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THE PERFORMANCE OF AAL-2 CARRYING CDMA VOICE TRAFFIC[†]

N. Gerlich and M. Menth

Due to cost efficiency, future personal communication networks likely will utilize the Asynchronous Transfer Mode (ATM) technology to connect components of the land network infrastructure. In order to cope with bandwidth limitation on the radio access, voice is transmitted as compressed low bit-rate information. The ATM Adaptation Layer 2 (AAL-2) is designed to handle this type of low bit-rate traffic. This paper discusses the capability of using AAL-2 connections to carry compressed voice between components of a CDMA network. To this end we analyze a discrete-time queuing model of the the AAL-2 mechanism combined with traffic shaping.

1 Introduction

Code Division Multiple Access (CDMA) and the Asynchronous Transfer Mode (ATM) belong to the key technologies of third-generation personal communication networks. Current standardization activities of International Mobile Telecommunications 2000 (IMT-2000) and its European counterpart, the Universal Mobile Telecommunication System (UMTS), show that CDMA technology will dominate the radio transmission part of the access network while ATM will be the major transport technology in the mobile infrastructure network and the core network.

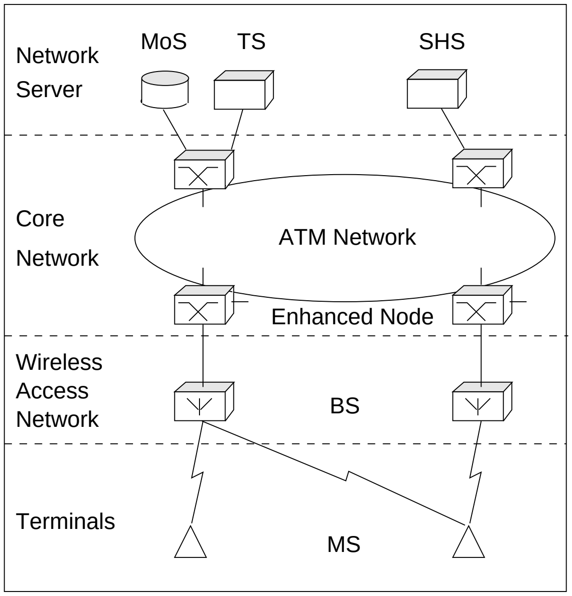

Figure 1: Mobile Network Architecture

The emerging future mobile network architecture is depicted in Fig. 1. The mobile terminals (MS) are connected to the Base Station (BS) by CDMA-based radio links. A wire-line link

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connects the BS to an enhanced node of the core network that is able to cope with mobile services. This operation is supported by network servers that are also connected to the core network. Mobility Servers (MoS) support functions related to terminal mobility, replacing the location registers of second generation systems. Transcoding Servers (TS) are required for interworking of different access and core networks, e.g, they are employed for transcoding vocoder packets to PCM format and vice versa for mobile-to-land voice calls. Soft handoff servers (SHS) assist soft handoff by selecting the packet that promises the best speech quality of the packets originating from the same voice source but have been transmitted on different radio links. A thorough discussion of the new architecture and the evolutionary steps to be taken in order to transform current net structure to the future architecture can be found in [3] and [9].

In this paper we concentrate on the wire-line part of the mobile access network. We are interested in assessing the efficiency of using an ATM link for connecting the BS of an IS-95 cell to the ATM core network. Owning to the low bit rate of the IS-96 voice codec employed in the IS-95 system the ATM Adaptation Layer Type 2 (AAL-2) is considered appropriate for tunneling vocoder traffic. The same problem was studied by simulation in [5] and for a different vocoder in [9]. The slightly different problem of employing ATM links for mobile-to-mobile traffic bypassing the transcoders of the current IS-95 architecture is studied in [15], again by simulation.

Starting from a short description of the IS-96 vocoder traffic characteristics and the AAL-2 multiplexing mechanism in Section 2, we develop and analyze a discrete-time queuing model of the AAL-2 multiplexer combined with a traffic shaper in Section 3. Section 4 presents a numerical study of performance parameters; Section 5 concludes the paper.

2 Carrying Mobile Traffic over ATM

IS-96A [12] standardizes the rate set one speech services option of the North-American CDMA cellular standard IS-95 [11]. The vocoder operates at four different rates: 8.6 *kbps* (full rate), 4.0 *kbps* (half rate), 2.0 *kbps* (quarter rate), and 0.8 *kbps* (eighth rate) according to speech activity and noise conditions. Depending on the rate, the vocoder generates variable length speech frames from 160 speech samples in uniform PCM format accumulated during a 20 *ms* interval. The speech frame lengths are 171, 80, 40, and 16 *bit*, respectively.

The BS receives one such packet every 20 *ms* from each connection. After padding to full octets, 10 octets of address, error control, and frame quality information for soft handoff support are added. In steady state the packet length distribution of Table 1 can be observed. In the

Table 1: Steady state packet length distribution of 8k vocoder

Rate [*bps*]	Packet Length [*bit*]	Probability
9600	256	0.291
4800	160	0.039
2400	120	0.072
1200	96	0.598

current architecture the BS employs a cyclic scheme of 16 time slots per 20 *ms* for transmission scheduling. During connection setup the BS assigns one of the 16 time slots to each connection for transmission. Since the number of connections handled by a cell is usually larger than the number of slots, multiple connections may be assigned to the same slot. The free assignments of slots to connections is restricted by the fact that calls in soft handoff require the same slot number at all BSs to which they are connected. Such assignment ensures that packets originating from the same voice source arrive at approximately the same time at the SHS for selection of the packet promising the best speech quality.

In order to provide bandwidth efficient ATM transmission to such traffic that is characterized by low bit-rate, short and variable length packets, and, as voice transmission, delay sensitiveness, ITU-T specified the ATM Adaptation Layer Type 2 (AAL-2) [8].

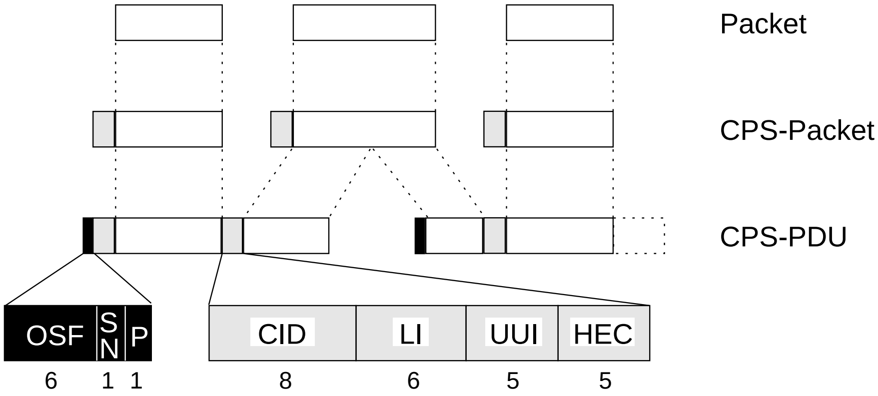

Figure 2: AAL-2 structure

A packet on the Common Part Sublayer (CPS) of AAL-2 consists of a 3 octets CPS-packet header (CPS-PH) followed by the CPS-packet payload less than 45 octets (cf. Fig. 2). The header contains a channel identifier (CID) that identifies the connection, reserved bits for user-to-user information (UUI), and header error control bits (HEC). Since the length of the CPS-packet is variable to support variable bit-rate, the length indicator (LI) gives the length of the CPS-packet.

The transmitting system multiplexes CPS-packets into a protocol data unit (CPS-PDU) of 47 octets length that is passed as ATM cell payload on to the ATM layer. If one CPS-PDU has not enough space to accommodate the CPS-packet, the CPS-packet is split and overlaps two CPS-PDUs. The second CPS-PDU then does not start with a CPS-PH. If the ATM cell carrying the first CPS-PDU, should be lost, the receiver cannot find the CPS-PH in the second CPS-PDU. Therefore, a one octet starter field is prepended to each CPS-PDU. The offset field (OSF) indicates the position of the first CPS-PH; the sequence number (SN) and the parity bit (P) are used to detect errors and cell losses.

In order to ensure a maximum multiplexing delay a timer function can be used. Each time a new CPS-PDU is started to be filled the common usage timer (TimerCU) may be started. If the timer times out before the CPS-PDU is filled, the unused payload of CPS-PDU is filled with padding octets and the cell is scheduled for transmission.

The AAL-2 uses the ATM layer service to transport service data units from one end system to another end system through an ATM network. The underlying ATM layer service may be Constant Bit Rate (CBR) or real-time Variable Bit Rate (VBR) [2].

If CBR is chosen, the traffic stream must be shaped according to the Peak Cell Rate negotiated in the traffic contract. A traffic shaper ensures that the ATM cells of the connection keep the minimum inter-cell distance $T = 1/\mathrm{PCR}$ by delaying cells if necessary.

If VBR is to be used, the Sustainable Cell Rate (SCR) and the Burst Tolerance (BT) have to be declared. The dimensioning of these traffic parameters is determined by the Generic Cell Rate Algorithm GCRA(1/SCR, BT). The algorithm determines whether a cell is generated to close to the last cell (non-conforming) or not (conforming); it accepts inter-cell distances smaller than 1/SCR but within a tolerance given by BT. Vice versa, given a maximum ratio of non-conforming cells, the GCRA defines parameters SCR and BT.

3 Model and Analysis

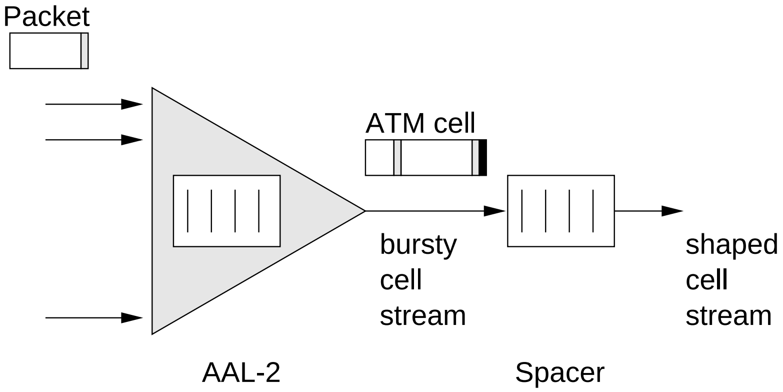

Figure 3: Model of AAL-2 combined with spacer

Fig. 3 depicts the model we are going to analyze. Packets arriving at the AAL-2 are being multiplexed into ATM cells; the cells are subject to spacing. By comparing the GCRA model of [10] and the way we model the spacer it will become apparent later that from modeling point of view both mechanisms are dual to each other. That means, the result we derive for the spacer model and CBR can be easily translated into results for a GCRA when we consider VBR transport.

Since ATM is based on fixed-size cells, the waiting time of a packet is a multiple of a smallest time quantum, the cell transmission time. Thus, discrete-time models provide a means to model AAL-2 multiplexing and the operation of the spacer. With this type of model, time is discretized into intervals of unit length Δ, for which the cell transmission time would be the natural choice. However, then the smallest spacing interval would be one cell transmission time, since all time intervals are multiples of Δ. Consequently, the largest fractional bandwidth would be half the link bandwidth. In order to model bandwidth requirements greater than half the link bandwidth, we choose Δ such that the cell transmission time is a integer multiple of Δ.

The modeling of the system is based on simpler discrete-time models, namely the GI/GI/1 model [1, 14], the $\mathrm{M/M}^{[a,b]}/1$ model with bounded idle time [4], and the GI/GI/1 model with bounded delay [13, 7, 10].

We model the arrival process by two random variables (*r.v.*). The *r.v.* A marks the inter-arrival time, i.e., A_n counts the number of time units between the $(n-1)$-th and n-th arrival. The packet size of the n-th packet is denoted by *r.v.* V_n. For ease of notation, we think of V_n as already containing the CPS-PH.

The *r.v.* for the system state $Z = (U, T, S)$ describes the state of the AAL-2 multiplexer and the spacer; components U and T are recording the state of the AAL-2 and S is marking the state of the spacer. The *r.v.* U denotes the unfinished work, i.e., the number of data units packed already into the CPS-PDU; the *r.v.* T records the age of the oldest packet contained in the CPS-PDU; *r.v.* S indicates the amount of time a cell submitted to the spacer will have to wait prior to transmission.

The constant L_u denotes the size of the CPS-PDU, L_t is the AAL-2 time-out value, L_s marks the maximum delay in the spacer queue, and T_s is the spacing interval.

Some restrictions apply in order to ease the derivation. Note that the restrictions are well justified from application point of view. Relaxing the restrictions is possible at the cost of higher notational complexity. We assume that $0 < V < L_u$ and we do not allow batch arrivals, i.e., $A > 0$. Further we assume that $L_s > L_t$. Otherwise, the offered traffic would exceed the traffic serviceable and the system would become unstable.

For the analysis of the model we employ discrete-time analysis techniques. Discrete-time analysis [1, 14] derives system characteristics like the packet waiting time distribution and the packet loss probability from the stationary state probabilities at packet arrival instants. In order to derive these state probabilities, we follow the state process in two steps. First, we observe the transition of the state variable from the state assumed just prior to the arrival to the state immediately after the arrival epoch. In the second step we observe the system evolution from the state assumed immediately after the arrival to the state just prior to the next arrival. This is the starting point of the next two steps of observation. Iterating thus from arrival epoch to arrival epoch, the state probabilities eventually converge to the stationary state probabilities at arrival instants.

3.1 State process

Let $Z_n = (U_n, T_n, S_n)$ denote the system state at the arrival of the n-th packet. Further, let for any *r.v.* R denote R_n^+ (R_n^-) R observed just prior to (after) observation point n; let $r(k)$ denote the probability mass function (*pmf*) of *r.v.* R.

Fig. 4 illustrates the following derivation of the state evolution. We start with observing the transition from Z_n^- to Z_n^+. Obviously we have to distinguish two cases depending on whether the arriving packet completes the CPS-PDU (time instants marked 2 and 3 in Fig. 4) or not (time instants 1 and 5).

If the packet completes the CPS-PDU, i.e., $U_n^- + V_n \geq L_u$, then the PDU is sent to the

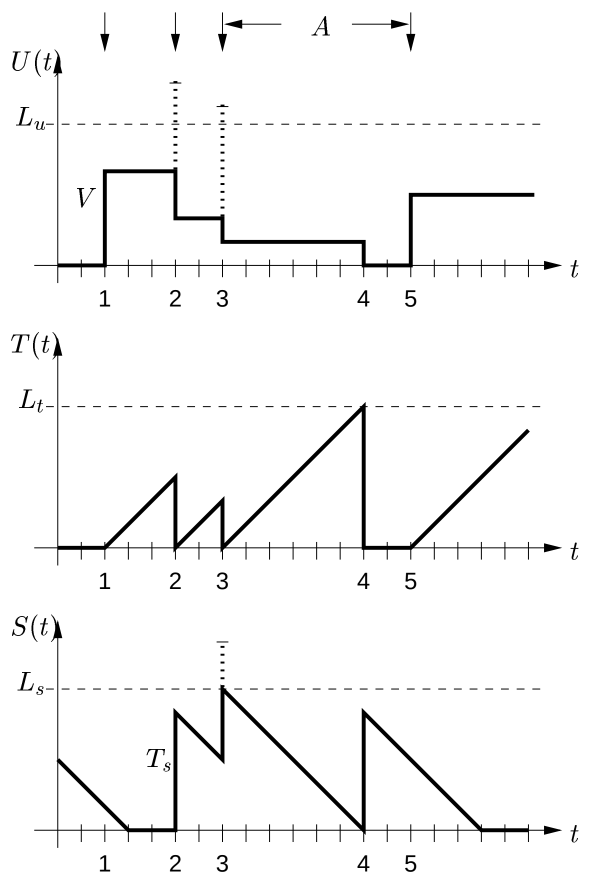

Figure 4: State evolution

spacer. Consequently, the amount of time the next cell submitted to the spacer will have to wait is incremented by T_s. The new PDU is filled with the part of the packet that did not fit into the PDU if there is any part left. This data then is the oldest data in the PDU. In formulae we have

$$\begin{aligned} U_n^+ &= U_n^- + V_n - L_u; \\ T_n^+ &= 0; \\ S_n^+ &= S_n^- + T_s. \end{aligned}$$

Actually, S_n is bounded by L_s which is given by the waiting room of the spacer. If the submission of a cell results in $S_n^- + T_s > L_s$ the cell is discarded (cf. Fig. 4 instant 3). However, we allow S_n^+ to take on 'virtual' values in $(L_s, L_s + T_s]$ in order to ease notation when we derive the packet loss probability later.

If the arriving packet does not complete the CPS-PDU, only the content of the CPS-PDU changes. Thus,

$$\begin{aligned} U_n^+ &= U_n^- + V_n; \\ T_n^+ &= T_n^-; \\ S_n^+ &= S_n^-. \end{aligned}$$

From both equations we get the following relations for the *pmf* $z_n^+(u,t,s)$:

$$\begin{aligned}
&\underline{s < T_s:} \\
&z_n^+(u,t,s) = \sum_{i=1}^{u-1} z_n^-(i,t,s) \cdot v_n(u-i); \\
&\underline{T_s \leq s, \quad t = 0:} \\
&z_n^+(u,t,s) = z_n^-(0,0,s) \cdot v_n(u) \\
&\qquad + \sum_{i=1}^{L_u-1} \sum_{j=1}^{L_t} z_n^-(i,j,s-T_s) \cdot v_n(u+L_u-i); \\
&\underline{T_s \leq s \leq L_s, \quad t \neq 0:} \\
&z_n^+(u,t,s) = \sum_{i=1}^{u-1} z_n^-(i,t,s) \cdot v_n(u-i).
\end{aligned}$$

Note that S_n^+ assumes values greater than L_s only if $T_n^+ = 0$.

Having derived the equations for the transition from Z_n^- to Z_n^+ we proceed by observing the transition from Z_n^+ to Z_{n+1}^-. Between arrivals the system state may evolve along three different paths. If there are no packets waiting for completion of the CPS-PDU only the spacer state changes (cf. Fig. 4 instant 1); if there is a incomplete CPS-PDU and no time-out of TimerCU happens, additionally the timer state variable changes (instant 3); a time-out (instant 4) impacts all three state variables.

For ease of notation, let S_n^{++} denote the true value of S_n^+, i.e., the value S_n^+ would have taken if cell discarding by the spacer was accounted for in the previous step:

$$S_n^{++} = \begin{cases} S_n^+ & : \quad S_n^+ \leq L_s \\ S_n^+ - T_s & : \quad S_n^+ > L_s. \end{cases}$$

If there are no packets waiting (Fig. 4 instant 1) the spacer state variable is decremented by one unit each time unit unless it reaches 0. Since the inter-arrival time is given by A_{n+1} we derive

$$\begin{aligned}
U_{n+1}^- &= U_n^+; \\
T_{n+1}^- &= T_n^+; \\
S_{n+1}^- &= [S_n^{++} - A_{n+1}]^+.
\end{aligned}$$

As common, $[x]^+$ denotes the maximum of x and 0.

If there are packets waiting and no time-out occurs, i.e., $T_n^+ + A_{n+1} \leq L_t$, one gets (cf. Fig. 4 instant 3)

$$\begin{aligned}
U_{n+1}^- &= U_n^+; \\
T_{n+1}^- &= T_n^+ + A_{n+1}; \\
S_{n+1}^- &= [S_n^{++} - A_{n+1}]^+.
\end{aligned}$$

In case of a time-out (Fig. 4 instant 4) the CPS-PDU is submitted to the spacer. Thus, at the next arrival instant the unfinished work is zero and the age of the oldest packet is defined to be zero. The spacer state at the next arrival instant depends on the time instant of the time-out

$(L_t - T_n^+)$ after the last arrival. Thus, at the time-out instant the spacer state is $[S^{++} - L_t + T_n^+]^+$. Since the stability condition $L_s < L_t$ ensures that a time-out cell is never discarded, the spacer state is incremented by T_s. The next arrival happens $(A_{n+1} - L_t + T_n^+)$ after the time-out. During this interval the spacer state is continuously decreased as in the other cases above. Altogether we get

$$\begin{aligned} U_{n+1} &= 0; \\ T_{n+1} &= 0; \\ S_{n+1} &= [[S^{++} - L_t + T_n^+]^+ + T_s - A_{n+1} + L_t - T_n^+]^+. \end{aligned}$$

Using these relations among the *r.v.*'s the *pmf* $z_{n+1}^-(u,t,s)$ can be derived in a similar fashion like $z_n^+(u,t,s)$. We omit the derivation here due to lack of space.

If the inter-arrival times are independent and identically distributed for all packets we get the equilibrium *pmf*'s by iterating over packet arrivals

$$\begin{aligned} z^-(u,t,s) &= \lim_{n\to\infty} z_n^-(u,t,s); \\ z^+(u,t,s) &= \lim_{n\to\infty} z_n^+(u,t,s). \end{aligned}$$

3.2 Waiting time

Waiting of packets occurs in two stages of the system. First, a packet must wait for completion of the CPS-PDU; second, the CPS-PDU and, hence, the packet has to wait for the transmission of the cell after spacing. Thus, we derive the packet waiting time *pmf* in two steps. First we compute the probabilities $w(u,t,k)$ for a packet to wait k time units for completion of the CPS-PDU leaving the system in state $(U^+ = u, T^+ = t, \cdot\,)$ after arrival.

If the packet completes the CPS-PDU $(U^+ = 0)$ or TimerCU immediately times out after the arrival $(T^+ = L_t)$ the waiting time of the packet is zero. Thus, employing Kronecker's δ we may write

$$\begin{aligned} w(0,t,k) &= \delta(k); \\ w(u,L_t,k) &= \delta(k). \end{aligned}$$

Otherwise the packet has to wait for either the completion of the CPS-PDU by some later packet, say, the j-th arrival after the current one, or a time-out. The probability for the packet to wait k time units for the $j-th$ packet to complete the CPS-PDU is the probability that j arrivals take exactly k time units to fill up the CPS-PDU while $(j-1)$ arrivals did not so. Defining thus, $A^{(j)} = \sum_{i=1}^{j} A$ and $V^{(j)} = \sum_{i=1}^{j} V$, we get

$$w(u,t,k) = \sum_{j=1}^{k} \Pr(A^{(j)} = k\,,\ V^{(j)} \geq L_u - u\,,\ V^{(j-1)} < L_u - u)$$

for $k < L_t - t$. Since in case of a time-out the waiting time is $k = L_t - t$ we have to add the time-out probability for $k = L_t - t$ to yield

$$\begin{aligned} w(u,t,k) &= \Pr(A > L_t - t) \\ &\quad + \sum_{j=1}^{k} \Pr(A^{(j)} = k\,,\ V^{(j)} \geq L_u - u\,,\ V^{(j-1)} < L_u - u). \end{aligned}$$

The probabilities $\Pr(A^{(j)} = k\,,\, V^{(j)} \geq n\,,\, V^{(j-1)} < n) = \Pr(A^{(j)} = k) \cdot \Pr(V^{(j)} \geq n\,,\, V^{(j-1)} < n)$ are calculated using

$$\begin{aligned} \Pr(V^{(1)} \geq n\,,\, V^{(0)} < n) &= \Pr(V \geq n); \\ \Pr(V^{(j)} \geq n\,,\, V^{(j-1)} < n) &= \sum_{i=0}^{n-1} v^{(j-1)}(i) \cdot \left(1 - \sum_{k=0}^{n-i-1} v(k)\right) \qquad j > 1. \end{aligned}$$

This completes the derivation of the waiting time for completion of the CPS-PDU.

Now we proceed with adding the waiting time for spacing. The waiting time in the spacer for a packet leaving $Z^+(U^+, T^+, S^+)$ after arrival is given by S^+. Since the waiting times for completion of the CPS-PDU and for spacing are independent the complete waiting time *pmf* $w(k)$ is defined by

$$w(k) = \sum_{u,t} \sum_{i=0}^{\min(k,L_s)} w(u,t,k-i) \cdot z^+(u,t,i).$$

3.3 Packet loss probability

In order to calculate the packet loss probability we have to consider two cases: the arriving packet completes the CPS-PDU which is discarded by the spacer ($S^+ > L_s$); the packet waits (say i time-units) for a later packet to complete the CPS-PDU which is discarded by the spacer ($S^+ > L_s$). The two cases are reflected by the two sums in the following equation for the loss probability:

$$p_B = \sum_{u,\, s>L_s} z^+(u,0,s) + \sum_{u>0,\, t>0,\, s>L_s} \sum_{i=0}^{[T_s - L_s + s - 1]^+} w(u,t,i) \cdot z^+(u,t,s).$$

4 Numerical Results

Throughout this section the following scenario is considered. The inter-arrival time of CDMA voice packets is governed by a geometrically distributed random variable. This way, the number of packets emitted in a time slot is binomially distributed which agrees with the model of the N-ISDN based BS infrastructure given in [6]. The distribution of the packet size is the distribution given in Table 1.

The IS-95 BS is connected to the core network by a 2 *Mbps* ATM link, i.e., the maximum bandwidth accessible by the connection is limited to 2 *Mbps*. The bandwidth of 2 *Mbps* equals the transport capability of T1/E1 links that are widely used in todays mobile land network infrastructure.

The Quality of Service (QoS) requirement of the mobile traffic is determined by a delay budget and a maximum packet loss ratio: the 10^{-4} delay budget should be limited to 4 *ms*, i.e., 99.99% of the packets are not to be delayed longer than 4 *ms*; the loss ratio should be less than 10^{-6}. In order to fulfill these requirements the TimerCU is set to 4 *ms* and also the maximum spacing delay is limited to 4 *ms* by setting the size of the spacer buffer accordingly.

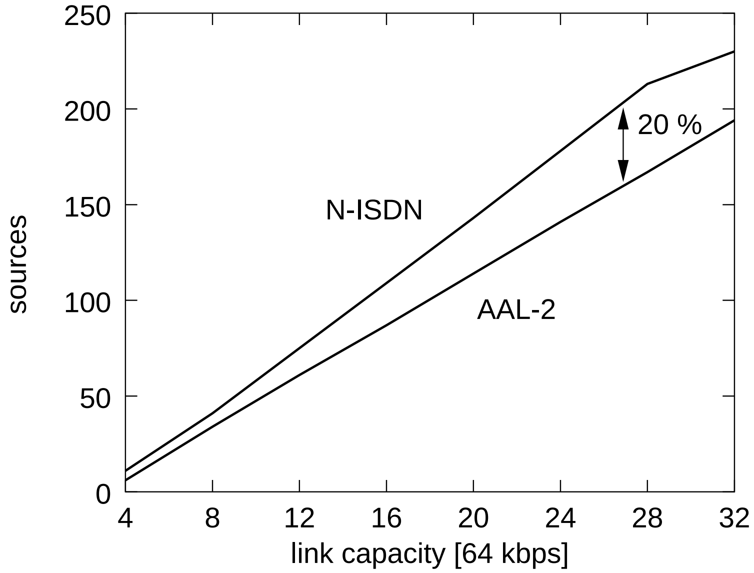

Figure 5: Maximum number of voice channels supported

Fig. 5 shows the maximum number of voice channels that can be supported on the link given a certain reserved bandwidth such that the QoS requirements are met. The horizontal axis gives the reserved bandwidth of the link: in the ATM case that is the reserved PCR converted to $kbps$; in the N-ISDN case it is the data rate of a fractional unchannelized T1/E1. The lower curve shows the maximum number of voice channels that can be supported using a AAL-2 connection on a ATM link. The upper curve presents the maximum number of voice channels supported by an unchannelized T1/E1 link (the results are taken from [6]). In both curves we note the known behavior of packet multiplexers that the number of supported voice channels increases linearly with the reserved bandwidth. The curves show that the ATM link on the average supports 20% less voice channels than the T1/E1 link. This capacity loss is due to the increased overhead of the AAL-2. For each cell of 53 $Byte$ we have 5 $Byte$ cell header, 1 $Byte$ AAL-CPU header, and on average $2 \times 3\,B$ CPS-PDU header. Thus the overhead amounts to 12/53, or 22% of the capacity.

The dimensioning of source traffic descriptors for the ATM connection is addressed by Fig. 6. As noted earlier, the dicrete-time spacer model employed here and the discrete-time GCRA model of [10] are equivalent from tele-traffic point of view. Thus, by means of our model we are able to determine source traffic descriptors defined by the GCRA as well. In order to interprete our model as GCRA(I, L) we just have to equate $T_s = I$ and $L_s = L$. The analysis of the GCRA(I, L) model then determines the ratio of non-conforming cells which we chose to name loss probability. Vice versa, given a maximum loss probability, the model defines GCRA parameters I and L.

If the CBR service category is chosen, GCRA(1/PCR, spacing delay) defines the source traffic descriptors; in case of VBR the descriptors are determined by GCRA(1/SCR, BT). Fig. 6 shows the GCRA parameters for the multiplexed traffic of 18, 36, 54, and 72 voice sources under the constraint of not exceeding the loss probability 10^{-6} given by the QoS demands. The

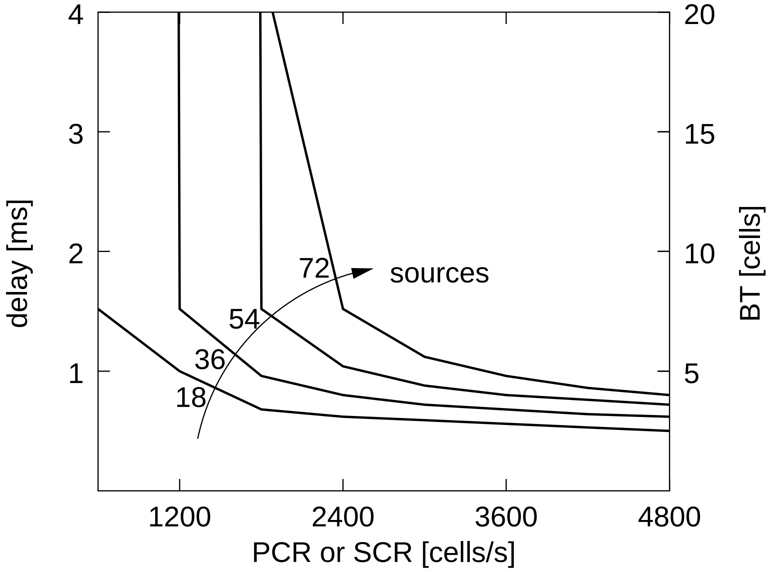

Figure 6: Source traffic descriptors

horizontal axis shows I transformed to PCR and SCR, respectively, in cells/ s. L is given in vertical direction: the left scale shows the expected spacing delay in ms when using CBR; the right scale gives the BT in cells.

The average cell rates being 409, 818, 1226, and 1636 cells/ s for 18, 36, 54, and 72 sources, respectively, approximately 1.5 times the average cell rate must be declared PCR if one uses CBR and 2 ms delay are allowed for spacing. Less than 2 ms for spacing leads to PCRs too high. Allowing 2 ms for spacing, however, means that TimerCU must be set to 2 ms in order to keep the 4 ms delay budget. Doing so may affect the cell utilization considerably as shown in [5]. For a VBR connection a relatively small BT $<$ 100 cells can be declared if the SCR is greater than 1.5 times the mean cell rate.

5 Conclusion

We studied the efficiency of AAL-2 multiplexing for carrying CDMA voice traffic over ATM links. To this end we analyzed a discrete-time model of the AAL-2 multiplexing mechanism in combination with a spacer. The model allows for delay and loss characteristics to be investigated. Furthermore, source traffic descriptors for underlying CBR and VBR transportation can be derived.

The numerical results show that with typical T1/E1 bandwidth AAL-2 multiplexing is only capable to transport 80% of the traffic the unchannelized ‘raw’ T1/E1 link can handle. The variability of the traffic requires about twice the mean cell rate to be declared PCR and SCR for CBR and VBR service category, respectively. The question is, whether the expected lower cost of ATM multiplexing devices as compared to specialized multiplexing devices for the raw T1/E1 link evens out the loss in capacity.

Nevertheless, using ATM offers additional advantages. With ATM it is possible to adapt the bandwidth of the BS to core network connection to current load conditions of the cell. During busy hours the booked capacity (PCR or SCR) may be higher than during off-time. The application of ATM to carry mobile traffic may help settle another important question: Whether ATM switches should offer AAL-2 switching or not.

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