STATISTICAL PACKET ASSIGNMENT MULTIPLE ACCESS FOR WIRELESS ASYNCHRONOUS TRANSFER MODE SYSTEMS

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ABSTRACT

Statistical Packet Assignment Multiple Access (SPAMA) is proposed, based on a statistical allocation of bandwidth resources to terminals which share a slotted, framed channel. The statistical nature of the centralized slot assignment scheme allows an accurate matching of bitrate requirements for different multimedia services with a minimal amount of signalling, while maintaining a throughput of up to 93%.

1. INTRODUCTION

In this contribution a novel multiple access scheme is proposed, which we refer to as the Statistical Packet Assignment Multiple Access (SPAMA) protocol. The new scheme attempts to achieve an efficient and simple bandwidth allocation for multi-rate users in high-rate systems, such as wireless Asynchronous Transfer Mode (ATM) extensions [1]. The basic principle of SPAMA accrues from a non-deterministic bandwidth assignment, performed by the base station on the basis of knowing only the average rate a certain service requires. A time division duplex (TDD) system is assumed, where the base station broadcasts packetized information in the downlink channel, whereas geographically dispersed terminals transmit packets to the base station in the uplink slots, according to slot allocations of the considered medium access (MAC) protocol [2]. Section 2 outlines the SPAMA algorithm, while Section 3 characterises its performance, before concluding in Section 4.

2. THE SPAMA ALGORITHM

At the end of each TDD-frame, assuming that all uplink slots for the following frame are initialized as available, slot assignments are performed by the base station according to the SPAMA algorithm. We firstly describe the general principle of the algorithm and then describe its detailed implementation, as it is displayed in Figure 2.

The new approach of the SPAMA algorithm is its non-deterministic assignment of slots according to the average rate of a certain service. Assuming that an active spurt of the service has an average bitrate of R_S and that the assignment of one slot per frame corresponds to a virtual channel of bitrate R_{VC}, the required number of slots per TDD-frame is calculated as $x_S = R_S/R_{VC}$. Note that an active spurt is a transmission phase, which is long in comparison to the frame duration, i.e. usually one or more seconds, such as a talk spurt in speech transmission or a whole call in a service without silent gaps. Given x_S, the interval $\tilde{I}_S$ (expressed in terms of the number of frames), in which the considered service needs to transmit one packet, equals $1/x_S$. In previous approaches, such as all Packet Reservation Multiple Access (PRMA) based [3] [4] access schemes, these requirements had to be translated into integer expressions, allowing the users to occupy only an integer number of slots per frame on the average. These translations always implied complex algorithms and a suboptimal bandwidth allocation. In the SPAMA algorithm, however, the proposed statistical assignment allows us to meet 'non-integer' slot allocation needs. Namely, since only integer numbers of slots can be assigned, an assignment of x_S slots per frame can be interpreted as an assignment of one slot with a probability of $p_A = x_S$. For example, in a framed wireless ATM system, such as that represented by the parameters in Table 1, a one slot per frame virtual channel provides a bitrate of R_{VC} = 963.264 kbps. Considering a speech service in accordance with the GSM standard [5], that is an FEC-coded sourcerate of R_S = 22.8 kbps during a talkspurt, the number of slots required per frame is calulated as:

$$x_S = \frac{R_S}{R_{VC}} = \frac{22.8\,kbps}{962.264\,kbps} = 23.694 \cdot 10^{-3}\,. \qquad (1)$$

This corresponds to an assignment of one slot per frame

SUBMITTED TO ACTS SUMMIT'97, AALBORG, DENMARK with a probability of $p_A = x_S = 0.02369$ or to an assignment of one slot in $\tilde{I}_S = 42.205$ frames. Note that slot assignments with a probability of p_A in each frame lead to a high variance in the assignment interval duration, that is in terms of the number of slots between two assignments, which implies an inefficient bandwidth allocation. This is due to potential premature assignment of slots that cannot be used by a terminal, because it does not have a ready-to-send packet in its buffer. In order to avoid this problem, we do not base the slot allocation regime of the SPAMA algorithm on the computed assignment probabilities for each frame, but on the cumulated assignment probability for each interval $\tilde{I}_S$. In our example above a slot should be assigned with a cumulated probability of one in $\tilde{I}_S = 42.205$ frames, i.e. with a cumulated probability of $\sigma_p = 42/42.205 = 0.995$ in an interval of $I_S = 42$ frames. In other words, it is necessary to guarantee an assignment of one slot in 42 frames with a cumulated probability of $\sigma_p = 0.995$. The distribution of the per-frame assignment probabilities in each frame of the interval I_S can theoretically be chosen without any restrictions, knowing of course that the choice will significantly influence the system's performance. In order to avoid the above mentioned early assignments of slots, the per-frame assignment probabilities have to increase with the number of frames elapsed since the last assignment. In a first approach, we assume a simple assignment probability growth function:

$$p_A(n) = q_k\, n^k\,, \tag{2}$$

where n is the number of elapsed frames since the last assignment and the parameter k, defining the constant q_k, remains to be chosen in order to obtain a good system performance. For reasons of simplicity, we assume an integer value for k and then express the cumulated probability constraint given by:

$$\sigma_p = \sum_{n=1}^{I_S} p_A(n) = \sum_{n=1}^{I_S} q_k\, n^k = q_k \sum_{n=1}^{I_S} n^k\,, \tag{3}$$

which yields the constant q_k as

$$q_k = \frac{\sigma_p}{\sum_{n=1}^{I_S} n^k}\,. \tag{4}$$

Still keeping k as a parameter, we obtain the per-frame assignment probability as a function of the number of frames n elapsed since the last assignment by inserting Equation 4 in Equation 2, yielding:

$$p_A(n) = \frac{\sigma_p}{\sum_{n=1}^{I_S} n^k}\, n^k\,. \tag{5}$$

Equation 5 defines explicitly the assignment probability growth function. The assumption of an integer value for k allows us to express the denominator of Equation 5 in a simpler form, for example, for $k = 1,3,5$ and 7, we have:

$$\sum_{n=1}^{I_S} n = \frac{I_S\,(I_S+1)}{2} \tag{6}$$

$$\sum_{n=1}^{I_S} n^3 = \frac{{I_S}^2\,(I_S+1)^2}{4} \tag{7}$$

$$\sum_{n=1}^{I_S} n^5 = \frac{{I_S}^2\,(I_S+1)^2\,(2\,{I_S}^2+2\,I_S-1)}{12} \tag{8}$$

$$\sum_{n=1}^{I_S} n^7 = \frac{{I_S}^2\,(I_S+1)^2\,(3\,{I_S}^4+6\,{I_S}^3-{I_S}^2-4\,I_S+2)}{24}\,. \tag{9}$$

Referring to the example introduced above, we use Equation 5 and obtain the assignment probabilities as displayed in Figure 1.

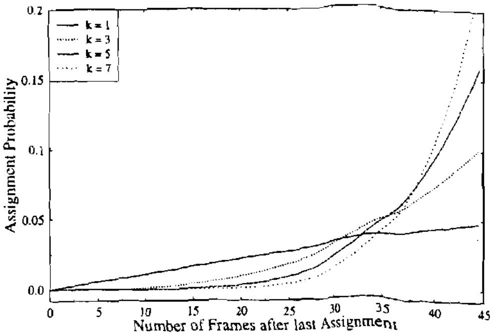

Figure 1: Assignment probability growth function for our example, $\sigma_p = 0.995$ and $I_S = 42$.

Once the base station has calculated the assignment probabilities p_A for each of the different rate services supported, a binary random decision based on p_A defines, whether the service is granted a slot assignment in the current frame. This computation is performed once a frame and then communicated to all terminals in the broadcast cell at the beginning of the following frame, so that each terminal is informed as to the slots it can use for transmitting packets. Note that if a service needs more than one slot per frame, i.e. $x_S > 1.0$, it is assigned a number of slots, corresponding to the integer part of x_S in each frame. In order to cater for the 'non-integer' fraction, the algorithm is applied as described above.

In order to give a more detailed description of the proposed SPAMA algorithm, its Nassi-Shneiderman diagram [6] is displayed in Figure 2. Assuming that each

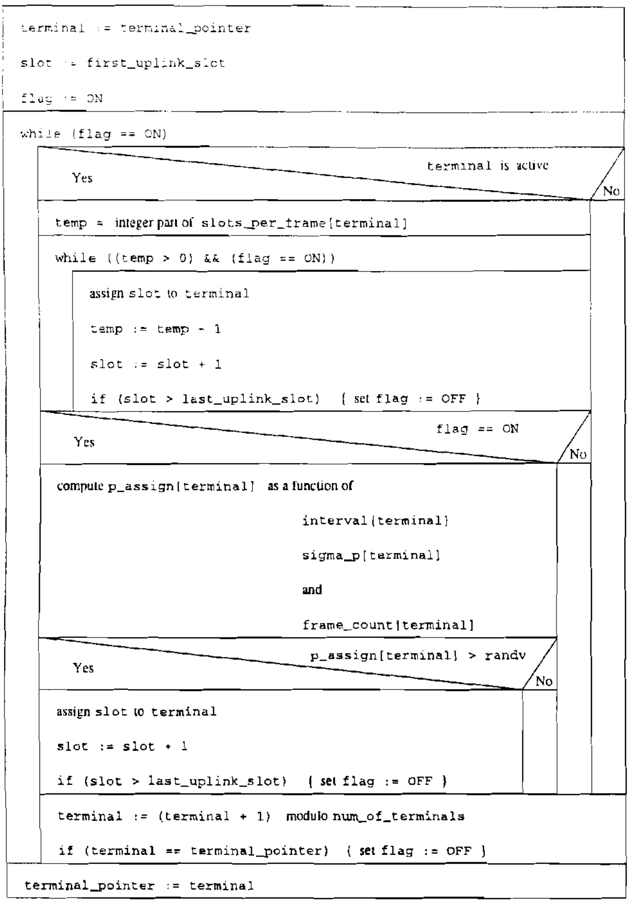

Figure 2: Core part of the SPAMA algorithm, displaying one assignment cycle.

terminal is only involved in one service, the interval I_S and the cumulated probability σ_p are denoted by `interval[terminal]` and `sigma_p[terminal]` can be calculated for each terminal as described above. All terminals are supposed to be cyclically numbered, so that the terms previous and next terminal can be used. At the beginning of each assignment cycle, the variable `terminal` is set to the terminal which is next to the one considered last in the preceding assignment cycle. Each assignment cycle starts in the first uplink slot, `slot:=first_uplink_slot` and ends, if either all uplink slots have been assigned, corresponding to `(slot > last_uplink_slot)` in Figure 2, or all terminals have been served, satisfying the condition `(terminal == terminal_pointer)`. For a specific terminal, in a first step, the integer part of the required number of `slots_per_frame[terminal]` is assigned, if necessary, as reflected by the Figure. Then the assignment probability `p_assign[terminal]` is computed, as described above, and a slot assignment is performed according to the binary random decision `if (p_assign[terminal] > randv)`, where `randv` is randomly chosen from a set of uniformly distributed numbers in the interval (0,1). Then the next terminal is considered. At the end of the assignment cycle of a certain frame, `terminal_pointer` is set to the terminal, which is next to the one considered last, which is represented by `terminal_pointer := terminal` in Figure 2.

For call set up, a terminal has to signal the average bitrate of the service it is going to require. In a first approach, each terminal contends with an initialization-packet, containing the necessary information. Assuming 64 slots per frame and 15 speech, 15 video users, as in the simulations below, it proved to be sufficient to guarantee one contention slot in every second frame. At the end of a call, another signalling packet is transmitted to the base station, this time in an assigned slot, indicating that assignments are no longer necessary.

Applying the assignment algorithm described above, not all uplink slots are necessarily used. In order to keep the average packet delay low, these slots could be assigned to users whose packets already exceeded a certain delay. In a first approach, minimizing the signalling amount, we assume that terminals indicate 'ageing' packets by using a one bit flag in the packet-header they are sending. If this bit is set to one and not all slots have been used in the current assignment cycle, the terminal gets an assignment for a number of slots depending on its average bitrate, which is already known to the base station. Both the time after which a packet is considered as 'ageing' and the relation between the average bit rate and the number of assigned slots will be identified according to our simulation results. Performance figures for the SPAMA algorithm are given in the next Section.

3. PERFORMANCE OF THE SPAMA PROTOCOL

Having presented the structure of the SPAMA algorithm, we now characterize its performance. In a first set of simulations, we examine the influence of the assignment probability growth function, which was presented in Equation 5. The throughput performance determined by the access protocol's efficiency is then examined by varying the number of uplink slots for a given traffic load.

For our simulations, we assume a frame length of $N = 64$ slots, where each slot carries $S_N = 384$ bits of payload, as for the ATM standard [7]. Let U_S and U_V denote the number of speech and video users present in the system. Their source rates are referred to as R_{SS} and R_{SV}, where R_{SS} is fixed at 22.8 kbps, according to the GSM standard [5]. The video source model emulates an H.263 encoder [8] [9]. The channel rate R_C is chosen in order to guarantee a two-way communication, which matches exactly the 34 Mbps ATM

Definition	Notation	Unit	Value
Channel Rate	R_C	Mbps	164.226
Frame Duration	T_F	msec.	0.3991
Slot Duration	T_S	msec.	0.0062
Speech Source Rate	R_{SS}	kbps	22.8
Video Source Rate (target)	R_{SV}	Mbps	2.0
Range of Video Rate		Mbps	1.62 - 2.40
Gross Slot Size	S_G	bit	1024
Net Slot Size	S_N	bit	384
Slots per Frame	N		64
Maximum Speech Delay	$D_{max,S}$	sec.	0.03
Maximum Video Delay	$D_{max,V}$	sec.	0.03
Number of Speech Users	U_S		15
Number of Video Users	U_V		15
Ageing Packet Constraint	t_{age}	sec.	0.015

Table 1: SPAMA parameters for a 34 Mbps WATM system

interface, i.e. ATM cells comprising (384 + 40) bits are transmitted at that bitrate in both directions. The remaining bits of the 1024-bit packets in each slot are required for FEC coding, for the packet header and for the quasi-periodic extension necessary in OFDM modulation techniques [10]. For both speech and video services, a maximum delay of 30 ms is tolerated, before a packet is dropped. All simulations are carried out for 15 speech and 15 video users. We refrain from simulating a constant rate data service in these initial simulations in order to create a randomistic worst-case scenario for the SPAMA algorithm. Specifically, since the protocol's efficiency increases with a decreasing variance of the average rate, a constant rate service implies good system performance. The span of time after which a packet is considered as 'ageing', triggering additional slot assignments, as mentioned above, is set to 15 ms. If any packet in the buffer of a terminal is older than 15 ms, then the additional request bit is transmitted to the base stations in the overhead of the following packet the terminal is sending. In simulations, this span of time proved to yield good performances for different sets of parameters. The number of additionally assigned slots for ageing packets is limited by the number of slots, which is still available in the frame after the standard assignment cycle. In order to prevent low-rate users with only a few ageing packets in the buffer to get assignments for too many slots, the number of additionally allocated slots per terminal corresponds to 5% of the average bitrate for the considered service. All system parameters are summarized in Table 1.

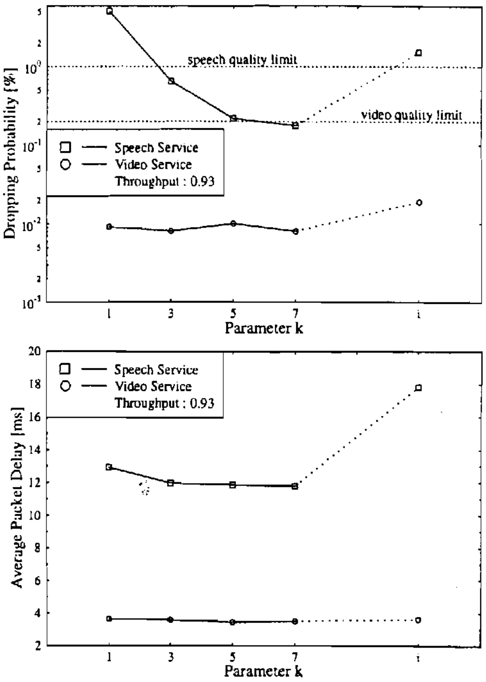

Figure 3: Delay induced packet dropping and delay performance versus exponent k of the assignment probability growth function.

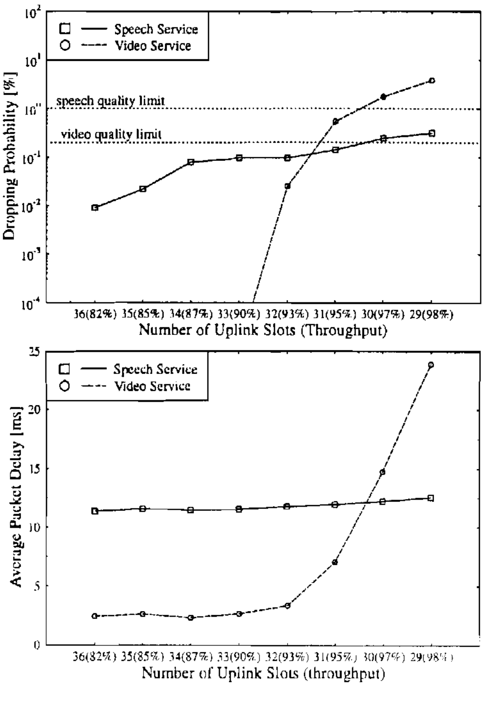

Figure 4: Delay induced packet dropping and delay performance as a function of the number of uplink slots. The numbers in brackets display the measured throughput.

We now examine the influence of the assignment probability growth function on the delay performance. Figure 1 displays the function given in Equation 5 for different values of k. For increasing exponents, the growth function has a very high positive gradient from a certain number of frames onwards and then it is reset to zero after the assignment. In order to model a strongly impulse-like growth function, hereafter referred to with index i, we fix the assignment probability in frame $(I_S - 1)$ at 0.25 and from frame I_S on at 0.75, meeting the cumulated assignment probability constraint. This choice gives an approximation of Equation 5 for high exponents k. Figure 3 show performance results for growth functions with $k = 1, 3, 5, 7$ and the aforementioned i-function. As observed in Figure 3, the delay and dropping performances for the low-rate speech service increase for increasing values of k, $k \leq 7$, but both the speech dropping and delay curves suggest significantly reduced performances for the previously introduced impulse-like i-function. The high-rate video service, however, remains nearly unaffected. Note that even for a throughput around 93%, both the speech and video services show dropping characteristics better than the required quality limits.

In the next set of simulations, the throughput performance of the SPAMA protocol is evaluated. In order to vary the traffic load in small equidistant steps without changing the one-to-one proportion of speech and video users, the number of uplink slots, i.e. the available channel bandwidth, will be varied while maintaining a constant number of 15 video and 15 speech users. Results for these simulations are displayed in Figure 4. For a throughput up to 90%, the video packet dropping rate is virtually zero and the speech dropping rate is at least a factor ten better than the required quality limit of 1%. Considering delay performances, the video packet delay is very low at less than 4 ms and with approximately 12 ms, the average speech packet delay is still less than half the allowed delay of 30 ms. Throughput values can rise up to 93% without infringing the imposed quality limits. For a higher traffic load, although the packet loss probability is not acceptable for video users, the system still shows a stable behaviour, with an only gradually increasing dropping probability.

4. CONCLUSIONS

In conclusion, Statistical Packet Assignment Multiple Access (SPAMA) is an algorithm of comparatively low complexity, which yields remarkably good performance results in the form we have proposed and studied. In addition, due to the central control of all slot assignments, SPAMA based medium access shows stable behaviour even in overloaded scenarios. Its throughput reaches 93%.

5. ACKNOWLEDGEMENT

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