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Medium Access in Wireless ATM Systems for Industrial Applications: Requirements and Solutions[1]

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***Abstract*-The paper highlines problems of medium access that arise when using WATM in an industrial environment. Especially, short frames and a very efficient and fast random access protocol for the signaling channel are necessary due to stringent constraints of industrial applications. The proposed access and backoff scheme for the random access ensures the provision of very time constraint services and also considers implementation. Simulation results show that the scheme is superior in terms of delay and cell discard.**

I. INTRODUCTION

The Broadband Radio Access Group (BRAN) within the European Telecommunications Standards Institute (ETSI) has defined 3 different wireless broadband systems (HIPERLANs) which will be standardized by ETSI. Possible applications of these standards are manifold and ranging from privately operated wireless LANs to public wireless local loop applications [1]. All these systems will be able to support the full range of ATM service classes known from fixed ATM networks, i.e. CBR, rtVBR, nrtVBR, ABR, UBR, GFR. Many applications using this kind of services will be found in future industrial production plants, e.g. video and audio services will be used for surveillance and maintenance purposes, new software releases and monitoring data will be sent via file transfer between machines or control stations. Flexible autonomous transport vehicles controlled via radio carry goods and communicate among each other to negotiate the destination and the right of way. The characteristics of such applications are as follows:

- many terminals producing a high net datarate
- low individual terminal datarate with periodic transmissions and spontaneous transmissions
- highly sensitive to loss of data packets and highly sensitive to transmission delays
- alarm data (data with very high priority) have to transmitted fast and securely

These characteristics lead to increased requirements for fast access to the communication medium. Through the application of the ATM technology with its inherent quality of service guaranty and the deployment of advanced radio transmission techniques and MAC protocols, it is possible to use wireless communications systems even in real time control applications which enables a very flexible production environment.

The remainder of this paper is organized as follows. Section II discusses existing proposals for wireless ATM MAC protocols and the need to adapt them to the industrial environment. In Section III our proposed scheme is presented. Section IV shows the simulation model which we used for performance evaluation. The results of simulation studies are presented and discussed in Section V.

II. CURRENT MAC PROTOCOL PROPOSALS

Most existing WATM MAC protocol proposals are based on time division multiple access (TDMA), e.g. [3, 6, 8, 9]. In order to increase the throughput in case of asymmetric traffic load a time division duplex (TDD) method is often applied. ETSI/BRAN agreed also on a centrally controlled load adaptive TDMA/TDD frame structure for HIPERLAN/2 systems. In Fig. 1 a typical WATM TDMA/TDD frame structure is depicted. The access point (base station) controls the medium access by allocating time slots for the mobile terminals and for itself for a given period of time, called frame. A frame is subdivided into time slots (short and long slots) and consists of broadcast, downlink, uplink and signaling periods. The length of each period is variable and depends on the traffic load of base station and mobile terminals.

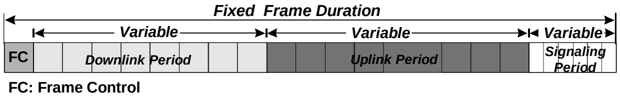

Fig. 1 General TDMA/TDD frame structure

At the beginning of a frame, general information relating the radio cell are broadcasted. Following, MAC frame related information concerning allocation of slots are broadcasted by the base station. The decisions of the scheduler are based on the available information about the number of outstanding cells and the delay requirements of cells in the mobile terminals and the base station itself. There are 3 principal methods for the mobile terminals to signal the status of their connections:

1. piggybacked with data in uplink period (using an additional short slot)
2. polling, i.e. periodical assignment of slots in uplink or signaling period, by the base station
3. random access in signaling period (short slot)

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The first method introduces moderate overhead since 9 byte are required based on the current decision made by ETSI/BRAN Hiperlan/2. The main drawback of this mechanism is that it cannot be applied if there is no bandwidth allocated for the mobile terminal. Moreover, if traffic with higher priority arrives at the mobile station this method is not sufficiently fast. Therefore this mechanism should always be applied but always in conjunction with one of the other two mechanisms. The polling method has got the trade-off between being inaccurate (i.e. a low polling frequency leads to high access delays) and wasting bandwidth due to unnecessary polling (i.e. the polling rate is larger than the data rate). Hence, random access in the signaling period method must be used for WATM in industrial environments and is a key component of the MAC protocol in this environment.

Several of the MAC protocol proposals do not specify a maximum length of the frame. The resulting frame length depends on the traffic situation and is computed by a specific algorithm, e.g. [5]. In order to allow fast reaction on changing traffic situations and to allow fast retransmit cells in case of transmission errors (ARQ) the overall frame length should be kept rather small. Previous simulations studies showed a good performance for maximum frame lengths of about 500 – 800 µs which is equal to 20 to 40 slots per frame depending on the chosen MAC protocol [7]. These results are in contrast to the goal to achieve maximum throughput which could be obtained by using rather long frames and techniques like long cell trains [8, 9] to decrease the overhead at the physical and MAC layer. ETSI/BRAN currently assumes to use a fixed MAC frame length of 2 ms.

Our approach for a WATM MAC protocol which is suitable for industrial applications is based on the DADRA protocol which is described in detail in [3]. An advantageous property of this protocol is its simplicity compared to other proposals. The principal components are as in Fig. 1 and its key features are as follows:

- fixed frame size with a slot allocation per mobile terminal
- signaling of bandwidth request piggybacked, polling or random access with a compressed traffic control field
- sequence number field for acknowledgements of downlink cells

III. PROPOSALS FOR THE WATM MAC LAYER OF INDUSTRIAL APPLICATIONS

As stated earlier, the protocol used for the random access channel is essential for industrial control applications [4]. The protocol must be able to support the high number of mobile vehicles in one radio cell, unpredictable traffic conditions, highly reliable message delivery and short transmission delays. If simple conflict-based schemes such as pure Slotted ALOHA are used to access request slots, the problem of long access delays in case of time sensitive data may occur. This simple scheme do not provide means to distinguish between different traffic flows in the random access section and therefore lead to undesired correlation among them. An additional problem arises if registration (association and handover) of terminals are considered. A mobile terminal must use random access if it wants to register with a base station unless the base station grants slots for this purpose. ETSI/BRAN has adopted a registration scheme based on random access.

A possible solution is to combine the S-ALOHA schemes with an appropriate collision resolution mechanism and priorities. Priorities on random access slots allow to de-couple flows since other service classes and associating terminals might use random access slots as well. We suggest a model with three priorities, where the highest priority is used for industrial control applications, the second for rt-VBR services and other traffic with real-time constraints and the lowest for UBR, association and handover. For all different priorities separate random access slots are allocated by the base station. Within the slots of one service class S-ALOHA is applied.

Moreover, for each priority class a separate efficient collision resolution protocol is performed to ensure low access delays even under heavy load. Our proposed scheme is compared to a traditional scheme without priorities in the random access. We define conditions which must be fulfilled by the mobile terminals in order to access the random access slots. These conditions are very vital for the system to avoid unnecessary random access. The access condition rules are defined as follows:

1. The mobile station saves the priority (service class) of the last sent bandwidth request. If a new cell arrives at the mobile terminal which has got a higher priority or a shorter remaining life time and the same priority, the station is allowed to access the random access section to signal the new requirements.
2. If the station has got a cell which threatens to expire and the station did not get a time slot in the last two frames the station may access the random access section.
3. The station has new unguaranteed cells to send and no outstanding bandwidth request for any other priority, the station is allowed to access the random access but with lowest priority.

In addition to these rules we designed collision resolution and prevention mechanisms. They are needed to adapt the number of random access slots and the probability to access a slot if one of the rules above applies. This mechanism is performed separately for each priority class at the base station starting from the highest to the lowest. Given a maximum length for random access it might happen that not all required slots especially for lower priorities can be granted. In this case the probability to access a slot is being decreased.

The random access adaptation algorithm is depicted in Fig. 2. It is always performed at the beginning of a frame starting from the highest to the lowest priority class.

- *nr_slot*: number of random access slots (min_slot ≤ nr_slot ≤ max_slot; max_slot is the maximum available number of slots taken into account the slots already used by higher priorities)
- *p_ac*: probability for granting access to a random access slot if access condition (1-3) are fulfilled (0 < p_ac ≤ 1; starting with p_ac = 1)
- *adap_sl*: factor to adapt the number of slots (in simulation set to 2)
- *adapt_ac*: factor to adapt the access probability (in simulation set to 2)

The first decision in the algorithm is whether there were collisions within the specific random access priority or not. It is a matter of optimization to use a certain threshold to trigger this decision. The following adaptations are straightforward.

In the new MAC frame the base station signals *nr_slot* and *p_ac* for each priority class to the mobile stations. If one of the access rules (1-3) are fulfilled a mobile terminal calculates a random number *p_mt* between 0 and 1. If *p_mt* < *p_ac* the access is granted and the mobile terminal chooses randomly one of the available random access slots (provided for its priority). If the frame does not provide random access slots for the access priority of the mobile terminal it has to wait for the next MAC frame.

This kind of collision resolution has the advantage to be well suited for standardization since the actual algorithm (like in Fig. 2) need not to be drafted. Each implementer can optimize the algorithm and signals the parameter to the mobile terminals which in turn must stick to these rules.

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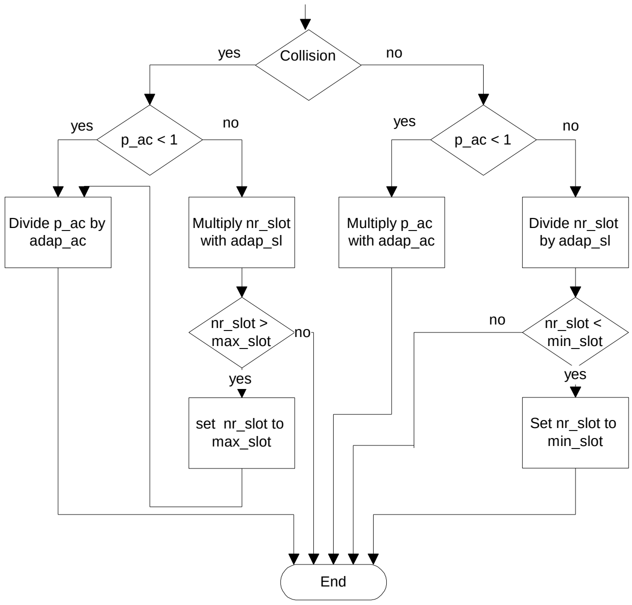

Fig. 2 Random Access Adaptation

One sub-variant is to implement only 2 priority classes provided that classical applications only use random access slots very rarely. The high priority slots can then be given to industrial control applications and the low priority slot to the remaining applications.

Other collision resolution schemes known from literature [11, 12] have also the ability to separate different flows in principal but require reliable collision detection (ternary feedback) on the physical layer whereas our proposed scheme only needs a positive feedback (binary feedback). Ternary feedback is not easily provided but rather need some effort and is currently not supported by the ETSI/BRAN specification. These proposals are therefore not considered in this paper.

IV. SIMULATION MODEL

The simulation scenario consisted of up to 100 stations. This number is high compared to other simulation scenarios but it is more realistic in an industrial environment. Traffic was generated by the following sources.

Table 1 Traffic characteristics

High Priority	Medium Priority	Low Priority
Industrial Appl.	VBR Video	IP, email, etc.
POISSON source, max. CTD 10ms, symmetric connections, 32kbit/s per connection	Autoregressive source [10], max. CTD 30ms, Uplink, 1Mbit/s per connection	POISSON source Max. CTD 50ms, symmetric, 12% of system load e.g. 3Mbit/s sum datarate

Simulation was carried out using 11 part tests of 5 sec realtime each to gather the statistical simulation results.

The requirements especially for the maxCTD (Cell Transfer Delay) were gathered by studies on real industrial control applications. The POISSON source is well suited since it allows no prediction of the traffic which leads to extensive use of random access.

The traffic in the system was varied by subsequently adding new sources of rt-VBR traffic (medium priority) to the system whereas high and low priority traffic was fixed to one source of each class for every mobile terminal. The transmission channel was assumed to be error-free. For a detailed description on the influence of errors on WATM system performance and overhead see [7].

The parameters of the physical channel where chosen to the following values.

Table 2 Physical channel parameter

Channel bandwith (equals 100% of load in diagrams)	25Mbit/s
Slot Guard Time (guard time between 2 slots)	$5 \cdot 10^{-7}$sec
Frame Sync (guard time between 2 frames)	$5 \cdot 10^{-6}$sec
Transmit/Receive Turnaround Time (guard time between down- and uplink)	10^{-6}sec
Random Access / Uplink Preamble (preamble for synchronization in uplink)	128 bit
Downlink Slot (duration of one downlink slot with 56 byte data)	$1{,}792 \cdot 10^{-5}$sec
Uplink Slot (downlink + 128 bit preamble)	$2{,}304 \cdot 10^{-5}$sec

The minimum number of random access slots (*min_slot*) was set to 1 and the maximum (*max_slot*) was set to 10. The slots are subdivided into 3 sub-slots (i.e. maximum number of random access slots is 30) since this is sufficient to transmit the 2 byte of signaling and the address information. Selective Repeat ARQ was active together with an acknowledgement bitmap field [3] allowing to send up to 9 acknowledgements within one data cell. Although the channel was error-free, ARQ produces some overhead since asymmetric connections may lead to polling of stations due to the need of acknowledgements.

V. SIMULATION RESULTS

In Fig. 3 the influence of the number of stations that take part in channel access versus overall throughput (32 slots per frame) is shown. The decrease of system throughput for larger number of stations indicates that industrial applications require special attention in system design. The X-axis label “Input” denotes the MAC input load of the system (excluding overhead like preambles and guard times) as a percentage of the maximum channel capacity (25Mbit/s). Y-axis “Output” denotes the MAC user data throughput.

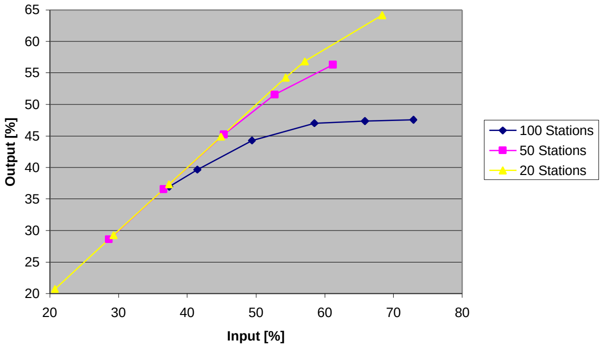

Fig. 3 Overall throughput vs. number of stations

Fig. 4 shows the influence of the MAC frame length on system throughput with 100 active stations. Longer frames lead to nominal higher throughput, due to a reduced overhead. The trade-off is the longer delay that the connections experience. The delay mainly comes from the time to signal new data from the mobile terminal to the base station. In Section II it is highlined that random access is the most used way of signaling in this case. Since a station might need more that one transmission attempt over random access the frame length directly influences the transmission delay.

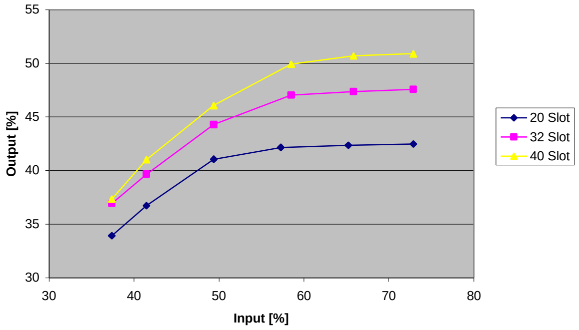

Fig. 4 Overall throuput vs. slots per frame

In Fig. 5 and Fig. 6 the discard rate and the cumulative distribution function (cdf) of the transmission delay for the high priority traffic is shown. Due to the very stringent time constraints of industrial control applications (10ms CTD) the trade-off between efficiency and delay is very significant. With higher transmission delays the discard rate especially for high priority traffic is greater for longer frames. To show the effect, i.e. to have cell discards, the system is on full load (100 Stations on a random access section with *max_slot* = 30). One can see in Fig. 6 that frames with 32 slots performs overall best, i.e. good throughput and lowest transmission delay. A 32 slot frame equals to a total frame length of about 670µs in this scenario depending on the distribution of downlink and uplink slots.

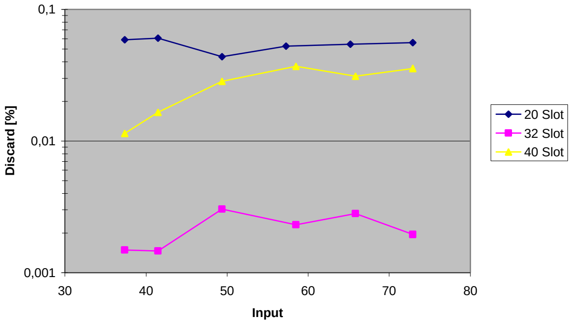

Fig. 5 Discard rate of high priority traffic vs. number of slots per frame

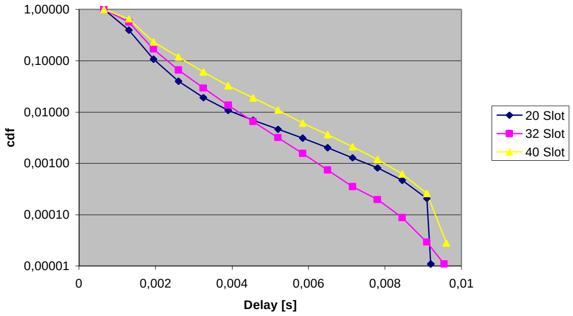

Fig. 6 CDF of transmission delay of high priority traffic vs. slots per frame

So far only the influence of the frame length were considered. In the following paragraph the advantages of priorities within the random access period of a frame are explained. Fig. 7 and Fig. 8 show some of the results obtained by applying the proposed 3 priorities on the random access section (32 slots per frame). The results are compared to a scheme without priorities (1 priority in the figures). Discard rates and delays for the high priority traffic are significantly lower with the proposed scheme than in the case without. This is achieved through the separation of flows within random access section. Also low priority traffic can profit due to the used packed request format [3] that allows to signal bandwidth requests for all priorities at once. Results were obtained with 100 and 90 active mobile stations respectively. Since the percentage of high priority traffic is lower in case of 90 stations there are less cell discards and a smaller CTD. The simulation did not include association or handover which would justify even more the usage of priorities within random access.

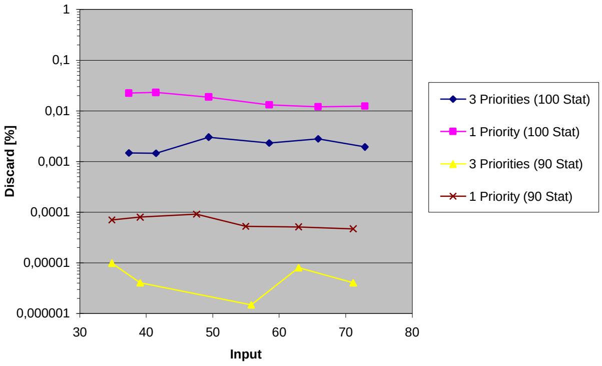

Fig. 7 Discard rate high priority traffic vs. priority classes

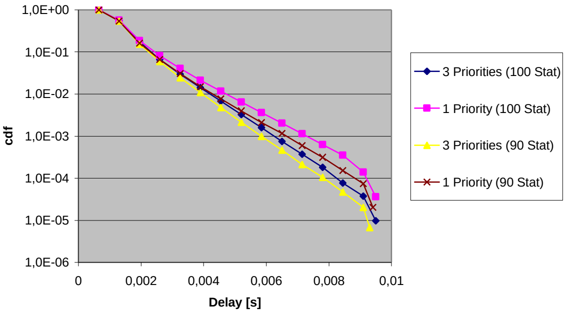

Fig. 8 CDF of transmission delay for high priority traffic vs. priority classes

V. Conclusion

The paper discussed the influence of industrial applications on the performance of WATM networks. The focus was set to random access which is very critical due to the stringent time constraints of the application. The proposed random access and backoff mechanism for WATM is superior compared to an algorithm without priorities. Moreover, the protocol is able to support highly time sensitive industrial applications and at the same time traditional WATM services (e.g. office applications). Priorities for random access guarantee the desired separation between different traffic classes and are vital for services with very stringent time constraints like industrial control applications. Since ETSI BRAN is going to standardize only the interface and not the scheduling algorithm at the base station the emerging standard leaves many options open to the designers in the actual implementation. The proposed scheme in the paper is a potential candidate for the random access and backoff for the HIPERLAN/2 standard. It also allows easy implementation due to the binary feedback.

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