An Adaptive MAC Layer Protocol for ATM-based LEO Satellite Networks

(Invited Paper)

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***Abstract*— German Aerospace Center (DLR), Fraunhofer FOKUS.cats, and Tesat-Spacecom have designed a future multimedia ATM-based LEO satellite network. Part of the development was an adaptive MAC and FEC scheme which is presented in this paper. The FEC implementation switches on the fly during a connection between several FEC and modulation modes to guarantee a maximum ATM cell error rate of 10^{-6}. In order to prevent influences of the changing FEC scheme on the user–level data rate, the MAC dynamically changes its packet lengths. Additionally, to minimize contention on the up–link, the MAC structures its TDMA frame into a fixed assigned part and a contention specific part. The boarder in between the two is dynamically altered according to the current link utilization.**

I. Introduction

Future satellite networks for multimedia communication will be seamlessly integrated into terrestrial networks. Therefore, they have to support inherently any kinds of quality of service. The design of such a — most possibly ATM–, all–IP–, or MPLS–based — broadband multimedia satellite system is a technically challenging task esp. for non geostationary (NGSO) constellations. Even though most of the presently proposed broadband satellite systems are GEO utilizing DVB–S and DVB–RCS, future satellite networks will incorporate NGSO constellations; regenerative payloads; and on–board switching, routing, and processing. The satellite community's view of seeing a "network in the sky" to consist of a bent pipe, transparent bit–stream channel continuously moves towards this new kind of network architecture [1]. As a result, new MAC and FEC schemes have to be considered.

This paper discusses a MAC protocol and FEC scheme which were developed by German Aerospace Center (DLR) and Fraunhofer FOKUS.cats for such a future broadband satellite network [2]. The MAC protocol has been designed for a better utilization of the available bandwidth and supports different QoS classes. The variable burst length of the MAC scheme allows not only a verly flexible allocation of the radio resources to the terminals, but also adaptive error control coding and moduation. A performance analysis shows that adaptive coding and modulation offers high availability even in Ka-band systems suffering from high rain attenuation.

The paper is structured as follows: Section II deals with the technical aspects of the designed MAC protocol including scheduling and FEC schemes. Section III afterwards explains how the different protocol entities are separated for implementation purposes for the demonstrator. Some measurements to verify the protocol functionality are outlined.

II. Protocol Design

The most natural approach to develop a satellite system supporting ATM is to develop a MAC layer which inherently supports different QoS classes. Several constrains deriving from a NGSO satellite constellation and the ATM protocol itself influenced the design, i.e:

- the lack of a dedicated QoS field within an ATM–cell;
- variable propagation delays; and
- swiftly changing channel error rates due to changes in the satellite's elevation angle, the severe impact of rain attenuation, and shadowing due to vehicular's movements.

The first is solved by an adaptive MAC framing structure and an introduced layer management entity while the latter is handled by an adaptive forward error correction scheme. Shadowing is to severe to be compensated by FEC.

A. Medium Access Control and Scheduling

1) Protocol Stack and Adaptations: In terrestrial ATM networks, service parameters are announced during the connection set–up phase together with a unique VPI/VCI value. The only way to identify a connection's QoS parameters afterwards is through its VPI/VCI value. Therefore the MAC layer has to embed any kind of lookup table to guarantee QoS constrains for the different connections. Figure 1 depicts the protocol stack in which the layer management entity (LME) connects UNI and MAC and bypasses service parameters during connection establishment.

In contrast to terrestrial networks, the MAC uses an *extended VPI/VCI* value. The footprint of the satellite is divided into several spotbeams each in turn served by a number of multi–carrier modulators. The latter are directly connected to the on–board ATM switching matrix (Fig. 2), thus resulting

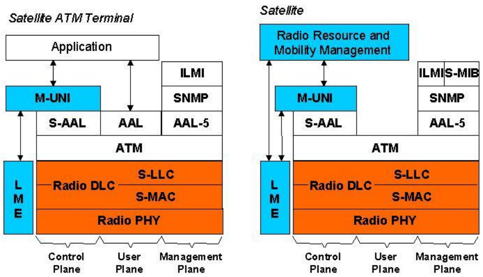

Fig. 1. ATM–Sat Protocol Stack

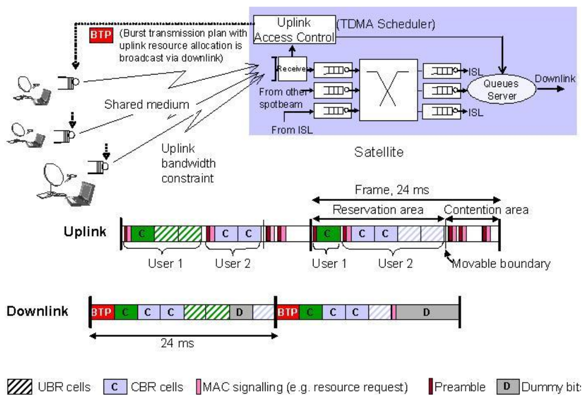

Fig. 2. TDMA Scheduler & MAC Up– and Down–link Frame Structure

in conflicts of the VPI/VCI values which are only unique for a given terminal–switch relation. To resolve this problem, the MAC extends the VPI/VCI by a unique value based on the terminal's MAC id.

2) Up–link Scheduler: The up–link scheduler is located on board the satellite. It serves constant bit rate (CBR) connections at highest priority followed by requests for an unspecified bit rate (UBR) with a minimum cell rate (MCR) guarantee. Resources for accepted connections with these QoS parameters can always be served as the call admission control (CAC) had otherwise declined the corresponding connection-setup request. Remaining capacity is equally distributed among connections with an unspecified bit rate (UBR). The scheduler broadcasts the final resource distribution in the next down–link frame in a *burst transmission plan* (BTP). The BTP is only valid for one up–link frame and conveys only the total number of slots assigned to each terminal; the latter may decide on its own on how to distribute them among pending traffic.

3) MAC Framing Structure: The MAC is based on a multiple frequency time division multiple access (MF–TDMA) scheme with frequency division duplexing (FDD) in the up– and down–link channel which is most convenient in power limited systems supporting guaranteed QoS. The duration of the TDMA frame in the up– and down–link is 24 ms. As a result, the system supports bandwidth allocations in steps of 16 kbit/s (i.e. one ATM cell per frame) which is a typical voice specific data rate.

The primary goal of the MAC for the up–link direction is to reduce or even eliminate contention. This is achieved by di-

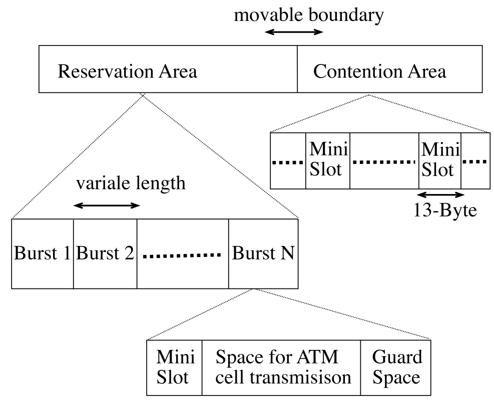

Fig. 3. Simplefied Uplink Frame Strucure

viding the up–link TDMA frame into two areas: a *reservation area* for contention–free data transfer and a *contention area* for initial connection setup and bandwidth requests. The boundary between the two areas adapts to the current link utilization and therefore reduces the contention probability within periods of low transmission activity.

The *reservation area* consists of variable length transmission bursts (Fig. 3). A burst belongs to a specific user terminal which may use the reserved cell slots within a burst to transmit pending ATM cells. Each burst in turn starts with a 13–byte long *mini–slot* which contains the unique terminal MAC ID and signaling information to modify the terminal's traffic contract. Afterwards, pending ATM cells may be transmitted. Therefore, space is assigned to hold a number of ATM cells and FEC information; the assignment has a granularity of 4 Bytes. Finally, each burst is terminated with an additional 4-Byte long guard time to avoids contention within the reservation area. The burst transmission plan at the beginning of each down–link frame informs the terminal on the position and length of the assigned burst in the next up–link frame. A traffic shaper located in the receiving MAC flattens the introduced delay variance in order to support CBR traffic. The hereby additionally added (constant) delay of one TDMA frame is well acceptable even for real–time applications.

The *contention area* follows right behind the *reservation area*. Its length varies according to the space allocated to the *reservation area* on a frame–by–frame basis. The *contention area* is used for initial connection setup and resource allocation request (if not picky-backed in assigned up–link bursts). For that matter, a terminal may transmit a 13–byte long *mini–slot* with the signaling information anywhere in the contention area.[1]

Each down–link frame starts with the BTP followed by slots containing down–stream ATM cells; dummy bits are added, if necessary, to uphold the 24 ms framing structure. The BTP consists of several 13–byte long *mini–slots* (see Fig. 4). Each *mini–slot* starts with a 4–bit long type field and contains the

[1]Actually, there is a 4–byte granularity to start any transmission which equals to the guard time. This granularity is a mere result of the MAC implementation and not of the design concept

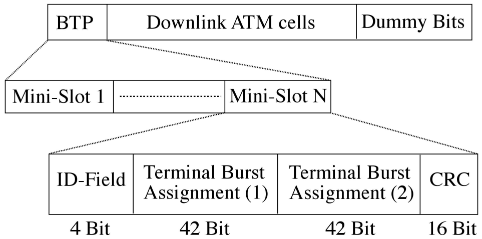

Fig. 4. Simplefied Downlink Frame Structure

assignment of up–link resources for two terminals. The 42–bit long assignment contains information on the position in the next up–link frame where the terminal's transmission burst starts, and the number of slots the burst may last.

We assume a unique relation between down–link frequency and up–link carries to determine the worst case overhead associated with the transmission of the BTP in each down–link frame which occurs if only resources to transmit a single ATM cell are assigned to a terminal (longest possible BTP).

Let T be the frame duration; $nettoBW_{up}$ and $nettoBW_{down}$ be the available netto bandwidth in the up– and down–link; $length_{ATMcellPayload}$ be the length of an ATM cell payload; $n_{cellsUp}$ and $n_{cellsDown}$ be the maximum number of ATM cells that a single up– or down–link frame can contain; $n_{assignmentsPerMinislot}$ be the number of terminal resource assignments a single mini slot may contain; $n_{miniSlotsBTP}$ be the number of mini slots the longest possible BTP may consists of; $l_{transATMcell}$ the effective length to transmit an ATM cell inclusive its header and FEC; $l_{miniSlot}$, l_{BTP}, and $l_{downlink}$ be the length of a mini slot, longest BTP, or down–link frame correspondingly. Then the associated $overhead$ can be written as:

$$
\begin{aligned}
n_{cellsUp} &= \frac{nettoBW_{up}}{length_{ATMcellPayload}} * T && (1)\\
&= \frac{2.048\ \frac{Mbit}{s}}{48 * 8\ bit} * 0.024 = 125\\
n_{cellsDown} &= \frac{nettoBW_{down}}{length_{ATMcellPayload}} * T && (2)\\
&= \frac{32.768\ \frac{Mbit}{s}}{48 * 8\ bit} * 0.024 = 2048\\
n_{miniSlotsInBTP} &= \left\lceil \frac{n_{cellsUp}}{n_{assignmentsPerMinislot}} \right\rceil && (3)\\
&= \left\lceil \frac{125}{2} \right\rceil = 63\\
l_{BTP} &= n_{miniSlotsInBTP} * l_{miniSlot} && (4)\\
&= 63 * 13\ Byte = 819\ Byte\\
l_{downlink} &= n_{cellsDown} * l_{transATMcell} && (5)\\
&= 2048 * 57 Byte = 116736 Byte\\
overhead &= \frac{l_{BTP}}{l_{downlink}} && (6)\\
&= \frac{757\ Byte}{116736\ Byte} < 0.65\%
\end{aligned}
$$

Most of the time, the associated overhead is by far lower than 0.65 % as a terminal will most likely receive transmission capacity for more than a single ATM cell. In addition, the presented overhead approximation is based on the framing structure as it is currently implemented. There may still be efficiency enhancements by, e.g., broadcasting only changes in the uplink resource assignments.

B. Forward Error Correction Schemes

The designed satellite system utilizes the Ka–band which mainly suffers from high rain attenuation and — in case of moving vehiculars — also from signal shadowing due to obstacles like trees or buildings. As for this project, vehicles are equipped with directional antennas, multipath fading is slight [3]. Signal shadowing due to obstacles is too high to be compensated by forward error correction (FEC) thus leaving its focus on the attenuation caused by rain.

As rain attenuation appears only from time to time and its maximum fade slope value for 0.01% of an average year is about 0.6 dB/s [4], adaptive forward error correction and also adaptive modulation techniques are applied to efficiently use the available bandwidth. This technique is a major improvement in contrast to traditional systems with non–adapting FEC schemes as the latter requires a rather high link margin which unnecessarily delimits up– and down–link capacity. The employed FEC scheme guarantees a fixed useful data rate by adapting the MAC packet lengths according to the used coding and modulation scheme.[2] The system design includes three major FEC schemes:

- No FEC is applied. The ATM cells are merely guarded with a 32–bit CRC with a block length of 57 bytes. The CRC is used for error detection only.
- Reed Solomon Code, RS(65,53) over GF 2^8, which can correct up to 6 byte errors.
- Rate 1/2 block turbo code concatenated with a RS(65,53) code.

Figure 5 illustrates that even at a minimum elevation angle of $20°$, the system can guarantee a cell error rate threshold (CER_{th}) of 10^{-6}. If we define link availability as the percentage of time the given CER_{th} is guaranteed, a simple CRC error detection scheme without any FEC correction methods results in a link availability of 99.14% (i.e. the link is not available for 72.7 hours per year). The RS(65,53) code increases the availability to 99.80% and the concatenation of RS and Turbo codes improves link availability to 99.92%. [3] As all used codes are systematic, the uncoded block error rate of the information part can be used together with the measured received power to decide when to switch between the codes.

We use the availability burst–length product (ABLP) to compare the efficiency of this adaptive FEC scheme with a permanent RS(65,53) coding at QPSK modulation. The ABLP

[2]The design supports also a fixed MAC packet length by adapting the useful data rate even though this option is not implemented in the demonstrator.

[3]Reference constellation: 72 satellites in 12 Walker orbits at 1350 km, $47°$ inclined. Link parameter: 30 GHz QPSK with 2447 ksymbols/s, EIRP 42.7 dBW, G/T 4.5 dB/°K, 2.5 dB Implementation losses.

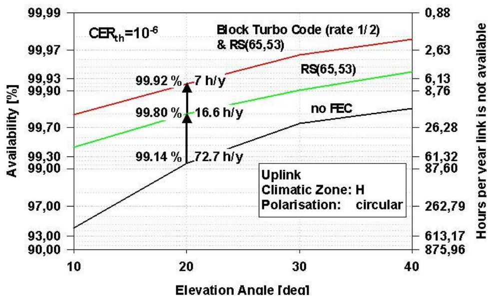

Fig. 5. TDMA Scheduler & MAC Up– and Down–link Frame Structure

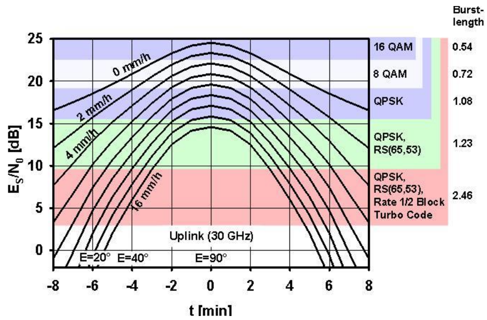

Fig. 6. E_s/N_0 for a satellite overpass at different rain intensities (in mm/h); required coding/modulation for an ATM CER_{th} of 10^{-6} and the resulting burst length

of the permanent scheme is 1.22 ($= 99.80\% * 65/53$). The adaptive FEC scheme has a higher availability of 99.92% and has nevertheless a lower ABLP of only 1.08 ($= 99.14\% * 57/53 + 0.66\% * 65/53 + 0.12\% * 130/53$).

In addition to adapting the FEC to the experienced rain attenuation and elevation angle, the modulation scheme can be changed in rain–less periods and high elevation angles to 8 or 16 QAM. Figure 6 illustrates the expected E_s/N_0 for a satellite overpass (i.e. for different elevation angles) at different rain intensities. The shaded background depicts the areas where the given CER_{th} of 10^{-6} can be guaranteed by using a specific FEC and modulation scheme. E.g., for a rain–less period, the system may switch to 8 QAM with a mere CRC checksum (at $t = -5.5min$ in Fig. 6 which corresponds to an elevation angle of approx. $30°$) or even to 16 QAM (at $t = -2.5min$, elevation angle of approx. $80°$). Only a E_s/N_0 below 10 dB requires QPSK with RS and Turbo code. Figure 6 also includes the burst lengths corresponding to each FEC–modulation pair.

III. Protocol Implementation and Tests

The designed protocol has been partially implemented using the FreeBSD–5.0–current version [5] for testing and demonstration purposes. The implementation is modular in terms of separating a satellite channel emulation entity from the implementation of the MAC protocol [6]. Therefore it is possible to run tests over various satellite constellations[4]

[4]In fact, the same environment is currently used to evaluate connecting the ISS' Columbus module via ATM to Earth.

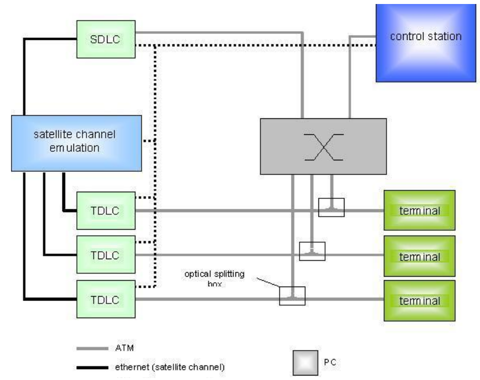

Fig. 7. Demonstrator Environment Overview

besides the original LEO target system. The system has been used to evaluate the performance of upper layer protocols (i.e. TCP) and applications (e.g. voice over IP) [2], [7], [8] as well as to study effects of shadowing on the overall LEO satellite target system [2], [9].

A. Demonstration Environment

The demonstrator is separated into three major components (Fig. 7): *a satellite channel emulator* (SCE), *satellite and ground terminal DLCs* (SDLC & TDLC), and a *control station* (CS). The ATM switch in the configuration is merely used for measurements on ATM link level; additionally it acts as the ATM switch on board the satellite to process data received from the MAC entity. The terminal connected to the TDLC entity can be any ATM–equipped computer communicating over the satellite system.

1) Satellite channel emulator: The SCE is configurable via snmp. It corrupts packets with a given probability which in turn depends on the current elevation angle of the satellite and the experienced rain intensity. Additionally, the SCE adds a variable propagation delay according to the satellite's position wrt. the ground terminal. Besides error corruption and delay, the SCE implements contention for terminals transmitting at the same time. Its functionality its independent of the network interface used to connect DLC and SCE. As an wireless interface has not been forseen for this proof–of–concept hardware, Ethernet is used for encapsulating the actual MAC frame structure.

2) Satellite and Ground Terminal DLC: The SDLC and TDLC units encapsulate the MAC implementation. They are separated from the SCE in order to be independent of satellite specific network characteristics. In addition, the TDLC is separated from the user terminal to allow the latter to run any kind of operation system (e.g. Windows, or Unix). The terminal and the TDLC are connected via a standard ATM interface thus making the TDLC entity acting as an external VSAT modem.

3) Control Station: The CS acts as a boot server for the SCE and xDLC entities. It distributes a common clock (NTP–Server) and may be used to configure and monitor the SCE and xDLC entities.

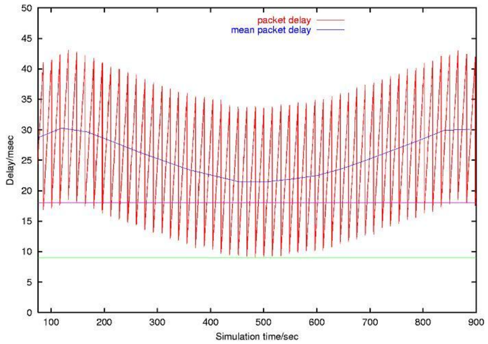

Fig. 8. Measured One Cell Delay

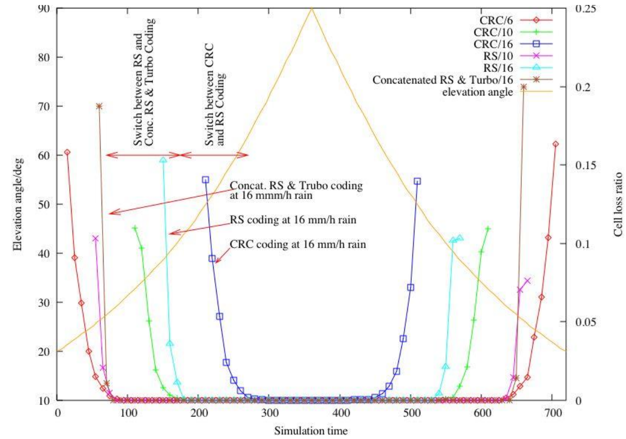

Fig. 9. Measured Error Rates for Various Codings and Rain Intensities

B. Measurements

After an extensive simulation phase of the MAC [10], [11], FEC schemes [12], and upper layer protocols [7], [8] over the proposed system architecture, measurements to verify the implementation's functionality are conducted. The SCE is well capable to merge the different up–link streams coming from each TDLC into a single up–link stream going to the SDLC (including the contention handling) in real–time. The experienced variable propagation delay is measured by transmitting one ATM cell per frame. Fig. 8 depicts the measured delay on application level. The lower limit of the envelope has an upper and lower bound of 9 and 4.5 ms respectively which is the theoretical range of the propagation delay. As the clock of the sending application sending at a cell rate of 1/24 ms is not synchronous with the clock of the MAC, the drift in the two clocks causes the ATM cell to be transmitted at different positions with respect to the beginning of a MAC frame. Thus, an additional delay of up to one frame length is experienced.

Further measurements included the effects of rain at an intensity of 6, 10, and 16 mm/h at different FEC schemes. Fig. 9 depicts the experienced cell loss ratio for various coding schemes and rain intensities for an entire satellite overpass. For the reader's convinience, it also includes the current elevation angle for a given time. Even for severe rain falls of 16 mm/h, the required CER_{th} can be guaranteed with a simple CER FEC scheme for elevation angles higher than approx. $65°$. For lower elevation angles, the MAC has to switch to RS coding and finally to the concatenated FEC coding scheme (RS and Turbo). The measurements also illustrate that for slight rain falls of only 6 mm/h, the bandwidth efficient CRC FEC coding may be used for almost an entire satellite overpass.

IV. Summary

The presented QoS aware MAC protocol suitable for ATM based NGSO satellite networks adapts to the changing satellite channel characteristics, i.e. to the effects of elevation angle dependent attenuation, rain fading, and shadowing. Its link utilization in terms of the ABLP is clearly higher than for a non–adaptive coding scheme as it changes the used FEC scheme on the fly according to the E_s/N_0 and CER. Dynamic MAC packet lengths guarantee a fixed useful data rate. A proof–of–concept demonstrator has been developed and was used to verify the functionality of the specified protocol with respect to the final LEO satellite target system. Measurements over the implemented MAC protocol illustrate the advantage of its adaptive coding scheme.

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