TUHH Institute of Communication Networks
ComNets

MCSOTDMA Specification

Inter Aircraft Network

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1 Introduction

1.1 Purpose of the Document

This document specifies the LDACS Air/Air (A/A) Data Link layer, in particular the Multi Channel Self-Organized Time Division Multiple Access (MCSOTDMA) protocol, as it has been proposed within the Inter Aircraft Network research project. It may be understood as a proposal for an appendix to the LDACS Air/Ground (A/G) link specification in [1]. It should enable others to implement the Data Link layer, and serve as a basis for integration into a future LDACS standard.

1.2 Organization of the Document

This document is structured by topic. It attempts to avoid repetitions where possible, and follows a thematic red thread which the authors find reasonable. Building blocks of the protocol that belong together to achieve a certain function are grouped together, so that the reader may follow along without jumping between pages. At the end of protocol functions, graphical examples often aim to reinforce the reader's understanding. This red thread is coarsely summarized as

- An introductory part that defines the nomenclature and general concepts behind the protocol.
- The requirements for the Physical (PHY) layer.
- A specification of message types and their formats.
- The Medium Access Control (MAC) sublayer
  - the Shared Channel (SH) and its medium access
  - the Voice Channel (VC) and its medium access
  - the Point-to-Point Channels (PP) and their medium access
- The Automatic Repeat Request (ARQ) sublayer.
- The Radio Link Control (RLC) sublayer.

This is a bottom-up traversation of the Data Link layer depicted in Fig. 1.

1.3 Motivation

The LDACS A/A data link enables direct communications between airborne stations (ASs). It shall support the operation of the LDACS A/G by extending the LDACS coverage into regions without ground infrastructure, such as oceanic regions. This can be achieved by using ASs as Network Layer-relays between the ground stations (GSs) and other ASs. It can also serve as a redundant link for important services if LDACS A/G is available.

The number of users that must self-organize communication through LDACS A/A varies strongly with the geographic region. In oceanic scenarios such as the North Atlantic Corridor (NAC), dozens of users may be within communication range. In continental scenarios, in particular around large, international airports,

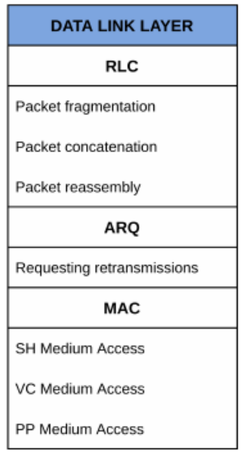

Figure 1: The LDACS A/A Data Link Layer.

this number might exceed 1000 users in the future. For this reason, a main challenge has been the design of the Medium Access Control (MAC) sublayer. To achieve coexistence with LDACS A/G, Time Division Multiple Access (TDMA) is employed. To achieve acceptable performance even in densely crowded areas, Frequency Division Multiple Access (FDMA) is employed. From these, LDACS A/A communication resources are slots in both time and frequency. This results in a multitude of logical channels that can be time-scheduled. To manage the necessary coordination, a Shared Channel (SH) is used. The medium access on the SH is specially designed to scale to arbitrary numbers of users, and the packet delay scales accordingly. The medium access delay on the PPs, on the other hand, is deterministic on established links, and link establishment requires only few channel accesses on the SH.

2 General Concepts and Nomenclature

2.1 An LDACS A/A User

An LDACS A/A user is defined as an LDACS A/A radio system.

2.2 Communication Resources

The aeronautical L-Band considered for LDACS spans the spectrum from 955.75 to 1164.25 MHz and some of its allocation to different technologies is visualized in Fig. 2. LDACS A/A is going to operate in this range, but must coexist with the present legacy systems. The range is subdivided into three parts: the Lower, Mid and Higher L-Band. The spectrum is divided into 500 kHz-wide subchannels. Some of these subchannels may locally not be usable by LDACS to account for the local operation of legacy users.

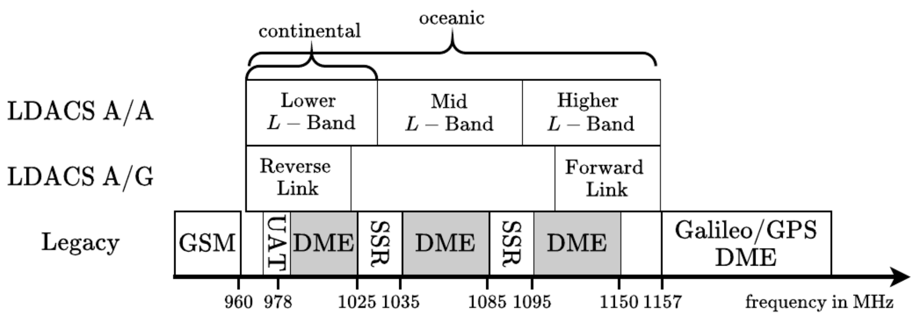

Figure 2: The aeronautical L-Band, some of its occupants, the LDACS A/G Forward and Reverse Links, as well as the possible LDACS A/A frequency allocations.

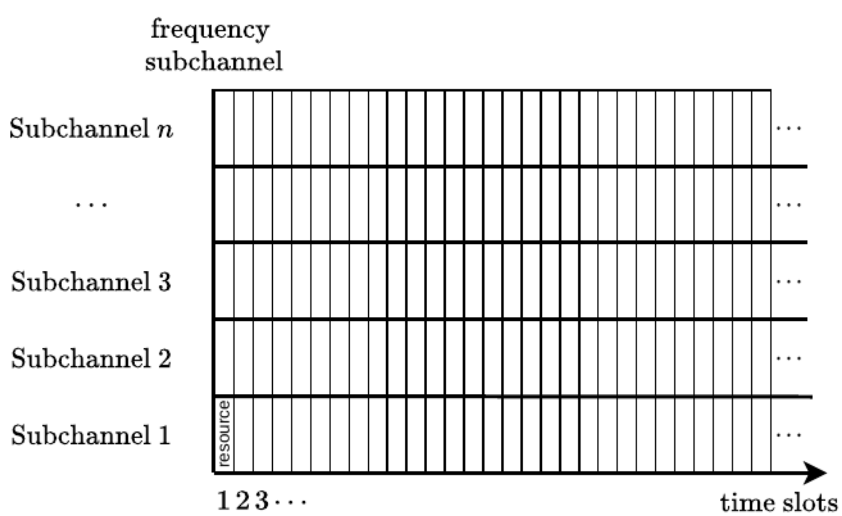

Figure 3: The LDACS A/A resource grid consists of communication resources (slots), each a pair of frequency subchannel and time slot.

LDACS A/A is likely going to be restricted to the Lower L-Band in continental regions to limit interference upon legacy systems. The MAC will realize FDMA and coordinate the access on the 500 kHz-wide subchannels. The MAC will also realize TDMA and divide time into time slots. The division of the two dimensions of frequency and time yields the communication resources that the MAC controls: each communication resource is a pair of frequency subchannel and time slot. Since both frequency and time are divided into "slots", it is natural to use "slot" as a synonym for such a communication resource, i.e. it means a specific slot in both domains. In consequence, a resource grid as depicted in Fig. 3 is obtained. A clear assignment of subchannel index to center frequency is necessary, however, and must be the same at all LDACS users within one geographical region, as shown in the following table.

Table 1: Assignment of center frequencies to roles for one geographic region. In border regions, two SH channels may be present. Additional SH channels may serve as backups when one is being disturbed.

Index	Role	Name	Center Frequency
$0, \ldots, i$	SH	Shared Subchannel	$\{f_i\}$
$i+1$	VC	Broadcast Voice Subchannel	f_{i+1}
$i+2$	PP_1	Point-to-Point Subchannel 1	f_{i+2}
$\ldots$	PP_j	Point-to-Point Subchannel j	f_{i+j}
$i+1+n$	PP_n	Point-to-Point Subchannel n	f_{i+n}

The utilization of these slots must follow two basic rules, as the installed hardware imposes restrictions on simultaneous reception and transmission. First, with m available receivers, one LDACS user can listen on m subchannels simultaneously; it can schedule m resources on different subchannels at the same time slot to receive on. Second, during transmission on one subchannel, reception on neighboring subchannels may be impossible as a local transmission potentially "blinds" the receivers.

2.2.1 Time Slot Durations

Time slots can have durations of either 6, 12 or 24ms.

2.3 The Shared Channel (SH)

The SH is one frequency subchannel that is shared among all users, and consequently has a contention proportional to the number of active LDACS users within communication range. Besides broadcast data communication, it serves as a control channel to manage scheduling point-to-point communication links between user pairs, for which the PPs are used.

2.4 The Point-to-Point Channels (PPs)

Point-to-Point Channels (PPs) are used for data communication between pairs of users. The number of PPs depends on the final decision on the LDACS A/A frequency range, and on the filter requirements as potentially guard bands are required to allow the simultaneous utilization of neighboring PPs by different user pairs. The medium access on PPs is mutually coordinated through control messages via the SH.

2.5 Broadcast Voice Channel (VC)

A Broadcast Voice Channel (VC) realizes one-hop broadcast voice communication. Point-to-point voice communication can be realized via any PP channel.

2.6 MAC IDs

Each LDACS user is associated to a unique MAC ID as shown in Fig. 4. It contains an 8-bit prefix of zeroes and the 24-bit ICAO ID. The 28-bit LDACS A/G Unique Address can be used when the prefix is reduced to 4-bit. A symbolic broadcast MAC ID consists of all-ones.

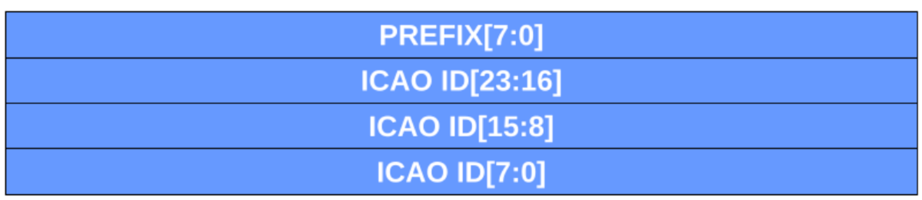

Figure 4: The LDACS A/A MAC ID.

2.7 Reservation Tables

After dividing the frequency domain into subchannels, the SH, VC and PPs are obtained. To time-multiplex these into time slots, reservation tables are employed. Each subchannel is therefore associated with a reservation table of a size `planning_horizon`. This table saves the planned actions (reservations) and a corresponding MAC ID of future time slots. The size of the table, i.e. the number of future time slots, must be large enough to cover the maximum slot offset in a SH header of 16384 in case of the SH table, and large enough to cover the maximum slot offset plus the latest slot of a PP link in case of PP tables. For example, if a PP link begins in 16384 time slots, then it is valid for a number of exchanges, and each exchange is separated by a link-specific number of time slots; the PP reservation table must be capable of saving these resource reservations.

The following actions can be saved:

- Reception `RX`, if the LDACS user is going to listen to the subchannel associated to the reservation table during the time slot.
- Transmission `TX`, if the LDACS user is going to transmit on the subchannel associated to the reservation table during the time slot.
- Busy `BUSY`, if the LDACS user has been informed that a neighboring user is going to transmit on the subchannel associated to the reservation table during the time slot.
- Idle `IDLE`, if none of the other actions apply; this is the default action of all resources.

During resource scheduling, the MAC makes use of these reservation tables to identify suitable resources for communication. In order to meet hardware limitations, reservation tables are also associated to transmitter and receiver hardware. Consequently, a resource can be deemed "suitable for communication" if and only if it is currently `IDLE`, and, depending on the action to be performed, the corresponding hardware's reservation table is `IDLE`, too. For example, a time slot on a PP channel could be `IDLE`, but to reserve it for transmission, the same time slot must also be `IDLE` in the transmitter's reservation table.

Each reservation is also associated to a MAC ID, so that a reservation clearly identifies to which user a transmission is addressed, or whose transmission is expected to be received. For example, if a time slot on the SH channel should be used for transmission, its reservation would read `TX@SYMBOLIC_BROADCAST_ID`.

2.8 Blocked Subchannels

Fig. 2 suggests that LDACS is going to coexist with a number of communication systems. In order to guarantee that communication through LDACS does not cause interference upon these systems, a channel blocklist is employed. The AS maintains a database that maps geographic positions to a set of frequency subchannels that are not allowed to be used within the geographic region. This database can be updated prior to takeoff. In consequence, when reservation tables are queried for suitable communication resources, a first check against this database must be performed, and if the corresponding frequency subchannel is locally blocked, then it must be ignored.

The database should have the following format, with a list of identifying corner points as triples of (latitude, longitude, altitude) spanning a polygon. Inside the described area, a list of subchannels must not be used.

List of identifiers	List of blocked subchannels
$(\text{lat}, \text{lon}, \text{alt})_1, \ldots, (\text{lat}, \text{lon}, \text{alt})_i$	$f_j, \ldots, f_k$

2.9 Coexistence between LDACS A/G and A/A

The LDACS A/A MAC schedules communication resources for transmission and reception. Point-to-Point channels in particular are scheduled for relatively long time spans. As stated before, communication hardware and the LDACS Reverse and Reverse Links are shared between LDACS A/G and A/A. Generally, LDACS A/G operation will take priority over LDACS A/A communication. Therefore, in order to achieve an efficient LDACS A/A MAC, it must know in advance which resources can be utilized. The LDACS A/G MAC must inform the LDACS A/A MAC about the resources it can utilize. First, it must broadcast with its cell info the channel blocklist described in Sec. 2.8. Second, it must inform recipients of the subchannel index that corresponds to the SH. Third, it must inform recipients which LDACS A/G multi-frame out of a superframe can be used for LDACS A/A communications. To achieve this, the offset of the multi-frame inside the superframe and the period are required at least. If necessary, e.g. to be able to meet requirements of voice channels, additionally start and end tiles of the multi-frame can restrict the portion of the multi-frame that can be used for LDACS A/A.

2.10 Minimum Processing Time

A minimum processing time of two 6ms time slots is imposed. No reaction of an LDACS A/A user before this processing time can be expected. For example, if a link request is transmitted, the time until a link reply can be prepared is at least two 6ms time slots. This matches a 12ms processing time specified for LDACS A/G.

2.11 Upper Layer Interface

The Data Link layer exposes an interface to an IPv6 upper layer. This interface has three parameters:

- `data`: The data to be transmitted.
- `destination`: The MAC ID of the destination.
- `priority`: The priority level between 0 and 7 of the transmitted data, either acknowledged or unacknowledged. The appropriate mapping of priority levels is left to the upper layer.

2.12 Physical Layer Requirements

The Physical Layer (PHY) must implement the following requirements.

- It must be possible for the Data Link Layer to tune hardware transmitters and receivers to particular subchannel's center frequencies.
- It must be possible to select the coding and modulation scheme for a packet transmission.
- The PHY must measure the received signal strength (SINR) and noise floor for each packet and forward this measurement to the MAC, which keeps a mapping from MAC ID to subchannel index and most recent signal strength as follows:

MAC ID	Subchannel Index	Value
`id`	i	v

3 Layer 2 Frame Format

In this section, the data structure of SH and PP packets are presented.

3.1 SH Frame Composition

Each data packet transmitted on the SH is structurally composed as shown in Fig. 5. In the following, each header field is presented in detail. In all packets, there will be

- a signature, see Fig. 6
- a source ID, see Fig. 7
- fields that identify the next SH channel access, see Fig. 8
  - the `offset` field indicates the number of slots + 1 until the next SH transmission
  - the `length` field indicates whether a $6, 12$ or 24 millisecond slot duration will be used as defined in Tbl. 4

Table 4: definition of `length` field

bits	meaning
`00`	unset
`01`	6 ms
`10`	12 ms
`11`	24 ms

- fields that indicate the current status at the user, see Fig. 9
  - the `util` field indicates the number of subsequent link utilization blocks, each one in the format of Fig. 10
  - the `direction` field corresponds to a bitmask of `N`, `E`, `S`, `W`
    * the user can indicate in which geographic direction they require a PP data link
  - the `prop` field indicates the number of subsequent link proposal blocks, each one in the format of Fig. 11
  - the `ext` flag requests a time value for two-way ranging
  - the `dpe` flag enables the `datapend` block with pending data categorized by direction and priority, each in $16 \cdot 2^x$ bytes
  - the `dre` flag enabled the `datarate` block with required data rates categorized by direction and priority, each in $16 \cdot 2^x$ bytes per second
  - a `lat` field with the Compact Position Report (CPR)-formatted latitude

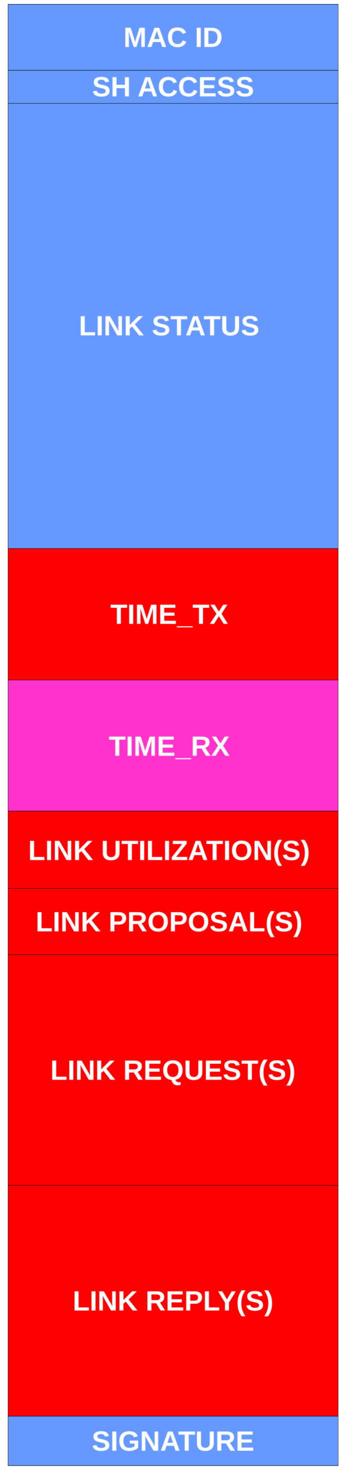

Figure 5: High-level overview of the SH data packet composition. Blue blocks are mandatory, red and magenta are both optional. Magenta is in response to another user's request for time synchronization.

SIGNATURE 64B(ECC-256) / 96B(ECC-384)

Figure 6: A signature of either of two security levels.

SOURCE[31:24]
SOURCE[23:16]
SOURCE[15:8]
SOURCE[7:0]

Figure 7: A 32b source MAC ID.

  - a `lon` field with the CPR-formatted longitude
  - an `alt` field with the CPR-formatted altitude
  - a `src` field that indicates whether the reference for time synchronization is GNSS, an LDACS ground station, or an LDACS airborne station
  - a `hops` field that indicates the number of hops the time reference
  - an `eo` bit that indicates whether the CPR-formatted position report was even or odd
  - an `rxe` bit that enables the `time_rx` field for start of reception in nanoseconds in response to the latest user's set `ext` flag
  - a `txe` bit that enables the `time_tx` field for start of transmission in nanoseconds

- potentially a number link utilization blocks, see Fig. 10
  - the `offset` field indicates the number of slots + 1 of the next channel access relative to the current packet
  - the `length` field indicates whether a 6, 12 or 24 millisecond slot duration will be used as defined in Tbl. 4
  - the `forward`, `reverse` fields indicate the number of transmissions by the link initiator or link recipient resp. per exchange
  - the `period` field indicates the periodicity of channel access on a link as $5 \cdot 2^x$ slots
  - the `frq` field indicates the frequency channel index
  - the `exchange` field indicates the number of exchanges + 1 left until

OFFSET[13:6]	
OFFSET[5:0]	**LENGTH[1:0]**

Figure 8: Information about the next SH channel access.

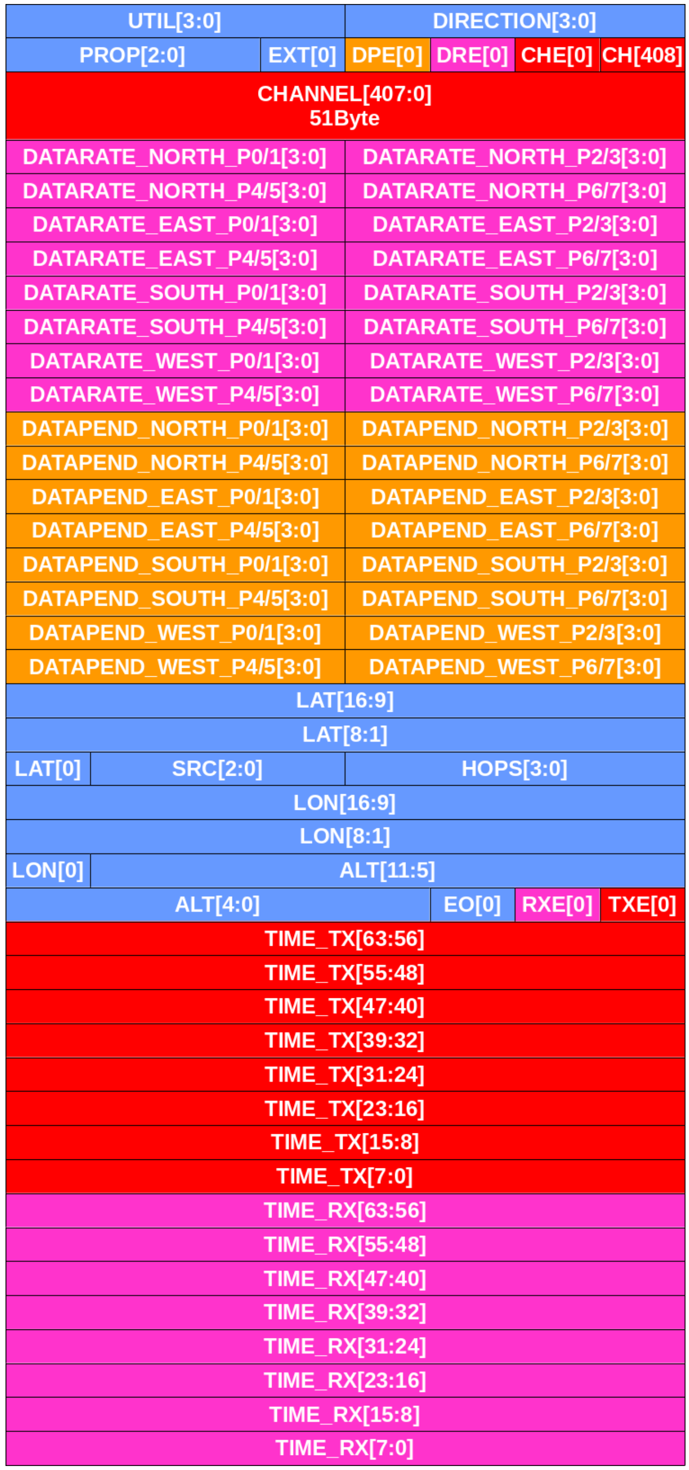

Figure 9: Information about the link status. Blue fields are mandatory, others are optional. Single-bit flags of the same color as later fields indicate which flag toggles them.

link expiry

<table>
<tr><td colspan="8">OFFSET[13:6]</td></tr>
<tr><td colspan="6">OFFSET[5:0]</td><td colspan="2">LENGTH[1:0]</td></tr>
<tr><td colspan="2">FORWARD[1:0]</td><td colspan="2">REVERSE[1:0]</td><td colspan="3">PERIOD[2:0]</td><td>FRQ[8]</td></tr>
<tr><td colspan="8">FRQ[7:0]</td></tr>
<tr><td colspan="8">EXCHANGE[7:0]</td></tr>
</table>

Figure 10: Information about PP link utilization.

- potentially a number of link proposal blocks, see Fig. 11
  - the `offset` field indicates the number of slots + 1 of the next channel access relative to the current packet
  - the `length` field indicates whether a 6, 12 or 24 millisecond slot duration will be used as defined in Tbl. 4
  - the `noise` field indicates the $3\mathrm{dB} \cdot x$ value of measured noise level above own receiver noise level
  - the `period` field indicates the periodicity of channel access on a link as $5 \cdot 2^x$ slots
  - the `frq` field indicates the frequency channel index

<table>
<tr><td colspan="8">OFFSET[13:6]</td></tr>
<tr><td colspan="6">OFFSET[5:0]</td><td colspan="2">LENGTH[1:0]</td></tr>
<tr><td colspan="4">NOISE[3:0]</td><td colspan="3">PERIOD[2:0]</td><td>FRQ[8]</td></tr>
<tr><td colspan="8">FRQ[7:0]</td></tr>
</table>

Figure 11: Information about proposed PP links.

- potentially link establishment messages, see Figs. 12 to 16
  - the `modulation` field indicates `0=BPSK_1/3; 1=BPSK_1/2; 2=QPSK_1/3; 3=QPSK_1/2; 4=QPSK_2/3; 5=QPSK_3/4; 6=16QAM_1/2; 7=16QAM_2/3; 8=16QAM_3/4`
  - the `type` field indicates `0=End-of-Messages; 1=LINK-ONE-WAY-DIS; 2=LINK-TWO-WAY-DIS-RQST; 3=LINK-TWO-WAY-DIS-RPLY; 4=LINK-TWO-WAY-STS-RQST; 5=LINK-TWO-WAY-STS-RPLY; 6=LINK-RENEWAL; 7=LINK-ERROR`
  - the `destination` field holds the destination's MAC ID
  - the `offset` field indicates the number of slots + 1 until first channel access relative to the current packet
  - the `length` field indicates whether a 6, 12 or 24 millisecond slot duration will be used as defined in Tbl. 4
  - the `forward`, `reverse` fields indicate the number of transmissions by the link initiator or link recipient resp. per exchange

– the `period` field indicates the periodicity of channel access on a link as $5 \cdot 2^x$ slots
– the `frq` field indicates the frequency channel index
– the `exchange` field indicates the number of exchanges left until link expiry
– the `mode` field indicates `0=AES-128-CMAC; 1=AES-256-CMAC; 2=AES-128-GCM; 3=AES-256-GCM`
– the `s` bit disambiguates the symmetry of the ECC-point
– the `value` field carries the ECC-point in uncompressed or compressed format
– the `error` field carries `[0=Insufficient-Resources; 1=Invalid-Message; 2=Invalid-Duty-Cycle; 3=Invalid-Frequency; 4=Invalid-Direction; 5=Invalid-Modulation; 6=Invalid-Time; 7=Invalid-Key]`
– the list of these messages is ended by a `type` field with only zeroes

<table>
<tr><td colspan="4">MODULATION[3:0]</td><td colspan="4">TYPE[3:0]</td></tr>
<tr><td colspan="8">DESTINATION[31:24]</td></tr>
<tr><td colspan="8">DESTINATION[23:16]</td></tr>
<tr><td colspan="8">DESTINATION[15:8]</td></tr>
<tr><td colspan="8">DESTINATION[7:0]</td></tr>
<tr><td colspan="8">OFFSET[13:6]</td></tr>
<tr><td colspan="6">OFFSET[5:0]</td><td colspan="2">LENGTH[1:0]</td></tr>
<tr><td colspan="2">FORWARD[1:0]</td><td colspan="2">REVERSE[1:0]</td><td colspan="3">PERIOD[2:0]</td><td colspan="1">FRQ[8]</td></tr>
<tr><td colspan="8">FRQ[7:0]</td></tr>
<tr><td colspan="8">EXCHANGE[7:0]</td></tr>
<tr><td colspan="7">MODE[6:0]</td><td colspan="1">S[0]</td></tr>
<tr><td colspan="8">VALUE[511:0]/[767:0]
64/96Byte</td></tr>
</table>

Figure 12: Link Request.

3.2 PP Frame Composition

Each data packet transmitted on any PP will contain the following header fields:

- a Message Authentication Code (MAC) `AES-128/256-CMAC` or `AES-128/256-GCM`
- an Acknowledgement bitmask for received frames from MSb = oldest to LSb = newest in last exchange

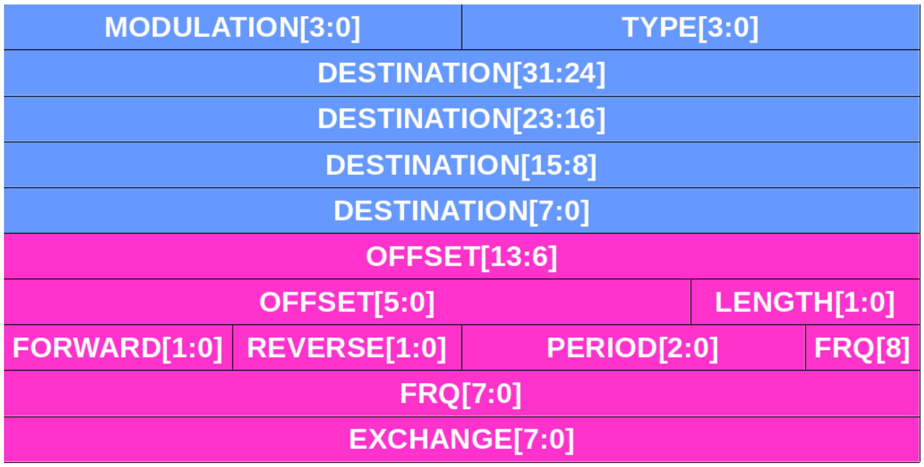

Figure 13: Link Reply (DIS). Magenta fields are optional.

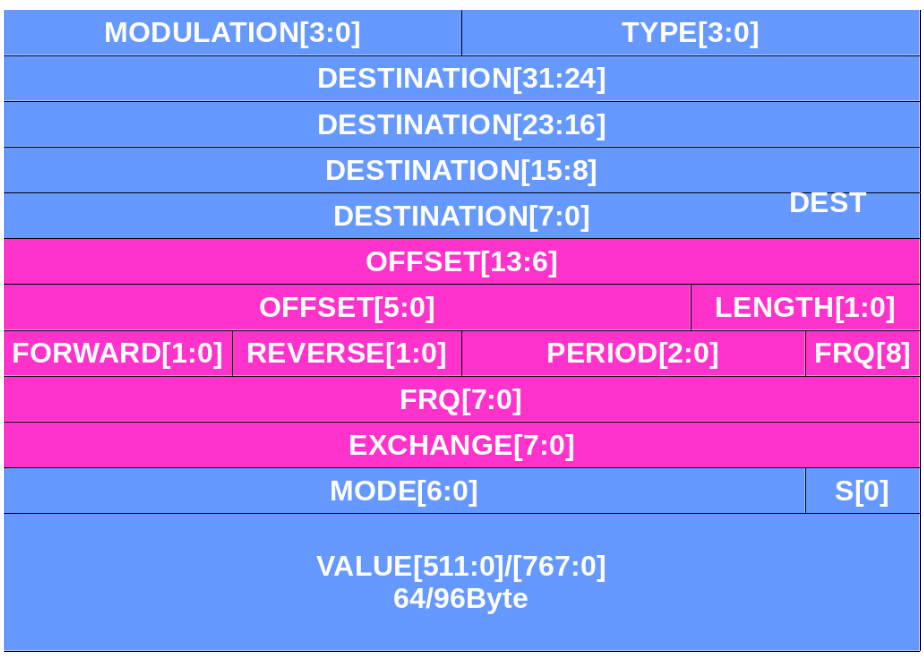

Figure 14: Link Reply (STS). Magenta fields are optional.

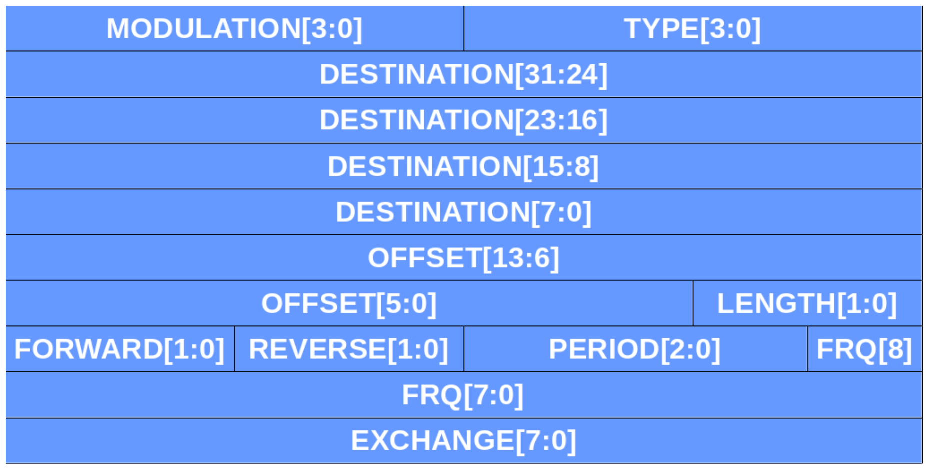

Figure 15: Link Renewal.

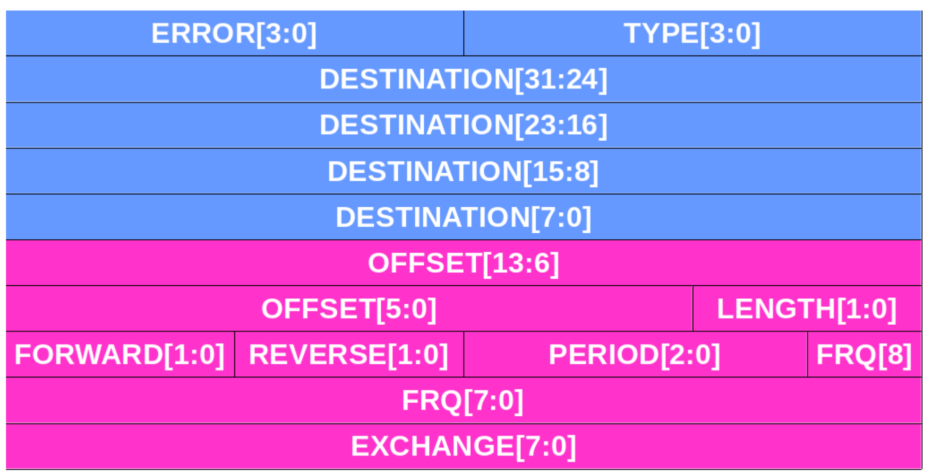

Figure 16: Link Error. Magenta fields are optional.

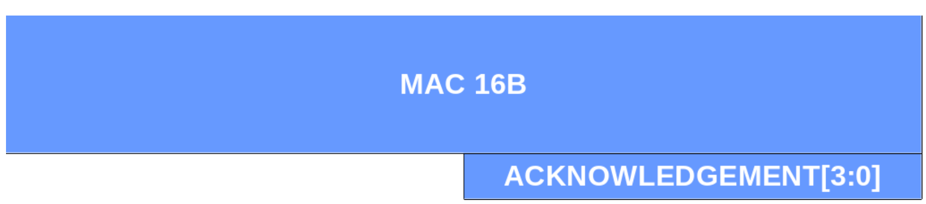

Figure 17: Message Authentication Code and Acknowledgement in PP packets.

- for fragmented, unfragmented and end-of-packet PP packets in Figs. 18, 19 and 20
  - a `FF` fragmenter's first frame flag for marking fragment as the beginning of a MAC-Payload.
  - a `LF` fragmenter's last frame flag for marking fragment as the end of a MAC-Payload.
  - a `FT` fragmenter type bit `0=Unfragmented; 1=Fragmented` to mark the method of delivering a MAC-Payload to the next hop.
  - a `CLASS` packet class field for class of service (see LDACS A/G Specification)
  - an `ACK` bit `0=Unacknowledged; 1=Acknowledged` for classification of MAC-Payload
    - if acknowledged, a 4-bit acknowledgement field is added
  - a `OFFSET` offset to data fragment in MAC-Payload
  - a `LENGTH` length of data fragment in MAC-Payload
  - a `PID` packet ID `ACCEPT;REJECT;IGNORE` for forcefully advancing new as well as ignoring old L2 packets
  - a `RES` bit that is reserved and zero

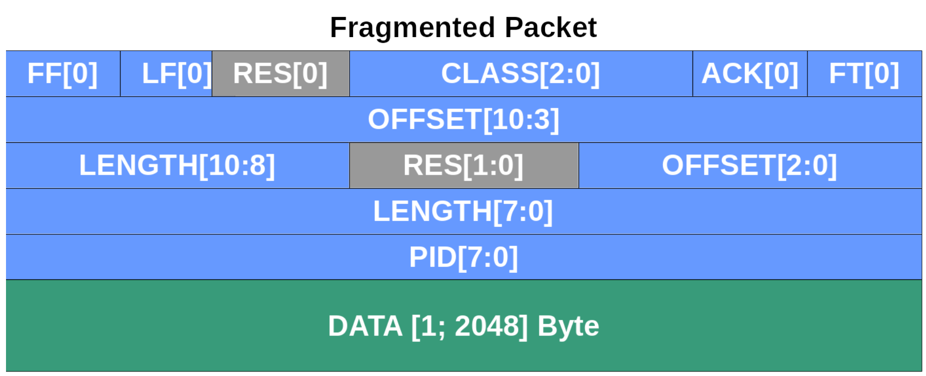

Figure 18: A fragmented PP packet.

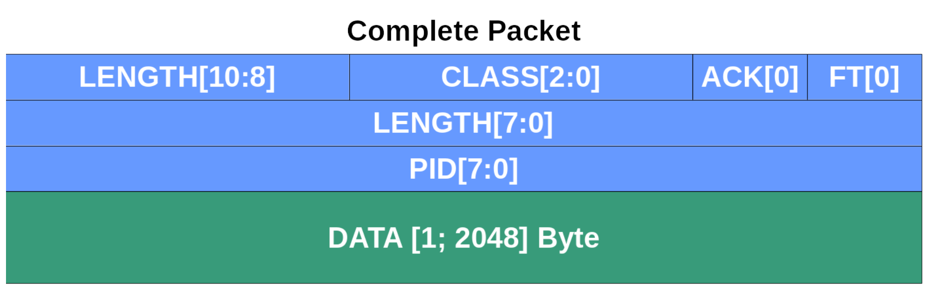

Figure 19: An unfragmented PP packet.

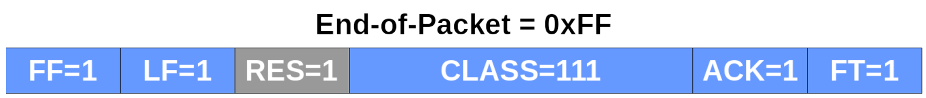

Figure 20: An end-of-packet message.

4 Medium Access Control (MAC) Sublayer

4.1 Duty Cycle

LDACS A/A users have to limit their transmission times to stay within power budgets and to adhere to interference constraints. By default, this restricts transmission times to 10% of the time. For the MAC, this imposes stringent constraints on the scheduling of communication resources. The duty cycle budget of 10% must be shared between all transmissions on SH, VC and PPs and through LDACS A/G, and the 10% threshold must not be violated. The exact procedure is left to the implementor, and it should allot some minimum budget for SH transmissions, and consider the number of PP links that it should be possible to maintain at all times. For example, one PP link per geographic direction is advisable to speed up geographic routing.

4.2 The Shared Channel (SH)

4.2.1 Randomized Reservation-based Slotted ALOHA

4.2.1.1 Incoming Interface for the Upper Layer Fig. 21 provides a high-level overview about the interface between the MAC and its upper layer. When new data arrives at the MAC from the upper layer, this is reported to the MAC. When this data should be sent via the SH, then a broadcast slot is scheduled if it hasn't, already. If it should be sent via a PP, then an existing link is used if possible, or a link is established and then used.

After scheduling a slot, the user must wait until a transmission slot arrives. When this slot arrives, data is requested from the upper layer, encapsulated into a MAC frame, and passed down to the PHY layer for transmission.

4.2.1.2 Scheduling a Broadcast Slot First, a minimum offset `min_offset` for the slot to schedule is determined. This depends on the available duty cycle budget, and it must be checked how much of the budget is being spent on VC, PP and LDACS A/G communication, and the additional transmission at `min_offset` must not violate the budget.

Next, the number of candidate slots `k` can be calculated as

$$k = \left\lceil \frac{1}{1 - \sqrt[n]{\frac{1}{e}}} \right\rceil \tag{1}$$

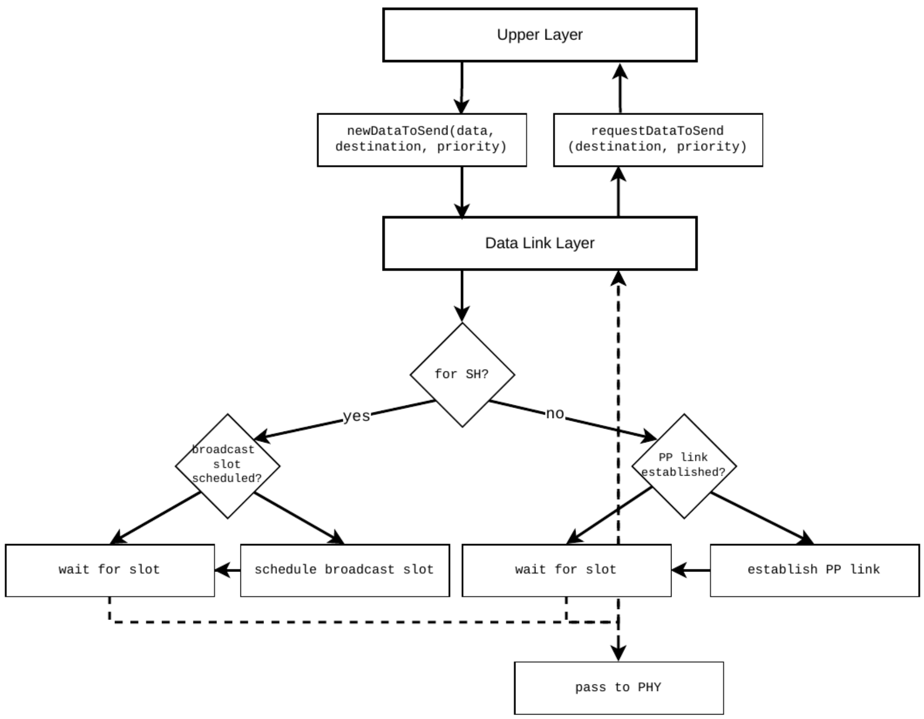

Figure 21: A high-level description of the interface between MAC and its upper layer, and how medium access is triggered for transmissions via SH or PP.

where n is the number of neighboring LDACS A/A AS.

The k candidate slots are found by querying the SH reservation table, starting at time slot offset `min_offset`, and looking for k `IDLE` resources. From this set of candidate slots, one slot is selected uniformly randomly, using a pseudo-random number generator that has been seeded with the user's MAC ID. The selected slot will be used for the next broadcast transmission, and so it is marked as `TX` in the SH reservation table and the transmitter table.

Note that Eq. 1 is a worst-case approach in a network where users have not advertised next transmission slots to each other. In such an unsynchronized network, when k is computed using Eq. 1, an average packet collision probability of $1 - \frac{1}{e}$ is achieved. This allows users to synchronize each other's transmissions over time. In synchronized networks, k can be limited to smaller values, which removes the guarantee on the average packet reception probability, but reduces packet delays.

4.2.1.3 Broadcasting Data A packet is prepared for transmission before a slot arrives that has been marked as `TX` in the SH reservation table. Packet content prioritization foresees that:

- at least every second SH data packet must contain the sender's geographic position
- link establishment-related control messages such as link requests and link replies may be delayed and sent on only every second transmission, if necessary
- link utilization takes priority over link proposals
- sending one's own transmission time in the `TIME_TX` link status header fields takes priority over replying to another user's request of their reception time in the `TIME_RX` link status header fields
- datarate-related fields that are toggled through `DRE` and `DPE` flags are optional and can be toggled off
- the channel bitmask is optional and can be toggled off through the `CHE` flag

4.2.1.4 PP Channel Definition To be concise, a PP channel is parameterized by the fields displayed in Fig 10. A link starts at the earliest transmission slot, `offset` time slots in the future, relative to the current time slot. For the entire duration of a link, one time slot length is used, indicated in the `length` field. The sender of the link request is named the link initiator, the sender of the link reply the link recipient. A link endures as many exchanges as the `exchange` field contains plus one. Each exchange consists of as many transmissions of the link initiator as the `forward` field contains, and as many transmissions of the link recipient as the `reverse` field contains. The number of time slots in-between transmission slots is found by reading the `period` field into a variable x and computing the number of slots in-between transmissions as $-1 + 5 \cdot 2^x$. The `frq` field contains the index of the PP channel that shall be used for this link. See Fig. 22.

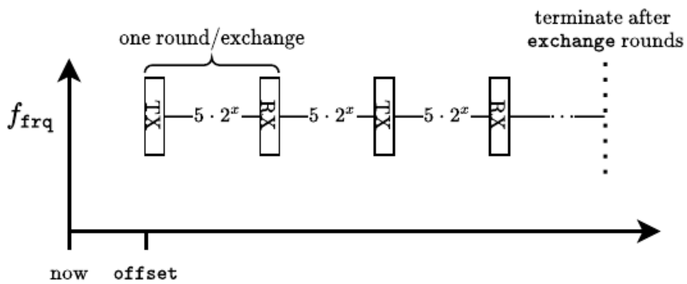

Figure 22: Exemplary PP channel.

When in the following sections a link request or reply or proposal contain a "link", then these parameters are explicitly meant, which translate implicitly to a set of time slots where link initiator or recipient transmit. For example, let $\mathtt{offset} = 3, \mathtt{forward} = \mathtt{reverse} = 1, \mathtt{exchange} = 2, \mathtt{period} = 1$. The effective offset is $3+1$, one exchange consists of two transmissions each, and $2+1$ exchanges happen with $-1+5\cdot 2^1$ time slots in-between channel accesses. The following channel accesses are made, with `TX` denoting a transmission by the link initiator, and `RX` a transmission by the link recipient:

- `TX@4,14`
- `RX@24,34`
- `TX@44,54`
- `RX@64,74`
- `TX@84,94`,
- `RX@104,114`

4.2.1.5 Determining viable links A viable link is found by searching local reservation tables. All resources for transmission and reception must be idle, receiver and transmitter must also be available, and the duty cycle budget must not be exceeded.

4.2.1.6 Populating a Link Request When a link request should be sent to a particular neighbor to establish a new PP link, a link request is added to a broadcast message. If available, that neighbor's proposed links are used. These are compared to local reservation tables, and the earliest viable, proposed link is used. If none are viable or no proposals are available, then the user selects the earliest links that are viable. These must have their first transmission later than the neighbor's next broadcast slot, giving that user time to send a reply. The processing time must be taken into account as defined in Sec. 2.10. If a link is established through a link reply, resources are scheduled as `TX` or `RX`. If no link reply is received before the first transmission of the proposed link, resources are set to `IDLE`.

4.2.1.7 Populating a Link Reply

Upon reception of a link request, the proposed links therein are checked for viability. In addition, a proposed link must start later than the next local broadcast transmission, so that there is an opportunity for a link reply. If several proposed links are valid, the earliest link is chosen, and a link reply is prepared that contains the chosen link's parameters. If no proposed links are valid, link establishment is started at this user, and an own link request is sent at the next opportunity. If several link requests are to be answered and not all can be due to packet capacity constraints, the highest-priority ones according to header fields are replied to. For all others, link establishment is started at this user.

4.2.1.8 Third-Party Link Replies

Link requests and replies inform the neighborhoods of the senders about new PP links. All recipients of a link reply mark the link contained therein as `BUSY`.

4.2.1.9 Populating a Link Proposal

Link proposals intend to inform the neighborhood about PP links that are locally usable, which speed up link establishment, as link initiators can use these proposed links when populating their link requests for this user. To populate a link proposal, local reservation tables are searched for the best-fitting link that is locally idle and where receiver and transmitter are available, and that satisfies data rate requirements that can be met according to the duty cycle. As a broadcast message can contain several proposals, these should cover several starting time slots as well as several PP channels to provide diversity both in time and frequency.

4.2.1.10 Neighbor List

The reception of packets on the SH from nearby LDACS users is used to update a list of neighbors. Each time a neighbor's packet is received, its MAC ID field is parsed and that neighbor's entry in this list is updated with the current time slot.

MAC ID	Reception Time	Reported Transmission Time	Position
`id`	t_{RX}	t_{TX}	`lat, lon, alt`

If a neighbor entry has not been updated for more time slots than it usually takes to receive three broadcasts from this neighbor, then the entry is erased from the list.

4.2.1.10.1 Receiving Broadcast Messages on the SH

Broadcast messages contain all the information indicated in Sec. 3.1. These are parsed and processed accordingly: neighbor positions are saved, link proposals and utilizations as well, link requests and replies are processed as either third-party or as destined to this user, the next broadcast is saved and the own next transmission potentially re-scheduled if it were to cause a packet collision.

4.2.1.11 Network Entry LDACS A/A is a Mobile Ad-Hoc Network (MANET) and thus follows no concept of "cells", as LDACS A/G does. Network entry is therefore a matter of discovering one's neighbors and their transmission schedules. Broadcast messages (beacons) are the main driver for this, as all users must periodically broadcast them, and they contain the transmission schedule in their payload.

At power-on, an LDACS user scans the SH until it has received one user's beacon twice, or until many time slots have passed during which no beacon has been received. This time should be sufficient to discover one's neighbors, and to mark their transmissions in the local reservation tables. Afterwards, the joining user's own beacon slot is scheduled.

4.2.1.12 Clock Synchronization LDACS clocks are to be synchronized through LDACS A/G. If LDACS A/G is unavailable, a user can request time values from its neighbors by setting the `ext` flag in its SH packet header. In response, neighbors set the `time_tx` and `time_rx` fields in their headers, allowing recipients to calculate the packet delay and then agree on a joint time.

4.2.1.13 SH Transition It is advisable to select a single LDACS channel as the SH that is globally available, even after taking into account that some channels must locally not be used so that no interference to DME is caused. If this is not possible, then at specific locations, the logical SH must change frequency channels. LDACS A/G ground stations should inform connected LDACS A/A users of the local SH center frequency. A SH transition procedure should cause minimal interruption to LDACS A/A operation when users switch their SH frequency.

4.3 The Point-to-Point Channels (PPs)

The SH subchannel described in Sec. 4.2 can be viewed as a control channel for PP link establishment. The SH channel access is randomized, while the PP channel access is negotiated between two users during PP link establishment. The control packets of this negotiation, link requests and link replies, are transmitted on the SH, so that neighbors are aware of newly-established links, and will refrain from using the same resources.

4.3.1 Incoming Interface for the Upper Layer

When new data arrives for a particular MAC ID. If no PP link is currently established or in the process of establishment, link establishment is triggered, which has been described in Sec. 4.2.

4.3.2 Voice Channels (VCs)

4.3.2.1 Point-to-Point Real-Time Voice Real-time voice communication is possible between two users via PP subchannels. Voice communication has stringent latency requirements, and 250ms is a general “rule of thumb” for a maximum, acceptable delay. The packet delay for PP links is determined by the number of time slots in-between transmissions of one user, from the $x =$ `period` parameter as $2 \cdot 5 \cdot 2^x$. It follows that a packet delay of 240ms can be kept if the `period` is set to 0. Note that this consumes a considerable amount of the duty cycle budget and might not always be possible.

4.3.2.2 Broadcast Push-to-Talk Voice A broadcast Voice Channel (VC) can be realized on its own frequency subchannel. Channel access is randomized as for the SH subchannel described in Sec. 4.2. The difference is that when the next transmission slot is scheduled, the same Eq. 1 is used, but for the number of neighbors n is, the number of participating users in the VC is used. The packet delay thus scales with the number of users of the channel.

5 Automatic Repeat Request (ARQ) Sublayer

The ARQ sublayer realizes reliable data transmissions. It recognizes when a message from a communication partner went missing and efficiently requests the retransmission of the information included in that message.

5.1 Interfaces

The ARQ sublayer interacts with the RLC sublayer above and the MAC sublayer below it. The interface between RLC and ARQ consists of 6 methods as depicted in Fig. 23.

The ARQ exposes `receiveFromLower(macFrame)` to the MAC which is used to pass up a received MAC frame. The same method is expected on the RLC to further pass up the frame. In similar fashion, the ARQ exposes the `requestFrame(numBytes, destId)` to the MAC, which is again also expected to exist on the RLC.

Further, it uses the `ack(destId, frameIdx)` and `nack(destId, frameIdx)` on the RLC to communicate the reception status of MAC frames.

5.2 Operation

The ARQ only operates on PP links. Here, transmissions alternate between communication partners so that there are never more than 4 MAC frames transmitted before the communication partner has the chance to answer and acknowledge the preceding transmissions. The ARQ holds an independen state for each PP channel, managed by a dedicated ARQ process as shown in Fig. 23. This state is composed of three variables: `frameIdx_next` is a counter that represents the index of the next MAC frame send in the current exchange. The list `frameIdx_inflight` contains the indices of all frames already sent in

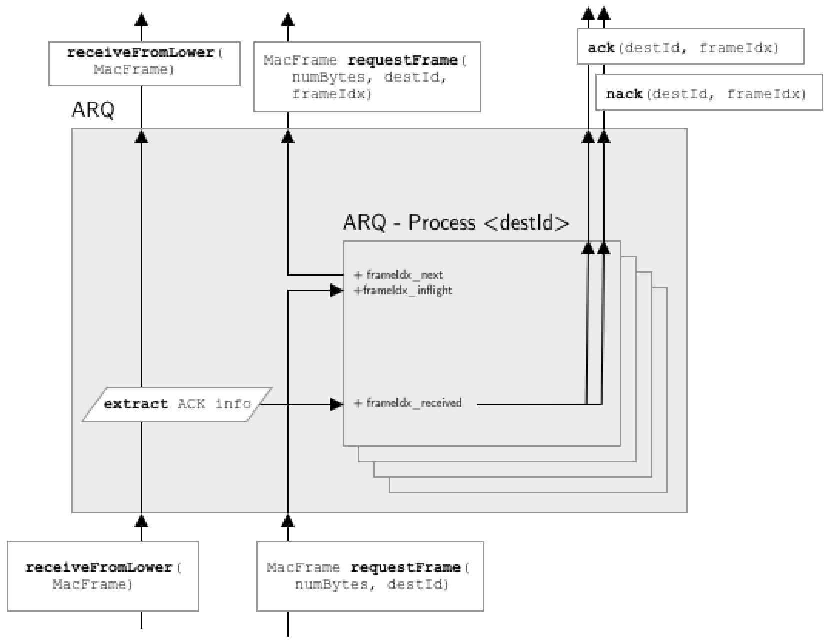

Figure 23: ARQ interfaces

this exchange. While frames are received from the communication partner, the indices of the received frames are stored in the `frameIdx_received` list.

Whenever a data exchange starts for a given destination and the `requestFrame(numBytes, destId)` is called, the corresponding ARQ process resets its `frameIdx_next` variable to 0, requests a MAC frame from the RLC with `frameIdx_next` as `frameIdx`, marks it as in-flight and increments it. The same procedure is repeated for all other transmissions in this exchange. Whenever a MAC frame is received, the `ACKNOWLEDGEMENT` header field is consulted for the acknowledgment status of in-flight MAC frames. Here, the most significant bit indicates `frameIdx = 0` and the least significant bit `frameIdx = 3`. If a bit is set to 1 the corresponding MAC frame is acknowledged, if if is set to 0 it is negative acknowledged. This information is passed up to the RLC. In addition, the `frameIdx` of the received frame on the other side (derived from the reservation tables) is added to the `frameIdx_received` list. Whenever a MAC frame is sent, the `ACKNOWLEDGEMENT` bitmask is filled from this list. When a exchange ends without the reception of a MAC frame from the other side, all `frameIdx` currently in-flight are negative acknowledged on the RLC layer over the `nack(destId, frameIdx)` interface.

6 Radio Link Control (RLC) Sublayer

The RLC sublayer is the highest sublayer in the Data Link layer. It receives network layer packets and creates MAC frames based on the needs of the MAC layer. The amount of network layer data a single MAC frame can carry depends on the currently used time-coding-modulation-scheme (TCMS). To use the available space efficiently, the RLC implements fragmentation and concatenation of network layer packets. This means, that a network layer packet can be transmitted in several fragments and a MAC frame can contain fragments from several network layer packets. Received fragments are reassembled by the RLC.

6.1 Interfaces

The RLC directly interacts with the network layer. It exposes an interface `receiveFromUpper(L3Packet, destId, CLASS, ACK?)` to receive packets from the network layer. Here, `L3Packet` is the network layer packet, `destId` is the MAC ID of the destination, `CLASS` the service class and `ACK?` whether acknowledged or unacknowledged transport is requested. Further it expects a `sendUp(L3Packet, CLASS, ACK?)` interface on the network layer to pass up received network layer packets.

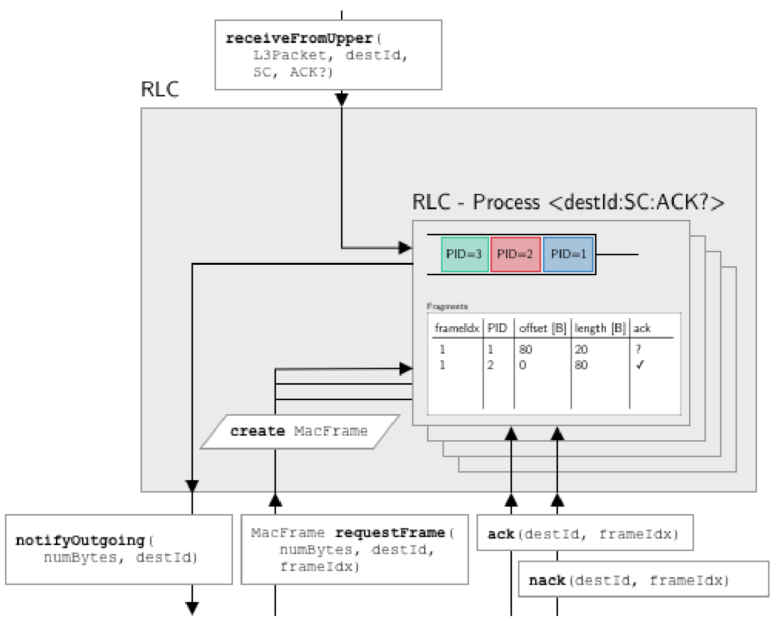

Figure 24: RLC interfaces

The interface to its lower layer consist of four methods. The method `notifyOutgoing(numBytes, destId)` is expected on the lower layer so that the RLC can inform the lower layer about pending data to be sent. Further, it exposes a `requestFrame(numBytes, destId, frameIdx)` to allow lower layers to request MAC frames of a given size for a given destination and `ack(destId, frameIdx)` and `nack(destId, frameIdx)` so that the lower layer can acknowledge or negative acknowledge the successful delivery of a MAC frame.

6.2 Operation

Internally, the RLC consists of a collection of RLC processes. These processes handle the fragmentation and reassembly procedure for each combination of destination MAC ID (`destId`), service class (`CLASS`) and whether it is acknowledged or unacknowledged transport (`ACK?`). Each of those processes has a queue for incoming network layer packets. Whenever a new packet comes into this queue, it gets assigned a packet ID (`PACKET_PID`). For this purpose, every process holds an 8 bit sequence number with modulo arithmetic from which the `PACKET_PIDs` are taken. Further, each process holds a table where it stores the state of the fragments it created.

Whenever a network layer packet comes into the RLC, it is passed to the corresponding RLC process and put into the queue. The RLC uses the `notifyOutgoing(numBytes, destId)` interface to inform lower layers about the pending data.

For every MAC frame requested through the `requestFrame(numBytes, destId, frameIdx)` interface, the RLC requests payloads from each of the processes related to the `destId`, starting from the highest service class. A RLC Process always creates payloads with the maximum amount of upper layer data while only encapsulating data from a single `PACKET_PID`. If a complete upper layer packet fits, the `FT` flag in the header is set to 0, otherwise it is set to 1 indicating a fragmented packet. In any case, the `PACKET_LENGTH` field is set to the length of the data in the payload, the `PACKET_PID` field is filled with the `PACKET_PID` and `CLASS` and `ACK` are set according to the same values from the RLC process. For a fragmented payload, additionally, the `PACKET_OFFSET` field is set to indicate the offset to the start of the included packet in bytes and `LF` and `FF` indicate whether a fragment is the first or last fragment of a packet. When a MAC frame is requested, but not enough network-layer data is aavailable to fill it completely, it is ended with a “End-of-Packet” payload that has consists of the fields `FF`, `LF`, `RES`, `CLASS`, `ACK` and `FT` all set to `1`. Each of the processes stores the `frameIdx` together with the payloads it created. `frameIdx` is a variable managed by the ARQ to indicated the index of a MAC frame in a given exchange between two numbers. As there are never more than 4 MAC frames created before the other side has a chance to answer, this variable ranges from 0 to 3.

Before a new data exchange is initiated, the lower layer calls the `ack(destId, frameIdx)` / `nack(destId, frameIdx)` interface, for each of the 4 `frameIdx` from the previous exchange. This information is again relayed to the corresponding processes and fragments are either marked as successfully delivered or marked for retransmission. If a new exchange begins without a previous explicit `ack()` / `nack()`, all frames from the previous exchange are considered negative acknowledged.

References

[1] T. Gräupl, C. Rihacek, B. Haindl, and Q. Parrod, "LDACS A/G Specification," SESAR Joint Undertaking, 2018.