Packet Scheduling in SDMA Based Wireless Networks

Ulrich Vornefeld
RWTH Aachen University of Technology
Chair of Communication Networks
Kopernikusstr.16 , 52074 Aachen, Germany
Ulrich.Vornefeld@comnets.rwth-aachen.de

Abstract

This paper deals with packet scheduling in SDMA based wireless cellular networks. Depending on the terminal's positions and the capabilities of the antenna and signal processing system it is possible for more than one mobile terminal to receive or to transmit simultaneously. We discuss the two dimensional scheduling problem and address the spatial as well as the temporal domain. Based on the framework of Batch Markovian Arrival Processes we develop an analytical model for the air interface and present some results for uplink capacity request transmissions.

1. Introduction

One of the drawbacks of modern broadband wireless multimedia networks such as HIPERLAN/2 or UMTS is the large amount of spectrum required. The deployment of array antennas enables SDMA (Spatial Division Multiple Access), which seems to be a possibility to increase spectral efficiency. SDMA enables the transmission and reception of more than one physical burst at the same time slot on the same frequency [7]. On the uplink this is realized by spatial filtering algorithms and on the downlink beam-forming algorithms allow directional transmission and simultaneous addressing of more than one terminal. Which terminals can be addressed simultaneously highly depends on the terminal's positions. To address more than one terminal requires the spatial separation of the terminals by the transmission system. This is only possible if there is a minimum distance between all locations of concurrently addressed users. Even then the transmission might fail due to multipath propagation, fading or interference effects. Based on an picocellular environment, we analyze the performance of different packet scheduling algorithms using *Batch Markovian Arrival Processes, (BMAPs)*. Since the accessibility of the radio channel depends on the actual spatial constellation of the terminals the capacity request transmission process model has to incorporate the spatial conditions and the actual transmission needs of the terminals.

2. The Spatial Dimension

Cellular mobile communication systems make use of the spatial dimension by reusing their frequencies at geometric intervals determined by the propagation attenuation [8]. The deployment 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 Space Division Multiple Access (SDMA). This access technique allows to serve different users on the same frequency at the same time. The ability to set up multiple antenna beams that can be directed to the mobile terminal (MT) locations adaptively, leads to an increase in capacity and reduces signal interference. In the following, we discuss the use of Uniform Linear Array (ULA) antennas consisting of M identical antenna elements. Although adopted for HIPERLAN/2 (H/2), the ideas are generally applicable and can be transferred to other systems. Mainly two spatial signal processing algorithms are required to enable SDMA: Spatial filtering separates the signals impinging on the antenna array during reception and beam-forming algorithms control the radiating directions of the array during transmission. Subsequently, we describe and evaluate concepts for a joint TDMA-SDMA approach for H/2, which is supported by the following H/2 system characteristics:

- 5 GHz frequency band: Permits compact construction of array antennas and at least base station deployment
- TDD: Same frequency for up- and downlink; gathered uplink channel information supports downlink beamforming.
- MAC frame duration 2ms: 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.

The medium access control (MAC) protocol of H/2 is extended by incorporating the spatial dimension, Fig. 1.

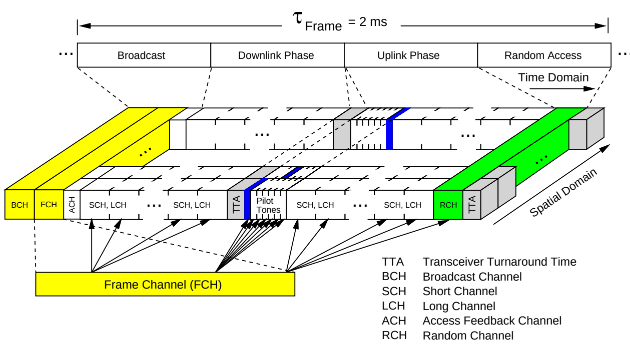

Figure 1. Spatially extended H/2 MAC protocol

3. Simulation Environment

Since no fully working H/2 network is available yet, we use a stochastic simulation model to obtain the input parameters for the subsequently outlined analysis. Although the described techniques and concepts can also be applied to outdoor environments or to Radio in the Local Loop (RLL) systems, in this paper, we focus in our simulations on picocellular indoor environments with a cell radius of less than 100 m, e.g. offices or exhibition halls.

Antennas: While terminals are equipped with omnidirectional antennas, we assume for our investigations the use of Uniform Linear Array (ULA) Antennas with M antenna elements at the base station. The distance d between the elements equals $\lambda/2$.

Channel model: One of the crucial issues for performance evaluation in such scenarios is the influence of multipath propagation effects. Especially uplink parameter estimation and spatial filtering are strongly affected by these effects. Hence, the channel model must not consider noise only, but it has to simulate a multipath propagation environment and has to offer *directional* propagation information. A scatter based stochastic channel model was parameterized for this environment

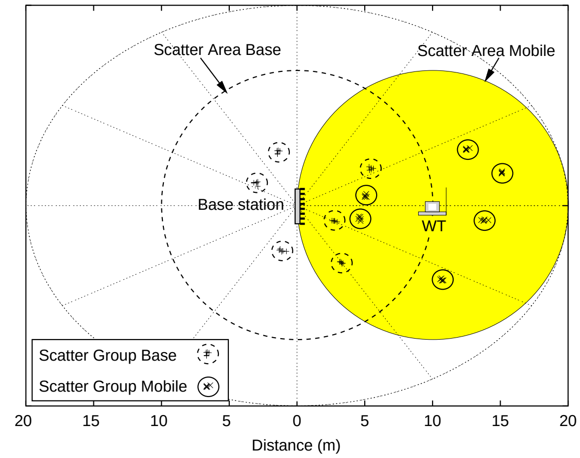

Figure 2. Scatter scenario for a pico cellular environment

and is illustrated in Fig. 2. It provides the required directional channel impulse response (CIR) functions.

Signals and Coding: A unique training sequence composed for synchronization and identification is assigned to each terminal. The training sequences precede the protocol data units (PDUs) and capacity request messages on up- and downlink. They allow synchronization and adjustment of the equalizer coefficients C_{eq}. Forward Error Correction (FEC) is performed using a Reed-Solomon (RS) code. The protection differs among the physical channels. The strongest protection is applied to the broadcast channels BCH and FCH, since these channels carry vital protocol control information, such as the transmission and reception schedule for the terminals.

Modulation: Quaternary Phase Shift Keying (QPSK) is applied to transform the binary source signals to continuous signals. Although ETSI-BRAN considers multi carrier modulation such as OFDM, we use in a first approach this common single carrier modulation scheme to limit the complexity of the simulation model.

Synchronization: All signals are delayed during their propagation through the channel, whereby the LOS path has the smallest delay and, because of not being reflected at scatterers, can be expected to be the strongest path. It is the task of the synchronizer to determine the delay corresponding to the strongest propagation path in LOS and non-LOS environments. The property of the training sequences

$$\frac{\varphi_{ss}(0)}{max|\varphi_{ss}(m)|} \quad \forall m \neq 0 \qquad (1)$$

where $\varphi_{ss}(m)$ is the discrete autocorrelation function of the signal $s(k)$ at instance m, makes it feasible to find the delay of the strongest path. In scenarios without LOS, the strongest path has to be searched among the scattered paths.

Equalization: The synchronizer is only able to find the strongest received signal. In multipath environments, this signal is composed out of several delayed versions of the source signal which overlay at the receiving unit. Employing training sequences and a Recursive Least-Squares (RLS) equalizer [5] with a tapped delay-line structure, this inter-symbol interference can be notably diminished.

3.1 Space-Time Scheduling

For an SDMA system packet scheduling is a two dimensional problem. The scheduler has to determine the temporal transmission sequence of MAC PDUs as well as the MTs, which can be simultaneously addressed or can be allowed to concurrently transmit their bursts. The applied algorithm is called space-time scheduling. Based on temporal input parameters (queue occupancy at base station and received resource request messages) and spatial input parameters, the algorithm determines the transmission and reception schedule obeying the agreed QoS requirements (Figure 3)

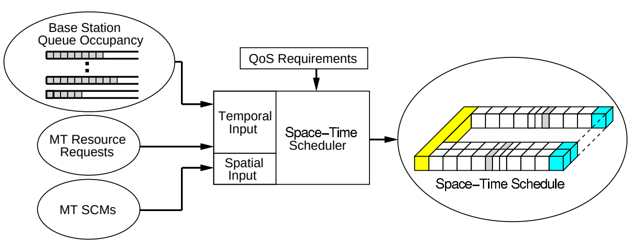

Figure 3. Space-time scheduling meeting QoS Requirements

3.1.1 Uplink Scheduling

The maximum number of concurrently transmittable MAC PDUs equals the number K of MTs operating in the system. The number of uplink MAC PDUs can be adjusted to meet the desired system dynamics obeying the downlink transmission needs and the maximum 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, which increase the expectancy of the number of successfully received bursts. However, 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, which cannot be separated in space. For performance evaluation,

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

Table 1. Successfully received MAC PDUs

the number of MTs under heavy traffic 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. The mean numbers of successfully received MAC PDUs in Table 1 clearly show the limitation of the signal resolution capabilities, since the number of successfully received bursts only slightly increases for more than 4 MTs. For more than 6 MT 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.

3.1.2 Downlink Scheduling

Space-time scheduling on the downlink is based on spatial information gathered on the uplink during the last MAC frame, provided that the channel coherence time is longer than the MAC frame duration and time division duplexing. Information on the spatial channel characteristics offers the possibility to group MTs, which are suited for concurrent reception of MAC PDUs. The scheduler forms sets of concurrently transmittable MAC PDUs for one time slot, while obeying the constraint that the interference power has to be kept below the level γ. Thus, all sets which elements cause less than γ as interference power at each other set element, are considered to be spatially compatible.

4. Analyzing The Uplink Arrival Process

To analyze the uplink arrival process, we try to model this process using a *Batch Markovian Arrival Process* (BMAP), which is a generalization of the *Markovian Arrival Process* to allow for batch arrivals.

4.1 The Batch Markovian Arrival Process

Similar to phase type distributions the BMAP is controlled by a finite Markov chain with an irreducible generator matrix. The state space consists of k transient phases and comprises an absorbing state. The duration of the transient phase i, $i = 1, \ldots, k$ is negative exponentially distributed with parameter λ_i. Two types of state transitions are distinguished:

Transient transition: A state change between two transient phases i and j, $(i, j \in \{1, \ldots, k\})$ occurs with with probability $p_{ij}(0)$, $i \neq j$.

Transition with absorption and restart: With probability $p_{ij}(k)$ a state change takes place from a transient phase i with absorption and restart to phase j, $(i, j \in \{1, \ldots, k\})$. Simultaneously n arrivals are generated.

These probabilities fulfill the following relation

$$\sum_{\substack{j=1\\ j\neq i}}^{k} p_{ij}(0) + \sum_{n=1}^{\infty}\sum_{j=1}^{k} p_{ij}(n) = 1, \quad 1 \leq i \leq k \qquad (2)$$

and form the elements of the matrices D_0 and D_n, $n > 0$

$$D_0 = \begin{pmatrix} -\lambda_1 & \lambda_1 p_{12}(0) & \ldots & \lambda_1 p_{1k}(0) \\ \lambda_2 p_{12}(0) & -\lambda_2 & \ldots & \lambda_2 p_{2k}(0) \\ \ldots & \ldots & & \ldots \\ \lambda_k p_{k1}(0) & -\lambda_k p_{k2}(0) & \ldots & -\lambda_k \end{pmatrix} \qquad (3)$$

$$D_n = \begin{pmatrix} \lambda_1 p_{11}(n) & \lambda_1 p_{12}(n) & \ldots & \lambda_1 p_{1k}(n) \\ \lambda_2 p_{12}(n) & \lambda_2 p_{22}(n) & \ldots & \lambda_2 p_{2k}(n) \\ \ldots & \ldots & & \ldots \\ \lambda_k p_{k1}(n) & \lambda_k p_{k2}(n) & \ldots & \lambda_k p_{kk}(n) \end{pmatrix} \qquad (4)$$

where D_n, $n \geq 0$ are $m \times m$ matrices. D_0 contains negative diagonal elements and nonnegative off-diagonal elements. D_n $n \geq 1$ are nonnegative and together they form the matrix D, which is defined by

$$D = \sum_{n=0}^{\infty} D_n \qquad (5)$$

and is an irreducible infinitesimal generator. The stationary probability vector π of the Markov process with generator D satisfies

$$\pi D = 0, \quad \pi \mathbf{e} = 1, \qquad (6)$$

where $\mathbf{e}$ is column vector with all its elements set to 1. The fundamental arrival rate rate for the process is given by

$$\lambda_1'^{-1} = \pi \sum_{n=1}^{\infty} n D_n \mathbf{e} = \pi \mathbf{d}, \quad \mathbf{d} = \sum_{n=1}^{\infty} n D_n \mathbf{e} \qquad (7)$$

4.2 BMAP/D/1

One radio cell can be seen as a distributed multiplexer. To derive characteristic performance measures, this distributed multiplexer is modeled as a BMAP/D/1 queuing system. The queuing system is parameterized using simulation results and analyzed following the matrix analytic approach in [1], which basic steps to obtain the queue length at departure instances are subsequently summarized. The vector $\mathbf{x}_i$ represents the probability of a departure leaving i customers in the system. Each element j of the vector corresponds to the phase of the arrival process. The vectors $\mathbf{x}_i$, $i \geq 1$ can be calculated recursively:

$$\mathbf{x}_i = \left[\mathbf{x}_0 \bar{B}_i + \sum_{j=1}^{i-1} \mathbf{x}_j \bar{A}_{i+1-j} \right] (I - \bar{A}_1)^{-1}, \quad i \geq 1 \qquad (8)$$

$\bar{B}_k$ and $\bar{A}_k$ are obtained by the backward recursions

$$\bar{B}_k = B_k + \bar{B}_{k+1} G \quad \text{and} \quad \bar{A}_k = A_k + \bar{A}_{k+1} G \qquad (9)$$

therefore A_n and B_n are needed:

$$A_n = \sum_{j=0}^{\infty} \gamma_j K_n^{(j)} \qquad (10)$$

$K_n^{(j)}$ is also defined recursively. $K_0^{(0)} = I$, $K_n^{(0)} = 0$, $n \geq 1$ and

$$K_0^{(j)} = K_0^{(j-1)} (I + \Theta^{-1} D_0) \qquad (11)$$

$$K_n^{(j)} = \Theta^{-1} \sum_{i=0}^{n-1} K_i^{(n-1)} + K_n^{(j-1)} (I + \Theta^{-1} D_0) \qquad (12)$$

Numerical integration yields γ_n. $H(x)$ is the service time distribution.

$$\gamma_n = \int_0^{\infty} e^{-\Theta x} \frac{(\Theta x)^n}{n!} dH(x), \quad n \geq 0 \qquad (13)$$

$$\Theta = \max_i (D_{ii}) \qquad (14)$$

B_n is derived from A_n:

$$B_n = -D_0^{-1} \sum_{k=0}^{n} D_{k+1} A_{n-k} \qquad (15)$$

Central for the analysis of the queue is the matrix G, see [3]. We compute G using the iterative approach of [1].

$$G_{k+1} = \sum_{n=0}^{\infty} \gamma_n H_{n,k}, \quad \text{with} G_0 = 0 \tag{16}$$

$$H_{n+1,k} = [I + \Theta^{-1} D[G_k]] H_{n,k}, \quad n \geq 0 \tag{17}$$

$$D[G] = \sum_{j=0}^{\infty} D_j G^j. \tag{18}$$

What remains is the computation of the vector $\mathbf{x}_0$ to start with in (8):

$$\mathbf{x}_0 = \lambda_1'^{-1}(1-\rho)\mathbf{g}(-D_0) \tag{19}$$

where the vector $\mathbf{g}$ is the stationary probability vector of the generator $D[G]$ and ρ represents the system-load. For further details on matrix analytical algorithms for the BMAP/G/1 queue, see [2]. One challenge to cope with implementing these algorithms is the numerical stability and the question how to terminate all the infinite sums, which is directly related to the obtained accuracy.

4.3 Parameterizing The Model

Our model is based on the following simplifying assumptions:

- We consider one radio cell with 6 MTs under heavy traffic that access the RCH simultaneously to request uplink transmission capacity.
- Each MT requests capacity depending on its current transmission demands.
- We restrict our analysis to the request of uplink transmission capacity and analyze the requested transmission capacity represented by the number of queued capacity requests.

Depending on the channel conditions and the signal processing capabilities of the base station, a collision might occur or n out of k MTs might be received successfully. In contrast to omni-directional antenna systems [1], smart array antennas are able to separate simultaneously transmitted bursts. This ability is limited by the signal processing system and interference power. For the uplink arrival process this leads to a simultaneously arrival of the successfully decoded capacity requests of the transmitting MTs, superposed by the number of requested slots. The number of requested slots determines the batch size of a parameterized BMAP. Capacity requests arrive at the base station once per frame. This deterministic interarrival times are approximated in the analytical model by an Erlang-k distribution, since the BMAP requires the representation of interarrival times by the superposition of negative exponential phases. Figures 4, 5 and 6 show the pdf of the number of requested slots for different antenna configurations. These values have been obtained using a stochastic simulation tool that allows to perform bit-level performance evaluation.

[1] Neglecting capture

4.4 Results

To gain some useful insight, the BMAPs have to be parameterized according to arrival and service time distributions occurring within the mobile network. We use the H/2 simulation model presented in more detail in [6] to obtain probability density functions which describe the number of requested slots for uplink transmission. The basic parameter settings are given in Table 2.

Center frequency	5.2 GHz
Modulation	5.6 MHz
Samples per symbol	32
Antenna element spacing	$\lambda/2$
Spatial separation	Unitary ESPRIT with spatial smoothing
ESPRIT Snapshots	70

Table 2. Simulation parameter settings

The probabilities depicted in Figures 4 5 and 6 represent the probability of requesting n slots for uplink transmission. These pdfs aggregate the process of spatial filtering and the packet arrival processes within the MTs. The results for three different antenna configurations (M = 6, 8 and 16 elements) are used to determine the probability of uplink group arrivals for the analytical BMAP model. The interarrival times of these requests are approximated by an Erlang-k distribution with 12 phases.

It is clearly visible that the probability of requested capacity decreases with the number of requests. This is a result of an increasing number of simultaneously requesting MTs, which leads to higher interference and reduces the overall probability of successful reception of capacity request messages.

A BMAP has been parameterized with the depicted probabilities and used as an arrival process of a BMAP/D/1 queuing system. The matrix analytical algorithms of [1] have been used to calculate the queue length at departure instances, which are shown in Fig. 7. To validate the calculated results the BMAP/D/1 queue has been evaluated by stochastic simulation and a good agreement between simulation and analysis has been found. With the increasing number of antenna elements the ability of the base station to

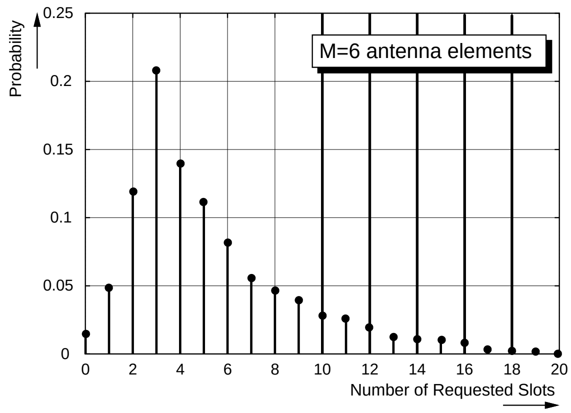

Figure 4. Pdf of requests for M=6 antenna elements

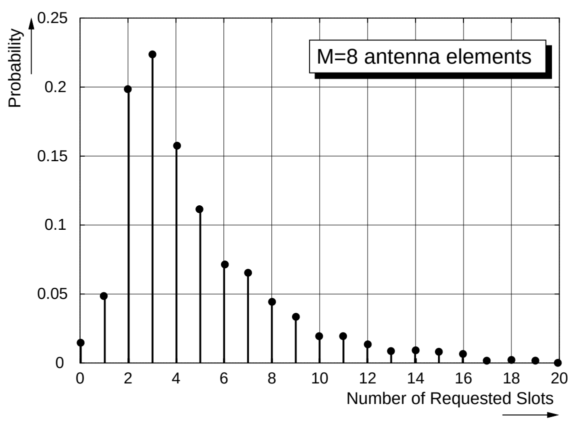

Figure 5. Pdf of requests for M=8 antenna elements

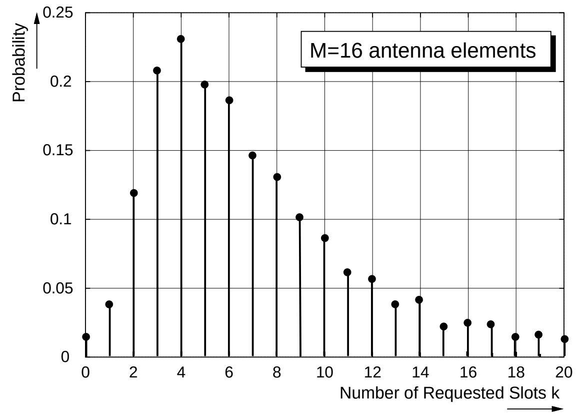

Figure 6. Pdf of requests for M=16 antenna elements

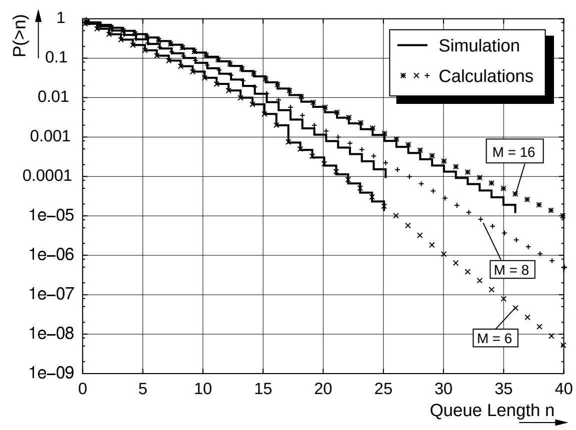

Figure 7. Cdf of queue length at departures instances for M=6,8 and 16 antenna elements

separate simultaneously transmitted signals increase. This leads to an increased number of simultaneously successfully decoded capacity requests and creates a higher load at the base station, see Tab. 3. But with an improved signal separation capability not only the throughput of the RCH increases, also the traffic channels can carry more packets simultaneously, which enables the base station to cope with the higher load.

5. Time Domain Scheduling

Once the signal processing unit has determined the set of MTs, which can transmit or receive simultaneously, the packet that should be transmitted next has to be selected. Considering the spatial domain, the transmission schedule is based on the signalling processing and the location of the individual MT with respect to the base station and to other interfering MTs. The transmission sequence of packets on the time axis is governed by the requested QoS of the application the packet belongs to. With special attention to real time services, we compare in the following four different scheduling strategies and evaluate their capabilities to meet prescribed QoS requirements in terms of packet loss and delay. Following [4], we show the principle results for the different scheduling disciplines using an example scenario comprising of three MTs, each operating a single connection with fixed QoS demands, see Tab. 4. We assume that packet losses only happen if the deadline of a packet is exceeded. Therefore the scheduling strategies have to reduce the delay to limit the desired packet loss ratio (PLR).

FCFS (First Come First Serve) The FCFS strategy treats all packets equally and transmits them in the order of their arrival. Fig. 8 shows the Cdf of the delays which

# antenna elements	fundamental arrival rate [1/ms]	load
6	0.1596	0.3775
8	0.1878	0.4443
16	0.2327	0.5504

Table 3. Arrival rates and resulting load

	Max. Delay [slot]	PLR
1	10	10^{-4}
2	22	10^{-2}
3	32	10^{-4}

Table 4. QoS parameters of example scenario

is equal for all three MTs. It is clearly visible that the QoS requirements of the individual MTs cannot be met applying this strategy.

SP (Static Priorities) Fig. 9 shows the application of static priorities. The priorities are assigned according to the QoS requirements of the MTs. MT 1 is served with the highest priority and MT 2 has the lowest priority. It is well known that static priorities normally do not provide enough flexibility and can create gaps in the PLR parameter space with increasing diversity of requirements. In our test scenario MT 1 and MT 3 experience a far better service than requested while the service achieved for MT 2 is not sufficient.

EDD (Earliest Due Date First) The scheduler assigns a deadline oriented priority to each packet i that increases while the packet approaches its deadline.

$$\tau_{DD_i} = t_0 + \tau_{d_{max,i}} \tag{20}$$

where t_0 is the time of packet arrival and $\tau_{d_{max}}$ describes the maximum allowed packet delay. The priorities of each connection are updated online by the scheduler at each transmission instance:

$$q_i(t) = \tau_{DD_i} - t = \tau_{d_{max,i}} - (t - t_0). \tag{21}$$

The scheduler selects the packet with the lowest value of $q_i(t)$ that represents the highest urgency for the next transmission. Applying this service strategy leads to the same PLR for all MTs and does not take the individual requirements into account. MT 1 experiences a violation of its QoS (Fig. 10).

ORU (Optimized Relative Urgency) The ORU scheduling strategy is based on the maximum delay and the maximum allowed PLR. Both parameters are combined and form the initial value of the urgency U_0. Like the EDD discipline, the scheduler updates the urgency values online at each transmission instance.

$$U_{RU_i}(t) = U_{0i} - (t - t_0) \tag{22}$$

For an algorithm to calculate the initial urgency values, see [4]. The ORU scheduling strategy is able to provide the desired QoS for all MTs and shares the resources between all MTs in a fair way. Fig. 11 shows this result for our example scenario.

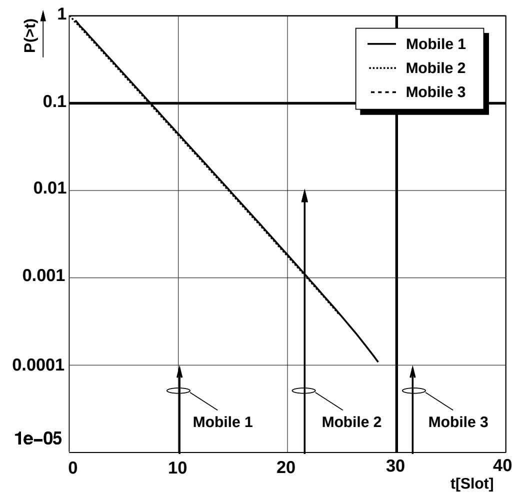

Figure 8. Cdf of delays, FCFS

Packet transmission over wireless links experience frequent packet losses compared to fixed network transmission. Error control protocols like Automatic Repeat Request (ARQ) protocols detect lost packets and request their retransmission. Each retransmission increases the delay of the individual packet and therefor the delay the application experiences. Thus, with each retransmission the urgency of packets increases. To satisfy the overall delay requirements, dynamic strategies are advantageous since these strategies reflect the increasing urgencies and allow to integrate the higher priority of urgent signalling messages like retransmission requests.

6. Conclusions

Motivated by improving the utilization of the scarce radio spectrum, we have discussed SDMA techniques for packet switching networks. Our investigations have been embedded into the framework of H/2, which serves as an

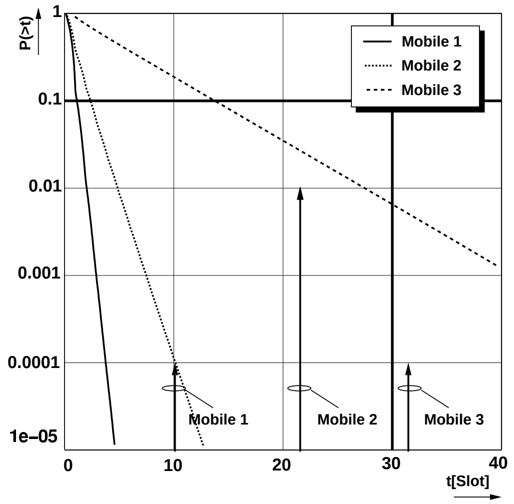

Figure 9. Cdf of delays, SP

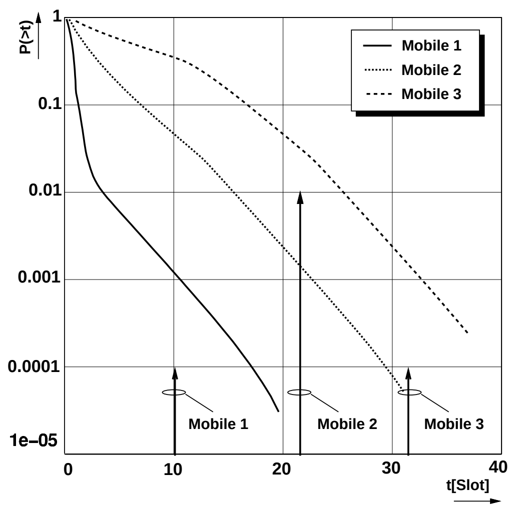

Figure 10. Cdf of delays, EDD

example of a modern packet switching radio network. Furthermore H/2 is able to guarantee QoS to the user. Nevertheless the presented concepts and ideas can be applied to other packet switching radio networks, e.g. such as the General Radio Packet Service (GPRS) of GSM. In this paper we have focused on discussing the two dimensional problem of packet scheduling considering the spatial as well as the temporal dimension. We have described how to use and parameterize BMAPs to gain some first insight into the arrival and queuing behavior of uplink transmission requests. Current work includes the extension of this framework aiming at a complete queuing model for the air interface of a packet switching mobile radio network. The spatial dimension is governed by interference produced by each mobile at the base station and at the mobiles in its vicinity. We have presented a spatial scheduling algorithm that is based on an

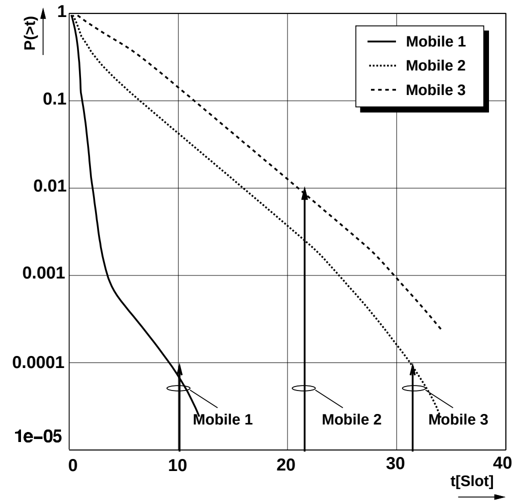

Figure 11. Cdf of delays, ORU

interference threshold. This algorithm is able to solve the scheduling problem in the spatial dimension. We have investigated several strategies for the temporal dimension. We have shown that a dynamic scheduling strategy called Optimized Relative Urgency (ORU) is not only able to achieve the requested QoS in terms of packet loss and delay, but also makes fair and efficient use of the shared resources.

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