Dynamic channel allocation in wireless ATM networks

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During the last few years extensive research has been carried out to extend fixed ATM networks to mobile users. Currently the European Telecommunications Standards Institute (ETSI) is standardising new types of Broadband Radio Access Networks (BRAN): HIPERLAN/2 and HIPERACCESS. In cellular systems like HIPERLAN/2 the aspect of channel allocation plays an important role. In this paper two approaches for channel allocation are introduced and compared with each other concerning the spectrum efficiency and their influence on the implementation of wireless ATM networks and wireless LANs.

1. Introduction

Several access protocols have been developed [1,8,9] and international projects are building the first wireless ATM demonstrators [3,7]. ETSI is currently standardising HIPERLAN/2 within the BRAN project. HIPERLAN/2 systems will operate in the unlicensed frequency band at 5 GHz. This air interface standard is able to support quality of service (QoS) requirements according to fixed ATM network standards and is also able to support TCP/IP, UMTS (third generation European cellular radio) and IEEE 1394 (Firewire) networks to a full extend. The base stations of different providers will compete for spectrum capacity in the same frequency band. Due to the increasing demand for higher data rates and the limited available bandwidth an efficient approach for transmit capacity allocation to base stations is required. Different aspects have to be fulfilled by the capacity allocation schemes.

We consider and present solutions to the problem where many base stations sharing one or more frequency channels each control the air interface concentrically in their radio cell but have to efficiently compete with other base stations for spectrum capacity to be able to fulfill Quality of Service (QoS) contracts agreed with their respective wireless terminals.

Owing to the high dynamics in bandwidth requirements and stingend QoS requirements of ATM connections statistical multiplexing of data packets has to be used at the air interface. This leads to a bursty spectrum occupancy by the wireless terminals and base stations. No other base station (BS) is able to predict the near future occupancy of spectrum capacity since any observed packet transmission from the reservation point of view is just history. Dynamic channel allocation schemes that perform radio signal strength measurements are known to be attractive to decentrally predict the future channel occupancy by extrapolation form the currently observed channel states [4,11].

For a high spectrum efficiency it is necessary that any BS only allocates the currently required capacity. Since in our proposed transmit capacity is allocated to base stations in terms of channels, the offered bandwidth of a channel should be relatively small to receive a sufficient degree of granularity of capacity allocations to base stations. Nevertheless, the overall data rate available to a base station should be high enough to serve their terminal's applications.

The paper is structured as follows: in section 2 the Medium Access Control (MAC) protocol is shortly introduced that is currently standardised at ETSI/BRAN and is used in our studies. Section 3 introduces two approaches for capacity allocation: one uses the frequency domain only to allocate channels to base stations, the other one in addition uses the time domain. Section 4 discusses the resulting problems and solutions when implementing the respective schemes. In section 6 a simple Connection Admission Control (CAC) algorithm is presented and the two channel allocation approaches are compared and evaluated by simulations in section 7.

2. Medium Access Control protocol of HIPERLAN/2

The statistical multiplexing of ATM is extended to the air interface by the ETSI/BRAN MAC protocol of HIPERLAN/2.

There, the access to a physical channel (this might be an FDMA or an TDMA channel) is co-ordinated by the BS as a central instance. It assigns capacity to its wireless terminals (WT) on a slot by slot basis according to the current capacity requirements as shown in figure 1.

In general, the MAC frame is periodically repeated in time and contains four physical channels which may vary their capacity per MAC frame:

Broadcast phase. Two logical channels are mapped on this physical channel: Broadcast Control Channel (BCCH) and the Frame Control Channel (FCCH) are mapped. The BCCH contains general information, while the FCCH contains a detailed description of the forthcoming frame. If the FCCH is not received the WT can neither transmit nor receive within this MAC frame.

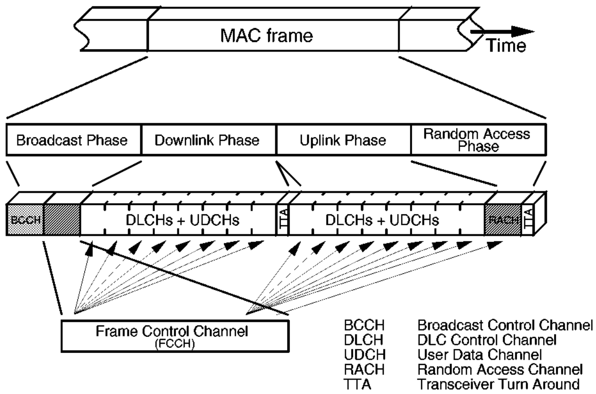

Figure 1. Structure of the periodic MAC frame.

Downlink phase. Two logical channels are mapped on this physical channel: Data Link control Channel (DLCH) and User Data Channel (UDCH).

Uplink phase. The same logical channels (DLCH, UDCH) are defined for this physical channel but in uplink direction.

Random access phase. This physical channel contains a variable number of slots for contention based transmission of control information from WTs to the base station.

The MAC protocol currently being standardised at ETSI/BRAN uses a fixed MAC frame length. Apparently a time division duplexing (TDD) mode of transmission is used.

3. Capacity allocation schemes

In this section two approaches are introduced, which both can be used with dynamic channel allocation (DCA) and fixed channel allocation (FCA), namely, allocation of

- FDMA channels,
- a combination of FDMA and TDMA channels to base stations to provide the needed capacity.

3.1. Capacity allocation through FDMA channels

A FDMA-based capacity allocation scheme has been introduced in [2]. The base station dynamically allocates FDMA channels according to its current capacity requirements.

For HIPERLAN/2 systems the bandwidth per FDMA channel is about 20 MHz corresponding to a gross bit rate of typically 25 Mbit/s, which might be too high capacity assignment for a given BS and lead to inefficient use of the spectrum.

One possible alternative would be to use lower capacity FDMA channels instead and to allocate as many FDMA channels as are currently needed by a BS. The spectrum efficiency would then be increased but BSs would need an appropriate number of transceivers then to be operated in parallel. This might also apply to WT, a solution which might be costly.

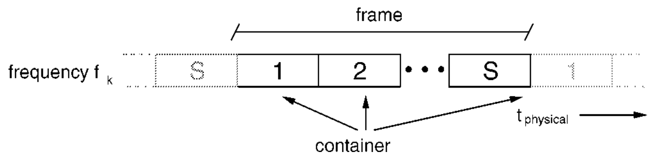

Figure 2. Frame and container structure on a physical channel.

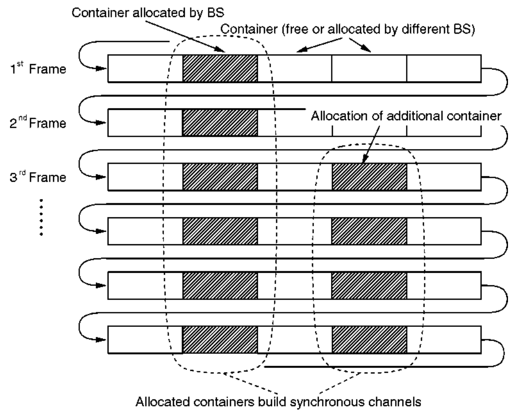

Figure 3. Allocated containers result in synchronous channels.

In the HIPERLAN/2 system owing to the TDD mode of operation this would result in unpredictable interferences crosswise between base stations, mobile stations and any combinations of mobile and base stations. Since uplink and downlink phases might be different across FDMA channels.

In section 4 the conditions to be able to efficiently operate a multicarrier air interface are described.

The main advantage of such a dynamic FDMA channel allocation approach is that BS need not to be synchronised.

3.2. Capacity allocation through FDMA and TMDA channels

In [5,6] a scheme was introduced that divides a FDMA channel into equal length units called *containers*. A fixed number of containers is grouped into a frame that is repeated periodically (cf. figure 2). A periodic container forms a TDMA container channel (CoCH) (cf. figure 3).

The BS may occupy as many CoCHs as needed to serve its WTs and open and release under decentral control by the base station CoCHs whenever appropriate and possible following the rules of the respective DCA algorithm.

Compared to the duration of a MAC frame a CoCH is operated for a much longer time duration and, therefore, allows all BSs and WTs to identify the CoCH used in their environment and to respect them. CoCHs are proposed to be occupied and released as standardised for TDMA channels in a DECT system.

The CoCH owned by a given BS together are used to transmit/receive the MAC frame (figure 4). There is no fixed relation between a MAC frame and a container – a MAC frame may cover more than one container. According to this proposal packets at air interface are statistically multiplexed to a TDMA container channel that uses part of the capacity of one or more FDMA channels.

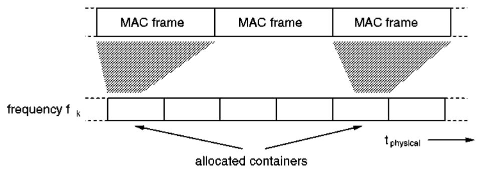

Figure 4. Relation between MAC frames and containers of a BS.

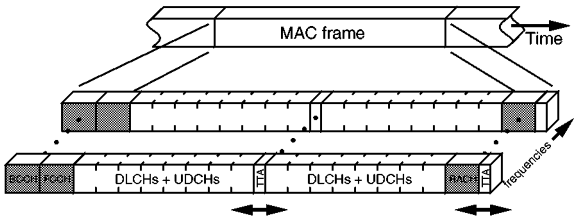

Figure 5. Correspondence of MAC frame on adjacent carriers.

Since several BSs are multiplexed to the same FDMA channel the BSs should be synchronised to the container frame to reduce unnecessary interference between CoCHs.

4. Multicarrier transmission

Since the WTs should be as simple as possible we assume that only the BSs are equipped with several transceiver units. Nevertheless, the following applies also if the WTs are equipped with several transceivers.

In an environment with heavy traffic it cannot be guaranteed that a BS is able to acquire FDMA channels that are sufficiently distant in the spectrum to avoid adjacent channel interference.

If a station transmits on adjacent carriers, the interference has to be considered that results from out-of-band RF power radiation.

Operation of adjacent channels by a BS is possible if the uplink and downlink phases of adjacent carriers are synchronised with each other. The correspondence of MAC frame on adjacent carriers is shown in figure 5.

If WTs are equipped with one transceiver only it might happen that a WT owing to frequency switching a number of given time slots cannot be used and system capacity is lost if the base station does not take this into account by its scheduler assigning slots of the MAC frame to WTs.

Another problem is that load balance across FDMA channels of a BS might not be possible at all times. In figure 6 an example is shown where a BS uses two FDMA channels in parallel and WT_1 consumes so many traffic on its downlink that the MAC downlink phase on frequency f_2 is completely filled although the same phase on frequency f_1 is partly unused. The more FDMA channels are being used to establish a given BS capacity the higher the complexity of MAC frame scheduling and the risk of unused capacity is. Since a WT typically has one transceiver only the maximum throughput is limited by the capacity of one FDMA channel and the transmit delay corresponds to the channel bit rate.

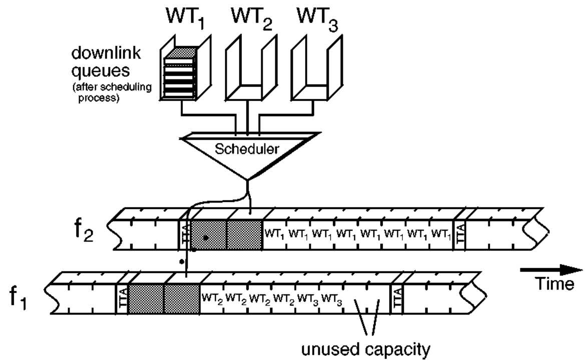

Figure 6. Unused slots which result from multicarrier transmission.

5. Optimum containers selection

5.1. *Influence of the container position on the delay*

The CoCHs are independent of each other and the positions of a container in the container frame is not important as long as a BS uses one CoCH only. Since one CoCH is the minimum a BS needs to establish a call, there will be time intervals during which a BS updates a number of CoCH to be able to serve it WTs.

During the duration of a container frame a BS has only transmit capacity available on its own containers. Their number depends on the total spectrum load by all BSs and the traffic load in a BS's cell.

To minimize transmission delay in a BS cell, the containers used by a BS should be distributed as uniformly as possible over the container frame. Our algorithm for the selection of a container to be occupied or released takes into account the positions of all containers in the container frame occupied by a given BS and aims at minimizing the maximum interval A_{max} between containers needed by a BS. The optimum distance A_{opt} determined by the number of containers per frame S and the number of containers B occupied by a BS is

$$A_{\text{opt}} = \frac{S - B}{B}. \tag{5.1}$$

The actual distance A can only be an integer number multiple of a container duration. We assume that the positions of occupied containers are not changed, i.e. only the position of the container to be occupied or released is considered and optimized. With DCA controlled by the BSs it is not always possible to select the CoCH that would be optimal since this channel might be too noisy. To be able to rank candidate CoCHs in the view of a BS a weight G is calculated in order to determine the best possible CoCH to be selected or released:

$$G = D_{\text{whole}} + \frac{\min(D_{\text{left}}, D_{\text{right}})}{D_{\text{whole}}}. \tag{5.2}$$

D_x is counted in multiples of D (cf. figure 7). The minimum weight G of a candidate container placed into a gap

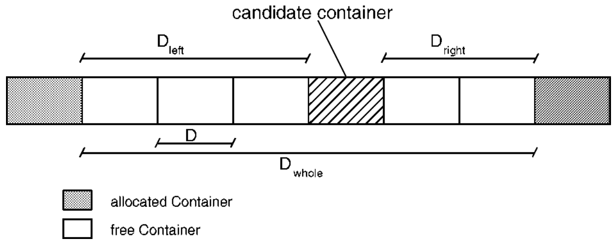

Figure 7. Relevant distances to determine the weight of a container.

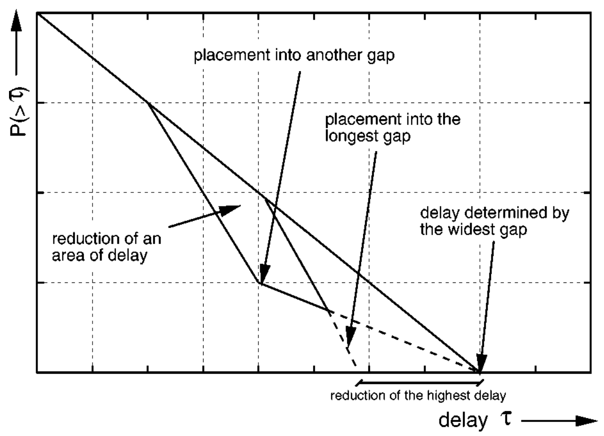

Figure 8. Influence of positioning of a new container on the cumulative distribution function of delay.

of width D_{whole} equals D_{whole}. If $D_{\text{whole}} = k$, all weights G of candidate containers are

$$k \leqslant G < k + 1. \tag{5.3}$$

Each position of a candidate container in a longer gap has a higher weight than a container in a smaller gap. This algorithm always identifies the largest gap between occupied containers. Since the maximum gap between CoCHs occupied by a BS determines the maximum packet delay over the air interface, the CoCHs in the middle of a gap are preferred.

Placement of a container into a smaller gap will only improve the delay distribution function of packets at the air interface unsatisfactorily. The maximum delay will remain unchanged (cf. figure 8). The smallest variance of delay is achieved if a candidate container is placed in the maximum gap. The mean delay is not effected by the container placement.

5.2. Algorithm for allocating a new container

We propose to identify candidate CoCHs based on a DCA algorithm under the control of the BSs as is standardised in [4], where all candidates CoCH are ranked according to the received signal level (a CoCH that is most silent has the highest rank).

The algorithm consists of 5 steps:

Step 1. Determine all containers that can be occupied from the view of the MAC protocol, eliminating these that need more than one transceiver.

Step 2. Select all the silent candidate CoCH that meet a given noise margin.

Step 3. Determine the weights of these containers.

Step 4. Select the container with the highest weight.

Step 5. If there is more than one container with the highest weight, select the container with the lowest noise (higher rank).

5.3. Algorithm for releasing a container

The bit error ratio of the CoCHs in use is taken as the main criterion according to the following priorities:

1. Release container with the highest bit error ratio.
2. Container with the lowest weight.

6. Connection Admission Control

To be able to guarantee for all accepted connections an agreed QoS like in fixed ATM networks a CAC algorithm has to decide whether a new connection can be accepted or not. In DCA systems there is one more degree of freedom since the capacity of the BS can be dynamically be changed, e.g., by occupying or releasing CoCHs.

To be able to evaluate the traffic performance of the HIPERLAN/2 MAC protocol using our proposed container based DCA scheme some cooperation between a CAC algorithm and our capacity allocation algorithm is needed.

We proceed in the following steps:

Step 1. If the CAC algorithm decides to accept the new connection request, no further considerations are needed.

Step 2. If CAC refuses the request, before informing the calling party so, the BS tries to acquire more capacity by allocation of one or more new CoCHs. After acquisition of a new CoCH step 1 is repeated.

Step 3. If no further CoCH is available the call is refused.

The CAC algorithm we use as part of our simulation study relies on the M/D/1 queuing system to model the air interface of HIPERLAN/2.

6.1. CAC derived from M/D/1 queuing system

For this model, the probability $P_{\text{MD}_1}(\tau < t)$ that a maximum waiting time t at the air interface is not exceeded is according to [10]:

$$P_{\text{MD}_1}(\tau < t) = 1 - \rho \sum_{i=0}^{k} \mathrm{e}^{\rho(\mu t - i)} \frac{-\rho(\mu t - i)^i}{i!} \tag{6.1}$$

with $k = [\mu \cdot t]$, where μ is the constant serving time of user data (ATM cells) and ρ the utilization of the server. Figure 9 shows the complementary distribution function of the waiting time for the M/D/1 queuing system.

We assume as a simple approach that the M/D/1 queuing system allows us to calculate the delay of the

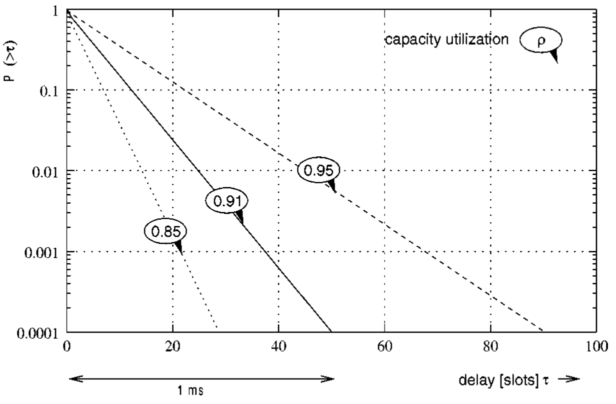

Figure 9. Complementary delay distribution function for M/D/1 ($\mu = 2^{-5}$).

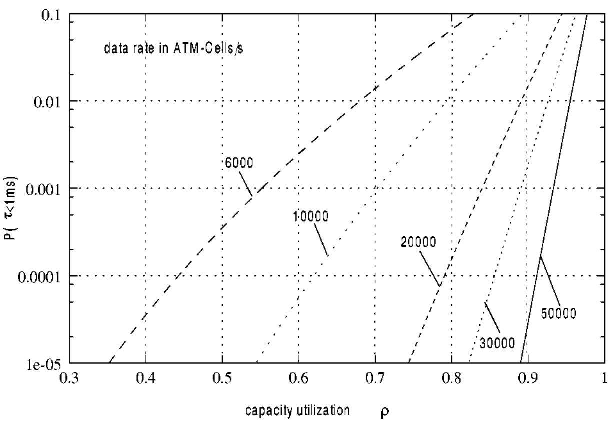

Figure 10. Delay probability over utilization (M/D/1).

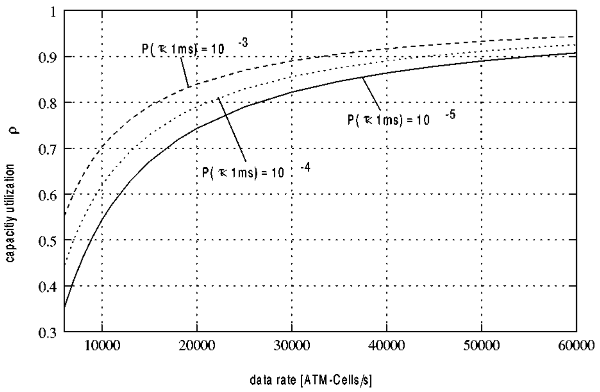

Figure 11. Capacity utilization ρ for 1 ms maximum of delay.

HIPERLAN/2 air interface and to derive from it whether some prespecified maximum delay can be guaranteed or not under a given load represented by the utilization.

Figure 10 shows the simulated results for the probability of delay not to exceed 1 ms over the utilization where the BS's capacity is a parameter.

From this the maximum utilization ρ can be determined that meets a given value of $P(<1\text{ ms})$. Figure 11 shows the same result. The maximum utilization over the capacity of a BS (in ATM cells per second) is shown with levels of

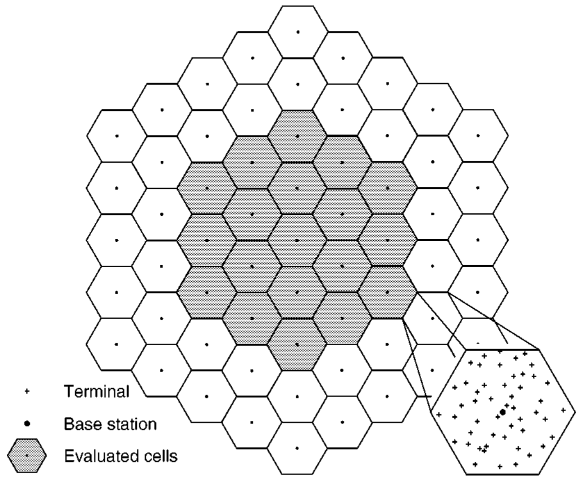

Figure 12. Scenario with 61 radio cells.

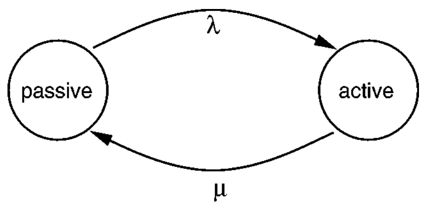

Figure 13. Source model for wireless terminals.

probability of 10^{-3}, 10^{-4} and 10^{-5} not to exceed 1 ms delay. These results can be used as a basis for CAC decisions, see step 1 above.

7. Simulation results

To evaluate the traffic performance of the system, simulations were performed with the following parameters if not stated otherwise.

Slot length	20 μs
MAC frame length	variable, up to 15 slots
Container length	100 μs = 5 slots
Containers per frame	32
Frame length	3.2 ms = 160 slots
Source model	Poisson
WTs per radio cell	$Q = 50$
One cell simulation	sections 7.1, 7.4, 7.5, one FDMA channel (50,000 cells per second)
61-radio cell simulation (cf. figure 12)	sections 7.2, 7.3, four FDMA channels (each 50,000 cells per second)

Each WT was modelled as a two-state machine. During the active state terminal's traffic source generates ATM cells from a Poisson arrival process with a mean equally distributed between 2000 and 3000 cells per second, while during the passive state no cells were generated at all (cf. figure 13). The probability p was taken as a parameter to generate variable traffic loads.

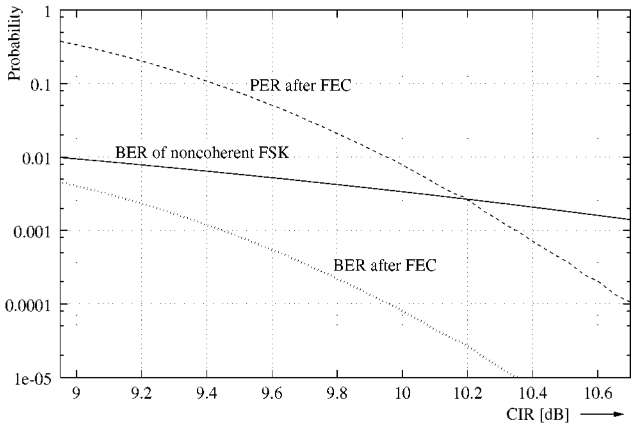

Figure 14. BER and PER.

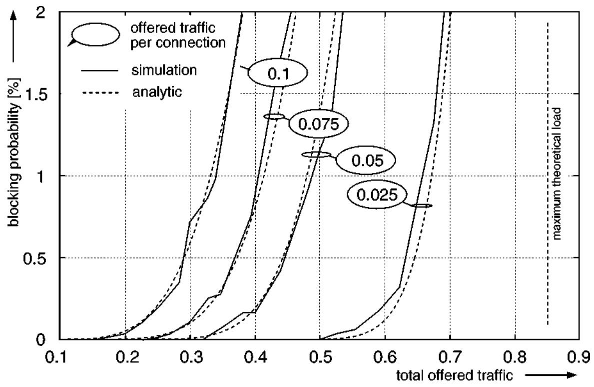

Figure 15. Maximum load over mean cell rate per connection.

The radio propagation conditions were modelled by the pathloss L. All BSs and WTs use omnidirectional antennas without additional antenna gain. The height of the antenna was not considered:

$$L = -40(1 + \log_{10} D). \tag{7.1}$$

The carrier-to-interference (C/I) ratio at the receiver is calculated for each slot of the MAC frame with all stations sending on the same FDMA channel. Based on the C/I ratio the BER (bit error rate) for noncoherent FSK modulation and the resulting PER (packet error rate) can be calculated.

In our simulations a Reed–Solomon (65, 55) FEC (forward error correction) code was used to reduce the BER on the air interface. Each slot carries one ATM cell plus signaling information in total 55 bytes. In figure 14 the resulting error probabilities over C/I can be seen. To take signal fading into account we added a fading margin of 3 dB to the pathloss.

7.1. Source model

The maximum load of an FDMA channel depends on the traffic source intensity and the maximum delay allowed. The results of a one-radio cell simulation using all CoCHs of a carrier can be seen in figure 15. Here the mean call rate per connection (the offered traffic) is varied and the blocking probability of new connections is shown over the offered traffic. It can be seen that the total allowed traffic can be increased with a smaller offered traffic per source (10% is equivalent to 10% of the FDMA channel's total cell rate capacity offered per source).

The total capacity of the physical channel is 50,000 ATM cells/s. Due to MAC overhead of the broadcast phase (a MAC frame is up to 15 slots long) the maximum net data rate is reduced to 46,666 ATM cells per second. The CAC algorithm is adjusted such that the maximum cell delay of 1 ms is exceeded with a probability of 10^{-4}.

According to figure 10 the maximum utilization ρ of the net data channel capacity should be below 0.91, which leads to a maximum allowed load ρ_{physical}:

$$\rho_{\text{physical}} = \rho\left(1 - \frac{1}{L}\right) \approx 0.85. \tag{7.2}$$

This maximum theoretically allowed load is indicated in figure 15. Using this value the number N of acceptable connections can easily be calculated (e.g., 17 connections loaded equal 0.05). By using the Engset formula that is valid for negative exponential distributed service times only the blocking probability Π can be calculated:

$$\Pi = \frac{\binom{Q-1}{N}\rho_q^N}{\sum_{i=0}^{N}\binom{Q-1}{i}\rho_q^i} \tag{7.3}$$

with ρ_q the offered traffic per source. A small ρ_q leads to a higher number of acceptable connection and owing the trunking gain to a higher totally acceptable load on the FDMA channel with the same blocking probability. Figure 15 shows the comparison of the simulation results with that of the Engset approximation. In the following simulation is $\rho_q = 5\%$.

7.2. DCA applied to FDMA and TDMA channels

Following section 3.2 the carriers are divided into TDMA CoCHs. A higher number of containers per frame allows a more precise capacity occupancy by BSs since a BS with low traffic load only uses a few CoCHs, the container frame length must not be too long to be able to meet the delay requirements of real time oriented services. We study the influence of the number of containers per frame and keep the container frame length fixed at 160 slots = 3.2 ms. The scenario of figure 12 was simulated with four FDMA channels and the blocking probability of new connection was studied. With an increasing number of CoCHs the container length is reduced. For comparison purposes also the results for FCA with cluster size 7 and a fixed number of CoCHs per BS allowed is shown. An increasing number of containers per frame allows a higher system load. The offered traffic for the 61-radio cells scenario has been normalized such that 50k cells/s are equivalent to an offered traffic of one.

To be more realistic in modelling a guard interval between adjacent containers is required to cope with the propagation delay of BSs. Since this interval is independent of

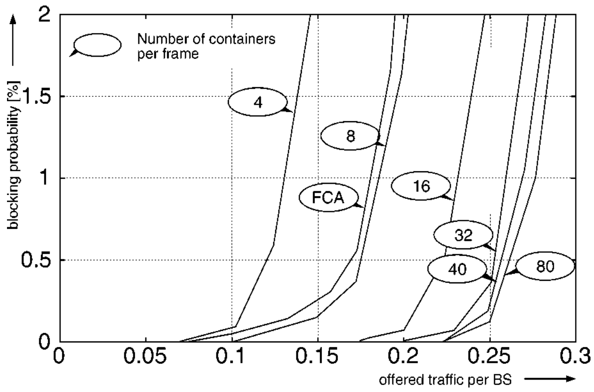

Figure 16. Influence of the number of containers per frame on the system capacity (offered traffic is normalized to 50k cells/s).

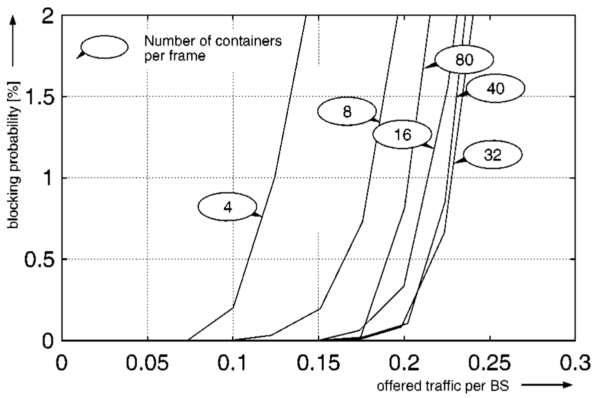

Figure 17. Influence of number of containers per frame on the system capacity with a guard interval between containers (offered traffic is normalized to 50k cells/s).

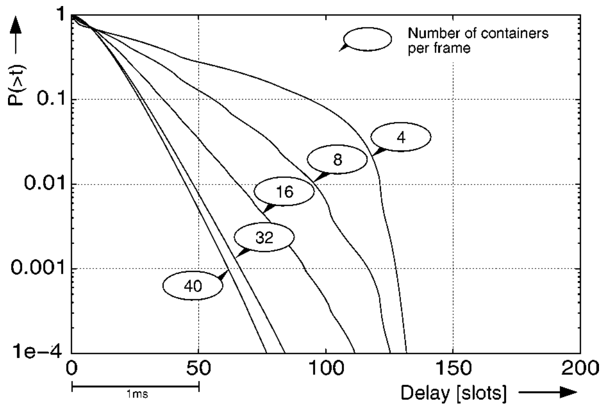

Figure 18. Influence of number of containers on the transmission delay over the air interface by blocking probability of 1%.

the container length, shorter container increases the guard channel overhead and reduces the available capacity. Our simulation results shown in figure 17 use a guard interval of half a slot (10 μs). It can be seen that there is an optimum value of 32 containers per frame. An evaluation of guard channels on the transmission delay can be found in [5].

In figure 18 the influence of the number of containers per frame on the cell transmission delay at the air interface is

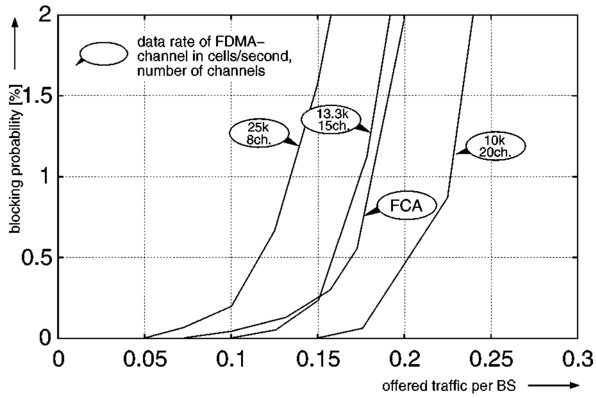

Figure 19. Influence of the number of carriers on the system capacity (fixed overall data rate of 200k cells per second, offered traffic is nomalized to 50k cells/s).

shown. The load was adjusted such that the same blocking probability of 1% was gained for all simulations. Since a higher number of containers per frame reduces the capacity offered per CoCH, more containers are required to achieve the same capacity that can be distributed more uniformly within a frame.

7.3. DCA applied to FDMA channels only

With no CoCHs available the capacity per FDMA channel has to be reduced to allow a more precise capacity allocation to BSs. Figure 19 shows the system capacity for various data rates of FDMA channels.

Since the WTs usually are equipped with one transceiver unit only, their data rate is limited to the FDMA channel capacity. QoS requirements of a WT applied data rate. Usually guard bands between carriers are required that reduce the total capacity. Since the guard band depends mainly on the modulation scheme and filter shape, it is approximately independent of the bandwidth. Thus, smaller channels increase the overhead per channel and reduce the total available capacity.

Our simulation assumes that a guard band of 500 kHz between two carriers in the 5 GHz band is required corresponding to a data rate of 1000 ATM cells per second (a 20 MHz channel offers around 50000 cells per second). The resulting decrease of the system capacity is shown in figure 20.

7.4. Container distribution

When a new CoCH is selected by a BS, not only its noise level (radio signal strength indicator, RSSI) but also the distribution of the containers within a frame has to be considered. Two extreme cases can be distinguished:

- *clustered allocation*: the BS selects consecutive containers;
- *uniform allocation*: containers are distributed uniformly within a frame.

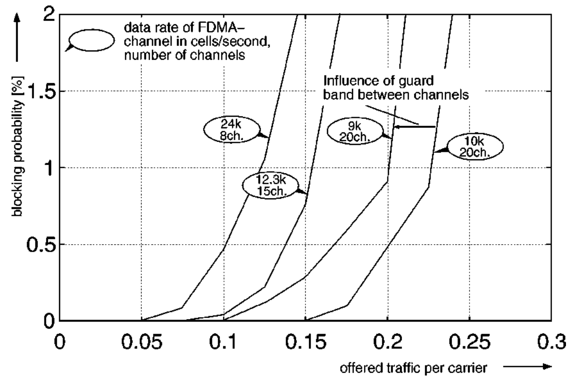

Figure 20. Influence of the number of carriers on the system capacity with guard bands between carriers (offered traffic is normalized to 50k cells/s).

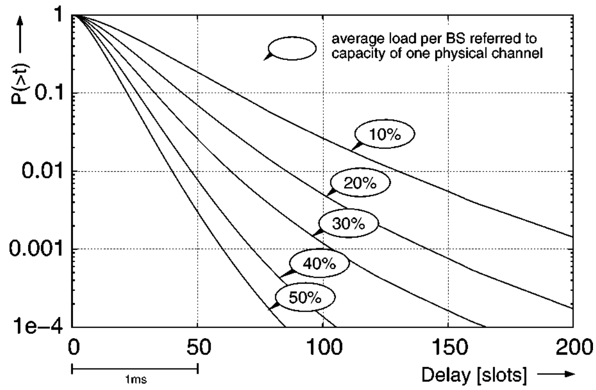

Figure 22. Transmission delay at the air interface with 20% capacity overbooking.

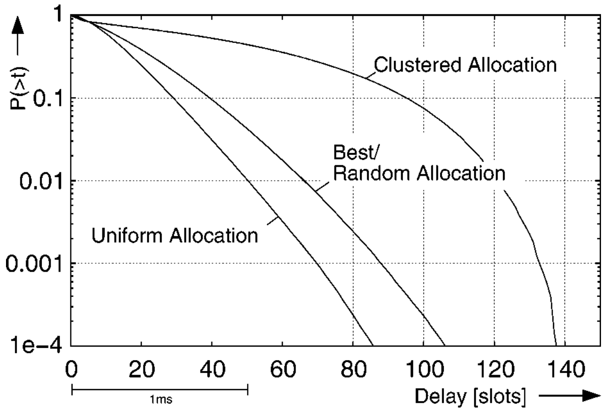

Figure 21. Delay uniform/clustered/best = random.

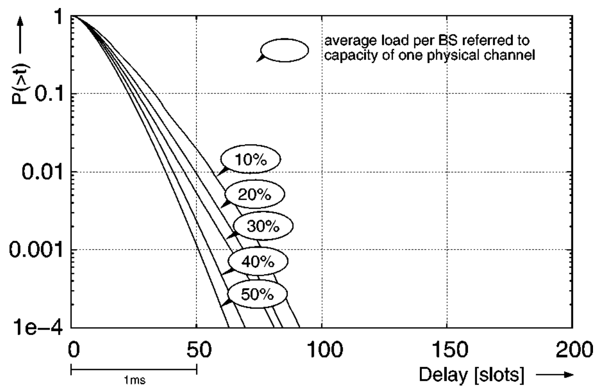

Figure 23. Transmission delay at the air interface with adaptive capacity allocation.

In figure 21 the complementary distribution function of the cell transmission delay is shown for different ways to select CoCHs. The simulations were carried out with an average data rate per BS that is equivalent to 20% of the capacity offered by one physical channel. It can be seen that the uniform allocation decreases the transmission delay since the capacity is distributed more homogeneously over a container frame. Whenever several containers have the same RSSI value, the BS chooses the container which leads to a more uniform distribution.

7.5. Influence of Connection Admission Control

This section studies the influence of the BS's load on the cell transmission delay under DCA with CoCHs. Whenever a new connection is requested, the BS determines the respective capacity. If the capacity available from the allocated CoCHs is not sufficient, one or more new CoCHs are allocated if possible.

A simple approach to determine the required capacity would be to take the requested throughput rate of the connection and add a certain percentage (e.g., 20%). The corresponding simulation results are shown in figure 22 and it can be seen that the transmission delay highly depends on the load situation of the base station.

Since the multiplexing gain increases with higher load of a BS the transmission delay decreases with increasing load, which is unusual for known queuing systems.

In figure 23 the same load simulated as in figure 22 is shown but with the CAC algorithm introduced in section 6. It can be seen that the cell transmission delay is nearly independent of the load situation.

8. Conclusions

In this paper two approaches for the transmit capacity assignment to BSs in wireless ATM networks are introduced and evaluated. One approach uses FDMA channels to divide a given band into smaller pieces while the other approach in addition uses TDMA channels. The results clearly show that at least for synchronised BSs TDMA channels perform better because they offer a more precise capacity allocation, require less processing power and provide a higher maximum data rate for a WT. It has also been shown how to combine multicarrier transmission with the container channels introduced to enlarge the system capacity and the total available data rate of a BS.

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