an MT, as the FMT generates RRs to the AP for the SF including F-BCH and F-RCH phases, its own UL data, and the data of the associated RMTs. This fact has to be reflected in the strategy adopted for the RGs in the AP.

There are two basic strategies to handle RGs in systems with FMTs:

- AP-controlled concept: The AP has knowledge of the SFs used to provide forwarding links and is able to take the respective resources into account. This concept would need to change the H/2 specification in many ways.
- FMT-controlled concept: The AP has no knowledge of an FMT and its SF used for forwarding. This concept fits into the H/2 system with minor modification only to the AP and requires a small modification of one part of the MT specifications. The MT has to search for the BCH Phase immediately after the end of the RCH phase.

In the following, the FMT-controlled concept is further explained, as it has a minimum implication to existent H/2 specifications. Since the SF is controlled by the FMT, it is acting for the RMTs as an AP, and for the AP, both RMT and FMT are seen as MTs. The AP is not aware of the forwarding link. An RMT is connected to the AP via a two-hop link consuming approximately twice the capacity of a one-hop link.

The UL phase granted to the FMT is *rescheduled* by the FMT into an SF and its own UL phase. The FMT has its own scheduler and other routines to handle the SF management. The RGs received for the SF from the AP depend on the scheduling strategy there.

It is easy to understand that the proposed forwarding scheme can be recursively applied. An RMT could also be used as a remote forwarder to connect a far remote terminal via the RMT and it is serving FMT to the AP, etc. Besides point-to-point communication, the forwarding concept is especially beneficial for multicast and broadcast applications since no capacity appears to be wasted then through the multihop transmission.

B. *Traffic Performance*

To verify the FMT concept and to study the impact of FMTs on the QoS parameters, transfer delay, and system throughput, simulation studies have been carried out.

In the simulation scenario of Fig. 35, some MTs were placed out of the range of the AP to act as RMTs that are associated to FMTs. The FMTs are directly associated to the AP. Both FMTs and RMTs are assumed to have one MAC connection each. Six FMTs and six RMTs are grouped together in the example scenario around the AP.

The simulator has been loaded with a mix of constant, Poisson, and video traffic sources.

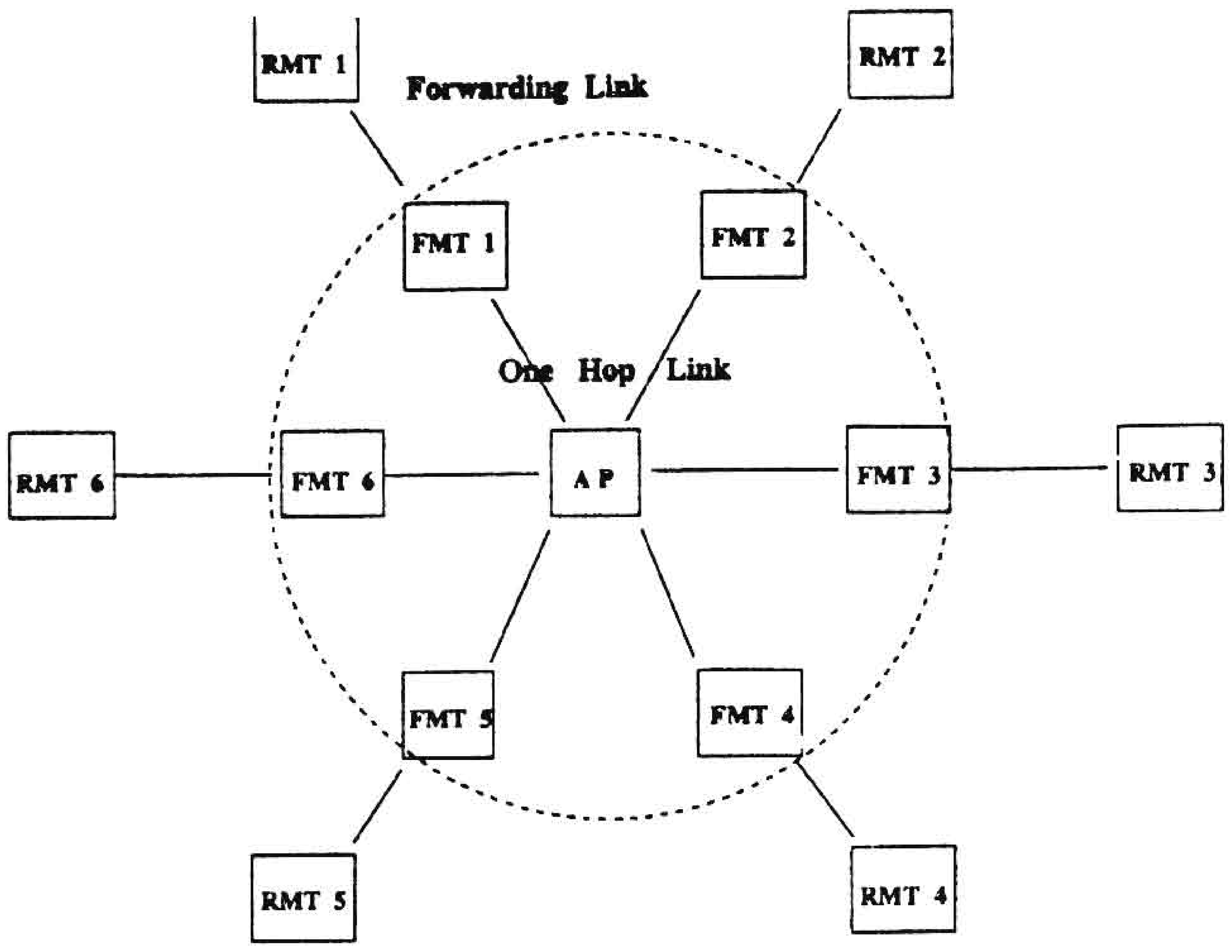

Fig. 35. Scenario setup.

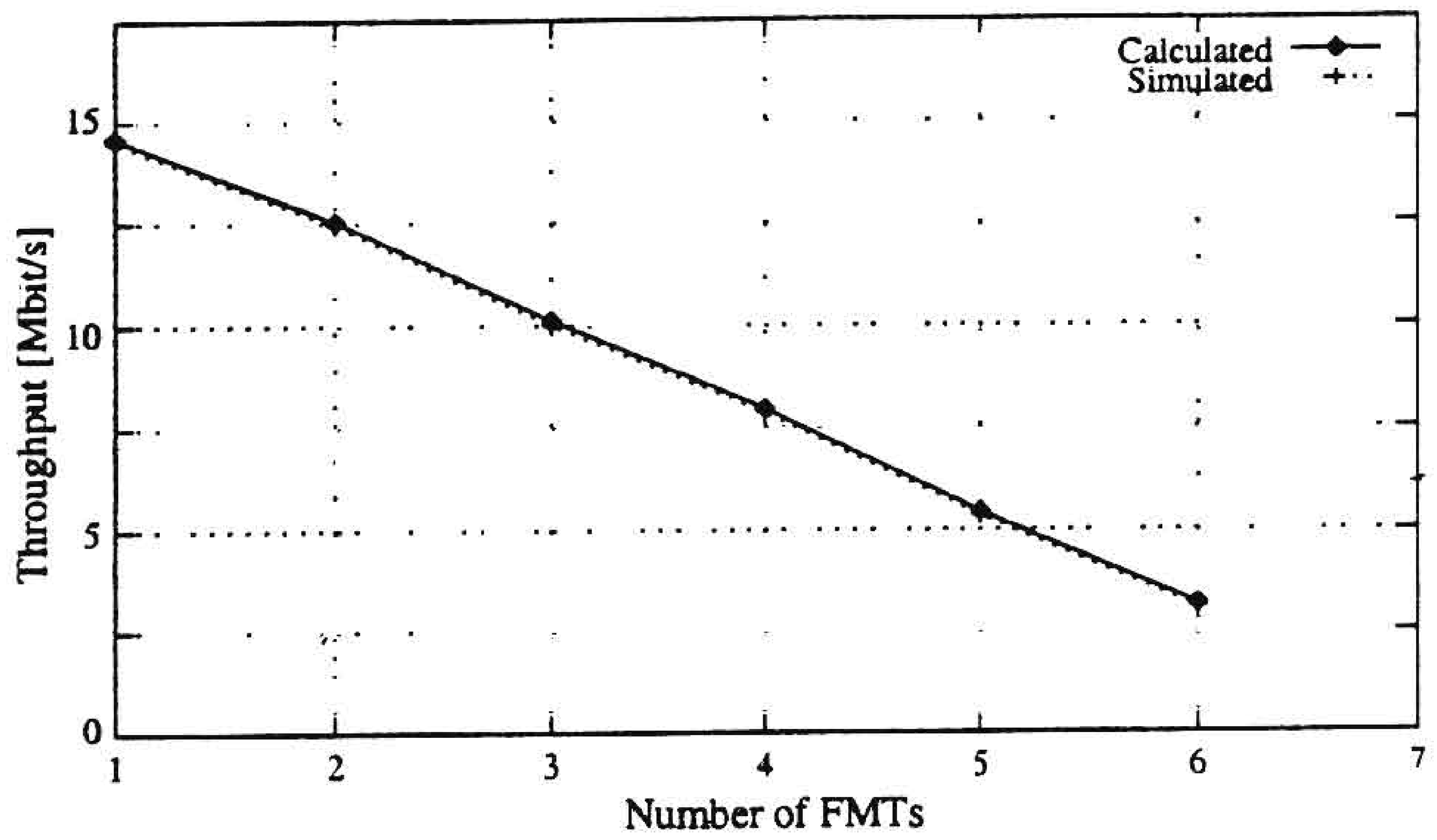

Fig. 36. Maximum AP-to-RMT throughput versus number of FMTs.

1) Maximum Throughput: The simulation gained the maximum system throughput for a varying number of FMTs/RMTs (see Fig. 36).

A set of one FMT and one RMT results in a maximum end-to-end (AP-to-RMT) throughput of approximately 14 Mb/s, as shown in Fig. 36, using 16QAM 3/4 as the PHY mode for LCH transmission on one-hop and forward links. An increasing number of FMTs that are all serving one RMT strongly decreases the capacity available for AP-to-RMT connections as more and more capacity is needed for the overhead introduced by the SFs. A value of approximately 3.5 Mb/s is gained for the example scenario of Fig. 35. The results are compared with the throughput calculated in a similar way as shown in Section V-A taking into account the proposed SF structure. As can be seen from Fig. 36, a small difference results since the calculation does not take into account access to the RCH and the possible collisions there.

2) Delay: In Fig. 37, the CDFs of delay for the one-hop and the two-hop forwarding links are shown.

An additional delay of about 2 ms in UL and DL directions for the two-hop forwarding link compared to the one-hop link is observed. The data packets have to travel one extra hop which takes at least one more MAC frame.

The overall delay experienced by an RMT can be further reduced, but not without changing the structure of the H/2 MAC frame.

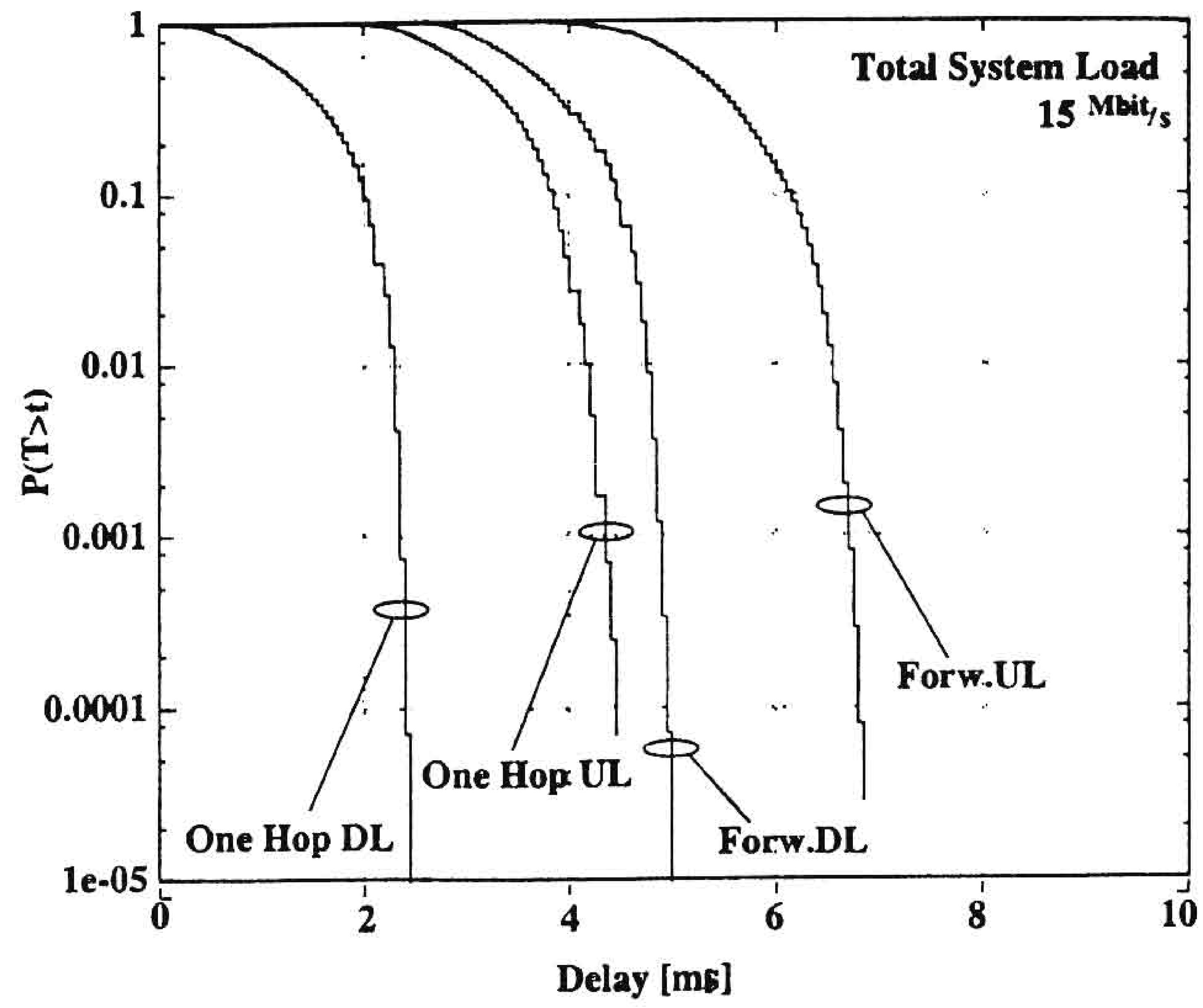

Fig. 37. CDF of delay under forwarding.

X. CONCLUSION

IP over wireless mobile ATM with a guaranteed QoS has been proven to be well supported from the H/2 system. W-ATM with H/2 means that an ATM terminal can be directly connected wirelessly. It has been explained that H/2 also provides a CL to connect directly wireless IP-based applications to an IP network without involving any ATM-related (UNI) signaling or ATM-fixed infrastructure. What is used then for wireless IP is the ability of H/2 to support any ATM class of services whereby the less stringent requirements of hard QoS (Integrated Services) and soft QoS (Differentiated Services) are being covered completely.

The traffic performance under a traffic mix of IP-related services has been investigated. Throughput and the delay distributions have been presented service specifically from simulating the protocols formally specified in SDL.

To be able to rate the system, the H/2 performance has been compared to that of IEEE 802.11a under the same load conditions with respect to the ability to guarantee QoS parameters and to coexist with each other.

We have compared the traffic performance of H/2, especially its ability to guarantee QoS, with that of IEEE 802.11a. *Ad hoc* networking supported by H/2 has been explained and the related performance quantified.

A forum has been formed to support the introduction of H/2 worldwide [14].

In phase 2 of the H/2 standardization, the authors expect the inclusion of smart antenna systems and of wireless base stations into the standard and have described possible solutions and the related traffic performance for that. Therefore, it has been demonstrated that there is a high potential for H/2 to further evolve.

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