SDMA Techniques for Wireless ATM

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ABSTRACT The introduction of space-division multiple access techniques into wireless ATM systems is presented. The concepts are embedded in the framework of the HIPERLAN/2 system, which is currently under standardization by the ETSI project BRAN. HIPERLAN/2 aims at the provision of broadband services with guaranteed QoS. Originally started as a WATM standardization initiative, its scope has been broadened and now aims at core network independence. Essential system functions, such as scheduling algorithms and random access, are reviewed in light of the spatial dimension. To give an impression of their performance, some key results are briefly discussed. Although adopted for HIPERLAN/2, the ideas are generally applicable and can be transferred to various systems.

The rapid growth of the telecommunications world with its emerging new services produces a steadily increasing demand for transmission bandwidth. While fixed network technologies are almost able to provide bandwidth in abundance, the situation for wireless networks is different. The scarcity of available radio spectrum strictly limits the obtainable user data rates and has triggered vivid research work to enhance the spectral efficiency, a measure that relates the traffic capacity to the required frequency bandwidth and the covered area (e.g., a radio cell). Especially in wireless broadband systems, which are mainly characterized by providing a much higher transmission rate than the primary rate interface of the integrated services digital network (ISDN) (2048 kb/s) [1], the spectral efficiency becomes a crucial issue. One possible approach to squeeze more out of the spectrum is to take advantage of the spatial dimension, which is sometimes seen as one of the final frontiers when it comes to next-generation wireless communication systems. Another driving force in telecommunications research is the integration of different services within a single network and the provision of fixed network services to the mobile user. These objectives have initiated numerous proposals and standardization activities on how to integrate wireless links into the framework of the asynchronous transfer mode (ATM) of broadband ISDN (B-ISDN). One of these still ongoing activities, which originally started as a wireless ATM (WATM) standardization initiative, is the HIPERLAN/2 system (Fig. 1) in the scope of the Broadband Radio Access Networks (BRAN) project of the European Telecommunications Standards Institute (ETSI) [2, 3]. Meanwhile, this system has become core-network-independent by introducing a convergence layer (CL). It shall support mobility and be able to provide the quality of service (QoS), including typical required data transfer rates of 25 Mb/s, that users expect from a wired IP, ATM, Universal Mobile Telecommunications Service (UMTS), or IEEE 1394 (FireWire) network. The radio subsystem operates between 5 and 6 GHz on a time-division duplex (TDD) channel with a bandwidth of 20 MHz/frequency channel. Multiple access is realized as time-division multiple access (TDMA). The following system-oriented discussion and evaluation of the application of SDMA techniques is embedded in the context of HIPERLAN/2, which serves here as an example of a modern broadband wireless access system.

THE SPATIAL DIMENSION

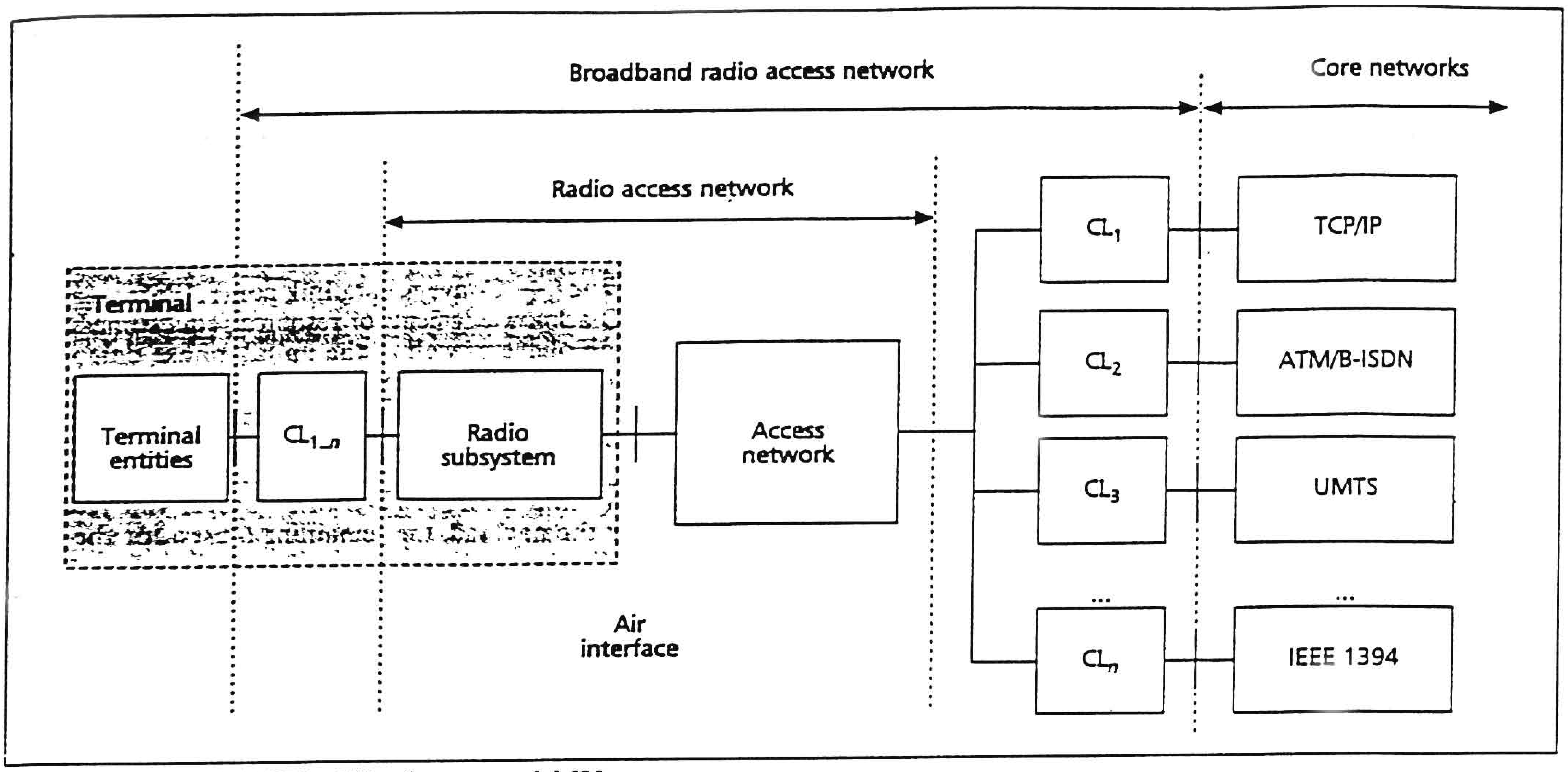
Every cellular mobile communication system takes advantage of the spatial dimension by reusing its transmission frequencies at appropriate geometric intervals determined by the propagation attenuation of electromagnetic waves [1]. The deployment of a smart array antenna with several antenna elements opens up the spatial dimension within the single radio cell and permits, together with advanced signal processing techniques, the use of true space-division multiple access (SDMA). This access technique allows different users to be served on the same frequency channel at the same time. The ability to set up multiple antenna beams that can be electronically directed to the mobile terminal (MT) locations adaptively leads to an increase in capacity and reduces signal interference. For phased array antennas, beamforming is performed at the RF level by controlling the amplitudes and phases of the feeding currents via attenuators and phase shifters. Smart antennas form their beams in the baseband, that is, the feeding currents of the sensor elements are directly proportional to the modulated baseband signals. The single antenna elements can be arranged in various geometric patterns (e.g., linear, rectangular, or circular) [4]. In the following the discussion is restrained to uniform linear array (ULA) antennas consisting of M identical antenna elements. Due to the single-element antenna characteristic, the covered area of the ULA is restricted to values below 180°; a triangular configuration of three ULAs might be used to cover the whole radio cell. This also takes into account that the individual beam becomes broader when steered from broadside to endfire of the array (Fig. 2).

Mainly two types of spatial signal processing algorithms are required to enable SDMA: spatial filtering separates the signals impinging on the antenna array during reception and beamforming algorithms control the radiating directions of the array during transmission.

The crucial issue for spatial filtering as well as for beamforming is the accurate estimation of the spatial covariance matrix (SCM) of each active MT, which contains essential spatial channel parameters and describes the current state of the transmission channel. Two main classes of algorithms for this task can be distinguished depending on whether they use a priori information (e.g., training sequences) or not. Nonblind channel estimation algorithms make use of training sequences to directly measure the SCMs, while Multiple Signal Classification (MUSIC) and Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) are independent of any a priori information and belong to the class of blind estimation algorithms [5]. Assuming that each signal propagates on multiple but discrete paths, the estimation of:

- The number of dominant propagation paths of each user
- The directions of arrival (DOAs) of all dominant propagation paths
- The attenuation (transmitted power in relation to received power) each dominant propagation path undergoes

allows us to construct the SCMs of all users for the blind esti-



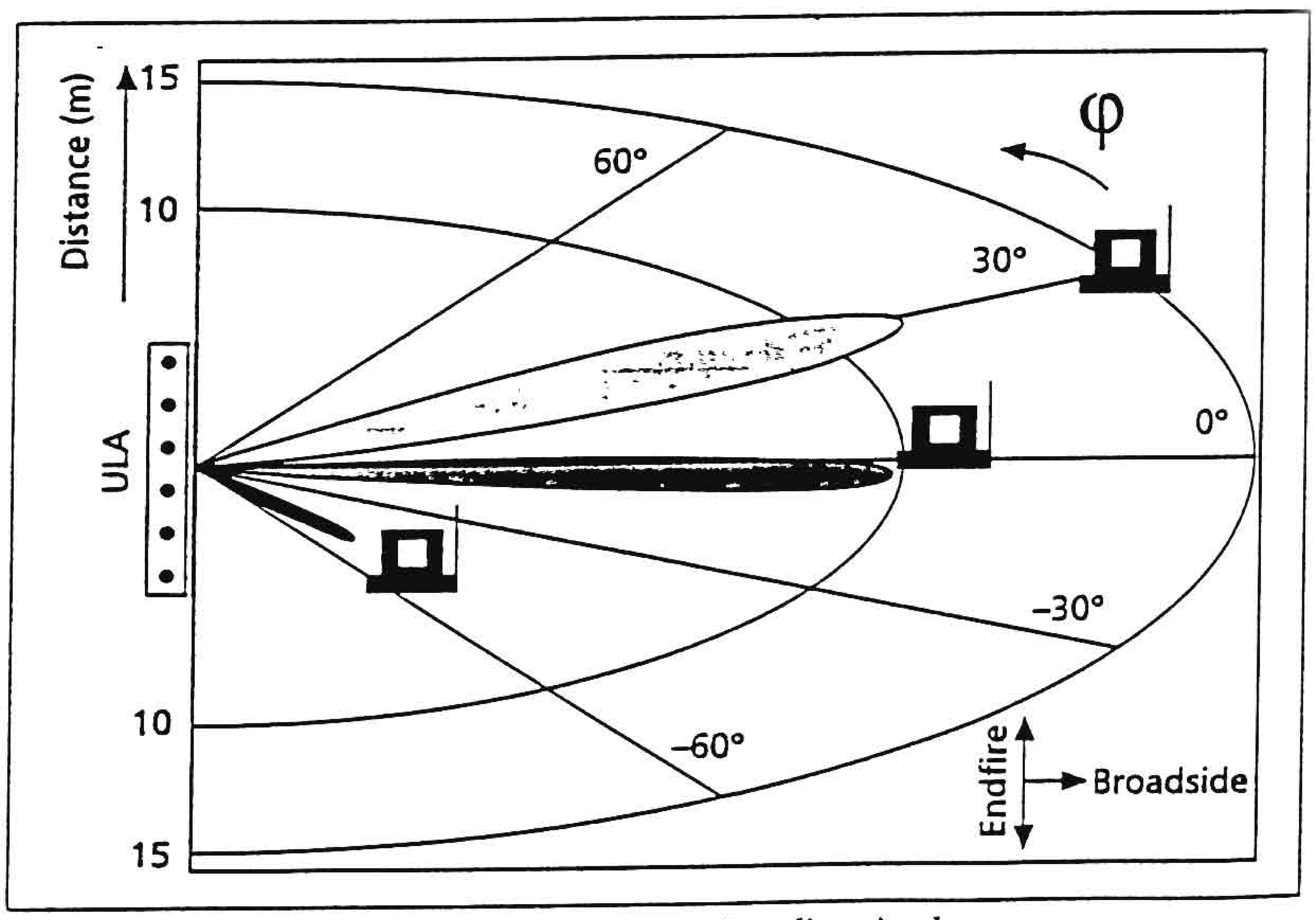
■ **Figure 1.** *The HIPERLAN/2 reference model [2].*

mation techniques. The determination of the number of dominant propagation paths used for spatial filtering (the model order) becomes a difficult task in a multipath propagation environment, since individual user signals have to be separated from reflected coherent signals impinging on the array via alternative paths. Possible approaches are, for example, threshold algorithms or sequential hypothesis testing [6]. The SCM eventually permits reconstruction of the individual user signals received on the same frequency channel at the same time. Depending on the period of time, the transmission channel can be regarded as stationary, the so-called *channel coherence time*; the parameter estimation can be executed less frequently compared to individual burst receptions. To enhance the number of successfully separated and reconstructed signals, the spatial filtering algorithm can be applied iteratively. The idea is to subtract already detected signals from the reception data and feed the result into the spatial filtering algorithm once again. Since this enhanced resolution capability has to be paid for by increased computational complexity and accumulation of errors, a compromise in the number of iterations for each individual system has to be found.

A beamforming algorithm computes a weight matrix for each time slot that adjusts the phases at the antenna elements to steer the main beam pointing direction toward the estimated DoA of the desired MT. In general, these algorithms make use of the spatial information contained in the SCMs. The SCM can only be used directly if the channel shows a sufficient grade of reciprocity, which is mostly the case in TDD systems. But for frequency-division duplex (FDD) systems, which utilize different frequencies for both transmission directions, this is normally not the case, and a frequency transformation of the SCMs is required. Depending on the number of antenna elements and the applied algorithm, array antennas are able to simultaneously direct several beams to different positions conveying individual user signals (Fig. 2).

The use of smart array antennas and advanced signal processing offers an additional degree of freedom to the medium access control (MAC) protocol. In the following, we describe and evaluate concepts for a joint TDMA-SDMA approach in the context of HIPERLAN/2, which is supported by the following system characteristics:

- 5 GHz frequency band: Permits compact construction of array antennas and the deployment of this antenna type at least at the base station.
- TDD: Same frequency for up- and downlink; gathered uplink channel information supports downlink beamforming.
- MAC frame duration, 2 ms: Typically shorter than the channel coherence time, spatial parameter estimation can take place less frequently, and the computational load is reduced.
- Reservation-based MAC protocol: Permits a flexible frame structure considering QoS requirements and the actual transmission situation.
- Automatic repeat request (ARQ) error recovery at the radio interface: Provides fast retransmission in case of transmission errors and inaccurate parameter estimation.



■ **Figure 2.** *Simultaneous transmission using directive beams.*

Medium Access Control

The task of a MAC protocol is to coordinate the access of MTs to the shared radio channel. The reservation-based HIPERLAN/2 MAC has adopted some of its basic ideas from the DSA++ protocol [7, 8]. This protocol grants transmission capacity to the MT with a granularity of a single time slot, according to current transmission capacity demands. The resources are not statically assigned to the individual MTs, but may vary dynamically from frame to frame. The protocol is centrally controlled by the base station, which operates a scheduler that groups the various control and data channels into MAC frames of flexible structure and τ_{Frame} = 2 ms duration. Therefore, the MTs have to transmit their resource request messages on the uplink to the base station. A MAC frame starts with two broadcast channels, the broadcast channel (BCH) and the frame channel (FCH), followed by a downlink phase, an uplink phase, and the random access channels (partitioned, RCH-P, and unpartitioned, RCH-UP). Figure 3 shows a possible frame structure already considering the spatial dimension, reflected by the parallel use of transport channels and an additional pilot tone phase to support accurate uplink spatial parameter estimation. Although the payload size of a MAC protocol data unit (PDU) still equals the payload size of an ATM cell, in the following the generic term *MAC PDU* will be used to stress the general applicability of the presented concepts. According to the current working assumptions of BRAN, the protocol makes use of the following transport channels [9]:

BCH — Conveys signaling information concerning the whole radio cell in the downlink direction. Announces the location of the FCH and RCH within the actual MAC frame. Every frame starts with a BCH.

FCH — Used to transmit the information about the structure of the MAC frame for the up- and downlink phases. This channel is broadcast in the downlink direction. It contains announcements and reservations of long and short transport channels the individual MTs have to transmit or receive in.

Access Feedback Channel — Broadcast in every frame in downlink direction. The ACH serves to announce the random access results of the previous MAC frame. The base station informs the MTs whether their access to the RCH has been received correctly or not.

Short Channel — Conveys data link control information, such as ARQ acknowledgments or resource request messages. The downlink phase as well as the uplink phase comprises SCHs, which carry PDUs of 9 bytes.

Long Channel — The LCH serves to transmit user data (e.g., the payload of ATM cells) bidirectionally on the up- and downlink. Within an LCH PDU of 54 bytes, 48 bytes are reserved for the payload, the remaining 6 used for the data link control (DLC) header.

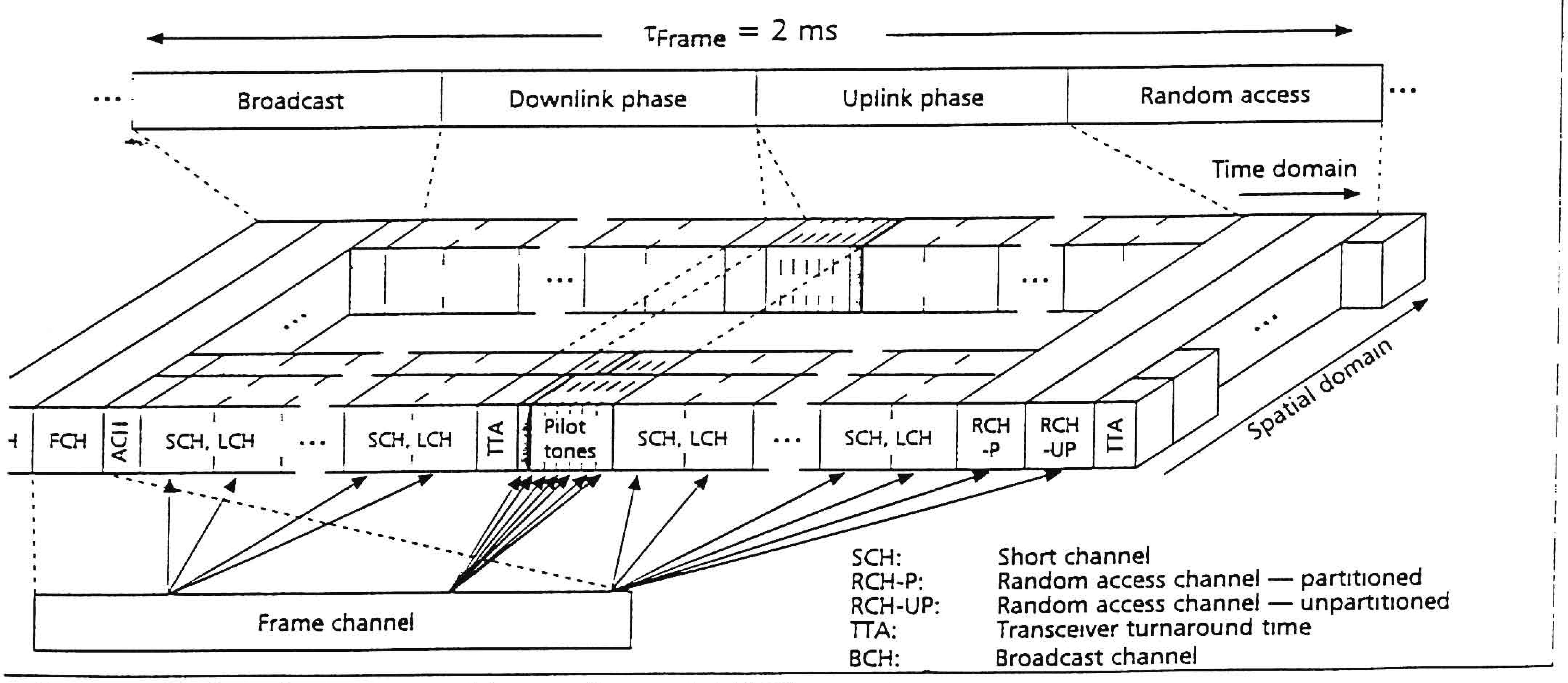
RCH-P — A partitioned uplink-based contention channel a varying subset of associated MTs is allowed to access, depending on the applied collision resolution algorithm.

RCH-UP — An uplink contention channel that can be accessed by any MT.

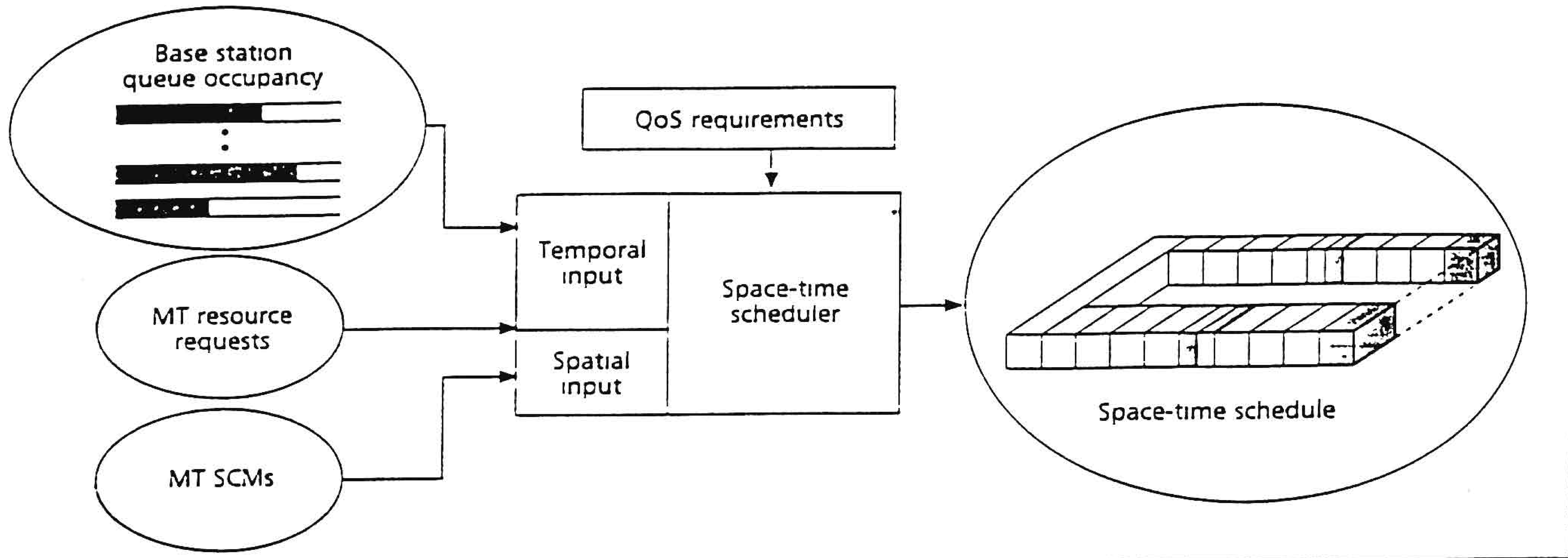
The user data and control information transmitted via SCHs and LCHs dedicated to a single terminal are grouped together. These groups are called *cell trains* and help to reduce the physical overhead.

To meet the QoS requirements especially of delay-sensitive real-time services, fast and in-time signaling of resource request messages to the base station is essential. The HIPERLAN/2 MAC protocol provides two methods for transmission of resource request messages to the base station on the uplink:

- Explicit signaling using the SCH: The base station scheduler reserves an SCH slot to receive a terminal's resource request message.
- Random access using the RCH: The terminals can arbitrarily access the RCH slots to transmit their resource request messages. Depending on the applied collision



■ **Figure 3.** *The basic frame structure of the spatially extended MAC protocol.*



■ **Figure 4.** *Space-time scheduling meeting QoS requirements.*

resolution algorithm, basically resource request messages will be transmitted via the RCH-P.

At the end of each MAC frame the scheduler updates its information database about the terminal's capacity demands by evaluating the received resource request messages. This information, together with the downlink transmission demands, provides the input for the scheduling algorithm, which determines the structure of the subsequent MAC frame. The base station broadcasts this structure on the FCH to inform all the terminals about their individual transmission and reception schedules for the next MAC frame. With the deployment of a smart antenna at the base station the system can benefit from enhanced functionality:

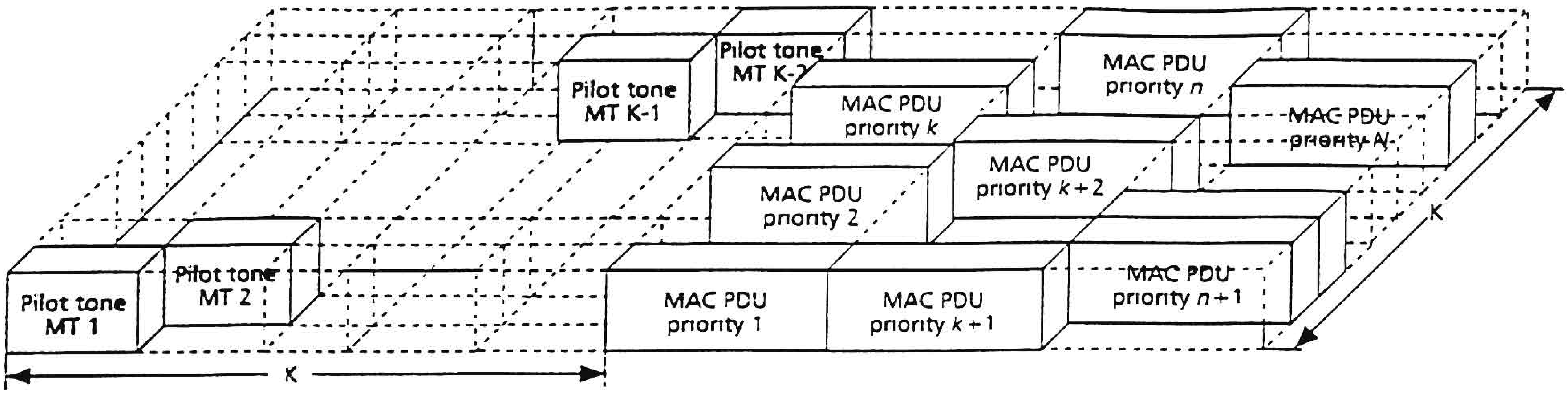
- Simultaneous downlink transmission: Forming directive beams instead of radiating spherically enables the base station to send different information to several locations in the same time and frequency slot. Thus, the number of necessary downlink slots can be reduced. The transmit power of each beam can be adjusted, helping to reduce the total array output power and to decrease interference in neighboring cells.
- Simultaneous uplink reception: Concurrent transmission of MTs in one slot becomes possible if accurate uplink parameter estimation and spatial filtering are performed.
- Spatial separation of concurrent random accesses: Smart antennas are capable of receiving signals from multiple users in the same time and frequency slot, simplifying collision resolution algorithms, increasing throughput, and reducing delays of contention-based transmission.

Space-Time Scheduling

One of the ambitious goals of HIPERLAN/2 is to provide QoS in terms of guaranteed values for packet loss and delay in order to support services with strict real-time requirements. Therefore, scheduling (i.e., the determination of the transmission sequence of MAC PDUs) becomes a crucial issue, although it will not be standardized for HIPERLAN/2. For an SDMA system this is a two-dimensional scheduling problem. The scheduler has to determine the temporal transmission sequence of MAC PDUs as well as the MTs that can simultaneously be addressed or allowed to concurrently transmit their bursts. The applied algorithm is called *space-time scheduling*. Based on temporal input parameters (queue occupancy at the base station and received MT resource request messages) and spatial input parameters (the SCMs of the MTs), the algorithm determines the transmission and reception schedule obeying the agreed-upon QoS requirements (Fig. 4). One strategy to meet a predefined maximum delay is to assign dynamic priorities $q(t)$ to each MAC PDU. The sum of the arrival time t_0 of the packet and the maximum allowed delay τ_{dmax} forms the due date τ_{DD} of the PDU, which describes the time at which the packet has to be transmitted at the latest. Otherwise, it would exceed the maximum delay, become worthless for the receiving site, and need to be discarded. Based on the assigned priorities $q(t)$, which represent the remaining lifetime of the packet, the Earliest Due Date (EDD) strategy controls the transmission sequence. This strategy minimizes the probability of packet loss due to expired due dates. The Optimized Relative Urgency (ORU) scheduling strategy [10] goes one step further and additionally takes into account the agreed-upon packet loss parameters. This leads to increased throughput and provides a fair share of transmission capacity to each connection according to the individual QoS parameters. Assuming the deployment of a smart antenna at the base station only, the description of scheduling algorithms distinguishes between up- and downlink scheduling.

Uplink Scheduling

The most intuitive space-time scheduling approach for the uplink is to fix an upper threshold of concurrently transmittable MAC PDUs per time slot and to schedule the MAC PDUs with decreasing temporal priority $q(t)$, as depicted in Fig. 5. It is then the task of the receiver signal processing algorithms to spatially separate the concurrent signals. The maximum number of concurrently transmittable MAC PDUs equals K, the number of MTs operating in the system. The number of uplink MAC PDUs can be adjusted to meet the desired system dynamic obeying the downlink transmission needs and the maximum MAC frame length of 2 ms. A more sophisticated scheduling approach incorporates additional knowledge about individual MT positions. By tracking these positions and monitoring reception success, the scheduling algorithm can try to find spatially compatible groups of MTs, which increases the expectancy of the number of successfully received bursts. However, both approaches are limited by the reception capabilities of the antenna system; 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 successful signal separation even further. Another limiting factor is 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, which cannot be separated in space.



■ **Figure 5.** *Uplink space time schedule for* K *associated MTs.*

Downlink Scheduling

Space-time scheduling on the downlink is based on the due dates of MAC PDUs in the MT-specific base station queues and on spatial information gathered on the uplink during the last MAC frame, assuming TDD and that the SCMs have not changed significantly since the last measurement, that is, the channel coherence time is normally longer than the MAC frame duration. Knowledge of the SCMs offers the possibility to group MTs which are suited for concurrent reception of MAC PDUs. The SCMs of the K users detected during uplink parameter estimation are examined in order to form sets of MTs that are spatially compatible. The decision algorithm then takes the following shape:

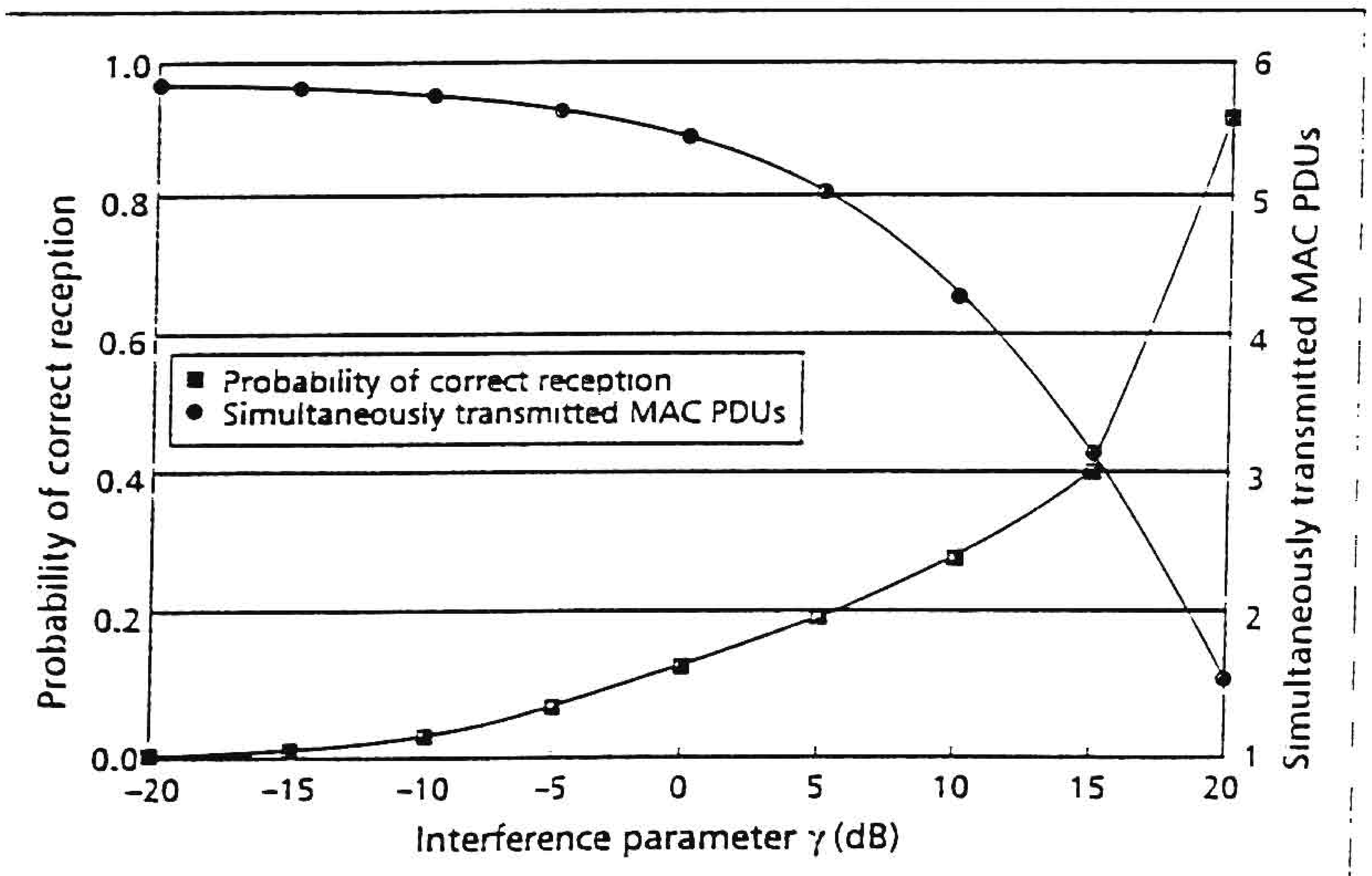
1. Calculate the K unit weight vectors that control the beam pointing directions to maximize the amount of useful energy for MT k.
2. Determine the corresponding interference powers at the other $K - 1$ MTs.
3. Form sets of concurrently transmittable MAC PDUs for one time slot, while obeying the constraint that the interference power has to be kept below level γ. Thus, all sets whose elements cause less than γ interference power at each other set element are considered to be spatially compatible. The parameter γ adjusts the degree of spatial compatibility.
4. Schedule the MAC PDUs within the sets according to their dynamic priorities (e.g., EDD or ORU).

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

■ **Table 1.** *Successfully received MAC PDUs.*

Random Access and SDMA

Smart antennas enable the correct reception of more than one simultaneously transmitted burst within the same time slot at the same frequency by means of spatial filtering. However, 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 carrier-to-interference ratio (C/I) decreases, and correct reception of a burst becomes less likely. The present interference situation depends on the number of simultaneous transmissions, the MTs' positions, and the surrounding channel. Since no further restrictions can be imposed on the initial access to the RCH (i.e., the interference situation cannot 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 must be applied which can make use of the enhanced reception capabilities. Thus, the transmission of resource request messages will benefit from increased throughput and reduced delay. In HIPERLAN/2, MTs can access the RCH to transmit their resource request messages to the base station. Especially for delay-sensitive services, this access should be carried out as fast as possible; that is, 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 in [11] (Slotted ALOHA) and [12] (splitting algorithms). HIPERLAN/2 facilitates the task of fast collision resolution by broadcasting the outcome of random access via the ACH of the next frame. This allows very dynamic adaptation of the collision resolution algorithm to the current access constellation. Collision resolution can be seen as one example of the fading boundaries between signal and protocol processing, where the physical layer of SDMA systems takes over some classic protocol functionality.



■ **Figure 6.** *Successful reception and spatial exploitation.*

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 uniform linear array (ULA) with 12 antenna elements and interelement spacing of $\lambda/2$ was used. The spatial filtering was performed by the Unitary ESPRIT algorithm with Spatial Smoothing [13]. Table 1 gives the expectation $E_k[X]$ of the number of MAC PDUs successfully received by the base station on the uplink. 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 base station 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 four 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 intracell interference. This effect clearly shows the interference limitation.

A performance evaluation of the presented downlink space-time scheduling algorithm was performed with $K = 6$ MTs under heavy traffic load. The probability of successful reception and the exploitation of the available spatial channels have been evaluated as a function of the interference parameter γ. The logarithmic values of γ relate to the normalized transmit power $S = 1$. Figure 6 clearly underlines the trade-off 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 spatial exploitation of the available time slot to the QoS requirements of the service to which the PDUs to transmit belong. On the uplink, a low threshold for the number of concurrently transmittable MTs could be applied for time-critical PDUs, while for non-real-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 choice of γ, which stands for nearly perfect spatial compatibility, is suitable for real-time services, whereas a large γ leads to the desired high throughput of non-real-time services with the drawback of low reception probabilities. Aiming at very low delays (i.e., the transmission is expected to be as successful as possible), the scheduling of MAC PDUs belonging to real-time connections in an exclusive time slot is the best one can do, although the additional capacity of the spatial dimension is lost. Together with position tracking of the MTs, more elaborate scheduling algorithms will permit further increase in efficiency, while obeying the delay constraints of real-time services.

Conclusions

We discuss SDMA techniques for WATM embedded in HIPERLAN/2. Based on the enhanced signal processing capabilities, it is shown how the HIPERLAN/2 MAC protocol can be extended to the spatial domain for the up- and downlink. Parameter estimation accuracy, which is essential for successful downlink beamforming, is ensured by the introduction of pilot tones during the uplink phase. Concurrent access of several terminals on the uplink is enabled by spatial filtering. Downlink beamforming allows several MTs to be served simultaneously in the same time slot on the same frequency channel. Some basic ideas for scheduling algorithms have been described which aim at effective usage of the joint TDMA-SDMA scheme, while preserving agreed-upon QoS requirements. Furthermore, it is outlined how contention-based transmission could benefit from SDMA. The utilization of the spatial dimension helps to increase the transmission capacity, reduces intra- as well as intercell interference, and leads to more efficient usage of the scarce radio spectrum. A possible drawback of a broad introduction of these techniques to systems might be the computational complexity of the algorithms. But considering the development of digital signal processing and processors in the past, this will certainly become a minor issue in the near future.

Acknowledgments

This article is based on our previously published material from wmATM '99, organized by the Wireless Mobile ATM Task Force of Delson Group.

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