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Foreword

This Technical Specification (TS) has been produced by ETSI Technical Committee Electromagnetic compatibility and Radio spectrum Matters (ERM).

Modal verbs terminology

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1 Scope

The present document specifies the radio protocols of three radio technologies, referred to as "families". It contains an implementable description of physical and MAC/link protocol layers. It concludes with a section on implementation commonalities between the three LTN families.

NOTE 1: ETSI TR 103 249 [i.8] describes LTN use cases and system characteristics.

NOTE 2: ETSI TS 103 358 [i.9] specifies the architecture of LTN systems.

NOTE 3: Based on the above documents, radio technologies have been developed with a focus on different subsets of applications, where the optimal balance of technical parameters differs.

2 References

2.1 Normative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

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The following referenced documents are necessary for the application of the present document.

[1] IEEE™ Std 802.15.4-2011: "IEEE Standard for Local and metropolitan area networks; Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)".

[2] Publication 197 (2001): "Specification for the Advanced Encryption Standard (AES)", NIST Processing Standards".

NOTE: Available at: http://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.197.pdf.

[3] NIST Special Publication 800-38B (2005): "Recommendation for Block Cipher Modes of Operation: "the CMAC Mode for Authentication".

NOTE: Available at: https://csrc.nist.gov/publications/detail/sp/800-38b/final.

[4] ISO/IEC 29192-2:2012: "Information technology - Security techniques - Lightweight cryptography - Part 2: Block ciphers".

[5] CEN EN 13757-4:2013: "Communication systems for meters and remote reading of meters - Part 4: Wireless meter readout (Radio meter reading for operation in SRD bands)".

[6] IEEE™ Guidelines for Use of Extended Unique Identifier (EUI), Organizationally Unique Identifier (OUI), and Company ID (CID).

NOTE: Available at: http://standards.ieee.org/develop/regauth/tut/eui.pdf.

2.2 Informative references

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NOTE: While any hyperlinks included in this clause were valid at the time of publication, ETSI cannot guarantee their long term validity.

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ERC Recommendation 70-03 (Tromsø 1997 and subsequent amendments): "Relating to the use of short range devices (SRD)", Recommendation adopted by the Frequency Management, Regulatory Affairs and Spectrum Engineering Working Groups, Version of 21 October 2016.

[i.2] ETSI EN 300 220-1 (V2.4.1) (05-2012): "Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment to be used in the 25 MHz to 1 000 MHz frequency range with power levels ranging up to 500 mW; Part 1: Technical characteristics and test methods".

[i.3] CFR Title 47 Part 15 section 15.247: "Operation within the bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz".

[i.4] ARIB STD-T108: "920 MHz-Band Telemeter, Telecontrol and data transmission radio equipment", Version 1.0 of February 14th 2012.

[i.5] Recommendation for Block Cipher Modes of Operation (Methods and Techniques), Morris Dworkin, NIST Special Publication 800-38A, Edition 2001.

NOTE: Available at: http://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-38A.pdf.

[i.6] IETF RFC 4493: "The AES-CMAC Algorithm", 2006.

NOTE: Available at: https://tools.ietf.org/html/rfc4493.

[i.7] CEN EN 13757-7:2018: "Communication systems for meters - Part 7: Transport and security services".

[i.8] ETSI TR 103 249 (V1.1.1) (10-2017): "Low Throughput Network (LTN); Use Cases and System Characteristics".

[i.9] ETSI TS 103 358 (V1.1.1) (06-2018): "Short range devices; Low Throughput Networks (LTN) Architecture; LTN Architecture".

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3 Definitions, symbols and abbreviations

3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

CLEFIA: A lightweight block cipher defined in ISO/IEC 29192-2 [4].

data-burst: sequence of consecutive radio bursts transmitted by an LTN entity

network element: term used to refer to a node in the DD-UNB system. It can refer to an EP, RP, OEP, BS, or SC

orphan end-point: EP which is connected through a relay point

radio-burst: radio transmission over the air which starts with a ramp up, finishes with a ramp down and which has a continuous centre frequency and constant transmission power (apart from modulation)

radio-frame: area in time and frequency plane containing all radio bursts belonging to one packet

sub-packet: fragment of a packet after telegram splitting

subframe: portion of the basic 24 s frame which is allocated to a specific link, direction and content (i.e. A or A"-interface with DL, UL data or UL Ack)

superframe: set of 64 consecutive frames

TSMA carrier: transmission carrier within the LTN channel on which a radio burst is transmitted

TSMA pattern: time and frequency transmission scheme of a radio frame

3.2 Symbols

For the purposes of the present document, the following symbols apply:

$\Delta f_{slowchirp}$	Frequency difference between the start and end of secondary modulated PPDU as a result of chirp
ΔT	Symbol duration
B_c	Carrier spacing
$BW_{UL\text{-}Ch}$	Bandwidth of UL channel used by EP in band of operation
C_{RB}	Radio-burst carrier number of TSMA pattern
C_{offset}	Carrier offset of radio frame
dB	decibel
f_0	Start frequency of a radio frame
f_c	Channel centre frequency
f_h	Frequency of high tone
f_l	Frequency of low tone
f_{offset}	Additional pseudorandom radio frequency offset to the centre frequency
f_{RB}	Carrier frequency of a radio burst
n_b	Number of PSDU data bytes
$N_{repetitions}$	Number of repetitions of a PPDU
n_{ts}	Timeslot offset of radio frame
p_{TSDL}	Downlink TSMA pattern number
P_{TX}	Transmission power
S_{TOTAL}	Total number of sub-packets in a radio frame
S_C	Number of sub-packets in core frame
S_E	Number of sub-packets in extension frame
S_{RF}	Timeslot offset of radio frame
T_0	Start time of the radio frame transmission
T_{DN}	DL Interblock Distance
T_{PPDU}	PPDU duration in seconds
T_{RB}	Time difference between two consecutive radio bursts in number of symbols
T_{SB}	Sync-burst time
$T_{tx\text{-}gap}$	Repetition gap between PPDUs in seconds

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

AC	Acknowledge Codeword
ACK	Acknowledge
AES	Advanced Encryption Standard
BC	Broadcast
BCH	Bose–Chaudhuri–Hocquenghem code
BDU	Block Data Unit
BFSK	Binary Frequency Shift Keying
BPSK	Binary Phase Shift Keying
BS	Base Station
BSGP	Base-System Group
BSID	Base Station ID
BT	Bandwidth-bit period product

BW	Bandwidth
CC	Control Codeword
CI	Control Information
CMAC	Cipher-based Message Authentication Code
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
DAPCH	Downlink Acknowledge Physical Channel
DATA_A	Data field A of a TS burst
DATA_B	Data field B of a TS burst
DATA_C	Data field C of a TS burst
DBPCH	Downlink Broadcast Physical Channel
DC	Duty Cycle
DCPCH	Downlink Control Physical Channel
DD-UNB	Dynamic Downlink Ultra Narrowband
DL	Downlink
DL-ER	Downlink, Extended Reach for TS-UNB
DLL	Data Link Layer
DLRX	Downlink Receive (status)
DL-SB	Downlink Single Burst (Basic profile)
DMPCH	Downlink Multicast Physical Channel
DPG	Downlink Pattern Group
DSP	Digital Signal Processing
DSPCH	Downlink Sync Physical Channel
DWPCH	Downlink Wakeup Physical Channel
DXPCH	Downlink Connection Physical Channel
EFI	Extension Frame Indicator
EP	End-Point
EPID	End-Point Identifier
ER	Extended Reach
EUI	Extended Unique Identifier
FEC	Forward Error Correction
FMAC	Frequency Medium Access Control
FSK	Frequency Shift Keying
GFSK	Gaussian Frequency Shift Keying
GMSK	Gaussian Minimum Shift Keying
GP	Grid Position
GPS	Global Positioning System
IC	Integrated Circuit
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IPv6	Internet Protocol version 6
ISO	International Organization for Standardization
IV	Initialization Vector (payload encryption)
LAPCH	Local Acknowledge Physical Channel
LBPCH	Local Downlink Broadcast Physical Channel
LBT	Listen Before Talk
LCPCH	Local Control Physical Channel
LDPC	Low Density Parity Check
LFSR	Linear Feedback Shift Register
LMPCH	Local Multicast Physical Channel
LPDU	Link Layer Protocol Data Unit
LSB	Least Significant Bit
LSPCH	Local Sync Physical Channel
LTN	Low Throughput Network
LWPCH	Local Wakeup Physical Channel
LXPCH	Local Connection Physical Channel
MAC	Medium Access Control
MC	Multicast
MCL	Minimum Coupling Loss
MMODE	MAC MODE
MPDU	MAC Protocol Data Unit

MPF	MAC Payload Format
MSB	Most Significant Bit
MSDU	MAC Service Data Unit
MSK	Minimum Shift Keying
NET	Network layer
NIST	National Institute of Standards and Technology
OEP	Orphan End-Point
OFB	Output Feedback
OSI	Open System Interconnection
P	Power
PA	Power Amplifier
PDU	Protocol Data Unit
PHR	PHY Header
PHY	Physical layer
PLL	Phase Locked Loop
PN9	Pseudo Noise sequence of length 9
PPDU	PHY Protocol Data Unit
PRN	Pseudo-Random Number
PS	Pilot Sequence
PS_A	Pilot Sequence A
PS_B	Pilot Sequence B
PS_DA	Pilot Sequence field A of a TS DL burst
PS_DB	Pilot Sequence field B of a TS DL burst
PS_DS	Pilot Sequence field of a DL Sync burst
PS_US	Pilot Sequence field of a UL Sync burst
PSDU	PHY Service Data Unit
PSI	Packet Size Indicator
RF	Radio Frequency
RFC	Request For Comments
RFS	Random Frequency Selection
ROS	Relay Outstation
RP	Relay Point
RSSI	Received Signal Strength Indication
RX	Receiver
SBDU	Sync-Burst Data Unit
SC	Service Centre
SCC	Strong Control Codeword
SDU	Service Data Unit
SE	Secure Element
SFEC	Strong Forward Error Correction
SIF	Sync-burst Info Field
SIGN	Signature field of TS burst
SRD	Short Range Device
SSID	Short System ID
SXC	Strong Connection Codeword
Sym	Symbols
Sync	Synchronization
TCXO	Temperature Compensated Crystal Oscillator
TDD	Time Division Duplex
TS	Telegram Splitting
TSI	Transmission Start-time Indicator
TSMA	Telegram Splitting Multiple Access
TS-UNB	Telegram Splitting Ultra Narrow Band
TX	Transmitter
UAPCH	Uplink Acknowledge Physical Channel
UDPCH	Uplink Data Physical Channel
UL	Uplink
ULP	Ultra Low Power
UNB	Ultra Narrowband
WAC	Weak Acknowledge Codeword
WMBUS	Wireless M-BUS
WMC	Weak Multicast Codeword

WU	Wakeup
XC	Connection Codeword
XOR	logic eXclusive OR

4 General description

A LTN system according to the architecture document shall support one or more of the three protocol families described in the present document. The protocol families are designed to operate effectively in sub-GHz frequency bands. The protocol description offers particular mechanism to allow the operation of the LTN system under different national or regional radio spectrum regulations (e.g. [i.1], [i.2], [i.3], [i.4]).

5 Lfour family

5.1 Overview

If a LTN System supports LFour family, the following protocol description shall apply. The Lfour LTN family is a low power, wideband technology and supports star network topology in radio access network. The Lfour air interface description applies to A-interface between Class Z EP and one or more BSs.

The Lfour LTN family has several key characteristics:

- Uni-directional link aiming to achieve the lowest power consumption with simple architecture.
- Three different modes of operation to choose from depending on likelihood of interference, regulation, and sensitivity requirements.
- Ability to coherently add re-transmitted packet(s) to enhance transmission range and/or combat with interference.
- LDPC forward error coding to achieve best sensitivity and mobility performance.

The three modes of operation are differentiated by modulation type and bandwidth as per the parameters in Table 5-1.

Table 5-1: Modes of operation

	Mode A	Mode B	Mode C
Modulation Type	Chirp modulated BPSK	BPSK	BPSK
Symbol Rate	26 MHz/4 096 =~6,35 kSym/s	26 MHz/512 = ~50,8 kSym/s	26 MHz/256 = ~101,6 kSym/s
Occupied BW	160 kHz	50,8 kHz	101,6 kHz
Check Sum	CRC24	CRC24	CRC24
FEC	Rate=1/4 LDPC	Rate=1/4 LDPC	Rate=1/4 LDPC
T_{PPDU}	2 496/Sym rate = ~393,2 msec	9 616/Sym rate = ~189,4 msec	9 616/Sym rate = ~94,7 msec
Re-transmission	Yes (Coherent)	Yes (Coherent)	Yes (Coherent)
MCL	>155 dB	>150,6 dB	>150,6 dB

Uplink transmissions are triggered by EPs and resultant data packets can be received by one or more BS(s). The system supports two sizes of MSDUs, 128 bits and 64 bits denoted by Type 1 and Type 2 respectively. The symbol rate of modulated PPDU bits is derived from 26 MHz TCXO which is used in Lfour transmitter design.

An overview of MAC and PHY layer functions and PDU formats is shown in Figure 5-1.

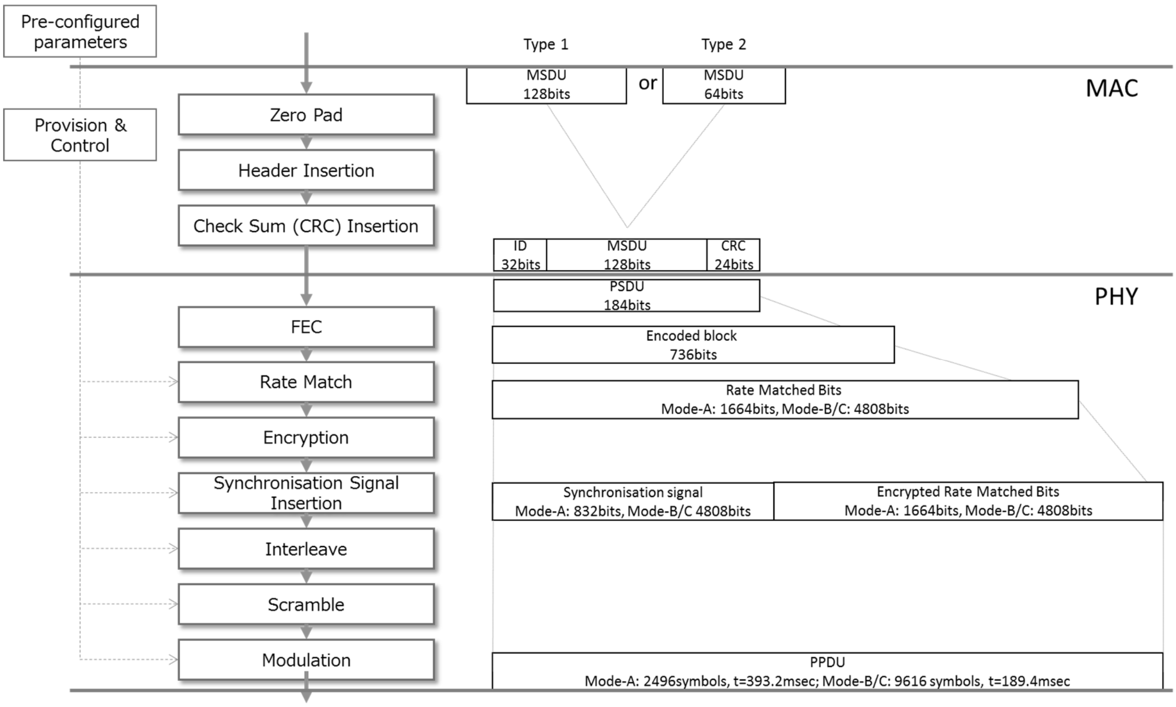

Figure 5-1: Overview of MAC and PHY flow and PDU format

Lfour system makes use of time, frequency and code space domains for multiple access to accommodate large number of devices requesting service in a coverage area as shown in Figure 5-2 and Figure 5-3. Lfour may use auxiliary time synchronization methods (e.g. GPS) to reduce the complexity of the receiver in BS.

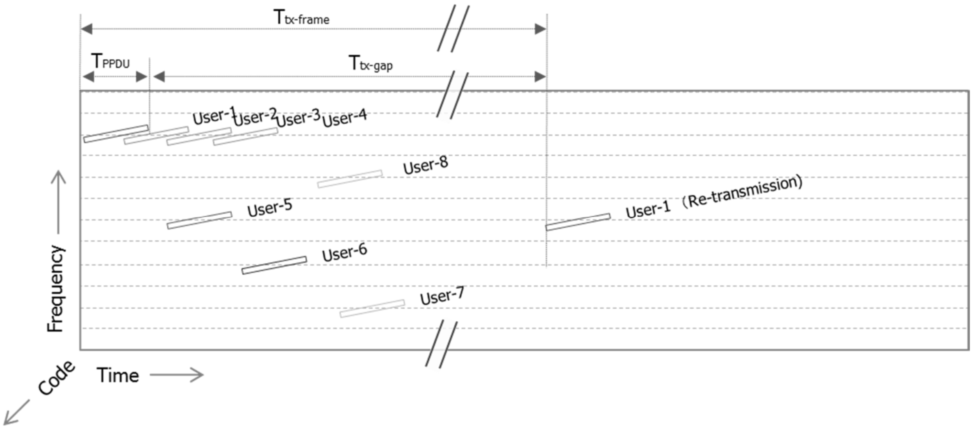

Figure 5-2: Multi-user Access Overview for Mode A Operation

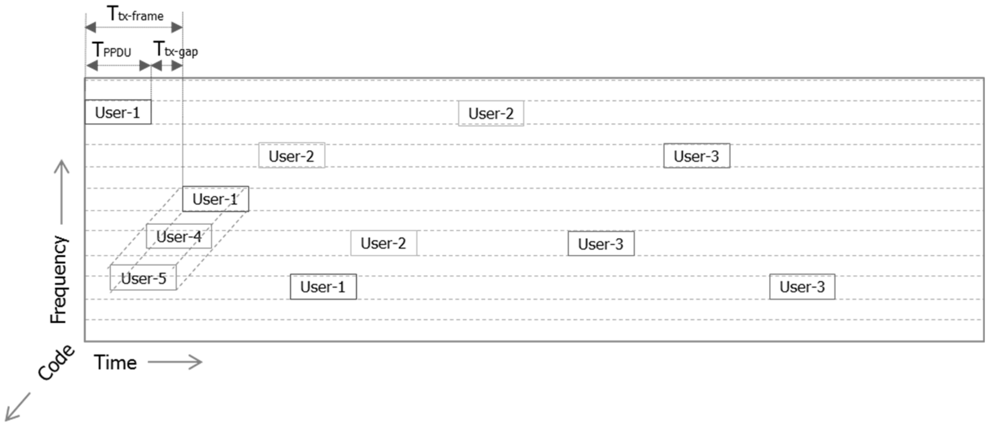

Figure 5-3: Multi-user Access Overview for Mode B/C Operation

5.2 MAC layer description

5.2.1 Overview

MAC sub-layer specification applies to UL only as Lfour is an UL system.

The MAC sub-layer for LTN air-interface provides following services:

- Passing and Receiving User Plane Data to and from higher layer entity
- Assembling and Disassembling of MSDU
- Assembling and Disassembling of MAC Header Information
- Assembling and Disassembling of CRC
- Passing and Receiving MPDU to and from PHY layer
- Provision of re-transmission parameters
- Provision of Encryption parameters
- Provision of PHY parameters

Figure 5-4 denotes MAC services for an EP transmitter. Reverse procedure applies at corresponding BS receiver.

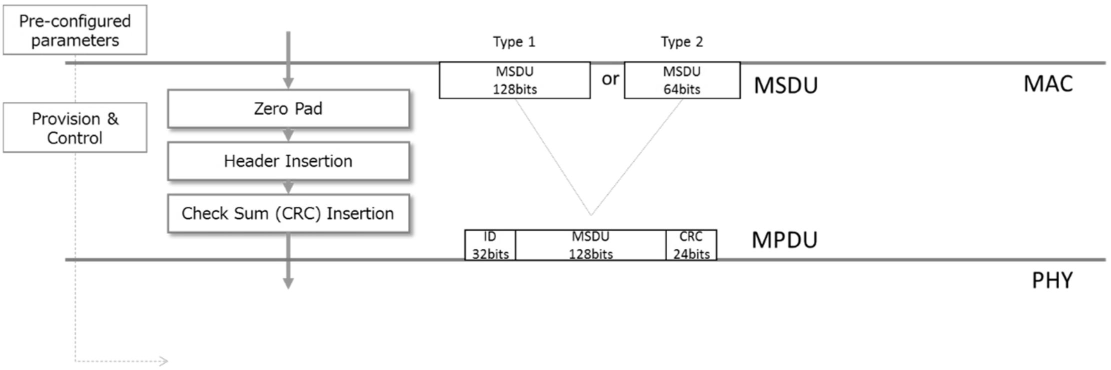

Figure 5-4: MAC Functional Overview

5.2.2 MAC format in UL

MPDU shall be of fixed length of 184-bit and composed as shown in Figure 5-5. MSDU lengths of 128-bit (Type 1) and 64-bit (Type 2) shall be supported.

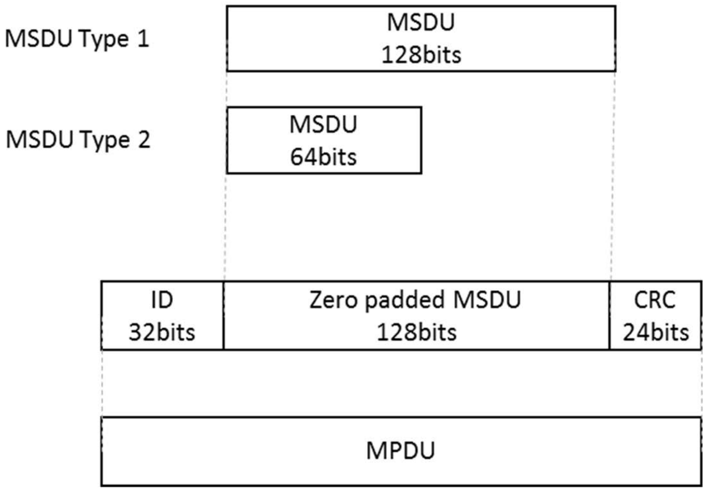

Figure 5-5: MPDU format

5.2.3 MAC function in UL

5.2.3.1 Assembling of MSDU

A 128-bit fixed length MSDU shall be formed from byte aligned MSDU of size less than or equal to 128-bits. If MSDU payload size is less than 128-bits, then it shall be padded with zero (0) to form 128-bit MSDU. The payload size is pre-configured for an EP and known to the BS(s).

5.2.3.2 Assembling of Header Field

A 32-bit header comprising entirely of address field shall be concatenated to the start of zero-padded MSDU payload.

5.2.3.3 Insertion of Check Sum

24-bit CRC shall be generated using following polynomial and initial state set to all one's (0xFFFFFF).

$$p(x) = x[24] + x[23] + x[18] + x[17] + x[14] + x[11] + x[10] + x[7] + x[6] + x[5] + x[4] + x[3] + x[1] + 1$$

The CRC shall be concatenated to the end of zero-padded MSDU payload.

5.2.3.4 Provisioning of PHY Parameter

5.2.3.4.1 PHY Mode

The PHY Mode of operation for an EP shall be set to one of Mode A, B, or C. This is pre-configured for the EP and known to the BS(s).

5.2.3.4.2 Repetitions

The value of $N_{repetition}$ shall be provided and set as below. This value is pre-configured for an EP and known to the BS(s).

$$0 \leq N_{repetition} \leq 31$$

5.2.3.4.3 Encryption Parameters

The parameters for encryption control and operation shall be provided as in Table 5-2. These parameters are pre-configured for an EP and known to the BS(s).

Table 5-2: Encryption Parameters

	Parameter provided to PHY
Type	AES128 or ISO/IEC 29192-2 [4] CLEFIA
Key	128-bit sequence
Pseudo random number	128-bit sequence
Control	MSDU Type, PHY Mode, Encryption_on

5.2.3.4.4 PHY Parameters

Parameters used in pseudo-random code generation for synchronization and scrambling shall be provided. These parameters are pre-configured for an EP and known to the BS(s).

5.2.3.4.5 Operation Band

Operational frequency band(s) for EP UL operation shall be provided. This parameter is preconfigured for an EP and known to the BS(s).

5.2.3.4.6 Channel Access

Parameters used to access channel for EP UL operation shall be provided. These parameters are pre-provisioned for an EP and known to BS(s).

Table 5-3: Channel Access Parameters

Parameter	Value	Description
Access Type (N_{Access})	0-7 (integer)	0: Access Type is duty-cycle (DC) 1-6: Access Type is Listen-before-talk (LBT) and integer value represents number of channel assessment attempts (if channel not found clear) before Abort 7: Reserved
Transmission Type	0-255 (integer)	0: Asynchronous 1: Synchronous Pattern-1 2-255: Reserved

5.2.3.4.7 Transmission Frame

Parameters used to calculate time of transmission for initial and repetition PPDUs as defined in Table 5-4 shall be provided. These parameters are pre-provisioned for an EP and known to BS(s).

Table 5-4: Transmission Frame Parameters

Parameter	Value	Description
Frame Duration ($T_{tx\text{-}frame}$)	0-15 (integer)	0: 5 s (Mode A), 0,3 s (Mode B), 0,2 s (Mode C) 1-15: Reserved
Slot Duration ($T_{tx\text{-}slot}$)	0-15 (integer)	0: 8 ms (Mode A), 10 ms (Mode B), 8 ms (Mode C) 1-15: Reserved
UL Data Slots	0-15 (Integer)	0: 570 (Mode A), 10 (Mode B), 12 (Mode C) 1-15: Reserved
NOTE: Frame parameters vary according to PHY Mode; therefore each parameter value corresponds to three different settings. Only one setting shall apply depending on PHY Mode.		

5.2.4 MAC procedures

5.2.4.1 Overview

As Lfour is an UL-only system, medium access is defined for EP, but not for BS. While MAC processing is the same for each PHY Mode, operational parameters related to time and frequency are dependent on the following pre-provisioned parameters:

- PHY Mode, see clause 5.2.3.4.1
- Operation Band see clause 5.2.3.4.5
- Channel Access see clause 5.2.3.4.6

5.2.4.2 End-point Operation

5.2.4.2.1 Overview

The EP operation for channel access shall apply to initial transmission and repetition of PPDUs and comprises of frequency selection, time selection and channel assessment procedures respectively.

5.2.4.2.2 Repetition Procedure

An EP shall make $N_{repetitions}$ repetitions of a PPDU following its initial transmission, value of which is defined in clause 5.2.3.4.2.

5.2.4.2.3 Frequency Selection Procedure

Upon initiating the transmission of initial PPDU or repetition PPDU, frequency selection shall be performed by EP in two step procedure:

Step 1: Centre frequency

Channel Centre frequency (f_c) shall be determined as follows:

If "Transmission Type" is set to "0", then f_c shall be centre frequency of randomly selected channel from available set of channels in the "Operation Band" as defined in clause 5.2.3.4.5.

If "Transmission Type" is set to "1", then f_c shall be centre frequency of the channel corresponding to initial or repetition PPDU using procedure specified in clause 5.3.4.2.

Step 2: Transmit frequency

PPDU transmit frequency shall be determined as follows:

If PHY Mode as defined in clause 5.2.3.4.1 is Mode A:

- Transmit frequency shall be $f_c - \Delta f_{slowchirp}/2$ and sweep upward toward $f_c + \Delta f_{slowchirp}/2$ across PPDU as per chirp parameters defined in clause 5.3.3.7.3.
- Frequency error shall be less than or equal to ±100 Hz.

If PHY Mode as defined in clause 5.2.3.4.1 is Mode B or Mode C:

- Transmit frequency shall be (f_c) and remain constant over PPDU.
- Frequency error shall be less than or equal to ±100 Hz.

5.2.4.2.4 Transmission Start Time Selection Procedure

The transmission start time t_0 of initial PPDU shall be determined based on pre-configured Channel Access Parameters in Table 5-3.

If "Transmission Type" is set to "0", transmission time t_0 shall be selected at random.

If "Transmission Type" is set to "1", transmission start time selection shall be performed by an EP in two step procedure:

Step 1: Time slot based on "Transmission Frame" parameters defined in clause 5.2.3.4.7.

A time-slot t_{slot} referenced by index GP derived using procedure in clause 5.3.4.2 shall be selected.

Step 2: Transmission start time

Transmission start time t_0 of initial PPDU shall be aligned to the start of t_{slot} with permissible error of ±300 µs.

The transmission start time of a repetition PPDU shall be after a fixed time interval $T_{tx\text{-}frame}$ calculated from the start of previous transmission ($PPDU_0$ or $PPDU_i$, where i = 1, 2, …, $N_{repetition}$-1). The value of $T_{tx\text{-}frame}$ shall be as defined in Table 5-4.

Additionally, an EP shall comply with duty cycle parameters applicable to "Operation Band" defined in clause 5.4.2 if Channel Access Parameter "Access Type" is set to "0".

5.2.4.2.5 Channel Assessment Procedure

Channel assessment procedure shall apply to initial and repetition PPDU if Channel Access Parameter "Access Type" in Table 5-3 is set to a value between 1 and 6. A flow chart depicting steps is shown in Figure 5-6.

Assume counter i = 1:

- Carrier Sense

  Presence of signal shall be assessed over UL channel of operation $BW_{UL\text{-}Ch}$ for duration of at least t_{listen} prior to transmission. Back-off procedure shall be applied if a signal of strength more than $SS_{threshold}$ is detected at the EP receiver antenna input. Otherwise, transmission of PPDU shall be executed.

- Back-off

  If maximum attempts of carrier sense as defined in Table 5-3 has not been reached, then following steps shall be carried out.

  Select new centre frequency $f_c(i) = f_c(i) + \Delta f$ (wrap around if exceeds the upper channel) where
  $\Delta f = 2 \times BW_{UL\text{-}Ch}$.
  Select new transmission time $t(i) = t(i) + t_{back\text{-}off}$
  Increment counter value "i" by 1.

- Abort

  Abort transmission if channel is found busy after "Access Type" attempts at carrier sense.

The values of t_{listen}, $t_{back\text{-}off}$ and $SS_{threshold}$ shall be set so as to comply with regulation as applies to "Operation Band".

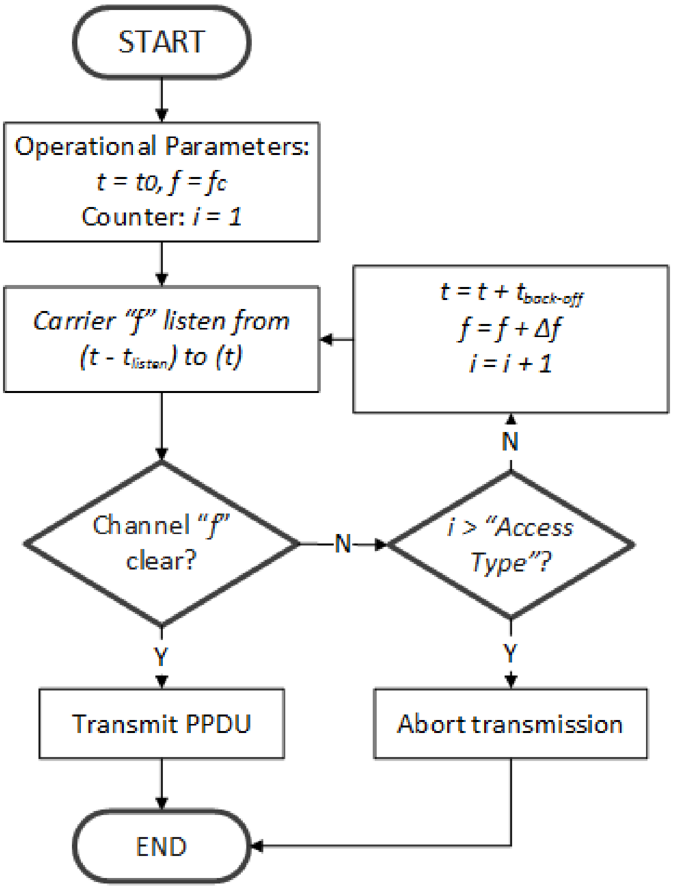

Figure 5-6: LBT procedure

5.3 PHY layer description

5.3.1 Overview

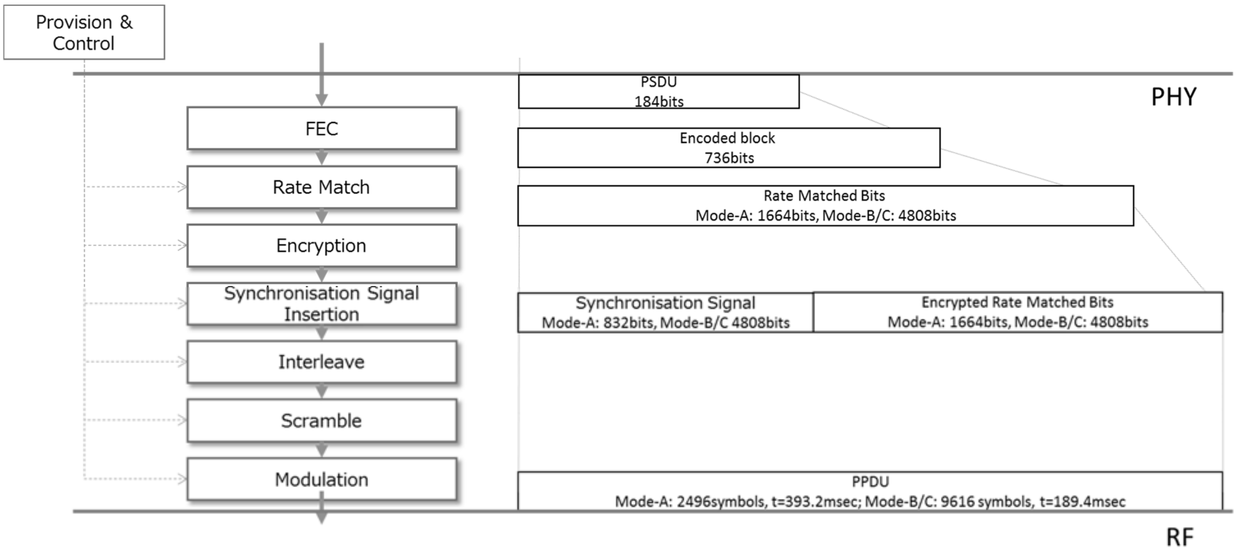

Figure 5-7: PHY Functional Overview

5.3.2 PHY format in UL

A PHY PDU or PPDU shall be of fixed size dependant on PHY Mode defined in clause 5.2.3.4.1 as shown in Table 5-5 and comprises of interleaved synchronization signal and coded payload bits as illustrated in Figure 5-7.

Table 5-5: PPDU Size

PHY Mode	PPDU Size (number of bits)
Mode A	2 496
Mode B	9 616
Mode C	9 616

5.3.3 PHY function in UL

5.3.3.1 Forward Error Correction

All PSDUs shall be coded for forward error correction with LDPC parameters in Table 5-6 as per the description below.

Table 5-6: LDPC Parameters

Code rate	1/4
K_{ldpc}	184
N_{ldpc}	736
M_{ldpc}	552

LDPC code with rate R=1/4 shall be applied to form Coded Block size of $L_{codedblock}$=4 × $L_{codeblock}$ where $L_{codeblock}$= SizeMPDU, i.e. 184-bit.

Input: 184 bits (128 + 32 + 24), denoted as $i_0, i_1, \dots, i_{K_{ldpc}-1}$ with K_{ldpc} = 184
Output: 736 code bits, denoted as $\lambda_0, \lambda_1, \dots, \lambda_{N_{ldpc}-1} = i_0, i_1, \dots, i_{K_{ldpc}-1}, p_0, p_1, p_2, \dots, p_{M_{ldpc}-1}$, with N_{ldpc} = 736 and M_{ldpc} = 552

A systematic binary LDPC code with quasi-cyclic structure (information part) and dual staircase (parity part) shall be used, i.e. parities shall be accumulated (see below). Encoding shall be performed as follows:

- First:
  K_{ldpc} = 184 parities shall equal information bits: $\lambda_k = i_k,\ for\ k = 0,1,\dots,K_{ldpc} - 1$
- Initialize:
  $p_0 = p_1 = p_2 = \cdots = p_{M_{ldpc}-1} = 0$
- Accumulate the first information bit, i_0, at parity bit addresses specified in the first row of Table 5-7. For example, (all additions are in GF(2)):

  $p_1 = p_1 \oplus i_0 \qquad p_7 = p_7 \oplus i_0$

  $p_{90} = p_{90} \oplus i_0 \qquad p_{172} = p_{172} \oplus i_0$

  $p_{209} = p_{209} \oplus i_0 \qquad p_{359} = p_{359} \oplus i_0$

  $p_{401} = p_{401} \oplus i_0 \qquad p_{420} = p_{420} \oplus i_0$

  $p_{483} = p_{483} \oplus i_0 \qquad p_{487} = p_{487} \oplus i_0$
- For the next 7 information bits, i_m, m =1, 2, ..., 7, accumulate i_m at parity bit addresses [x + (m mod 8)×Q_{ldpc}] mod M_{ldpc}, where x denotes the address of the parity bit accumulator corresponding to the first bit i_0, and Q_{ldpc} = 69. So for example for information bit i_1, the following operations are performed:

  $p_{70} = p_{70} \oplus i_1 \qquad p_{76} = p_{76} \oplus i_1$

$p_{159} = p_{159} \oplus i_1$ $\quad p_{241} = p_{241} \oplus i_1$

$p_{278} = p_{278} \oplus i_1$ $\quad p_{428} = p_{428} \oplus i_1$

$p_{470} = p_{470} \oplus i_1$ $\quad p_{489} = p_{489} \oplus i_1$

$p_0 = p_0 \oplus i_1$ $\quad p_4 = p_4 \oplus i_1$

- For the 9th information bit i_8, the addresses of the parity bit accumulators are given in the second row of Table 5-7. In a similar manner the addresses of the parity bit accumulators for the following 7 information bits i_m, m = 9, 10, ..., 15 are obtained using the formula [x + (m mod 8)×Q_{ldpc}] mod M_{ldpc}, where x denotes the address of the parity bit accumulator corresponding to the information bit i_8, i.e. the entries in the second row of Table 5-7.
- In a similar manner, for every group of 8 new information bits, a new row from the Table 5-7 is used to find the addresses of the parity bit accumulators.

After all of the information bits are exhausted, the final parity bits shall be obtained by accumulation as follows:

- Sequentially perform the following operations starting with i = 1:

  $p_i = p_i \oplus p_{i-1}$ $for\ i = 1, 2, ...,$ M_{ldpc} -1

- Final content of p_i , i = 0, 1,.., M_{ldpc} -1 is equal to the parity bit p_i.

Table 5-7: Parity bit addresses for LDPC code

Row and col index	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1	7	90	172	209	359	401	420	483	487
2	57	164	192	197	284	307	174	356	408	425
3	22	50	191	379	385	396	427	445	480	543
4	32	49	71	234	255	286	297	312	537	550
5	30	70	88	111	176	201	283	322	419	499
6	86	94	177	193	266	368	373	389	475	529
7	134	223	242	254	285	319	403	496	503	534
8	18	84	106	165	170	199	321	355	386	410
9	129	158	226	269	288	316	397	413	444	549
10	33	113	133	194	256	305	318	380	507	
11	317	354	402							
12	53	64	374							
13	83	314	378							
14	162	259	280							
15	166	281	486							
16	185	439	489							
17	119	156	224							
18	26	62	244							
19	8	246	482							
20	15	72	91							
21	43	69	390							
22	127	186	506							
23	55	81	412							

5.3.3.2 Rate Matching

The output from FEC, coded block of size $L_{codedblock}$, shall follow the Rate matching procedure based on parameters defined in Table 5-8 and as per steps illustrated in Figure 5-8 and described below.

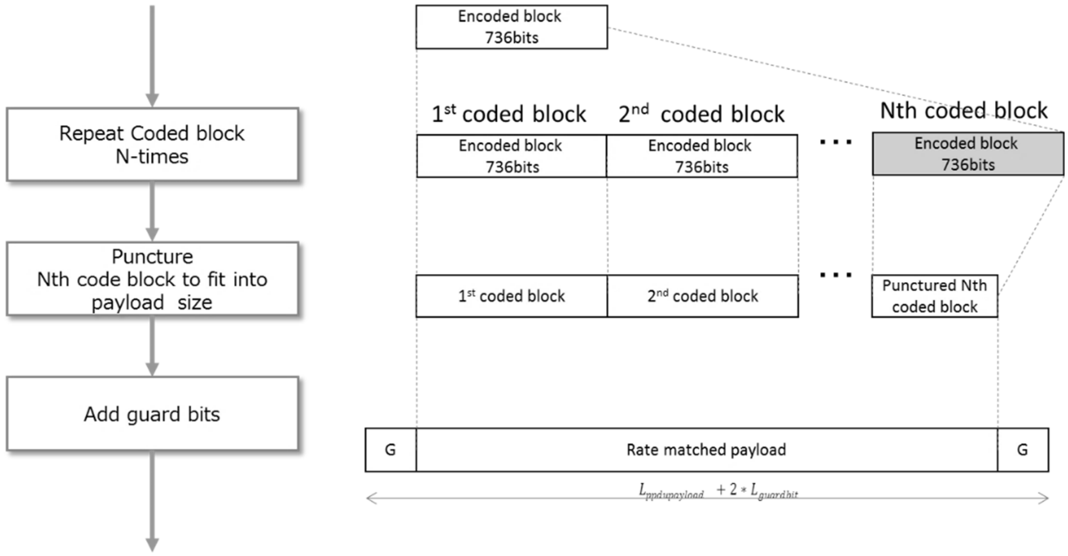

Figure 5-8: Rate match procedure

Table 5-8: Rate match parameters

Size (bits)	Mode A	Mode B	Mode C
$L_{codedblock}$	736		
$L_{ppdupayload}$	1 656	4 800	
$N_{ratematch}$	3	7	
$L_{guardbit}$	4		

Output from FEC shall be repeated $N_{ratematch}$ times, where:

$$N_{ratematch} = Ceil(\frac{L_{ppdupayload}}{L_{codedblock}})$$

Excessive bits shall be removed to match PPDU payload size $L_{ppdupayload}$ by applying puncturing to Nth coded block as described below.

For PHY Mode A, puncturing shall be performed such that only every 4th bit of coded block remains. This is depicted in Figure 5-9.

For PHY Mode B and PHY Mode C, puncturing shall be performed in steps:

- Remove 1st 184 bits from coded block N
- Partition remaining block into 24 sub-blocks of length 23 bits each
- Apply puncturing such that only 16 out of 23 bit remains from each sub-block

This is depicted in Figure 5-10.

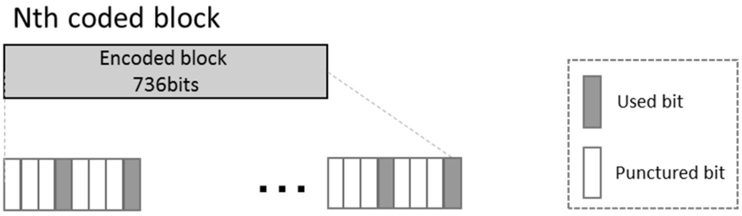

Figure 5-9: Puncturing for PHY Mode A

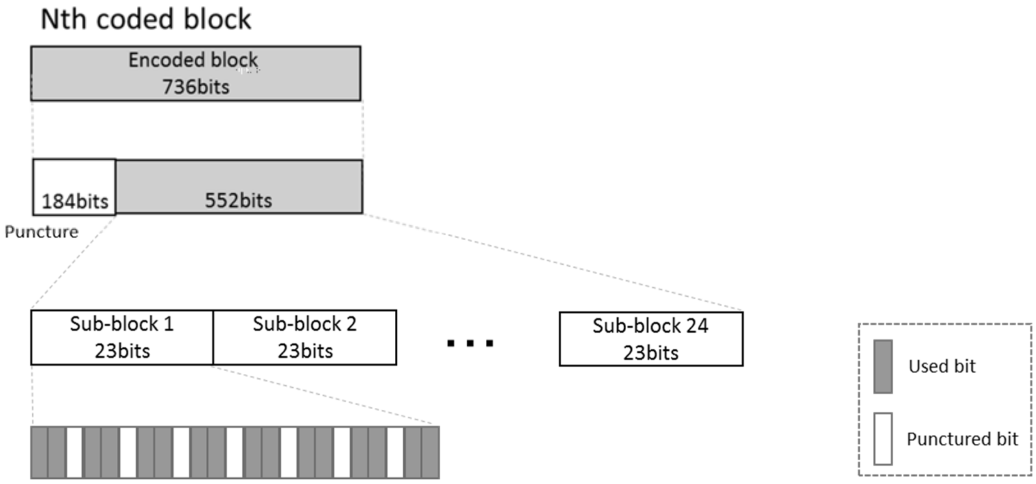

Figure 5-10: Puncturing for PHY Mode B and C

The last step of rate matching procedure concatenates header and trailer guard bit filed with length $L_{guardbit}$ as defined in Table 5-8. The content of guard bit shall be set to all zeros (0b0).

$L_{guardbit} \equiv Number\ of\ guard\ bits\ to\ be\ concatenated.$

5.3.3.3 Encryption

Encryption code generated from 128-bit key shall be applied to PPDU payload. Encryption is based on AES128 or ISO/IEC 29192-2 [4] CLEFIA set through Encryption parameters described in clause 5.2.3.4.3 and operates under counter mode. Encryption scheme is shown in Figure 5-11. A 128-bit Pseudo random number, 128-bit key, and parameters needed for control shall be provided by MAC layer as described in clauses 5.2.3.4.3 and 5.2.3.4.4.

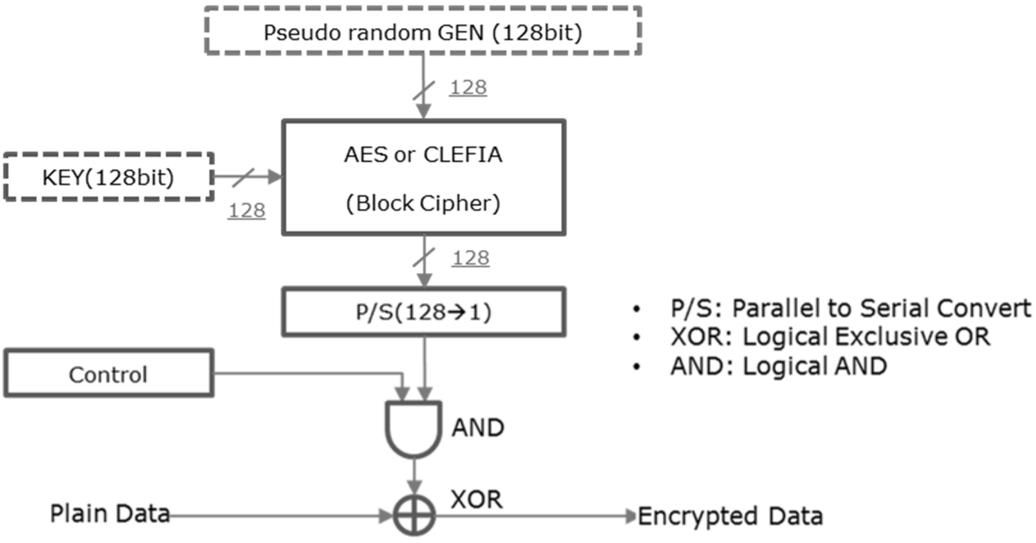

Figure 5-11: AES and CLEFIA encryption

Sequence of control signal shall be generated according to PHY Mode (A, B, or C) and MSDU Type (1 or 2) as illustrated in Figure 5-12 and Figure 5-13.

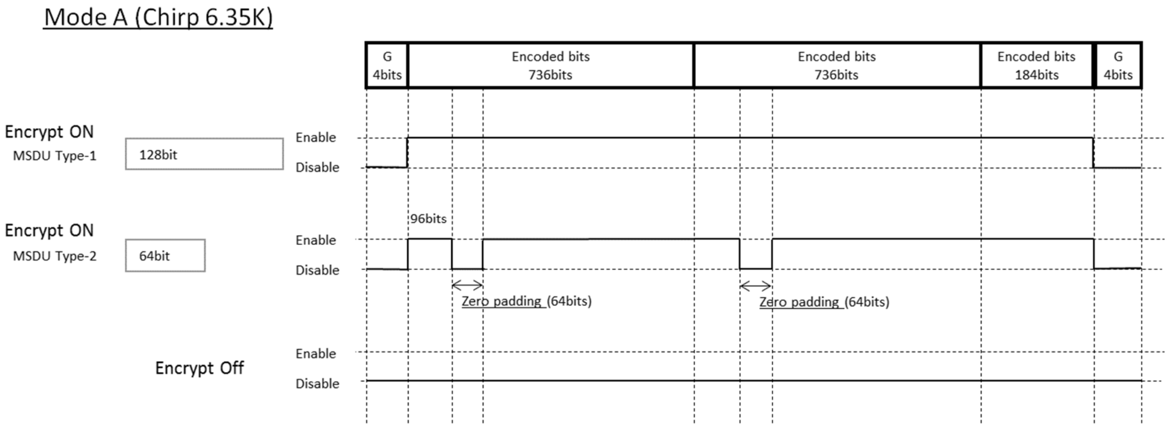

Figure 5-12: Output of control signal for PHY Mode A

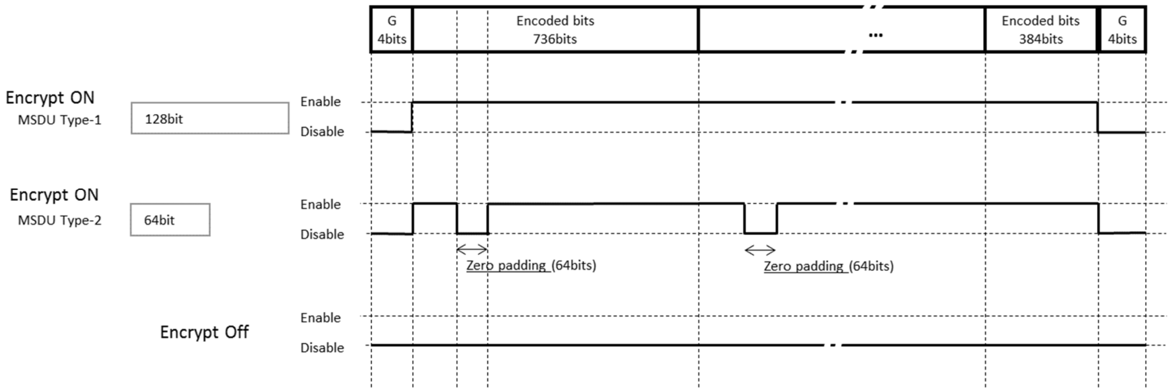

Figure 5-13: Output of control signal for PHY Mode B and C

5.3.3.4 Synchronization Signal Insertion

The rate matched PPDU payload including the guard bits shall be concatenated with a synchronization signal of length L_{sync} where:

$$L_{sync} = 832 \text{ bits (Mode A) and } 4\,808 \text{ bits (Mode B and C)}$$

Synchronization signal shall be a truncated gold code with polynomials as follows:

$$\text{M-Sequence 1: } p1(x) = x[25] + x[3] + 1$$

$$\text{M-Sequence 2: } p2(x) = x[25] + x[3] + x[2] + x[1] + 1$$

This is shown in Figure 5-14.

Initial state of generator polynomials shall be set to a value as per clause 5.2.3.4.4. The states of polynomials shall be initialized to the value of PPDU.

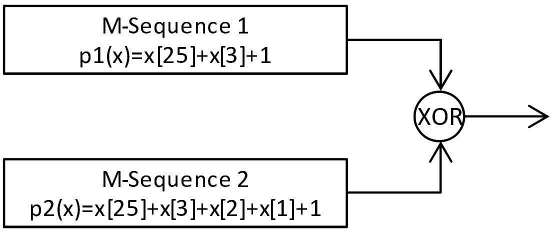

Figure 5-14: Synchronization Signal Generator

5.3.3.5 Interleaving

5.3.3.5.1 Mode A Interleaver

The input to interleaver comprises of:

- 832 synchronization signal bits denoted by b_{s0}, $b_{s1} \ldots b_{s831}$
- 8 guard bits denoted by b_{g0}, $b_{g1} \ldots b_{g7}$
- 1 656 encoded bits denoted by b_{e0}, $b_{e1} \ldots b_{e1655}$

The interleaver shall follow below procedure:

- First two synchronization signal bits are each followed by two guard bits in order, i.e. $b_{s0}\ b_{g0}\ b_{g1}\ b_{s1}\ b_{g2}\ b_{g3}$
- The next 828 synchronization signal bits are each followed by two encoded bits in order, i.e. $b_{s2}\ b_{e0}\ b_{e1}\ b_{s3}\ b_{e2}\ b_{e3} \ldots.\ b_{s828}\ b_{e1652}\ b_{e1653}\ b_{s829}\ b_{e1654}\ b_{e1655}$
- The last two synchronization signal bits are each followed by two guard bits in order, i.e. $b_{s830}\ b_{g4}\ b_{g5}\ b_{s831}\ b_{g6}\ b_{g7}$

The resultant interleaving pattern is illustrated in Figure 5-15.

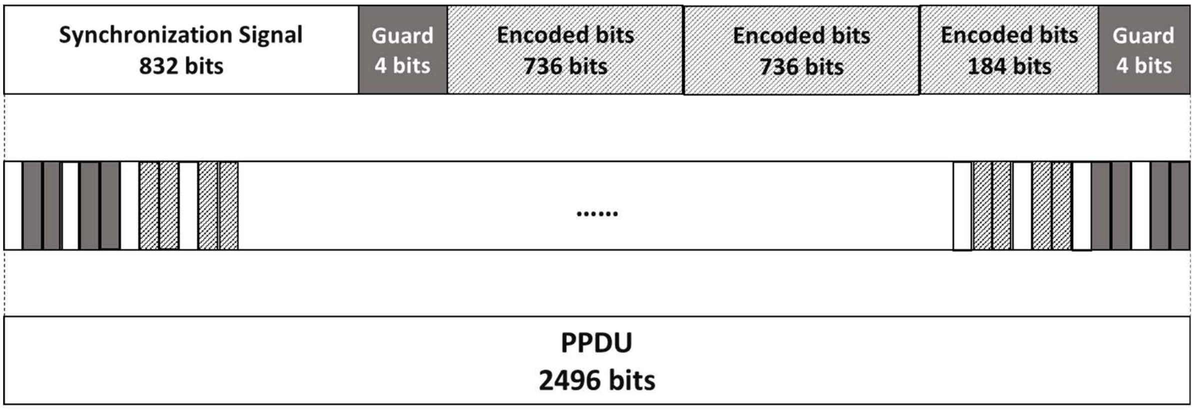

Figure 5-15: Interleave pattern, Mode A

5.3.3.5.2 Mode B and C Interleaver

The input to interleaver comprises of:

- 4 808 synchronization signal bits denoted by b_{s0}, $b_{s1} \ldots b_{s4807}$
- 8 guard bits denoted by b_{g0}, $b_{g1} \ldots b_{g7}$
- 4 800 encoded bits denoted by b_{e0}, $b_{e1} \ldots b_{e4799}$

The interleaver shall follow below procedure:

- First four synchronization signal bits are each followed by one guard bit in order, i.e. $b_{s0}\ b_{g0}\ b_{s1}\ b_{g1} \ldots b_{s3}\ b_{g3}$
- The next 4 800 synchronization signal bits are each followed by one encoded bit in order, i.e. $b_{s4}\ b_{e0}\ b_{s5}\ b_{e1} \ldots.\ b_{s4803}\ b_{e4799}$
- The last four synchronization signal bits are each followed by one guard bit in order, i.e. $b_{s4804}\ b_{g4}\ b_{s4805}\ b_{g5} \ldots b_{s4807}\ b_{g7}$

The resultant interleaving pattern is illustrated in Figure 5-16.

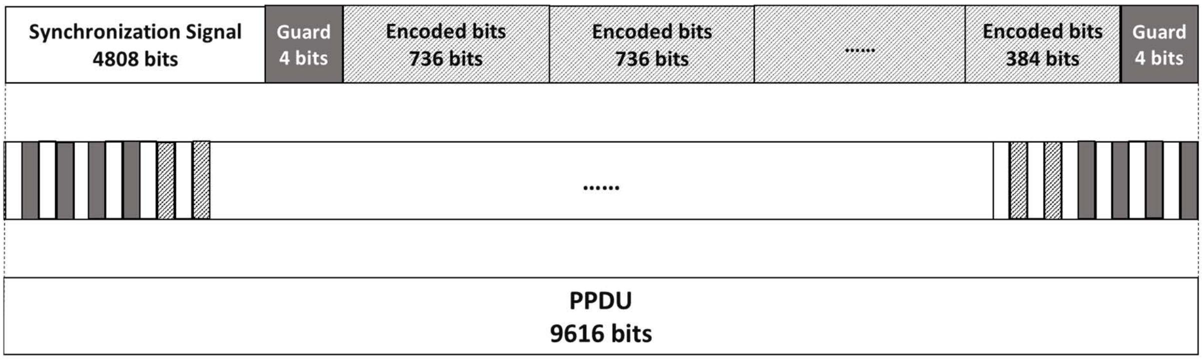

Figure 5-16: Interleave pattern, Mode B and Mode C

5.3.3.6 Scrambling

Scrambling shall be applied over PPDU with M-sequence generator shown as below and illustrated in Figure 5-17.

$$x[24]+x[23]+x[18]+x[17]+x[14]+x[11]+x[10]+x[7]+x[6]+x[5]+x[4]+x[3]+x+1$$

Initial state of generator polynomial shall be set to a value as per clause 5.2.3.4.4. The state of polynomial shall be initialized to value of PPDU.

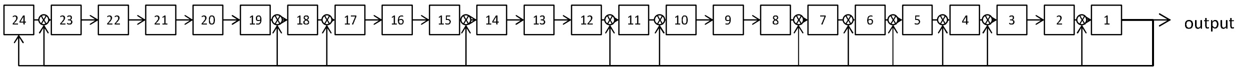

Figure 5-17: Scramble code generator

5.3.3.7 Modulation

5.3.3.7.1 Introduction

Modulation procedure shall comprise of primary and secondary modulation stages and applied according to PHY Mode defined in clause 5.2.3.4.1.

5.3.3.7.2 Primary Modulation

π/2-shift BPSK modulation shall be applied to scrambled PPDU, as shown in Figure 5-18, and based on bit mapping and phase assignment according to Table 5-9 and Table 5-10.

The modulated PPDU thus generated is ready for transmission on air for PHY Modes B and C.

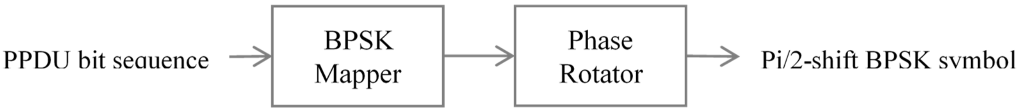

Figure 5-18: Primary Modulation

Table 5-9: BPSK Mapper

Bit	Modulated Symbol, (I, Q)
0	(-1, 0)
1	(+1, 0)

Table 5-10: Phase Rotator

b[n], Mod(n,4)	Radian
0	+π × (0/2)
1	+π × (1/2)
2	+π × (2/2)
3	+π × (3/2)

5.3.3.7.3 Secondary Modulation

If PHY Mode is set to Mode A in clause 5.2.3.4.1, then secondary modulation shall be applied to primary modulated PPDU.

Secondary modulation shall be a linear chirp sequence derived from chirp rate β = 387,430 kHz/s and applied over π/2-shift BPSK modulated signal.

The resultant sweep frequency is defined as:

$$\Delta f_{slowchirp} = \beta \times T_{PPDU}$$

The value of T_{PPDU} is defined in Table 5-1.

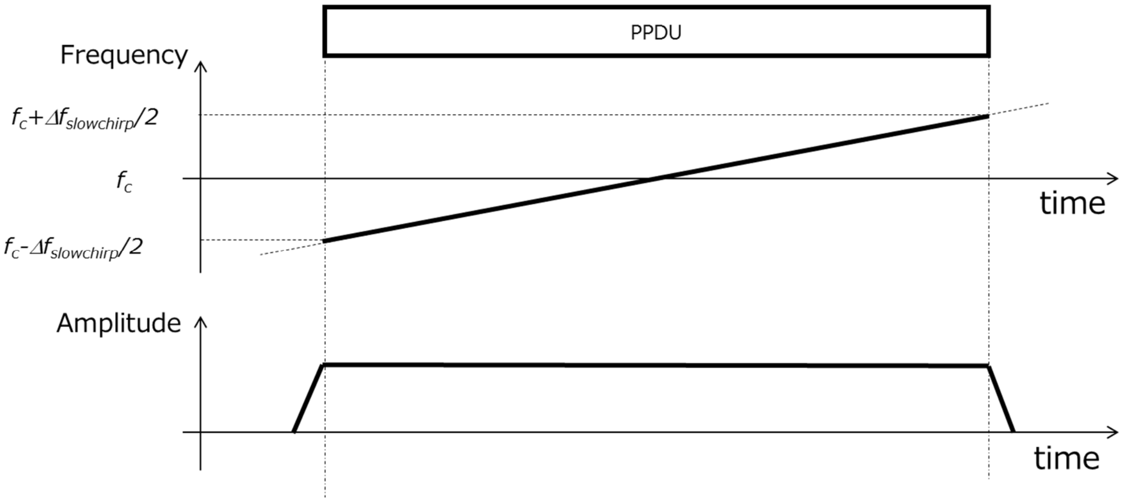

Figure 5-19: Chirp Modulation

5.3.4 PHY Procedures

5.3.4.1 Overview

The UL physical layer uses randomization in time and frequency for PPDU transmissions to achieve high system capacity. Channel Access parameters defined in clause 5.2.3.4.6 determines if transmission is asynchronous or synchronous. While time synchronization may be achieved using various methods, "Synchronous Pattern-1" relies on GPS time. "Transmission Type" parameter in Table 5-4 has reserved values to allow other synchronous patterns and methods in future.

5.3.4.2 Synchronous Pattern-1

5.3.4.2.1 Frame structure

If "Transmission Type" in Table 5-3 is set to "1", then transmission of PPDUs shall be carried out by EPs in a synchronous manner according to procedure specified in this clause.

In time domain, a frame structure is employed as per parameters "Frame Duration" and "Slot Duration" in Table 5-4. A resultant frame with a grid structure is illustrated in Figure 5-20 for Mode A. For example, a 5 s frame with 8 ms slot duration leads to 625 slots. Each such slot is indexed using parameter called Grid Position (GP). All or some of the slots within frame may be used for UL data transmission. This is determined by parameter "UL Data Slots" in Table 5-4.

Similar frame structure is employed for Modes B and C using parameters in Table 5-4.

The start of a PPDU transmission shall be aligned to start of one of the available data slots which is selected together with a transmit frequency according to hopping procedure specified in clause 5.3.4.2.2.

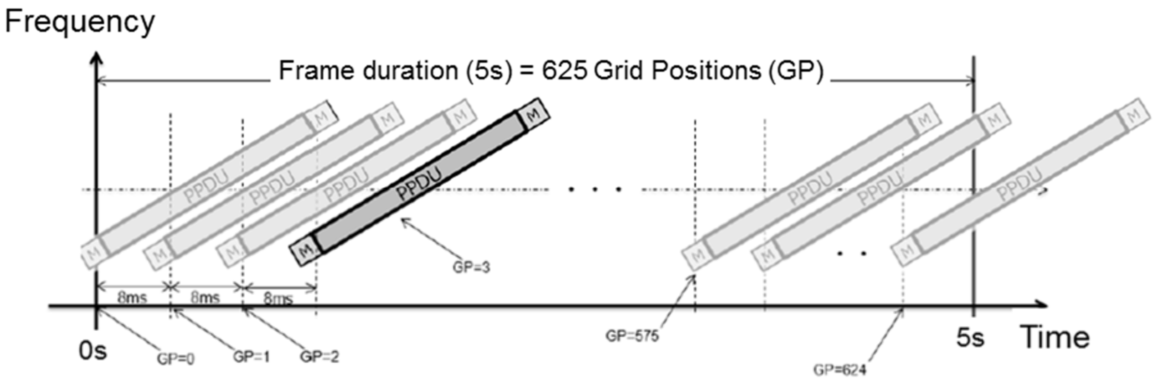

Figure 5-20: Lfour Transmission Frame Example - Mode A

5.3.4.2.2 Time and frequency hopping

Lfour enabled EPs shall perform frequency hopping for initial and repetition PPDUs and time-slot hopping within defined frame for initial PPDU as a function of following parameters:

- FH_RNG denotes available number of channels in the "Operation Band" as defined in clause 5.2.3.4.5.
- GP_RNG denotes available number of grid positions indicated by parameter "UL Data Slots" in Table 5-4.
- TXID denotes 32-bit address used as MAC header as defined in clause 5.2.3.2.
- GPSTIME denotes 32-bit GPS time of transmission composed of 12-bit MSBs of GPS weeks (GPSW) followed by 20-bit LSBs of GPS week-seconds (GPSWS).

  Where:

  - GPSW = floor(AccumulatedSeconds / 60 × 60 × 24 × 7);
  - GPSWS = modulo(AccumulatedSeconds, 60 × 60 × 24 × 7); and
  - AccumulatedSeconds is duration in seconds since date 1980/1/6 00:00:00.

The frequency channel index (CH) and GP shall be determined for initial and repetition PPDUs using following steps:

- Calculate size of pseudo-random seed PRN_BW as:

$$\text{PRN\_BW} = \text{ceil}(\log_2(\text{MPATH}))$$

Where:

$\text{MPATH} = \text{GP\_RNG} \times (\text{FH\_RNG} \wedge (N_{\text{repetitions}}+1))$

- Calculate scaling factor α as:

  α = ceil((MPATH/ (POWER2 - 1)) × 64) / 64

Where:

POWER2 = 2 ^ (PRN_BW)

- Calculate seed MSEED_{raw} of size "PRN_BW" bits using procedure specified in clause 5.3.4.2.3.
- Derive candidate MSEED_{cand} as follows:

  $\mathrm{MSEED}_{cand} = \mathrm{floor}(\mathrm{MSEED}_{raw} \times \alpha)$

- If MSEED_{cand}<MPATH, then MSEED = MSEED_{cand}; else, repeat process to derive MSEED_{cand} from regenerated MSEED_{raw} until MSEED_{cand}<MPATH or up to four attempts, whichever condition is satisfied first.
- If MSEED_{cand}<MPATH, then MSEED = MSEED_{cand}; else MSEED = MSEED_{cand}/2.
- Derive GP using divmod moderator as follows:

  Divmod(MSEED, GP_RNG) = {GP, QUO[0]}

  The GP shall be used for transmission start time of initial PPDU and repeated PPDUs.

- Derive CH_0, $\mathrm{CH}_1 \ldots \mathrm{CH}_n$ where $n = N_{repetitions}$ using divmod operator iteratively as follows:

  Divmod(QUO[0], FH_RNG) = {CH_0, QUO[1]},

  Divmod(QUO[1], FH_RNG) = {CH_1, QUO[2]} and so on up to

  Divmod(QUO[n], FH_RNG) = {CH_n, QUO[1]}

  The CH_0 shall be used for transmission frequency of initial PPDU and $\mathrm{CH}_1 \ldots \mathrm{CH}_n$ for that of repeated PPDUs respectively.

This process is illustrated in Figure 5-21.

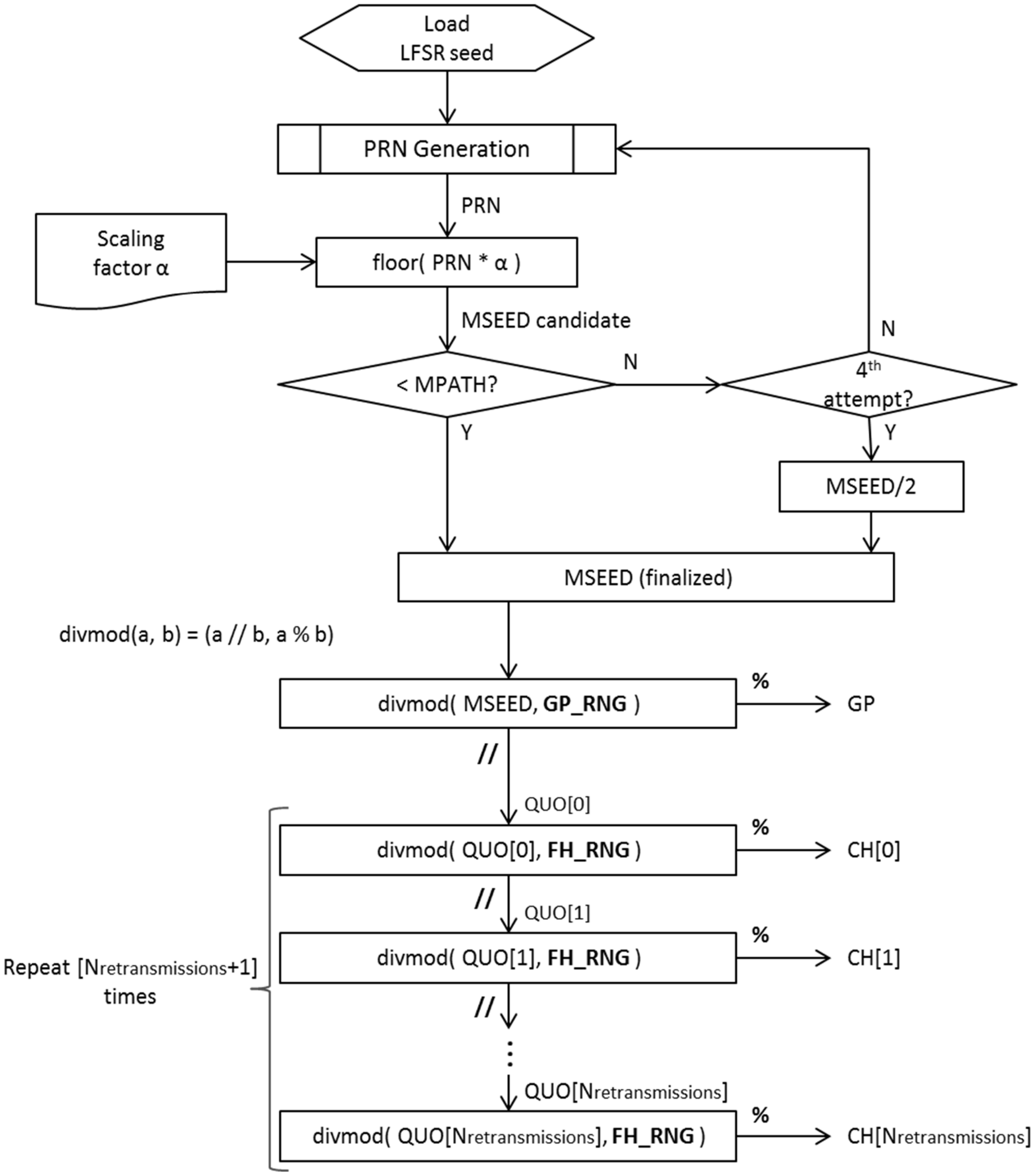

Figure 5-21: Determination of time-slot and frequency channel for transmission

5.3.4.2.3 Pseudo-random seed generation

A PRN generator comprises of two LFSRs, LFSR1 and LFSR2 respectively, where:

LFSR1 uses 32-bit shift register initialized to polynomial TXID as defined in clause 5.3.4.2.2 and with polynomial P(x) in its feedback path:

$$P(x) = x[32] + x[7] + x[5] + x[3] + x[2] + x[1] + 1$$

LFSR2 uses 32-bit shift register initialized to polynomial GPSTIME as defined in clause 5.3.4.2.2 and with polynomial Q(x) in its feedback path:

$$Q(x) = x[32] + x[30] + x[17] + x[12] + x[3] + x[1] + 1$$

A bit-wise XOR is performed on outputs of LFSR1 and LFSR2 to generate unique PRN seeds denoted by "$\text{MSEED}_{\text{raw}}$" of size "PRN_BW" iteratively.

This process is illustrated in Figure 5-22.

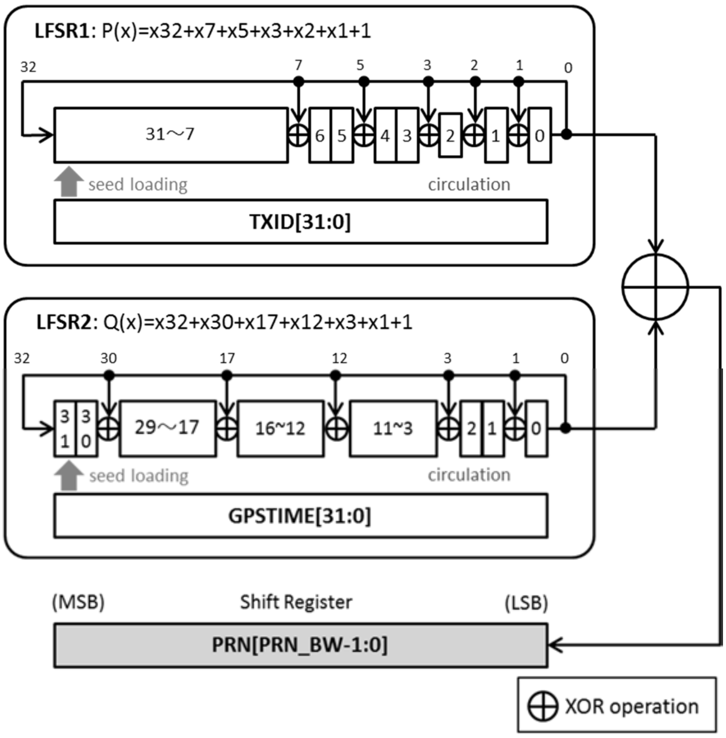

Figure 5-22: PRN Generator for Synchronous Pattern-1

5.4 Radio characteristics

5.4.1 Overview

Lfour enabled EP shall be configured to comply with the regional harmonized or global regulations applicable to spectrum of use. An EP may be configured to operate in more than one, i.e. non-contiguous frequency bands.

5.4.2 Band-plan

Lfour UL operation requires frequency spectrum of at least 200 kHz for Access Type "0" and at least 600 kHz for Access Type values "1..6", where Access Type refers to parameter defined in clause 5.2.3.4.6.

If total bandwidth of Operation Band(s) defined in clause 5.2.3.4.5 is more than 200 kHz, then the band(s) are split evenly in channels of 200 kHz each and frequency of operation f_c, shall be defined at centre frequency of each channel. A channel of operation is denoted by $BW_{UL\text{-}Ch}$. This channelization shall apply to all PHY modes.

6 Telegram splitting ultra narrow band (TS-UNB) family

6.1 Overview

6.1.1 General description

The TS-UNB family is a low power wide area network with star topology based on an UNB approach using Telegram Splitting Multiple Access (TSMA). TSMA is a random channel access method wherein the radio transmission of a packet is divided into several short radio-bursts, which are sent discontiguous over the radio channel with transmission-free time intervals in between. The radio-bursts are pseudo-randomly distributed over time and frequency within a radio frame. This method offers high interference resilience against radio transmissions of other radio devices, either from own or foreign radio systems, since only a part of the radio-bursts need to be received by the base station to decode the transmitted payload.

Randomness is achieved by crystal reference tolerance, additional message dependant frequency offset and random channel access in time due to the asynchronous mode of system operation. The start of communication is initiated by the end-point at any time transmission data is available. No network synchronization is needed. The protocol supports Class Z (uplink only) and Class A (bidirectional) end-points. The downlink communication is triggered by an uplink transmission. After the reception of an uplink transmission, the base station may send a downlink transmission after a defined period of time.

To further keep transmission duration short, especially for battery or energy harvesting operated end-points, channel coding together with coherent MSK or GMSK demodulation is used to increase the sensitivity in the receiver to a level of -139 dBm without narrowing the signal bandwidth too much. Hence for the transmission of application data with a size of 10 bytes, the accumulated on air radio transmission time is less than 400 ms. Therefore TS-UNB offers ultra-low power consumption down to 10 µWh per message in the end-point and can be operated also in a low-duty cycle band (DC=0,1 %). Due to the ultra-narrowband and short-time transmission as well as the high interference resilience TS-UNB can reliably handle a network capacity of more than one million messages per day and per base station within a 200 kHz spectrum.

The TS-UNB family is capable of handling variable application data with a length of up to 245 bytes in uplink and up to 250 bytes in downlink. The protocol is optimized for an application data length of 10 bytes, which builds the core frame of the TS-UNB protocol. Data is encrypted with AES128. For authentication and integrity check a 32 Bit Cipher-based Message Authentication Code (CMAC) is added to the MAC Protocol Data Unit. A 24 bit packet counter is used for replay protection. An optional variable MAC mode can be used for user specific MAC functionalities.

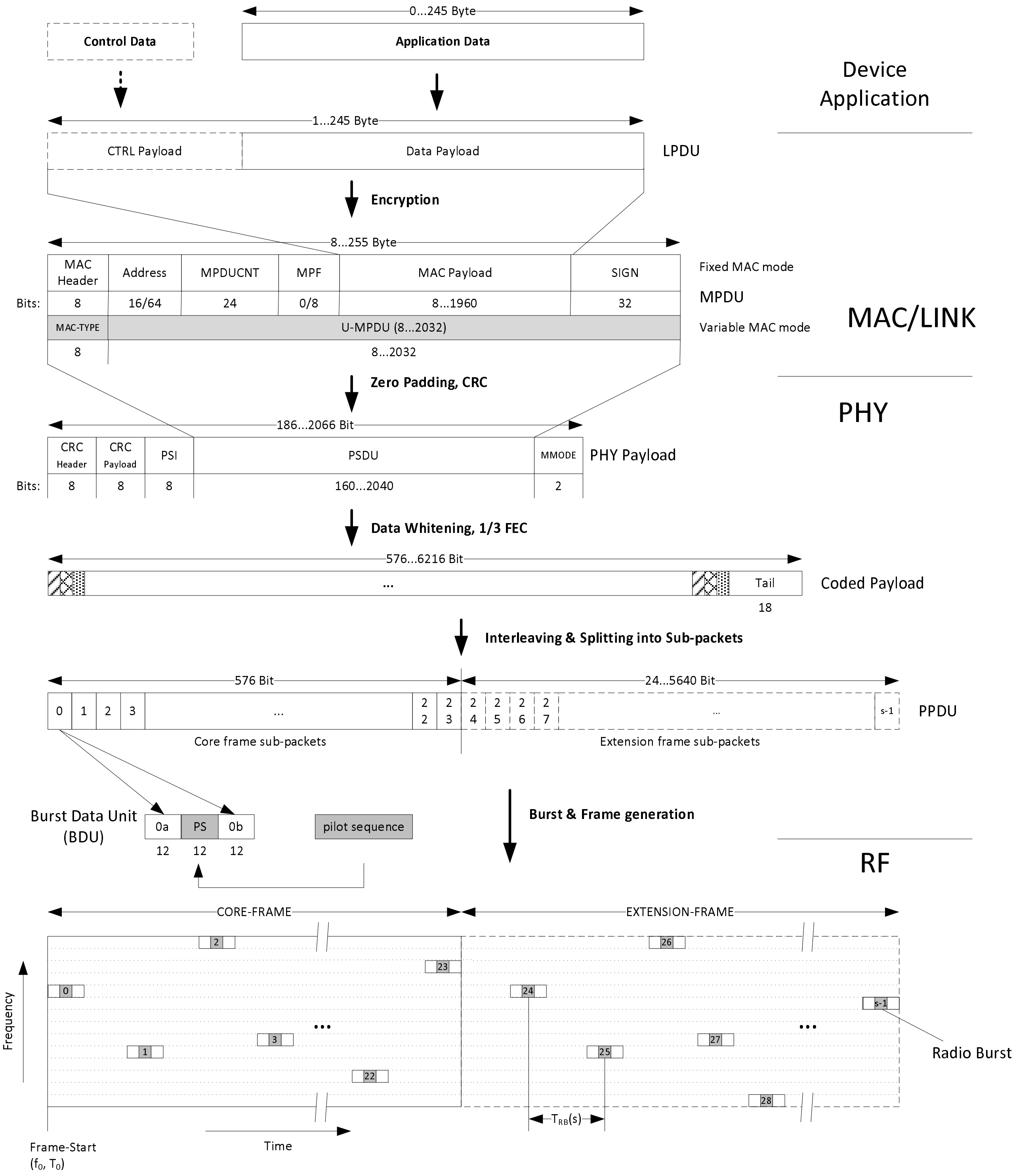

Figure 6-1: Overview Uplink Formats

Figure 6-1 gives an overview of uplink formats and functions.

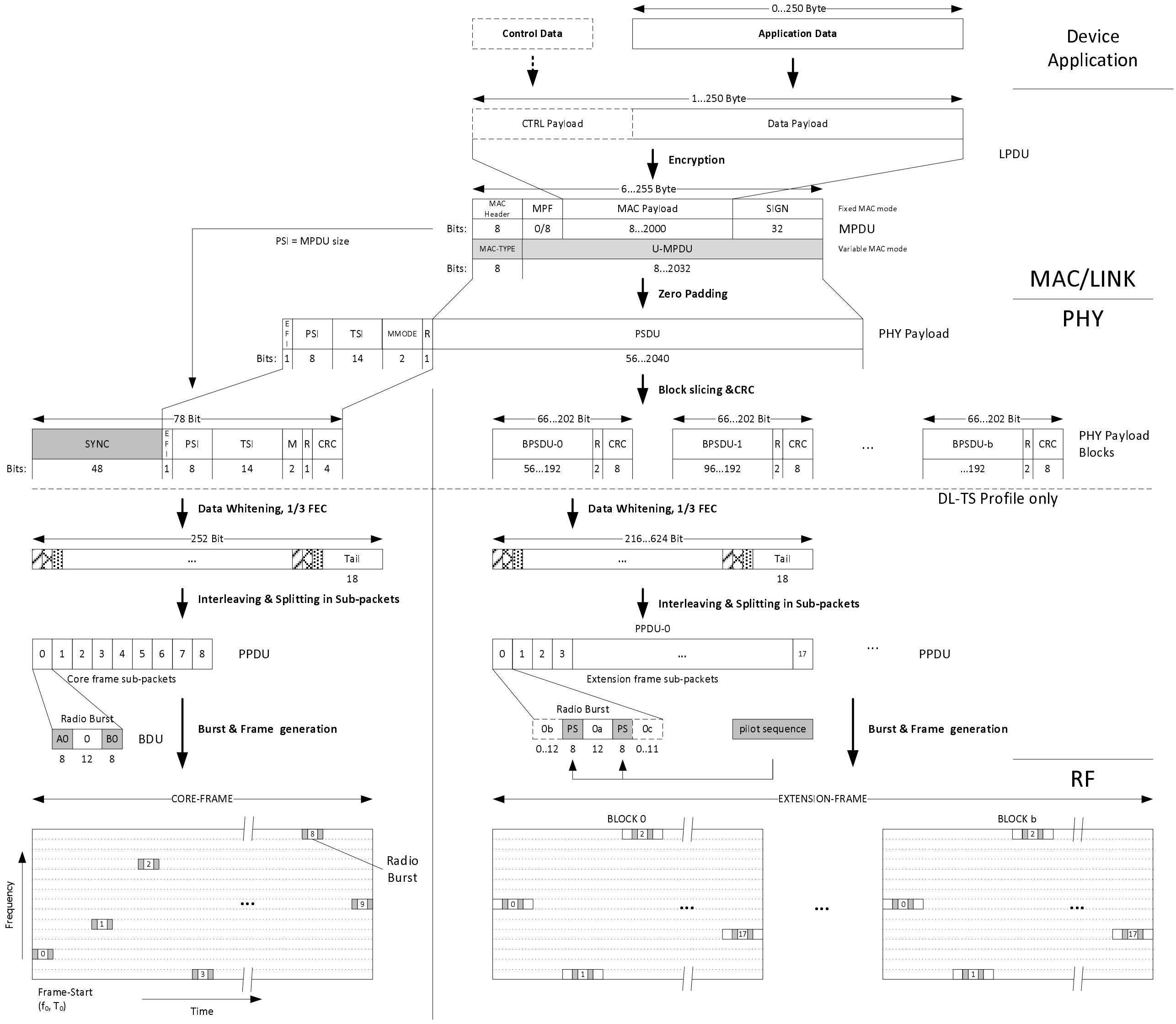

Figure 6-2: Overview Downlink Formats

Figure 6-2 gives an overview of the DL-TS and DL-SB formats and functions.

6.1.2 Modes of operation

The TS-UNB protocol offers several modes of operation in up- and downlink. If a LTN System is using TS-UNB protocol, it shall implement one subset of the different modes of operation according to Table 6-1. Some recommended sets of modes called profiles can be found in the annex A. The input data at the end-point for uplink communication according to the TS-UNB protocol (see clause 6.3.2) shall be the application data from a device application (e.g. sensor data sensed or generated by a sensor of the end-point). A LTN System using TS-UNB protocol shall support uplink only communication (class Z devices) and may optionally also support bidirectional communication with uplink triggered downlink (class A devices). In uplink a LTN system using TS-UNB protocol shall support UL-ULP symbol rate and may optionally also support UL-ER symbol rate. In downlink either telegram splitting (DL-TS mode) or single burst transmission (DL-SB mode) may be used. No support of relay points is foreseen in the TS-UNB protocol.

Table 6-1: TS-UNB Modes of operation

	Uplink	Downlink	
MAC Mode	Fixed MAC Variable MAC (e.g. MAC-TYPE=WMBUS)		
PHY Mode	Telegram Splitting (TS)		Single Burst
Modulation	(G)MSK	(G)MSK	GFSK
Symbolrate	ULP: 2 380,371 Sym/s (MCL: 153 dB) ER: 396,729 Sym/s (MCL: 164 dB)	DL-TS-ULP: 2 380,371 Sym/s (MCL: 161 dB)	DL-SB: 600 Sym/s (MCL: 152 dB)
TSMA Mode	Narrow (Carrier spacing: 396,729 Hz) Standard (Carrier spacing: 2 380,371 Hz) Wide (Carrier spacing: 28 564,453 Hz)		None
Sync Burst	on/off		off
Retransmission	on/off		off
Channels	Single Channel Dual Channel		
NOTE 1: Uplink MCL based on transmit power of P_{TX} = 14 dBm and Noise figure of 4 dB. NOTE 2: Downlink MCL based on transmit power of P_{TX} = 27 dBm and Noise figure of 8 dB.			

6.2 Link Layer

6.2.1 Link Layer Overview

The Link Layer shall handle control procedures required to establish and maintain a connection between an end-point and a base station. The Link Layer definition shall be applied to the fixed MAC mode and can also be applied to the variable MAC mode of the present document.

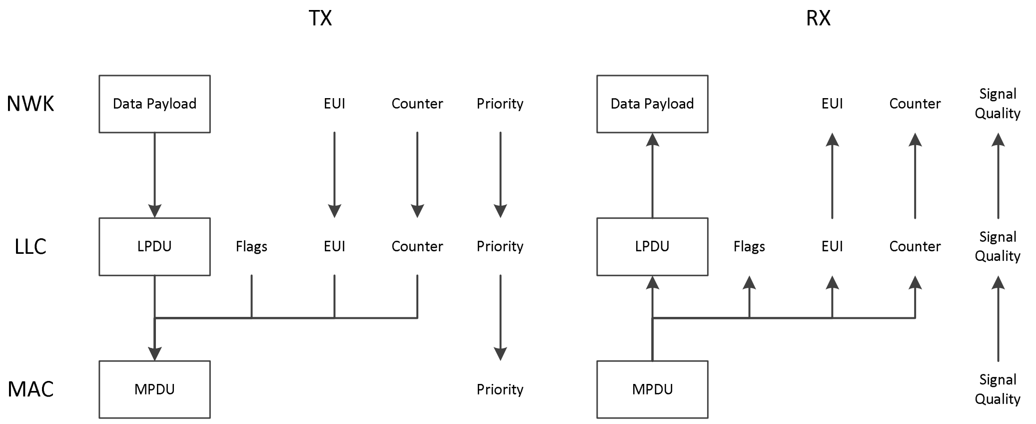

Figure 6-3: Link Layer interfaces with adjacent layers on the Base Station

6.2.2 Link Layer Format

6.2.2.1 Link Layer Protocol Data Unit (LPDU)

Table 6-2: Link Layer Protocol Data Unit (LPDU) Format

Bytes: 1	1	Variable		1	Variable	Variable (0 to 245)
Control Length	Control Segment 1			Control Segment n		Data Payload
	Control Header 1	Control Body1	…	Control Header n	Control Body n	
Control Payload; Only present if MAC Header Control flag = 1						

The control flag in the MAC Header (see clause 6.3.2.2.2) shall determine whether a control payload is present in the packet or not. The control payload of the LPDU shall comprise the control length field and one or more control segments. The control length field shall specify the total length in bytes of all control segments of the control payload.

6.2.2.2 Control Segment

6.2.2.2.1 Overview

The control segments shall consist of the control header and the control body. The control header specifies the type and the size of the control segment. The control header values according to Table 6-3 shall be used for the fixed MAC mode of the TS-UNB protocol.

Table 6-3: Link Layer Control Segments

Control Header	Direction	Control Segment Name	Control Segment Size
0x10	UL	Attach Request	11 Bytes
0x11	UL	Attach Request IPv6	19 Bytes
0x14	DL	Attach Accept	5 Bytes
0x18	UL,DL	Detach Request	5 Bytes
0x1C	DL,UL	Detach Accept	5 Bytes
0x20	DL	DLRX-Status Query	1 Byte
0x21	UL	DLRX-Status Response	3 Bytes
0x24	DL	Link Adaptation Request	3 Bytes
0x25	UL	Link Adaptation Confirm	1 Byte
0xC0-0xFF	UL,DL	User specific control segments	User specific
Others		Reserved	

6.2.2.2.2 Attach Request

The attach request control segment shall be used to attach the end-point to the base station. The following format shall be used, if an end-point does not support IPv6 addressing.

Table 6-4: Attach Request Control Segment Format

Bytes: 1	2	4	4
Control Header	Control Body		
0x10	End-point Info	Nonce	User Signature

If the end-point can handle IPv6 addressing, it may use the IPv6 attach request control segment according to Table 6-5 to transmit the IPv6 subnet information to the base station.

Table 6-5: Attach Request IPv6 Control Segment Format

Bytes: 1	2	8	4	4
Control Header	Control Body			
0x11	End-point Info	IPv6 Subnet	Nonce	User Signature

Nonce and user signature fields are user specific and should be used in the application layer to derive the network key in the end-point and the service centre from the pre-shared private key.

The end-point info field signals the end-point capabilities to the base station. The end-point info field shall have the format according to Table 6-13 in clause 6.2.2.3.

6.2.2.2.3 Attach Accept

The base station shall send a message with an attach accept control segment to answer the attach request received from the end-point. The attach accept control segment shall have the format according to Table 6-6.

Table 6-6: Attach Accept Control Segment Format

Bytes: 1	**2**	**2**
Control Header	Control Body	
0x14	End-point Info	short address

The end-point info field is used by the base station to select the actual capabilities to use from the capabilities advertised by the end-point in the attach request control segment. The bit positions are according to Table 6-13. The short address is a 16 bit address, which shall be assigned by the base station to the end-point.

6.2.2.2.4 Detach Request

If an end-point needs to disconnect from the network, the end-point shall send a message with a detach request control segment according to Table 6-7 to the base station. A base station may also send a detach request to an end-point to disconnect the end-point from the network.

Table 6-7: Detach Request Control Segment Format

Bytes: 1	**4**
Control Header	Control Body
0x18	User Signature

The user signature field may be used by the application to authenticate the detach request and may not be processed within the domain of the base station.

6.2.2.2.5 Detach Accept

A detach request from an end-point shall be answered with a detach accept control segment by the base station.
A detach request from a base station shall be answered with a detach accept control segment by the end-point. The detach accept control segment shall have the format according to Table 6-8.

Table 6-8: Detach Accept Control Segment Format

Bytes: 1	**4**
Control Header	Control Body
0x1C	User Signature

The user signature field may be used by the application to authenticate the detach request and may not be processed within the domain of the base station.

6.2.2.2.6 DLRX Status Query

The DLRX Status Query can be sent from the base station to an EP to request a DLRX Status Response from the EP.

Table 6-9: DLRX Status Query Control Segment Format

Bytes: 1
Control Header
0x20

6.2.2.2.7 DLRX Status Response

The DLRX Status Response is sent by an EP after receiving a DLRX Status Query from the base station.

Table 6-10: DLRX Status Response Control Segment Format

Bytes: 1	**1**	**1**
Control Header	Control Body	
0x21	RSSI	Signal to noise ratio

The RSSI is provided as unsigned fixed point with a least significant bit value of 1dBm and an offset of -174 dBm.

The signal to noise ratio is provided as signed fixed point with a least significant bit value of 0,5 dB.

6.2.2.2.8 Link Adaptation Request

If the base station needs to change the configuration of the connection with an end-point, it shall send a Link Adaptation Request control segment. The requested configuration shall conform to the end-point capabilities announced during the attachment procedure.

Table 6-11: Link Adaptation Control Segment Format

Bytes: 1	2
Control Header	Control Body
0x24	End-point Info

6.2.2.2.9 Link Adaptation Confirm

If an end-point receives a Link adaptation request control segment from a base station, it shall respond with a Link adaptation confirm control segment.

Table 6-12: Link Adaptation Confirm Control Segment Format

Bytes: 1
Control Header
0x25

6.2.2.3 End-point Info Field

The end-point info field is used to negotiate TS-UNB protocol settings between end-point and base station. In the attach request control segment, this field shall indicate the end-point capabilities to the base station. In the attach accept control segment the base station shall announce the configuration of the connection to the end-point via end-point info field. The end-point info field shall be formatted according to Table 6-13.

Table 6-13: End-Point Info Field Format

Bit	Function	Direction	Description
0	Channel Use	UL	0: Single channel 1: Dual channel
1	Repetition	UL	0: Repetitions not used 1: Repetitions used
2	Carrier Offset value	UL	0: $n_{co} = 3$ 1: $n_{co} = 11$
3	DL Interblock Distance	DL	0: short ($T_{DN} = 512$) 1: long ($T_{DN} = 7\ 168$)
4	UL-TS-ULP	UL	0: UL-TS-ULP data rate not supported 1: UL-TS-ULP data rate supported
5	UL-TS-ER	UL	0: UL-TS-ER data rate not supported 1: UL-TS-ER data rate supported
6	DL-SB	DL	0: DL-SB Mode not supported 1: DL-SB Mode supported
7	DL-TS-ULP	DL	0: DL-TS mode with ULP data rate not supported 1: DL-TS mode with ULP data rate supported
8-15	Reserved	-	Reserved for future use, set to zero

6.2.3 Link Layer Procedures

6.2.3.1 End-point Attachment

6.2.3.1.1 Introduction

Before an end-point and a base station exchange data, the end-point shall be attached to the base station. The end-point attachment procedure provides a base station with information about an end-point required for servicing the end-point and provides the end-point with a short address. Bidirectional end-points may initiate an over-the-air attachment procedure. Unidirectional end-points are pre-attached by the service centre associated with the end-point.

During the attach procedure the end-point shall be configured to the following protocol settings until it is reconfigured by the base station via end-point info field.

Table 6-14: End-point protocol settings during attach procedure

Parameter	Setting
Channel Use	Single channel use
Repetition	Repetition off
carrier offset value	$n_{co} = 3$
DL Interblock Distance	May be short or long
UL-ULP data rate	on
UL-ER data rate	off

6.2.3.1.2 End-point Configuration

The end-point capabilities are advertised to the base station during the attachment procedure. The base station can then select the operational mode to be used from the advertised capabilities. For class Z devices the configuration is static, class A devices can negotiate the configuration during an over-the-air attachment procedure.

6.2.3.1.3 Class Z end-point Attachment

Class Z devices are unidirectional devices and shall be pre-attached to a LTN System during manufacturing of the device. In the pre-attachment procedure the network key, the short address and the end-point info field shall be programmed in the end-point and stored in the service centre.

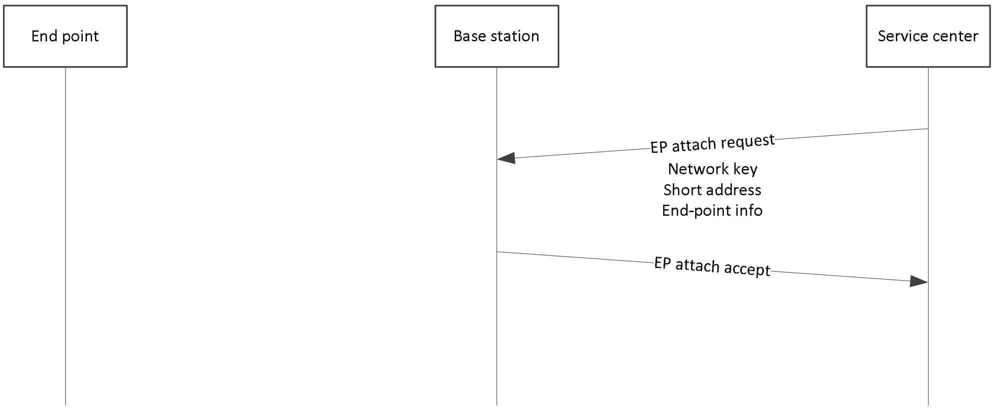

Figure 6-4: Service centre based attachment procedure (Class Z devices)

The service centre shall provide the base station with the preconfigured network key, short address and end-point info of the end-point.

6.2.3.1.4 Class A end-point Attachment

Class A devices may be attached over-the air to allow dynamic configuration by the base station.

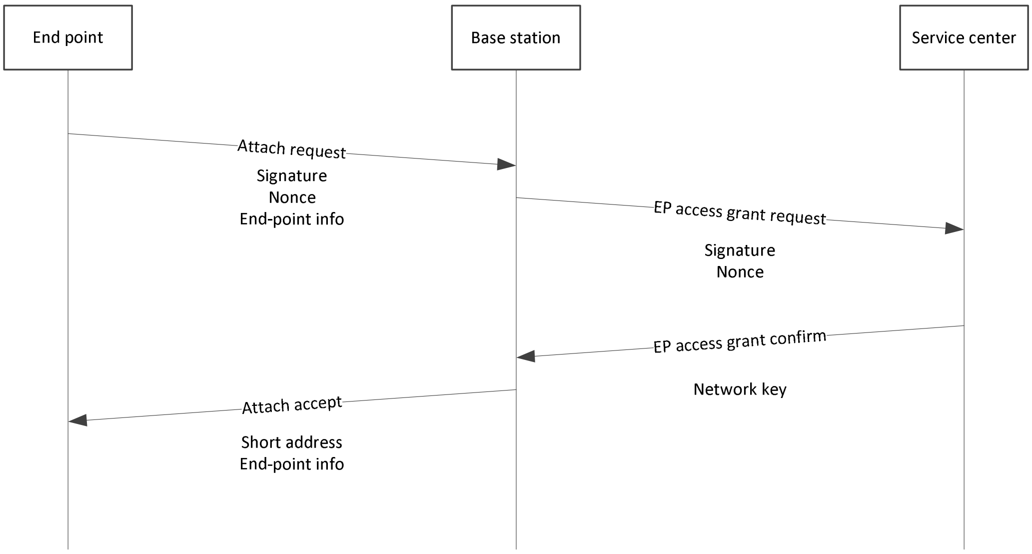

Figure 6-5: Over-the-air attachment procedure for class A devices

The over-the-air attachment procedure shall start with a message from the end-point to the base station containing an attach request control segment according to clause 6.2.2.2.2. The base station shall forward the attach request from the end-point to the service centre allowing the service centre to verify the end-point identity and to generate the network key. After successful verification the service centre shall provide the network key to the base station. The base station shall then assign a short address to the end-point and shall send a message containing an attach accept control segment to the end-point using the acquired network key for encryption. Further messages from the end-point may use the reduced addressing mode with the assigned short address and shall be encrypted with the network key.

6.2.3.2 End-point Detachment

The over-the-air end-point detachment procedure allows an end-point to deregister from a base station in a controlled manor. It allows the base station to remove end-points from the address resolution and to inform the service centre about the end-point detachment.

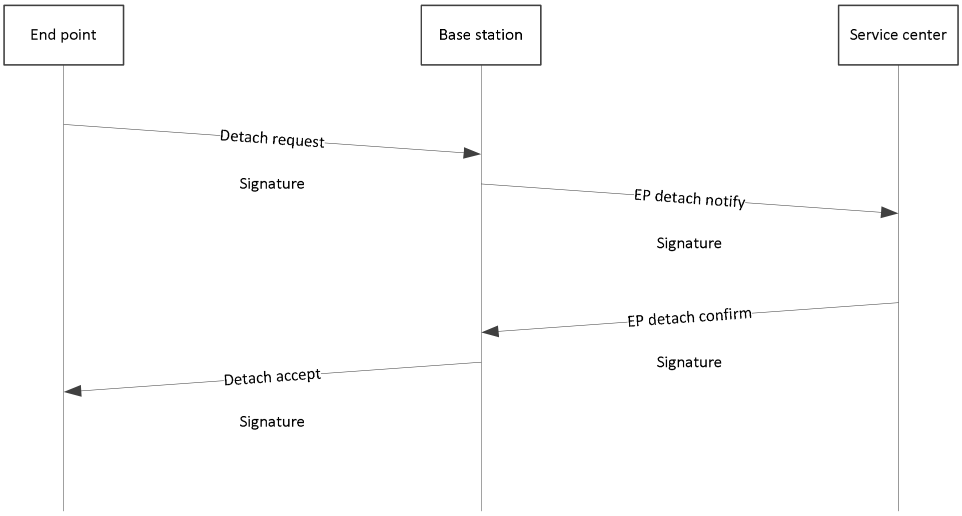

Figure 6-6: Over-the-air detachment procedure for class A devices

The service centre based detachment procedure might be used to deregister class Z end-points from a base station.

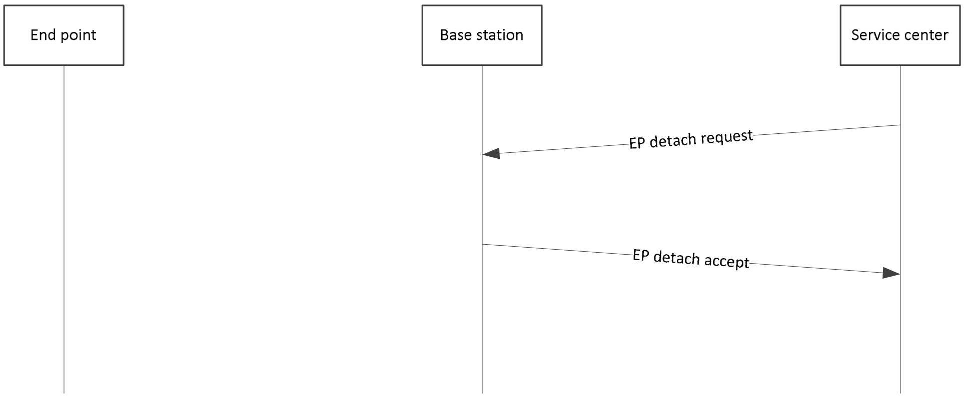

Figure 6-7: Service centre based detachment procedure for class Z devices

6.3 MAC Layer

6.3.1 Byte and Processing Order

Unless otherwise noted the byte order is most significant byte first and the processing of bit streams is most significant bit of most significant byte first. See Figure 6-8.

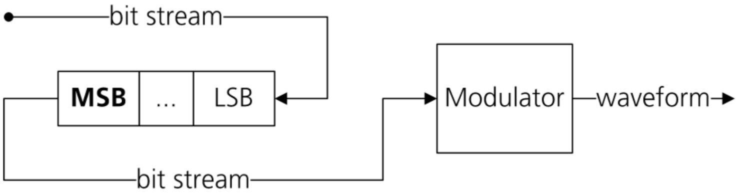

Figure 6-8: Byte and processing order

6.3.2 Fixed MAC Mode

6.3.2.1 Overview

The following MAC layer description applies to the fixed MAC mode, which is set by the MMODE field in the PHY layer (see clause 6.4.2.3.6).

The MAC layer controls the timing of transmissions and keeps track of transmission windows. Furthermore it is responsible for address resolution and provides network level cryptography and authentication.

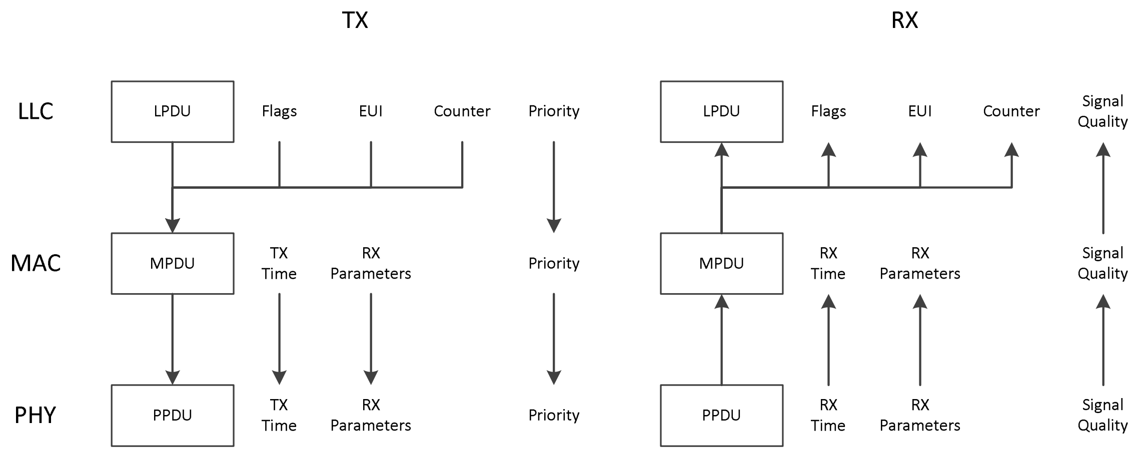

Figure 6-9: MAC layer interfaces with adjacent layers on the Base Station

In RX direction the MAC layer accepts the MPDU and associated meta information from the PHY layer. The meta information comprises the time of reception, signal quality information and a set of RX parameters. After address resolution and decryption of the LPDU, a set of flags, the end-point EUI and the packet counter are extracted from the MPDU and passed on to the link layer. The signal quality information is also forwarded to the link layer.

In TX direction the MAC layer is provided with the LPDU and associated meta information from the Link layer. The LPDU is combined with flags and addressing information and network level encryption is applied to form the MPDU. The MPDU is passed to the PHY layer with the according transmission time and the set of RX parameters of the associated uplink message. Additionally the message priority is passed through from the link layer to the PHY layer.

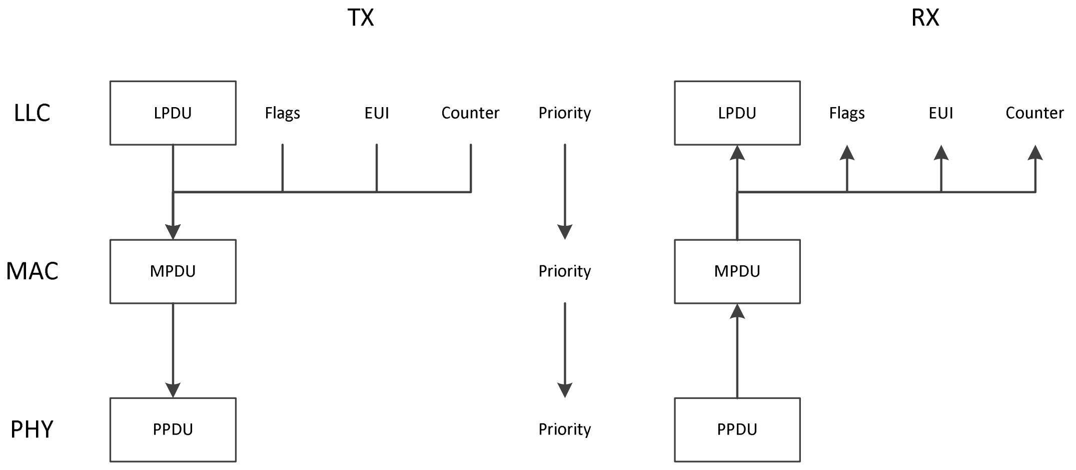

Figure 6-10: MAC Layer interfaces with adjacent layers on the end-point

6.3.2.2 MAC Formats in UL

6.3.2.2.1 MAC Protocol Data Unit (MPDU)

If the LTN system using the TS-UNB protocol is operated in the fixed MAC mode, the uplink MPDU format according to Table 6-15 shall be used.

Table 6-15: Uplink MPDU Format of fixed MAC mode

Bytes: 1	2 or 8	3	0/1	Variable (1 to 245)	4
MAC Header	Address	MPDUCNT	MPF	MAC Payload	SIGN

6.3.2.2.2 MAC Header

The MAC header shall be a one byte wide field signalling different MAC options for the packet. It shall be formatted according to Table 6-16.

Table 6-16: Uplink MAC Header Format

Bit	Function	Description
0	MAC version	0: Initial Version 1: Reserved
1	MPF flag	0: No MPF Field present 1: MPF Field present
2	Control flag	0: no control payload present (data only packet) 1: control payload present
3	Response flag	0: no response expected 1: response expected
4	RX Open flag	0: receive window for DL reception off 1: receive window for DL reception on
5	Addressing mode	0: short addressing mode, 16 bit short address 1: full addressing mode, 64 bit EUI
6	Attach flag	0: regular packet 1: attachment packet, also requires addressing mode = 1, control flag = 1, RX open flag = 1 and response flag = 1
7	ACK	0: no downlink message received since last uplink transmission 1: downlink transmission received

6.3.2.2.3 Address

The address field shall either contain a 16 bit short address or EUI64 of the end-point. The addressing mode bit in the MAC header determines which of these options is present in the packet.

6.3.2.2.4 MPDUCNT

The MPDUCNT field shall contain a 24 bit counter value according to clause 6.3.2.4.2. If the attach flag bit in the header is set, the attachment counter according to clause 6.3.2.4.3 is used instead of the packet counter.

6.3.2.2.5 MAC Payload Format (MPF)

The MPF field shall be present if the MPF flag of the MAC header is set to zero. The MPF field may be used to indicate the format of the MAC Payload. The MPF values shall be used according to Table 6-17.

Table 6-17: MAC Payload Formats

MPF Field value	MPF Name	Description
0x00-0xBF	Reserved	Reserved
0xC0-0xFF	Custom	User specific MAC Payload Formats

6.3.2.2.6 MAC Payload

The MAC payload shall contain the encrypted Link Layer Protocol Data Unit (LPDU). It may have a variable size between 1 and 245 bytes. The maximum variable size is reduced accordingly when the full addressing mode and/or MPF field is used or control segments are included in the transmission. If the attach flag bit in the header is set, the Link Layer Data Unit is unencrypted.

6.3.2.2.7 SIGN

The SIGN field shall contain a 32 bit Cypher-based Message Authentication Code (CMAC) according to clause 6.3.2.6.2 cryptographically signing the content of the MAC data unit.

6.3.2.3 MAC Formats in DL

6.3.2.3.1 MAC Protocol Data Unit (MPDU)

If the LTN system using the TS-UNB protocol is operated in the fixed MAC mode, the downlink MPDU format according to Table 6-18 shall be used.

Table 6-18: Downlink MPDU Format of fixed MAC mode

Bytes: 1	0/1	Variable (1 to 250)	4
MAC Header	MPF	MAC Payload	SIGN

6.3.2.3.2 MAC Header

The MAC Header shall be a one byte wide bit field signalling different MAC options for the packet. The MAC Header in downlink direction supports a subset of the uplink MAC Header flags. The MAC Header shall be formatted according to Table 6-19.

Table 6-19: Downlink MAC Header Format

Bit	Function	Description
0	MAC version	0: Initial Version 1: Reserved
1	MPF Flag	0: No MPF Field present 1: MPF Field present
2	Control flag	0: no control payload present (data only packet) 1: control payload present
3	Response flag	0: no response expected 1: response expected
4	RX Open flag	0: no further EP receive window required 1: Request to EP for further DL receive window after next uplink
5	Response Priority flag	0: EP response expected within regular time window 1: EP response expected within priority time window
6-7	Reserved	Reserved, shall be set to 0

6.3.2.3.3 MAC Payload Format (MPF)

The MPF field shall be present if the MPF field of the MAC header is set to 1. The MPF field may be used to indicate the format of the MAC Payload according to Table 6-17 in clause 6.3.2.2.5.

6.3.2.3.4 MAC Payload

The MAC Payload shall contain the encrypted Link Layer Protocol Data Unit (LPDU). It shall have a variable size between 1 and 250 bytes. The maximum size is reduced accordingly when control segments are included in the packet.

6.3.2.3.5 SIGN

The SIGN field shall contain a 32 bit Cypher-based Message Authentication Code (CMAC) according to clause 6.3.2.6.2 cryptographically signing the content of the MAC data unit.

6.3.2.4 MAC Functions in UL

6.3.2.4.1 Addressing

Every end-point shall uniquely be identified by a lifetime assigned IEEE EUI64 [6]. Additionally an end-point may be associated with a 16 bit, non-unique, short address via the attachment procedure, as described in clause 6.2.3.1.

Packets using the full addressing mode shall explicitly include the EUI64 of the corresponding end-point. No further address resolution is required in this case.

The reduced addressing mode shall be based on 16 bit explicit addressing using the short address assigned by the base station and 32 bit implicit addressing via the CMAC. Hence packets using the reduced addressing mode require the end-point identity to be derived from the included short address and the cryptographic signature contained in the CMAC.

6.3.2.4.2 Packet Counter

A 32 bit packet counter shall be used to the track the number of transmitted uplink packets in the end-point and the base station.

Table 6-20: Packet Counter Format

Bit 0 to 7	Bit 8 to 31
Extended Counter value	MPDUCNT value (transmitted)
Packet Counter (32 Bit)	

Every uplink packet except attachment packets shall contain the 24 least significant bits of the packet counter in the MPDUCNT field. The packet counter shall only be reset when a new network key is issued by the service centre during the attachment procedure and shall be incremented after each packet transmission.

6.3.2.4.3 Attachment Counter

A 24 bit attachment counter shall be used in the end-point and service centre to count the number of attachment procedures initiated by the end-point. The attach counter shall be incremented after each attach request message by the end-point. The MPDUCNT field of the MPDU shall be filled with the attach counter in attach request packets. The packet counter is therefore assumed 0 for attach request packets.

6.3.2.4.4 Payload Encryption

The MAC payload and the optional MPF field in uplink shall be encrypted according to clause 6.3.2.6.1.

6.3.2.4.5 Authentication

A CMAC according to clause 6.3.2.6.2 shall be used to authenticate the MAC payload in uplink. The CMAC shall be generated over the MPDU fields MAC Header, Address, MPDUCNT, the optional MPF field, if available and the MAC payload after encrypting the MAC payload as well as the optional MPF field (encrypt then MAC). It shall be preceded with the payload encryption initialization vector IV described in clause 6.3.2.6.2.

Table 6-21: Input Data of CMAC generation in uplink (SIGN field)

Bytes: 8	1	2/8	3	0/1	1 to 245
IV	MAC Header	Address	MPDUCNT	MPF	MAC Payload

6.3.2.5 MAC Functions in DL

6.3.2.5.1 Addressing

Downlink addressing is done implicitly via the time of transmission and the CMAC included in the Sync field of the downlink core frame. The end-point shall only accept transmissions at the defined time offset ΔT_{ud} after the previous uplink transmission, as described in clause 6.3.2.7.1. The comparison of the contained CMAC against the expected CMAC of the end- point rejects packets for other end-points accidentally transmitted simultaneously. Before transmission, the base station shall ensure that a CMAC in a downlink transmission is not considered valid by any other end-points than the intended one with simultaneously opened downlink windows.

6.3.2.5.2 Packet Counter

The packet counter of the associated uplink shall be implicitly used as packet counter in the downlink transmission. If the associated uplink uses the attach format and therefore includes the attach counter instead of the packet counter, the packet counter for encryption and signature generation shall be assumed 0.

6.3.2.5.3 Payload Encryption

The MAC payload and the optional MPF field in downlink shall be encrypted according to clause 6.3.2.6.1.

6.3.2.5.4 Authentication

A CMAC according to clause 6.3.2.6.2 shall be used to authenticate the MAC payload in downlink. The CMAC shall be generated over the MPDU fields MAC Header, the optional MPF field if available and the MAC payload after encrypting the MAC payload as well as the optional MPF field (encrypt then MAC) and shall be preceded with the payload encryption initialization vector described in clause 6.3.2.6.2.

Table 6-22: Input Data for CMAC Generation in downlink

Bytes: 8	1	0/1	1 to 250
IV	MAC Header	MPF	MAC Payload

6.3.2.6 Common MAC function

6.3.2.6.1 Encryption

The MAC layer handles the network level encryption of the MAC payload. The network level encryption shall be used for all packets except the attach request packet. Network level cryptography shall be based on the 128 bit network key provided through the attachment procedure described in clause 6.2.3.1 and the AES128 algorithm in counter mode of operation [2] and [i.5]. The initialization vector for each block shall be derived from the packet counter, the end-point EUI and the data direction (uplink/downlink).

Table 6-23: Payload encryption initialization vector format

Bytes: 8	1	1	4	2
EUI64	0x00	Data direction	Packet counter	Block counter

The block counter shall be reset to 0 at the beginning of every packet and shall be incremented for every consecutive 16 byte AES128 block within the packet. Each initialization vector shall only be used once to ensure the security of the encrypted data. Thus the extended counter value increases the usable initialization vector range before a new network key is required due to a counter wrap. The extended counter needs to be synchronized between base station and end-point. If no extended counter is tracked the extended counter field shall be set to 0. The 24 bit packet counter grants a resynchronization window of 16 777 216 packets. Within this window the extended counter shall be implicitly resynchronized at reception. If the number of consecutively lost packets exceeds the window length, the synchronization between end-point and base station shall be recovered. Recovery should be achieved via probing a range of extended counters against the packet authentication. In the case of bidirectional end-points a reattachment, resetting the packet counter and extended counter, also recovers synchronization.

The data direction field shall be set to 0x00 for uplink transmissions and 0x01 for downlink transmissions to allow reusing uplink packet counters in the downlink.

The initialization vector IV shall be AES encrypted with the end-point's network key. The encrypted initialization vector IV^* shall be truncated to the payload length if the remaining block is shorter than 16 bytes. The payload plaintext block P shall be combined with the encrypted and truncated initialization vector via an exclusive or operation to create the payload cipher text C.

$$IV^* = AES128(IV)$$
$$C = IV^* \oplus P$$

The procedure shall be repeated after incrementing the block counter within the initialization vector until the entire MAC payload has been processed.

6.3.2.6.2 CMAC generation

A cypher-based Message Authentication Code (CMAC) [3] and [i.6] shall be used to verify the integrity and authenticity of an uplink or downlink packet. AES128 shall be employed as the block cipher algorithm required within the CMAC procedure. The network key provided through the attachment procedure (see clause 6.2.3.1) shall be used as the cryptographic key for the AES128 algorithm to authenticate messages. If the attachment flag is set in the MAC header, the network key shall be substituted with all zeros. The function of the CMAC is then reduced to verification of the packet integrity. The CMAC initialization vector IV_{CMAC} shall formatted according to Table 6-24.

Table 6-24: CMAC initialization vector format

Bytes: 8	1	1	4	2
EUI64	0x00	Data direction	Packet counter	0xFFFF

The data direction field shall be set to 0x00 for uplink transmissions and 0x01 for downlink transmissions to allow reusing uplink packet counters in the downlink.

After processing the input data with the CMAC generation procedure the resulting value shall be truncated according to the description in clauses 6.3.2.4.5, 6.3.2.5.4 and 6.4.3.1.1.3.

Verification by the recipient shall be done by generating the CMAC for the received packet with the expected initialization vector and cryptographic key and comparing it against the CMAC transmitted with the packet.

6.3.2.7 MAC Procedures

6.3.2.7.1 Scheduling

In downlink data shall only be transmitted after the reception of an uplink transmission. Hence every downlink transmission needs to be preceded by an uplink transmission of an end-point. After sending an uplink packet to the base station, an end-point may open a downlink window for the reception of a downlink transmission from the base station. The downlink transmission shall start after a predefined time of 16 384 symbols after reception of the uplink transmission. The time is defined as the time between last radio-burst of last transmitted radio frame of the uplink transmission to the first radio-burst of the downlink transmission and is measured from the middle of the pilot sequence of the two radio-bursts.

The downlink window shall be announced in the preceding uplink telegram via the response flag in the MAC Header (see clause 6.3.2.2.2). The MAC layer shall track the time of arrival for uplink transmissions and schedule the according downlink response to meet a time offset according to Table 6-25.

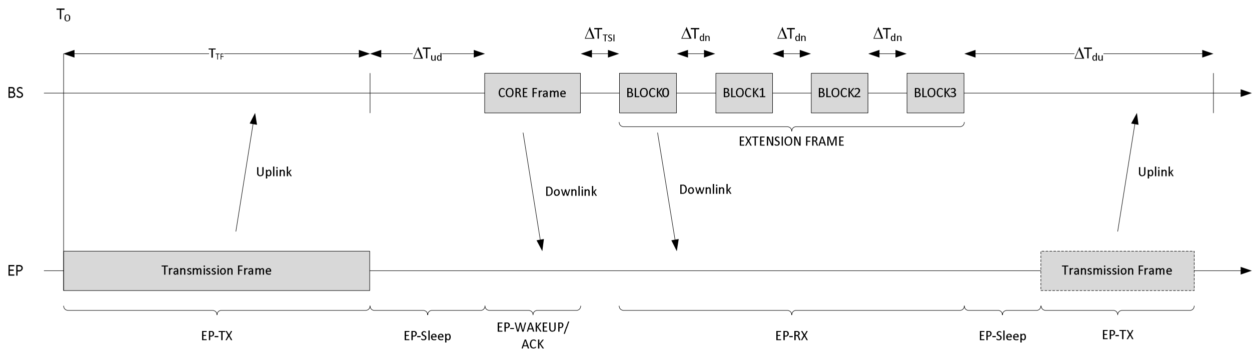

Figure 6-11: Uplink/Downlink Scheduling

Table 6-25 gives the time intervals for the uplink/downlink scheduling.

Table 6-25: Uplink/downlink time intervals

Parameter	Range of values	Default Value	Description
ΔT_{ud}		16 384 (±2) Symbols	Time interval between UL and DL transmission in number of symbol time periods
ΔT_{dn}	512 or 7 168	512	Time interval between blocks of extension frame in number of symbol time periods
ΔT_{TSI}	84…65 532	384	Time interval between core frame and extension frame in number of symbol time periods (4x TSI Value; see clause 6.4.3.3.1.5)
ΔT_{du}	5…1 024	120	Maximum time window for a high priority uplink response (Response priority flag = 1) in seconds
NOTE: The symbol time period is based on a symbol rate of 2 380,371 Sym/s.			

The time reference shall be the end-point time starting with the transmission of the first radio burst at T_0. The base station estimates the symbol rate offset of the end-point based on the received carrier frequency offset:

$$\Delta f_{sym} \sim \frac{f_{c,RX} - f_{c,expected}}{f_{c,expected}}$$

or based on the timing offset of the received radio bursts. Based on the estimated symbol rate offset the downlink symbol rate and carrier frequency shall be adapted.

If the base station expects an uplink message (e.g. for acknowledgment of downlink) it shall set the response flag in the MAC header (see clause 6.3.2.3.2) of the downlink transmission. If the base station expects the end-point uplink response within a limited time, it shall set the response priority flag in the MAC header of the downlink transmission.

If an end-point is ready to receive a downlink transmission from the base station, the end-point shall set the RX open flag in the MAC header field (see clause 6.3.2.3.2). After the predefined time ΔT_{ud} after the UL frame (see clause 6.3.2.7.1), the end-point shall open its receive window for the reception of a DL frame from the base station.

If a base station needs to transmit further downlink messages to the end-point, it shall set the RX open flag in the MAC header of the downlink transmission to indicate to the end-point that it shall open its receive window after the next uplink transmission.

6.3.2.7.2 Transmission Acknowledgment

6.3.2.7.2.1 Uplink Message ACK

If an end-point requires a downlink response from the base station after its uplink communication, e.g. for acknowledgment of the uplink message, it shall set the response flag in the MAC header field. Due to the limited duty cycle in the base station transmission, the base station may refuse the downlink transmission.

6.3.2.7.2.2 Downlink Message ACK

If a base station expects an acknowledgment of its downlink transmission, the base station shall set the response flag of the MAC header field in downlink. The end-point then shall send a separate uplink transmission to acknowledge the reception of the preceding downlink transmission. If the base station sets the response priority flag of the MAC header, it expects the uplink response message from the end-point within a time window of ΔT_{du}.

6.3.3 Variable MAC mode

6.3.3.1 Overview

A LTN system using TS-UNB protocol can run user specific MAC/LINK layer, when operated in the variable MAC mode. If a LTN system using TS-UNB protocol is operated in variable MAC mode the MMODE field in the PHY layer shall be set according to clause 6.4.2.3.6.

6.3.3.2 MPDU Format

In the variable MAC mode the MPDU format in uplink and downlink shall be formatted according to Table 6-26.

Table 6-26: Uplink MPDU Format of variable MAC mode

Bytes: 1	**Variable (1 to 254)**
MAC-TYPE	U-MPDU (Variable MAC according MAC Type)

A custom specific MAC Payload field U-MPDU shall be preceded by a MAC-TYPE field indicating the MAC/LINK layer used in the variable MAC Mode. Table 6-27 lists possible MAC types.

Table 6-27: List of MAC Types

MAC-TYPE Field value	**MAC Type Name**	**Description**
0x00	WMBUS	MAC/LINK Layer optimized for metering applications according to clause 6.3.4.1
0x30-0x3F	Custom	User specific MAC/LINK layer
Others	Reserved	Reserved

6.3.4 MAC Types

6.3.4.1 MAC type WMBUS

6.3.4.1.1 Overview

If the variable MAC mode with MAC type WMBUS is used, the same MAC/LINK layer as for the fixed MAC mode described in clause 6.3 shall be used with adaptations according to the following clauses.

6.3.4.1.2 MAC Formats

6.3.4.1.2.1 Uplink

The uplink U-MPDU format shall be formatted according to Table 6-28.

Table 6-28: Uplink U-MPDU Format of variable MAC with MAC type WMBUS

Bytes: 1	**8**	**3**	**1**	**0/1**	**Variable (1 to 238)**	**4**
MAC Header	WMBUS Address	MPDUCNT	CI	MPF	MAC Payload	SIGN

An 8-Byte WMBUS Addressing shall be used instead of EUI64 as shown in Table 6-29.

Table 6-29: WMBUS Address format

Bytes: 2	**4**	**1**	**1**
Manufacturer	Identification number	Version	Device type
NOTE: All multi byte fields are most significant byte first in contradiction to "normal MBus usage".			

An additional Control Information (CI) field shall be used according to [5] and [i.7]. The CI field declares the structure of the upper layers for metering applications. All other fields of the MPDU shall be the same as in clause 6.3.2.2.1.

6.3.4.1.2.2 Downlink

The same U-MPDU format as in fixed MAC mode downlink MPDU shall be used.

6.3.4.1.3 MAC functions

The MAC functions according to clauses 6.3.2.4 and 6.3.2.5 shall be used.

6.3.4.1.4 MAC procedures

The MAC procedures according to clause 6.3.2.7 shall be used.

6.4 PHY Layer

6.4.1 PHY Overview

In TS-UNB, the radio transmission of a packet (=radio frame) is split into several radio-bursts, which are distributed over time and frequency within the radio frame. For generation of the physical layer output the following processing blocks according to Figure 6-12 are necessary in the end-point (uplink transmission) and base station (downlink transmission).

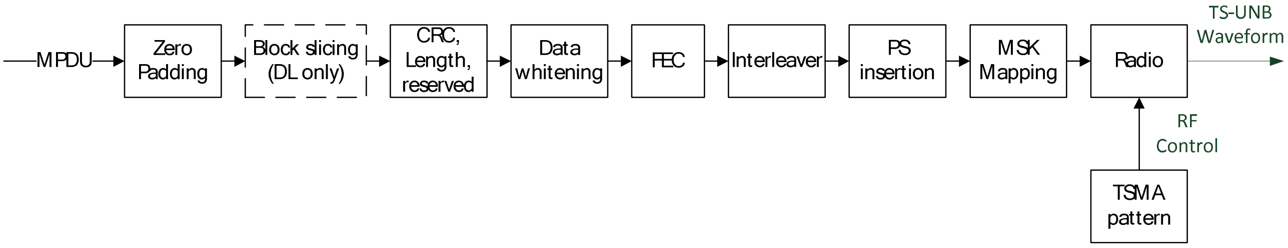

Figure 6-12: Block Diagram of PHY waveform generation

The input to the PHY Layer is the MPDU from the MAC Layer.

6.4.2 PHY Formats in UL

6.4.2.1 Radio-burst

6.4.2.1.1 Burst Data Unit (BDU)

The uplink transmission consists of several radio-bursts. Each radio-burst shall consist of one 12 bit long pilot sequence PS field and two accompanying 12 bit long data fields DATA according to Table 6-30.

Table 6-30: Uplink Burst Data Unit format

Bits: 0-11	12-23	24-35
DATA	PS	DATA

A 32 byte long synchronization sequence is split into pilot sequences of 12 bit, distributed over the core frame and recombined in the base station for proper receiver synchronization. The PS field shall be filled with the resulting12 bit pilot sequence (0, 1, 1, 1, 0, 1, 0, 0, 0, 0, 1, 0).

The PS field of each radio bursts in the extension frame (clause 6.4.2.2.3) shall be filled with the sequence (0, 1, 0, 0, 1, 1, 1, 1, 1, 0, 1, 0).

6.4.2.1.2 Sync-burst Data Unit (SBDU)

For easier synchronization in the receiver (e.g. for low complexity receivers) an optional synchronization radio-burst may be used before the core frame. The synchronization burst data unit shall consist of fields according to Table 6-31.

Table 6-31: Uplink Sync-Burst Data Unit format

Bits: 0-11	12-19	20	21-23	24-31	32-33	34-35
Preamble_S	PS_US	Reserved	Uplink TSMA Pattern Number	LSB Short Address	Uplink TSMA Pattern Group	Sync CRC
		SIF (Sync-burst Info Field)				

The fields are defined as:

- The Preamble_S field shall be filled with (0, 0, 1, 1, 0, 0, 1, 1, 0, 0, 1, 1).
- The pilot sequence field PS_US shall be filled with (1, 1, 0, 1, 0, 0, 1, 1).
- The Reserved field is reserved for future use and shall be set to (0).
- The Uplink TSMA Pattern Number shall indicate the TSMA pattern number p used for this transmission.
- The LSB Short Address shall be the eight least significant bits of the short address as described in clause 6.2.3.1.
- The uplink TSMA Pattern Group shall indicate the TSMA pattern group used for this transmission as described in Table 6-32.

Table 6-32: Uplink TSMA Pattern Group

Name	Abbreviation	Pattern
Uplink TSMA Pattern Group 1	UPG1	(0, 0)
Uplink TSMA Pattern Group 2	UPG2	(0, 1)
Uplink TSMA Pattern Group 3	UPG3	(1, 0)

- Sync CRC shall be 2 bit and calculated over the bits 20 to 33 of the SBDU according to clause 6.4.6.2.

6.4.2.2 Radio Frame

6.4.2.2.1 Overview

The uplink transmission shall consist of a core frame and shall comprise an additional extension frame, if the PHY payload length exceeds 186 bits.

6.4.2.2.2 Core frame

The uplink core frame shall consist of 24 radio-bursts.

6.4.2.2.3 Extension frame

The uplink extension frame structure shall be derived from the information of the core frame according to clause 6.4.7.1.6.2. For each additional byte in the PHY payload, the frame shall be extended by one radio-burst.

6.4.2.3 PHY Payload

6.4.2.3.1 Introduction

The PHY Payload in uplink shall consist of the following fields.

Table 6-33: UL-ULP PHY Payload

Bits: 8	8	8	Variable (160 to 2 040)	2
Header CRC	Payload CRC	PSI	PSDU	MMode
PHR				

Header CRC, Payload CRC and PSI form the PHY Header (PHR) based on which the radio burst transmission time and frequency of the extension frame is determined.

6.4.2.3.2 Header CRC

The Header CRC shall be 8 Bit and calculated according to clause 6.4.4.4.1.

6.4.2.3.3 Payload CRC

The Payload CRC shall be 8 Bit and calculated according to clause 6.4.4.4.2.

6.4.2.3.4 Packet Size Indicator (PSI)

The Packet Size Indicator (PSI) field shall be 8 bit long and shall indicate the length of the PSDU before zero padding in byte. Valid values range from 1 to 245 bytes.

6.4.2.3.5 PHY Service Data Unit (PSDU)

The physical layer service data unit (PSDU) may hold a variable length of up to 255 bytes of data. The minimum PSDU length shall be 20 bytes and shall be covered by the core frame.

The PSDU shall be filled with the MAC Protocol Data Unit (MPDU). If the MPDU size is below 20 bytes the PSDU shall be filled to 20 bytes by zero padding behind the actual PSDU. Therefore a minimum number of 20 bytes is always transmitted, regardless of the actual MPDU size. For CRC calculation, the padded zeroes shall be omitted.

6.4.2.3.6 MMode

The 2 bit long field MMODE shall indicate if fixed MAC or variable MAC is used. The MMODE field shall be formatted according to Table 6-34.

Table 6-34: MMODE field format

Bit	Function	Description
0/1	MMode	00: Fixed MAC Mode (see clause 6.3) 01: Variable MAC (customer specific MAC/LINK layer see clause 6.3.3) Others: Reserved

6.4.3 PHY Formats in DL

6.4.3.1 Radio-burst

6.4.3.1.1 DL-SB Mode

6.4.3.1.1.1 Overview

In DL-SB Mode, telegram splitting shall not be used. Therefore the PHY payload of one block shall be transmitted in one continuous radio-burst. The length of the radio-burst depends on the length of the PSDU of the PHY payload, which shall be a fixed length of 78 symbols for the core frame and variable length between 66 and 202 symbols for the PHY payload blocks in the extension frame.

Table 6-35: Burst Data Unit format of DL-SB Mode

Symbols: 32	32	78 / 66…202
Preamble	Sync	PHY Payload

6.4.3.1.1.2 Preamble field

The preamble field of the radio-burst shall be 32 bits filled with (0,1,0,1….).

6.4.3.1.1.3 Sync Field

The Sync field of the radio-burst shall be 32 bit with a value of 0x930B51DE.

6.4.3.1.2 DL-TS Mode

6.4.3.1.2.1 Burst Data Unit

The burst data unit of the downlink transmission in DL-TS Mode shall be formatted according to Table 6-36.

Table 6-36: Burst Data Unit format of DL-TS Mode

Bits: 0 - 11	**12 - 19**	**20 - 31**	**32 - 39**	**40 - 51**
DATA_B	PS_DA	DATA_A	PS_DB	DATA_C

The burst data unit in the downlink shall consist of at least one 12 bit data field DATA_A, accompanied by two 8 bit long pilot sequence fields PS_DA and PS_DB. The data fields DATA_B and DATA_C shall be added dependant on the PSDU length (see clause 6.4.3.2.2).

6.4.3.1.2.2 Sync-burst Data Unit

For easier synchronization in the receiver (e. g. for low performance receivers) an optional additional synchronization radio-burst may be sent. If an additional synchronization burst is sent, it shall be sent before the core frame and before each block of the extension frame. The Sync-burst data unit in the DL-TS Mode shall be formatted according to Table 6-37.

Table 6-37: DL-TS Sync-burst Data Unit format

Bits: 0-13	**14-25**	**26-38**
PS_Ext_A	PS_DS	PS_Ext_B

The pilot sequence field PS_DS shall be filled with (0, 1, 1, 1, 0, 1, 0, 0, 0, 0, 1, 0), the PS_Ext_A field shall be filled with (0, 1, 0, 1, 0, 0, 1, 1, 1, 1, 1, 0, 1, 0) and the PS_Ext_B field shall be filled with (0, 1, 0, 0, 1, 1, 1, 1, 1, 0, 1, 0, 0).

As the number and the size of the radio-bursts in downlink are dependent on the PHY payload length, the length of the synchronization radio-burst also differs.

In the core frame, the size of the Sync-burst data unit (n_{sb}) shall be always 21 symbols. In the extension frame, the size of the Sync-burst data unit shall be calculated according to the following formula:

$$n_{sb} = \begin{cases} 21 & for\ n_b \leq 7 \\ 21 + (n_b - 7) & for\ n_b > 7 \end{cases}$$

Where n_b is the number of PSDU data bytes in the block.

If the size of the Sync-burst data unit is lower than the maximum defined size of 39 Symbols in Table 6-37, the PS_Ext_A and PS_Ext_B field shall be truncated. The number of symbols in the fields are calculated according to the following formula:

$$n_{PS\_Ext\_A} = \lceil (n_{sb} - 12)/2 \rceil$$

$$n_{PS\_Ext\_B} = \lfloor (n_{sb} - 12)/2 \rfloor$$

In case of truncation the outer symbols of the PS_Ext_A and PS_Ext_B fields shall be omitted. The PS_DS field shall always indicate the middle of the synchronization radio-burst.

6.4.3.2 Radio frame

6.4.3.2.1 Core frame

The core frame is used as authenticated wakeup and acknowledgment of the previous end-point uplink transmission. Every downlink transmission shall consist of a core frame and may be followed by an optional extension frame. The succeeding extension frame shall be indicated in the core frame.

The core frame shall consist of 9 radio-bursts according to the structure described in clause 6.4.3.1, which may be repeated to fill the 18 radio-bursts of the downlink TSMA pattern. The base station should decide upon the signal strength of the uplink transmission if the same core frame is repeated. Pilot sequence field PS_DA and pilot sequence PS_DB of each radio-burst in the core frame shall be filled with symbols derived from the channel coded core PHY Payload. The optional DATA_B and DATA_C fields shall not be used for transmission of the core frame.

For synchronization purpose an additional Sync-burst may be transmitted before the start of the core frame. If an additional Sync-burst is used in front of the core frame an additional Sync-burst shall also be used in front of each block of the extension frame.

6.4.3.2.2 Extension frame

The extension frame is an optional transmission frame to transmit user data. The extension frame may contain a maximum of 250 bytes of PSDU data. The PSDU contains the MPDU data with additional zero padding if needed. The extension frame shall be split into blocks of at most 24 bytes of PSDU data per block. If the overall PSDU size is more than 24 bytes, multiple blocks shall be used for transmission. Each block of the extension frame shall comprise 18 radio-bursts according to clause 6.4.3.1. If an additional Sync-burst is used in the core frame, then an additional Sync-burst shall be transmitted also for each block of the extension frame.

The burst data unit of the extension frame shall use the pilot sequences defined in Table 6-38 for all radio-bursts except the Sync-burst.

Table 6-38: DL-TS extension frame pilot sequences

Pilot Sequence A	Pilot Sequence B
(0, 1, 0, 0, 0, 0, 1, 0)	(1, 1, 1, 0, 1, 0, 0, 0)]

The number of optional data symbols in data fields DATA_B and DATA_C utilized for data transmission is dependent on the number of symbols transmitted in the respective block of the extension frame.

The PSDU data shall be spread byte-wise evenly over the number of extension frame blocks required to accommodate for the whole packet.

The number of blocks B that shall be used for the transmission shall be determined according to the following formula:

$$B = \left\lceil \frac{P}{24} \right\rceil,$$

Where $P \in \{1,2 \ldots 250\}$, shall be the PSDU size in byte.

The extension frame blocks shall be numbered in ascending order to their respective transmission time. Block $b = 1$ shall be the block directly transmitted after the core frame, block $b + 1$ shall be transmitted after block b.

The number of PSDU data bytes n_b assigned to one block is a result of spreading the data evenly over all blocks. In case the number of bytes is not a multiple of the number of blocks, the remaining bytes $n_r = P - \left\lfloor \frac{P}{B} \right\rfloor * B$ shall be assigned to the blocks in ascending order.

$$n_b = \begin{cases} \left\lfloor \frac{P}{B} \right\rfloor, for\ b > n_r \\ \left\lfloor \frac{P}{B} \right\rfloor + 1,\ \ for\ b \leq n_r \end{cases}.$$

The data bits assigned to one block shall be spread over the radio-bursts by filling the field DATA_A of all bursts first and then consecutively filling the optional data fields DATA_B and DATA_C of all radio-bursts evenly. The procedure is described in detail in clause 6.4.5.5.2.2.

6.4.3.3 PHY Payload

6.4.3.3.1 Core frame

6.4.3.3.1.1 Introduction

The same core frame PHY Payload format shall be used for DL-SB and DL-TS Mode. The core frame PHY Payload shall have the format according to Table 6-39.

Table 6-39: PHY Payload of the DL-TS Core frame

Bits: 0-47	48	49-56	57-70	71-72	73	74-77
Sync	EFI	PSI	TSI	MMODE	Reserved	CRC

6.4.3.3.1.2 Sync

If fixed MAC mode is used, the Sync field shall contain a 48 bit cypher-based Message Authentication Code (CMAC) cryptographically signing the counter of the uplink MAC Data Unit received from the end-point. The CMAC is generated according to clause 6.3.2.6.2 with the CMAC initialization vector IV_{CMAC} for downlink direction as input data.

Table 6-40: Input Data for Sync CMAC Generation

Bytes: 8
IV

The 48 most significant bits of the result of the CMAC generation shall be used as Sync field.

If the variable MAC mode of the TS-UNB protocol is used the Sync field shall be filled with the pilot sequences PS_A and PS_B of the extension frame radio burst (Table 6-38) according to Table 6-41.

Table 6-41: Signature field in variable MAC mode

Bits: 0-7	8-15	16-23	24-31	32-39	40-47
PS_A	PS_B	PS_A	PS_B	PS_A	PS_B

6.4.3.3.1.3 Extension frame Indicator (EFI)

The Extension Frame Indicator (EFI) field indicates, if the core frame is followed by an extension frame. EFI shall be set to one, if an extension frame follows. If EFI is set to one PSI, TSI and MMODE fields shall be used. If EFI is zero, PSI, TSI and MMODE are reserved and shall be set to (0).

6.4.3.3.1.4 Packet Size Indicator (PSI)

The packet size indicator (PSI) shall indicate the size of the downlink PSDU of the extension frame before zero padding in bytes. Valid values range from 1 to 250 bytes.

6.4.3.3.1.5 Transmission Start Time Indicator (TSI)

The transmission start time indicator (TSI) indicates the time interval between core frame and extension frame. The time interval is measured from the last radio-burst of the repeated core frame to the first radio-burst of the first block of the extension frame and is measured from the middle of the pilot sequence of the two radio-bursts. The time offset shall be calculated from the TSI value (Table 6-25 in clause 6.3.2.7.1) according to the following formula:

$$\Delta T_{TSI} = TSI * 4 Symbols * \Delta T$$

The TSI value ranges from 21 to 16 383. The default TSI value shall be 128. ΔT is the symbol duration of DL-TS mode.

If the core frame is not repeated, the time of the last radio-burst of a core frame with 18 radio-bursts shall be used.

6.4.3.3.1.6 MMODE

The same MMODE field shall be used as in uplink (see clause 6.4.2.3.6).

6.4.3.3.1.7 Downlink Core frame CRC

A 4-bit CRC checksum shall be calculated over bits 48 to 73 of the PHY Payload according to clause 6.4.6.2 and placed at the end of the core frame.

6.4.3.3.2 Extension frame

The same extension frame PHY payload format shall be used for DL-SB mode and DL-TS mode. The extension frame is sliced in blocks. The PHY payload of a block shall have the format according to Table 6-42.

Table 6-42: PHY payload of a DL-TS Extension frame Block

Bits: 0-191	192-193	194-201
Block PSDU	Reserved	CRC

The overall PHY payload consists of the PSDU and is sliced into PHY payload blocks of at most 24 bytes PSDU data according to clause 6.4.3.2.2. The overall PSDU shall have a size between 7 and 250 bytes. If the MPDU is less than 7 bytes the overall PSDU shall be zero padded to the minimum possible payload size of 7 bytes. For CRC calculation, the padded zeroes are omitted.

The block PSDU is the variable size part of the overall PSDU assigned to a block. The PHY payload shall be filled with the block PSDU starting from bit 191 downwards with the MSB of the block PSDU independent of its size.

Bit 192 and 193 are reserved.

The 8-bit CRC checksum shall be calculated over the occupied bits of the block PSDU and the reserved bits according to clause 6.4.6.2.

6.4.4 PHY Functions in UL

6.4.4.1 Modulation

A LTN system using TS-UNB protocol shall use MSK Modulation or GMSK Modulation with BT = 1.0 in the uplink.

6.4.4.2 Symbol mapping

6.4.4.2.1 Overview

The bits of the Burst Data Unit and Sync-burst Data Unit shall be mapped according to the following symbol representation.

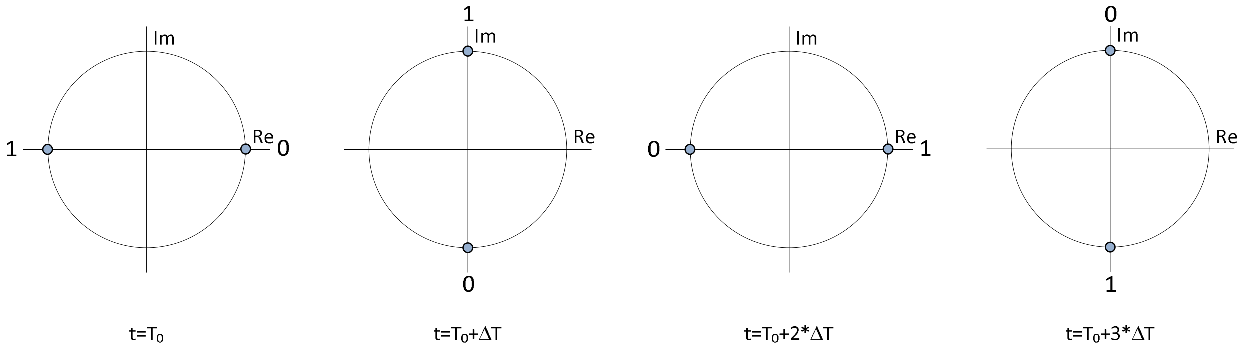

Figure 6-13: Symbol mapping for MSK/GMSK with absolute phase

The representation shall be repeated after 4 symbols. T_0 is the start time of the PHY transmission with a symbol duration of ΔT.

6.4.4.2.2 UL-ULP Symbol rate

The symbol rate of the (G)MSK modulation in the UL-ULP mode shall be 2 380,371 sym/s (preferably derived from 26 MHz reference frequency). The tolerance of the symbol rate shall be kept within a range of ±0,1 % during one radio-burst.

6.4.4.2.3 UL-ER Symbol rate

The symbol rate of the (G)MSK modulation in the UL-ER mode shall be 396,729 sym/s (preferably derived from 26 MHz reference frequency). The tolerance of the symbol rate shall be kept within a range of ±0,1 % during one radio-burst.

6.4.4.3 Data Whitening

The complete PHY Payload (see Table 6-33 and Figure 6-12) shall be whitened using the PN9 sequence defined in IEEE 802.15.4 [1].

6.4.4.4 CRC

6.4.4.4.0 General

An 8-bit cyclic redundancy check (CRC) according to clause 6.4.6.2 shall be used.

6.4.4.4.1 Payload CRC

The payload CRC shall be calculated over MPDU and MMODE field according to clause 6.4.6.2. In Case of zero padding the padded zeros shall be omitted for the CRC calculation.

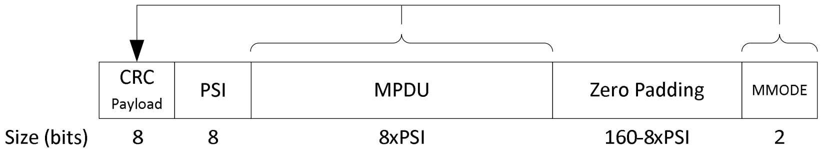

Figure 6-14: Calculation of Payload CRC

6.4.4.4.2 Header CRC

The additional Header CRC shall be calculated over Payload CRC and PSI according to clause 6.4.6.2.

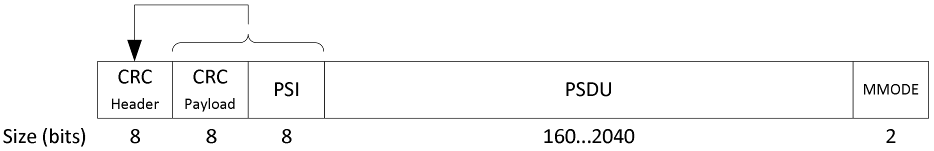

Figure 6-15: Calculation of Header CRC

6.4.4.5 Forward Error Correction

A Forward Error Correction code (FEC) according to clause 6.4.6.3 shall be calculated over the complete PHY payload after data whitening. The FEC extends the original series of 186 - 826 uncoded bits to a series of 576 - 2 496 encoded bits.

6.4.4.6 Interleaving

6.4.4.6.1 Introduction

After data whitening and FEC the FEC coded bit-stream of the PHY payload shall be distributed to sub-packets of the core and extension frame by the interleaver in a way, that the information of the PHR field (see clause 6.4.2.3) required to receive the extension frame are contained in the core frame.

The length of the bit-stream n_S determines how many sub-packets in the extension frame are used. If less or equal than 576 bits are transmitted, the extension frame shall be omitted completely. Otherwise the number of sub-packets in the extension frame S_E is given by $S_E = \left\lceil \frac{(n_S - 576)}{24} \right\rceil$.

The number of sub-packets in the core frame shall always be $S_C = 24$.

For the interleaving, the coded PHY payload is shifted cyclically by 48 symbols; hence the 48 last bits become the 48 first bits.

Interleaving is done in two steps:

1) Assign bits of the coded PHY payload to a sub-packet
2) Place the bits in the right order within the burst data unit

6.4.4.6.2 Bit assignment to sub-packets

The stream of cyclically shifted bits shall be indexed in ascending order with $i \in \{0, 1, 2 \ldots (n_s - 1)\}$, where $i = 0$ represents the first bit. These bits shall be placed into the $S_{TOTAL} = S_C + S_E$ sub-packets.

The sub-packet index $s \in \{0, 1, 2, \ldots, (S - 1)\}$ gives the index of the sub-packet a symbol will be placed in after interleaving.

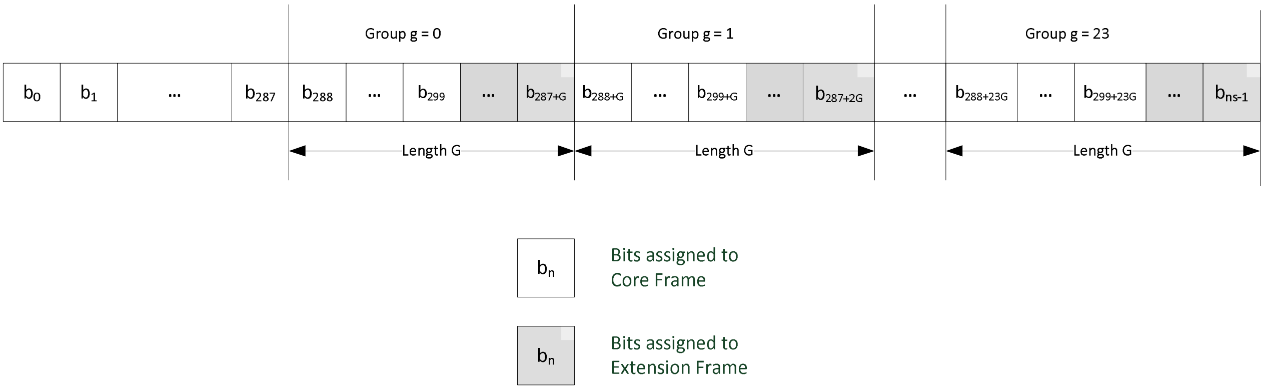

Figure 6-16: Bit order of coded PHY payload before interleaving

The bits $i \in \{0, 1, 2 \ldots 287\}$ shall be placed in the sub-packets of the core frame with starting by placing the first bit $i = 0$ in sub-packet $s = 0$; the next bit $i + 1$ shall be placed in the next sub-packet $s + 1$ and so on. This scheme shall be repeated until $s = S_C - 1$, where the assignment cycle starts again at $s = 0$.

This is represented by the following formula:

$$s(i) = i \text{ modulo } S_C \text{ for } i \in \{0, 1, 2, \ldots 287\}.$$

The remaining unassigned bits are placed in every other sub-packet of the core frame and in every sub-packet of the extension frame. To achieve this, the remaining bit stream starting from $i = 288$ shall be segmented in groups of length $G = S_E + \frac{S_C}{2}$ bits.

The group index g for the current index i is given by: $g(i) = \left\lfloor \frac{(i-288)}{G} \right\rfloor$.

The number of groups is always: $n_G = 24$

The group symbol index $i_g(i) \in \{0,1 \ldots (G-1)\}$ gives the index of a symbol i within the group and is used to determine whether the symbol is part of the core sub-packets or the extension sub-packets. It is given by:

$$i_g(i) = (i - 288) - (g(i) * G).$$

For every group, the first $\frac{S_C}{2}$ bits shall be placed in core sub-packets, hence bits with a group symbol index $i_g(i)$ smaller than $\frac{S_C}{2}$, shall be assigned to core sub-packets. Dependent on the group index, these bits shall be placed in either the even indexed core sub-packets for even group indices or the odd indexed core sub-packets for odd group indices. These assignments are represented by the following two formulas:

$$s(i) = i_g(i) * 2 \text{ for } i_g(i) < \frac{S_C}{2} \text{ and } g(i) = \text{even}$$
$$s(i) = i_g(i) * 2 + 1 \text{ for } i_g(i) < \frac{S_C}{2} \text{ and } g(i) = \text{odd}.$$

The remaining S_E bits of the group shall be assigned to extension sub-packets without distinguishing between even and odd groups:

$$s(i) = i_g(i) + \frac{S_C}{2} \text{ for } i_g(i) \geq \frac{S_C}{2}.$$

6.4.4.6.3 Bit placing within Burst Data Unit

Once all bits are assigned to a sub-packet, the bits shall be interleaved within a sub-packet and assigned to their position on the burst data unit. Bits with a lower index i shall be mapped to symbols around the pilot sequence and bits with a higher index shall be mapped to symbols closer to the start and the end of the radio-burst.

The set $I_s[o]$ holds all indices assigned to the same sub-packet s in ascending order, where $o = 0$ denotes the lowest bit index assigned to sub-packet s and $o = 23$ denotes the highest bit index assigned to sub-packet s.

The bits shall then be mapped to the symbols in the radio-burst according to Table 6-43, where $m = 0$ denotes the first symbol to be transmitted in a radio-burst.

Table 6-43: UL-ULP sub-packet bit to burst data unit symbol mapping

Index o	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
m when s is even	11	24	10	25	9	26	8	27	7	28	6	29
m when s is odd	24	11	25	10	26	9	27	8	28	7	29	6
Index o	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
m when s is even	5	30	4	31	3	32	2	33	1	34	0	35
m when s is odd	30	5	31	4	32	3	33	2	34	1	35	0

The 12 symbols $m \in \{12, 13, 14 \ldots 23\}$ shall be occupied by the symbols of the pilot sequence.

6.4.5 PHY Functions in DL

6.4.5.1 Modulation

6.4.5.1.1 DL-SB Mode

For the DL-SB Mode of the TS-UNB protocol a GFSK modulation with a symbol rate of 600 sym/s and modulation index h=1 (deviation 300 Hz) shall be used.

6.4.5.1.2 DL-TS Mode

6.4.5.1.2.1 Modulation Type

If the DL-TS Mode of the TS-UNB protocol is used a MSK Modulation or GMSK Modulation with BT = 1,0 shall be used.

6.4.5.1.2.2 Symbol mapping

The same symbol mapping as in uplink shall be used.

6.4.5.1.2.3 Symbol rate

The symbol rate of the (G)MSK Modulation in the DL-TS Mode shall be 2 380,371 sym/s. The tolerance of the symbol rate shall be kept within a range of ±0,1 % during one radio-burst.

6.4.5.2 Data Whitening

6.4.5.2.1 Core frame

The complete PHY payload of DL-TS Core frame (see Table 6-39) shall be whitened using the PN9 sequence defined in IEEE 802.15.4 [1].

6.4.5.2.2 Extension frame

The PHY payload of DL-ER Extension frame block (see Table 6-42) shall be whitened using the PN9 sequence defined in IEEE 802.15.4 [1].

6.4.5.3 CRC

6.4.5.3.1 Core frame

A 4-bit CRC, according to clause 6.4.6.2, shall be used for the downlink core frame. The same CRC shall be used for DL-SB and DL-TS Mode.

6.4.5.3.2 Extension frame

An 8-bit CRC, according to clause 6.4.6.2, shall be used for the downlink extension frame. The same CRC shall be used for DL-SB and DL-TS Mode.

6.4.5.4 Forward Error Correction

6.4.5.4.1 DL-SB Mode

No forward error correction shall be used in DL-SB Mode.

6.4.5.4.2 DL-TS Mode

6.4.5.4.2.1 Core frame

A forward error correction, calculated according to clause 6.4.6.3, shall be used to protect the PHY payload of the downlink core frame.

The FEC shall be calculated over all bits of the core frame PHY payload after data whitening. After FEC the sequence of 78 bits results in 252 encoded bits.

6.4.5.4.2.2 Extension frame

A forward error correction, calculated according to clause 6.4.6.3, shall be used to protect the PHY payload of the downlink extension frame block. Each PHY payload block shall be encoded separately.

The FEC shall be calculated over all bits of the PHY payload of the extension frame block after data whitening. One block can transmit 66 to 202 uncoded bits, which results in 216 to 624 encoded bits after the FEC.

6.4.5.5 Interleaving

6.4.5.5.1 DL-SB Mode

No interleaving is used in DL-SB Mode.

6.4.5.5.2 DL-TS Mode

6.4.5.5.2.1 Core frame

The coded PHY payload shall be interleaved according to Table 6-44, whereas:

- s = sub-packet index 0 … S-1
- m = symbol index in radio-burst
- the numbers in the table represent the bit number of the PHY payload of the core frame

Table 6-44: DL-TS core frame interleaver mapping of coded bits onto radio-bursts

m \ s	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	90	93	96	91	94	97	92	95	98
1	0	3	6	1	4	7	2	5	8
2	54	57	60	55	58	61	56	59	62
3	126	129	132	127	130	133	128	131	134
4	72	75	78	73	76	79	74	77	80
5	18	21	24	19	22	25	20	23	26
6	108	111	114	109	112	115	110	113	116
7	36	39	42	37	40	43	38	41	44
8	144	147	150	145	148	151	146	149	152
9	171	174	177	172	175	178	173	176	179
10	198	201	204	199	202	205	200	203	206
11	225	228	231	226	229	232	227	230	233
12	153	156	159	154	157	160	155	158	161
13	180	183	186	181	184	187	182	185	188
14	207	210	213	208	211	214	209	212	215
15	234	237	240	235	238	241	236	239	242
16	162	165	168	163	166	169	164	167	170
17	189	192	195	190	193	196	191	194	197
18	216	219	222	217	220	223	218	221	224
19	243	246	249	244	247	250	245	248	251
20	99	102	105	100	103	106	101	104	107
21	9	12	15	10	13	16	11	14	17
22	63	66	69	64	67	70	65	68	71
23	135	138	141	136	139	142	137	140	143
24	81	84	87	82	85	88	83	86	89
25	27	30	33	28	31	34	29	32	35
26	117	120	123	118	121	124	119	122	125
27	45	48	51	46	49	52	47	50	53

The interleaved bits of a sub-packet shall then be directly mapped to the symbols of the radio-burst:

- $m = 0 \dots 7$, are mapped to the symbols in pilot sequence field PS_DA
- $m = 8 \dots 19$, are mapped to the symbols in required DATA_A Field
- $m = 20 \dots 27$, are mapped to the symbols in pilot sequence field PS_DB

The DATA_B and DATA_C fields are not used.

6.4.5.5.2.2 Extension frame

Interleaving of the extension frame shall also be done block-wise. The minimal input length of the interleaver is 216 bits which corresponds to the number of required data bits in the DL-TS PHY payload of one block.

The table below gives the interleaver mapping of coded bits to the radio-burst, whereas:

- s = sub-packet index 0 … S-1
- m = symbol index in radio-burst
- the numbers in the table represent the bit number of the PHY payload of the extension frame

Table 6-45: DL-TS extension frame interleaver symbol mapping

m\s	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
0	612	615	618	621	624	627	613	616	619	622	625	628	614	617	620	623	626	629
1	576	579	582	585	588	591	577	580	583	586	589	592	578	581	584	587	590	593
2	540	543	546	549	552	555	541	544	547	550	553	556	542	545	548	551	554	557
3	504	507	510	513	516	519	505	508	511	514	517	520	506	509	512	515	518	521
4	468	471	474	477	480	483	469	472	475	478	481	484	470	473	476	479	482	485
5	432	435	438	441	444	447	433	436	439	442	445	448	434	437	440	443	446	449
6	396	399	402	405	408	411	397	400	403	406	409	412	398	401	404	407	410	413
7	360	363	366	369	372	375	361	364	367	370	373	376	362	365	368	371	374	377
8	324	327	330	333	336	339	325	328	331	334	337	340	326	329	332	335	338	341
9	288	291	294	297	300	303	289	292	295	298	301	304	290	293	296	299	302	305
10	252	255	258	261	264	267	253	256	259	262	265	268	254	257	260	263	266	269
11	216	219	222	225	228	231	217	220	223	226	229	232	218	221	224	227	230	233
12 … 19 pilot sequence field PS_DA																		
20	0	3	6	9	12	15	1	4	7	10	13	16	2	5	8	11	14	17
21	36	39	42	45	48	51	37	40	43	46	49	52	38	41	44	47	50	53
22	72	75	78	81	84	87	73	76	79	82	85	88	74	77	80	83	86	89
23	108	111	114	117	120	123	109	112	115	118	121	124	110	113	116	119	122	125
24	144	147	150	153	156	159	145	148	151	154	157	160	146	149	152	155	158	161
25	180	183	186	189	192	195	181	184	187	190	193	196	182	185	188	191	194	197
26	198	201	204	207	210	213	199	202	205	208	211	214	200	203	206	209	212	215
27	162	165	168	171	174	177	163	166	169	172	175	178	164	167	170	173	176	179
28	126	129	132	135	138	141	127	130	133	136	139	142	128	131	134	137	140	143
29	90	93	96	99	102	105	91	94	97	100	103	106	92	95	98	101	104	107
30	54	57	60	63	66	69	55	58	61	64	67	70	56	59	62	65	68	71
31	18	21	24	27	30	33	19	22	25	28	31	34	20	23	26	29	32	35
32 … 39 pilot sequence field PS_DB																		
40	234	237	240	243	246	249	235	238	241	244	247	250	236	239	242	245	248	251
41	270	273	276	279	282	285	271	274	277	280	283	286	272	275	278	281	284	287
42	306	309	312	315	318	321	307	310	313	316	319	322	308	311	314	317	320	323
43	342	345	348	351	354	357	343	346	349	352	355	358	344	347	350	353	356	359
44	378	381	384	387	390	393	379	382	385	388	391	394	380	383	386	389	392	395
45	414	417	420	423	426	429	415	418	421	424	427	430	416	419	422	425	428	431
46	450	453	456	459	462	465	451	454	457	460	463	466	452	455	458	461	464	467
47	486	489	492	495	498	501	487	490	493	496	499	502	488	491	494	497	500	503
48	522	525	528	531	534	537	523	526	529	532	535	538	524	527	530	533	536	539
49	558	561	564	567	570	573	559	562	565	568	571	574	560	563	566	569	572	575
50	594	597	600	603	606	609	595	598	601	604	607	610	596	599	602	605	608	611
51	630	633	636	639	642	645	631	634	637	640	643	646	632	635	638	641	644	647

The interleaved bits of a sub-packet shall then be directly mapped to the symbols of the radio-burst:

- $m = 0 \dots 11$, are mapped to the symbols in data field DATA_B
- $m = 12 \dots 19$, are mapped to the symbols in required pilot sequence field PS_DA
- $m = 20 \dots 31$, are mapped to the symbols in data field DATA_A
- $m = 32 \dots 39$, are mapped to the symbols in required pilot sequence field PS_DB
- $m = 40 \dots 51$, are mapped to the symbols in data field DATA_C

If the number of bits is not a multiple of the number of sub-packets in the block, the sizes of the sub-packets differ inside of one block.

6.4.6 Commonly used PHY Functions

6.4.6.1 Introduction

There are common PHY functions which are used in different sections of the physical layer. They are described here to be referenced in the appropriate sections.

6.4.6.2 CRC

All 2-bit CRCs shall be calculated with the following parameters:

- 2 bit length (CRC-2)
- Polynomial: 0x3
- Initial value: 0x3
- No XOR

All 4-bit CRCs shall be calculated with the following parameters:

- 4 bit length (CRC-4)
- Polynomial: 0x3
- Initial value: 0xF
- No XOR

All 8-bit CRCs shall be calculated with the following parameters:

- 8 bit length (CRC-8)
- Polynomial: 0x9B
- Initial value for calculation: 0xFF
- No XOR

6.4.6.3 FEC

All FECs shall be calculated with the following parameters:

- Convolutional code
- Rate: 1/3
- Polynomials (0155, 0123, 0137) (octal), (0x6D, 0x53, 0x5F)) (hex)
- Constraint length: 7
- Zero-tailing

6.4.7 PHY Procedures

6.4.7.1 TSMA Schemes

6.4.7.1.1 Overview

In the TS-UNB protocol the application message is not transmitted in one radio-burst. The PPDU of the TS-UNB protocol in uplink and downlink DL-TS mode shall be split into several radio-bursts, which are distributed over time and frequency. The set of radio-bursts belonging to one message are called radio-frame. A radio frame is further divided into a core frame and an extension frame. The radio bursts within a radio-frame are spread over 24 or 25 carriers with a carrier spacing step size of B_c.

In the uplink core frame and the downlink core and extension frame the way the radio-bursts are distributed over time and frequency is called TSMA pattern. A TSMA pattern consists of a set of carrier numbers and time spacings defining the transmission time and frequency of the radio-bursts within the radio-frame. The carrier numbers are chosen from a set of 24 carriers (C=0…23) with a carrier spacing of B_C. Carrier number C=24 shall be used only for the transmission of an optional Sync-Burst in front of the radio frames.

In the uplink extension frame all 25 carriers are used for the transmission of a radio-burst. The carrier numbers and time spacings are derived from the CRC (see clause 6.4.7.1.7.1).

In uplink the following TSMA pattern groups are possible:

- Uplink Pattern Group 1 (UPG1) with 8 patterns using 24 carriers (C=0…23), which shall be used if a radio-frame is transmitted once.
- Uplink Pattern Group 2 (UPG2) with 8 patterns using 24 carriers (C=0…23), which shall be used if the radio frame is repeated. The pattern group shall be used for both the initial transmission and repetition.
- Uplink Pattern Group 3 (UPG3) with 1 pattern using 24 carriers (C=0…23), which shall be used if a radio-frame is transmitted with low latency requirement. Repetition shall not be used with pattern of this group.

In downlink one pattern group DPG is available.

For the transmission of a radio-frame one TSMA pattern of the pattern group shall be selected. The TSMA pattern shall vary from radio frame to radio-frame. The start time T_0 and the start frequency f_0 of the TSMA pattern are varying between end-points.

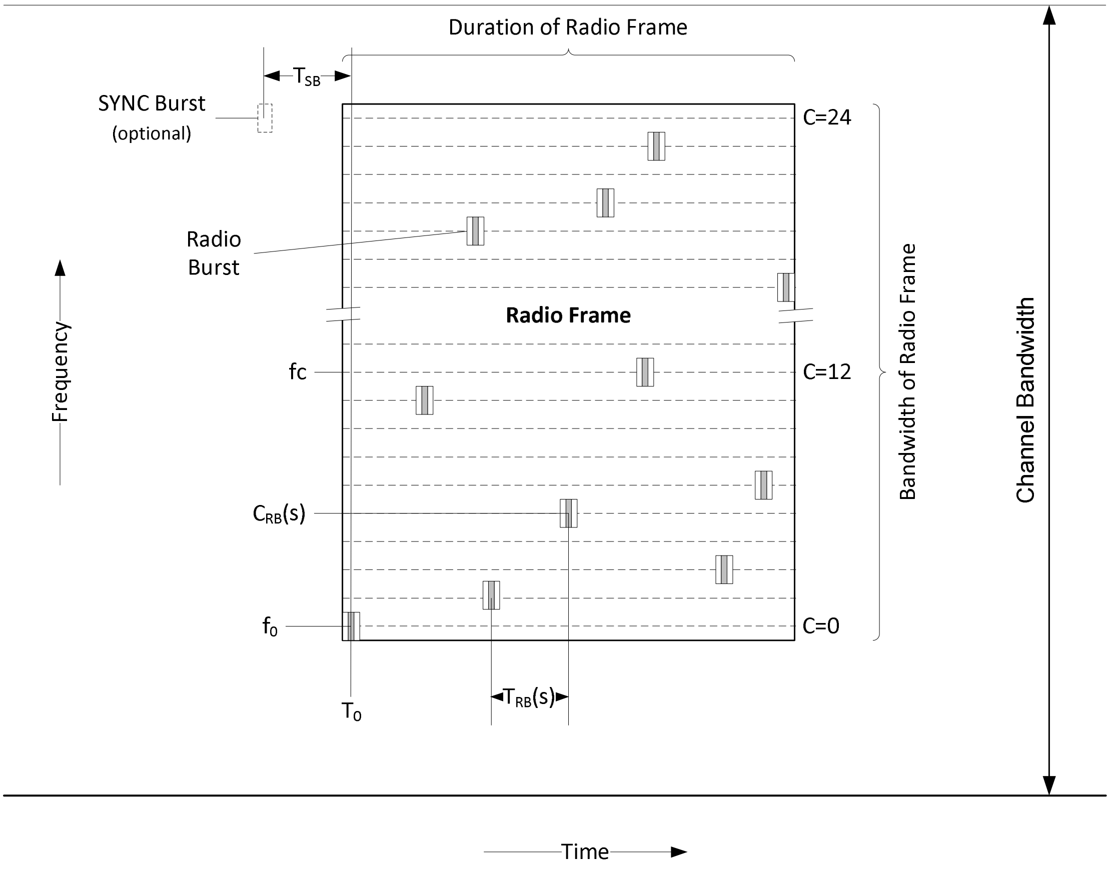

Figure 6-17: TSMA scheme of a radio frame

The radio frame shall be transmitted within the bandwidth B_{ch} of a channel with the channel centre frequency f_c taking crystal tolerances and pseudorandom carrier offset into account.

NOTE: If no frequency offset applies the nominal carrier frequency of carrier 12 is the centre frequency f_c of the channel.

The start frequency f_0 is the carrier frequency of carrier zero of the 24 carriers used by the TSMA pattern. It is derived from the channel centre frequency by:

$$f_0 = f_c - 12 * B_c + f_{Offset}$$

The frequency offset f_{offset} is a variable radio-frame offset, which is calculated according to the following formula:

$$f_{offset} = C_{RF} * B_{C0}$$

where: B_{C0} is the frequency offset step of 2.380,371 Hz ;

C_{RF} is an additional frequency offset in number of frequency offset steps B_{C0} selected by the end-point and set for every radio-frame depending on the payload CRC.

The transmission frequency f_{RB} of a radio-burst (Radio-burst Frequency) is defined as:

$$f_{RB}(s) = f_0 + C_{RB}(s) * B_C$$

where: C_{RB} is the radio-burst carrier number according to the TSMA pattern chosen for the transmission of the radio-frame;

B_C is the actual carrier spacing step size.

Three different carrier spacing step sizes B_c according to Table 6-58 in clause 6.5.1 are available to address different radio regulations.
The carrier spacing step size B_C of the standard TSMA mode used for one 100 kHz channel shall be 2 380,371 Hz. The carrier spacing accuracy shall be ±5,0 Hz across all radio-bursts within one radio-frame.

If two radio channels A and B are used, the frame transmissions shall be alternated between the two channels. The channel to be used for transmission shall be derived from the least significant bit of the payload CRC according to Table 6-48.

6.4.7.1.2 Frame Repetition

6.4.7.1.2.1 Uplink repetition

For performance improvement a radio frame may be repeated. The repeated radio frame rFRAME shall have the identical data format as the initial radio frame iFRAME. Both transmissions, iFRAME and rFRAME shall use the same TSMA pattern of the uplink TSMA pattern group UPG2 with a timeslot offset S_{RF}.

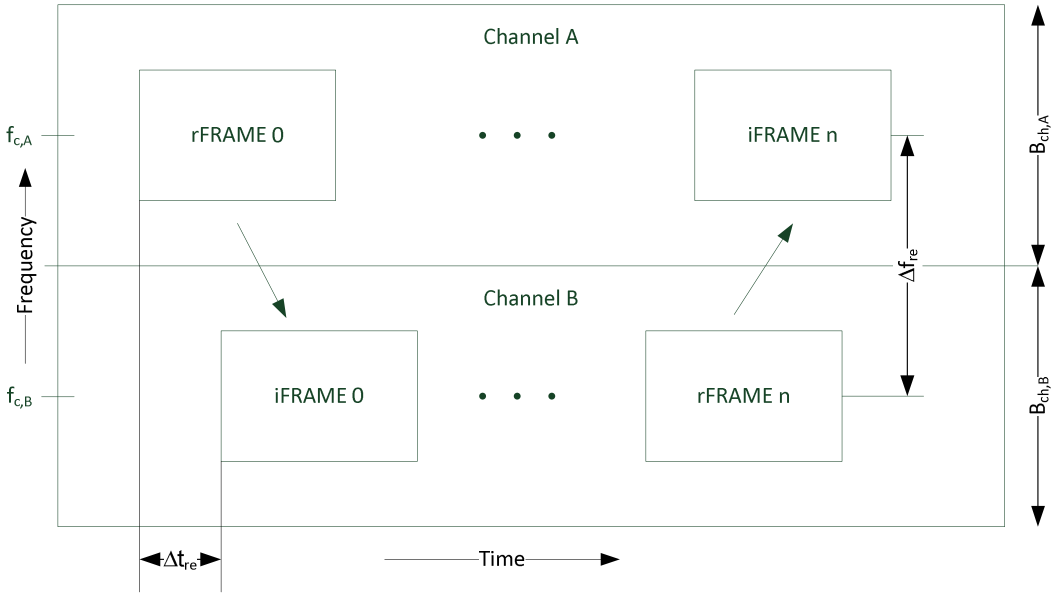

Figure 6-18: Frame transmission and repetition

Repetitions may be used in single and dual channel transmission mode. The repeated frame rFRAME shall have a fixed frequency offset Δf_{re} and a variable time offset Δt_{re} according to clause 6.4.7.1.5 from the initial frame transmission. If single channel transmission is used Δf_{re} shall be (0).

If dual channel mode is used, the repetition shall always be transmitted in the frequency channel opposite to the initial iFRAME transmission with a frequency offset of:

$$\Delta f_{re} = N_{re} * B_c$$

where: N_{re} is the number of carrier frequency offset steps and is adjusted to the radio regulations (see profiles in annex A).

The base station may configure the end-point to repetition mode when attaching the end-point to the LTN network.

6.4.7.1.3 Downlink repetition

In downlink TS-Mode, only the core frame may be repeated. The downlink extension frame shall not be repeated. The repetition of the downlink core frame uses the second half of the downlink TSMA pattern.

6.4.7.1.4 Radio burst time

The start time T_0 of the first radio-burst s=0 of a radio frame is randomly chosen by the end-point and defined as the middle of the pilot sequence of the radio-burst. The transmission time of a radio-burst (Radio-burst Time) $T_{RB}(s)$ is defined as the time difference between two radio-bursts from the middle of the pilot sequence of radio-burst s to the middle of the pilot sequence of the previous radio-burst s-1 in number of symbol durations as illustrated in Figure 6-19.

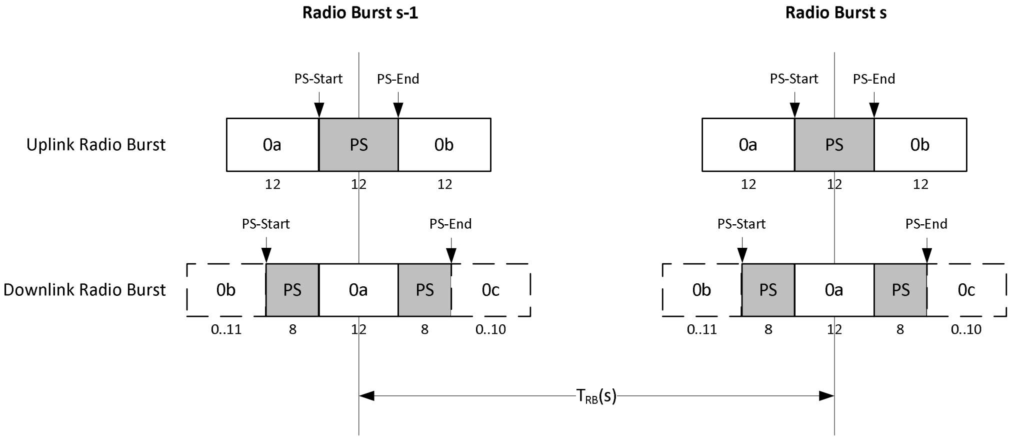

Figure 6-19: Definition of Radio-burst Time $T_{RB}(s)$

The end-point shall keep the radio-burst timing within a tolerance of $\pm \frac{\Delta T}{4}$ over the complete radio frame period from the first radio-burst to the last radio-burst, whereas ΔT is the duration of one modulated symbol.

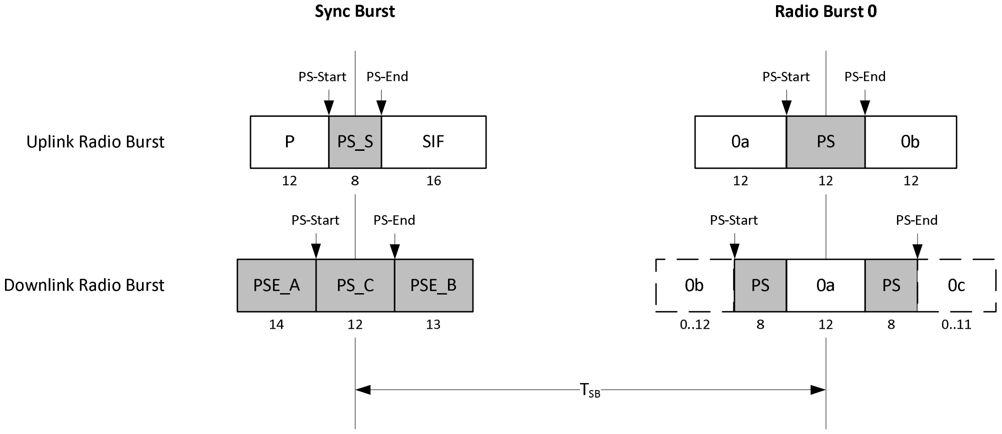

Figure 6-20: Definition of Sync-burst Time T_{SB}

If an additional Sync-burst is used, it shall be transmitted one carrier spacing above the highest carrier (C=24) of the carrier group and T_{SB} symbols before radio-burst 0 of the uplink and downlink core frame as well as before radio-burst 0 of each block of the downlink extension frame. The time spacings T_{UPG1-3} according to Table 6-46 shall be used for T_{SB}.

Table 6-46: Time spacings of Uplink Pattern Groups

Name	Time spacing
Uplink Pattern Group 1	T_{UPG1} = 337 symbols
Uplink Pattern Group 2	T_{UPG2} = 337 symbols
Uplink Pattern Group 3	T_{UPG3} = 66 symbols

The time spacing in Table 6-46 shall also be used for the calculation of radio-burst time in the uplink extension frame (see clause 6.4.7.1.6.2).

6.4.7.1.5 Frame time and frequency offset

A pseudorandom offset in frequency and time derived from the Header and Payload CRC shall be added to the selected TSMA pattern start frequency and start time according to Figure 6-21.

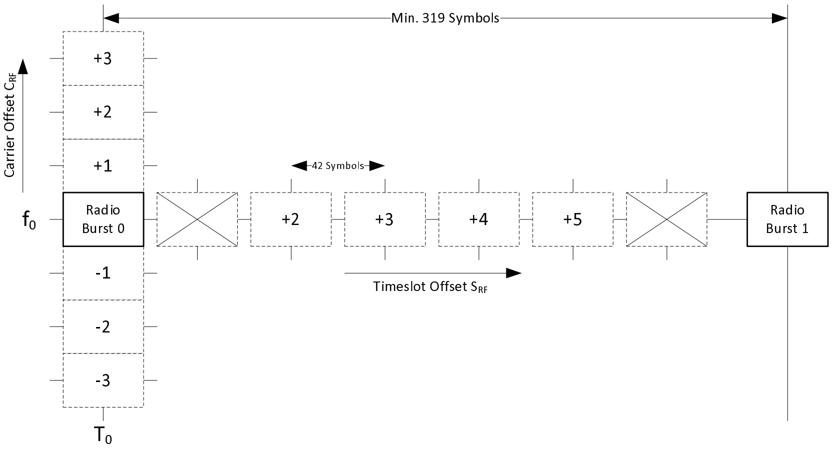

Figure 6-21: Definition of frame start offset parameter

The timeslot offset is only used for repetitions. The timeslot offset n_{ts} is given in number of timeslots. The duration of a timeslot is 42 symbols. For the initial frame transmission the timeslot offset shall be 0. The shifted start time of the first radio-burst of the repetition shall be then:

$$T_0' = T_0 + n_{ts} * 42 * \Delta T$$

The timeslot offset n_{ts} is derived from the header CRC (Table 6-47). The timeslot offset n_{ts} is calculated in the following way:

$$n_{ts} = v_{ts} + 2$$

Table 6-47: Bit representation of Header CRC

Header CRC	Value	Used as
Bit 0-1	0…3	Timeslot offset value v_{ts}
Bit 2-3		Reserved for future use
Bit 4-7	0…15	Downlink TSMA Pattern selection value v_{TSDL}

The base station shall select the downlink TSMA pattern p_{TSDL} using Bit 4-7 of the header CRC from the received uplink transmission according to the following formula:

$$p_{TSDL} = (v_{TSDL} \mathit{modulo}\ (PGsize)) + 1$$

Where $PGsize$ is the number of pattern of the downlink pattern group.

A frequency offset in integer multiples of the frequency offset steps B_{C0} shall be added to the start frequency f_0 of the selected TSMA pattern for every frame transmission. The same frequency offset shall be used for initial frame transmission and frame repetition. The offset parameter C_{RF} shall be derived from the payload CRC. Bit 0 of the payload CRC shall be used for the selection of the channel if dual channel operation is used. Bit 1-7 shall be used as carrier offset value to calculate the carrier offset value.

Table 6-48: Bit representation of Payload CRC

Payload CRC	Value	Used as
Bit 0	0/1	Channel selection for frame transmission (used only for two channel operation) 0: upper channel A 1: lower channel B
Bit 1-7	0…127	Carrier offset value v_{co}

The variable carrier offset C_{RF} shall be set within a range that the carrier offset together with the radio frame bandwidth and the natural crystal tolerance do not exceed the channel bandwidth. Two carrier offset ranges are possible and shall be defined during the attach process of the end-point:

- Range of ±1 carrier offset, where n_{co} is set to 3 (for crystal tolerance => 10 ppm)
- Range of ±5 carrier offset, where n_{co} is set to 11 (for crystal tolerance < 10 ppm)

The carrier offset shall be calculated according to the following formula:

$$C_{RF} = (v_{co}\ \mathit{modulo}\, n_{co}) - \left\lfloor {}^{n_{co}}/_{2} \right\rfloor$$

During the attach process the node shall use the lower range of carrier offset.

6.4.7.1.6 Uplink TSMA Pattern

6.4.7.1.6.1 Core Frame

The following tables give the sets of radio-burst carrier $C_{RB}(s)$ and radio-burst time $T_{RB}(s)$ of the uplink TSMA pattern.

Table 6-49: Radio-burst carrier set of Uplink TSMA Pattern Group 1 (UPG1)

s	$C_{RB}(s)$											
p	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	5	21	13	6	22	14	1	17	9	0	16	8
2	4	20	12	1	17	9	0	16	8	6	22	14
3	4	20	12	3	19	11	6	22	14	7	23	15
4	6	22	14	2	18	10	7	23	15	0	16	8
5	7	23	15	4	20	12	3	19	11	2	18	10
6	3	19	11	6	22	14	2	18	10	0	16	8
7	3	19	11	1	17	9	5	21	13	7	23	15
8	0	16	8	6	22	14	3	19	11	2	18	10

s	$C_{RB}(s)$											
p	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
1	7	23	15	4	20	12	3	19	11	2	18	10
2	7	23	15	2	18	10	5	21	13	3	19	11
3	0	16	8	5	21	13	2	18	10	1	17	9
4	1	17	9	4	20	12	5	21	13	3	19	11
5	6	22	14	0	16	8	1	17	9	5	21	13
6	7	23	15	1	17	9	4	20	12	5	21	13
7	0	16	8	2	18	10	6	22	14	4	20	12
8	4	20	12	7	23	15	5	21	13	1	17	9

Table 6-50: Radio-burst time set of Uplink TSMA Pattern Group 1 (UPG1)

s	$T_{RB}(s)$																						
p	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
1	330	387	388	330	387	354	330	387	356	330	387	432	330	387	352	330	387	467	330	387	620	330	387
2	330	387	435	330	387	409	330	387	398	330	387	370	330	387	361	330	387	472	330	387	522	330	387
3	330	387	356	330	387	439	330	387	413	330	387	352	330	387	485	330	387	397	330	387	444	330	387
4	330	387	352	330	387	382	330	387	381	330	387	365	330	387	595	330	387	604	330	387	352	330	387
5	330	387	380	330	387	634	330	387	360	330	387	393	330	387	352	330	387	373	330	387	490	330	387
6	330	387	364	330	387	375	330	387	474	330	387	355	330	387	478	330	387	464	330	387	513	330	387
7	330	387	472	330	387	546	330	387	501	330	387	356	330	387	359	330	387	359	330	387	364	330	387
8	330	387	391	330	387	468	330	387	512	330	387	543	330	387	354	330	387	391	330	387	368	330	387

Table 6-51: Radio-burst carrier set of Uplink TSMA Pattern Group 2 (UPG2)

s	$C_{RB}(s)$																							
p	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
1	4	20	12	0	16	8	3	19	11	5	21	13	1	17	9	7	23	15	2	18	10	6	22	14
2	3	19	11	7	23	15	2	18	10	5	21	13	4	20	12	0	16	8	1	17	9	6	22	14
3	6	22	14	0	16	8	1	17	9	4	20	12	3	19	11	5	21	13	2	18	10	7	23	15
4	3	19	11	1	17	9	4	20	12	5	21	13	2	18	10	7	23	15	6	22	14	0	16	8
5	5	21	13	2	18	10	0	16	8	6	22	14	7	23	15	1	17	9	4	20	12	3	19	11
6	1	17	9	3	19	11	4	20	12	6	22	14	7	23	15	5	21	13	2	18	10	0	16	8
7	5	21	13	1	17	9	2	18	10	4	20	12	3	19	11	0	16	8	6	22	14	7	23	15
8	3	19	11	6	22	14	5	21	13	1	17	9	7	23	15	2	18	10	0	16	8	4	20	12

Table 6-52: Radio-burst time set of Uplink TSMA Pattern Group 2 (UPG2)

s	$T_{RB}(s)$											
p	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	373	319	545	373	319	443	373	319	349	373	319	454
2	373	319	371	373	319	410	373	319	363	373	319	354
3	373	319	414	373	319	502	373	319	433	373	319	540
4	373	319	396	373	319	516	373	319	631	373	319	471
5	373	319	655	373	319	416	373	319	367	373	319	400
6	373	319	370	373	319	451	373	319	465	373	319	593
7	373	319	393	373	319	374	373	319	344	373	319	353
8	373	319	367	373	319	346	373	319	584	373	319	579
s	$T_{RB}(s)$											
p	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
1	373	319	578	373	319	436	373	319	398	373	319	
2	373	319	379	373	319	657	373	319	376	373	319	
3	373	319	428	373	319	467	373	319	409	373	319	
4	373	319	457	373	319	416	373	319	354	373	319	
5	373	319	415	373	319	342	373	319	560	373	319	
6	373	319	545	373	319	380	373	319	365	373	319	
7	373	319	620	373	319	503	373	319	546	373	319	
8	373	319	519	373	319	351	373	319	486	373	319	

Table 6-53: Radio-burst carrier set of Uplink TSMA Pattern Group 3 (UPG3)

s	$C_{RB}(s)$											
p	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	1	5	4	3	2	17	21	20	19	18	9	13
s	$C_{RB}(s)$											
p	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
1	12	11	10	6	0	7	22	16	23	14	8	15

Table 6-54: Radio-burst time set of Uplink TSMA Pattern Group 3 (UPG3)

s	$T_{RB}(s)$											
p	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	66	66	66	66	66	66	66	66	66	123	66	66
s	$T_{RB}(s)$											
p	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
1	66	66	60	66	66	198	66	66	255	66	66	

If UPG1 or UPG2 is chosen, the TSMA Pattern 1-6 of the selected uplink carrier group shall be used for uplink communication with the pattern sequence order (1,2,3,4,1,2,3,4,5,1,2,3,4,5,6). The sequence is cyclically repeated. TSMA pattern 6 of the selected carrier group shall be used during attach process, TSMA pattern 7 of the selected carrier group may be used for high priority messages (e.g. alarms) and TSMA pattern 8 is reserved for future use.

Pattern Group UPG3 shall be used only, if a radio frame with low latency requirement needs to be transmitted.

6.4.7.1.6.2 Extension Frame

The TSMA pattern for the extension frame is derived from information of the core frame. The TSMA pattern of the extension frame is generated using a pseudo random number derived from the core frame information.

A 16-bit Linear Feedback Shift Register (LFSR) shall be used to generate a random number $R[s_e]$ for every s_e-th radio-burst of the extension frame. The initial 16 bit seed for this LFSR $R[0]$ shall be the concatenated Header CRC and the Payload CRC with the Header CRC as the most significant bits and the Payload CRC as the least significant bits. The highest bit of this seed shall be always set to 1.

Table 6-55: LFSR Seed R[0]

Bits: 15	**14-8**	**7-0**
1	Header CRC [6-0]	Payload CRC [7-0]

The polynomial for the Galois-LFSR in hexadecimal notation shall be (0xB4F3). For every radio-burst of the extension frame, the LFSR shall be applied to derive the next 16 bit number. For radio-burst s_e of the extension frame, the number is given by:

$$R[s_e] = LFSR(R[s_e - 1])$$

Where s_e shall be (1) for the first radio-burst of the extension frame. The radio-burst time of radio-burst s_e in the extension frame shall be calculated by:

$$T_{RB}[s_e] = (T_{UPGx} + (R[s_e] \text{ modulo } 128)) * T_{sym_{UL-ULP}}$$

where: T_{UPGx} shall be the time spacing of the selected uplink pattern group x the transmitted core was part of according to Table 6-46.

For the first radio-burst in the extension frame, this time denotes the delay between the centre of the pilot symbols of the last radio-burst of the core frame and the centre of the pilot symbols of the first radio-burst of the extension frame. The radio-burst carrier number for deriving the transmission frequency of the radio-burst of the extension frame shall be calculated by:

$$C_{RB}[s_e] = \lfloor (R[s_e]/256) \rfloor \text{ modulo } 25$$

For repetition the same values are used for initial transmission and repetition of the frame.

6.4.7.1.7 Downlink TSMA pattern

6.4.7.1.7.1 DL-TS Mode

In downlink a radio frame shall consist of 18 radio-bursts. Therefore TSMA pattern sets with 18 parameters according to the following tables shall be used.

Table 6-56: Radio-burst carrier set of TSMA Pattern Group in downlink (DPG)

s	$C_{RB}(s)$																	
p	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
1	19	18	12	21	15	14	22	2	5	10	17	6	8	4	7	20	13	0
2	10	4	1	7	23	6	3	8	17	2	18	9	22	14	11	16	5	21
3	0	16	11	20	9	13	23	21	2	19	1	15	3	7	12	4	22	6
4	14	9	0	15	7	5	8	18	1	12	19	23	17	16	10	2	13	11
5	6	12	19	10	4	22	13	17	11	5	23	3	1	8	14	0	9	20
6	16	20	3	5	21	10	17	1	12	18	15	11	0	9	2	14	6	8
7	15	0	8	18	9	23	11	20	14	3	16	22	19	13	7	21	12	4
8	4	7	16	22	13	19	2	3	6	15	10	20	23	5	21	17	18	1

Table 6-57: Radio-burst time set of TSMA Pattern Group in downlink (DPG)

s	$T_{RB}(s)$ **T$_{RB}$(s)**																
p	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
1	471	595	594	496	545	445	440	535	601	522	430	545	519	439	484	438	605
2	512	424	649	447	550	611	624	418	501	464	606	509	636	443	465	434	431
3	625	548	540	434	520	559	488	531	501	465	459	428	444	459	505	459	633
4	457	489	612	450	457	440	567	538	516	514	540	474	592	445	577	444	493
5	488	643	626	541	560	550	450	475	520	456	618	447	455	440	455	510	477
6	548	444	459	529	453	525	440	553	583	527	520	461	575	457	464	533	421
7	461	607	501	534	505	569	561	472	509	450	555	440	423	494	448	525	485
8	577	611	464	552	451	508	478	438	443	507	420	553	520	576	580	564	404

The downlink transmission shall start at predefined time (see clause 6.3.2.7.1) after an uplink transmission.

The start frequency $f_{0,DL}$ of the DL TSMA pattern is determined as:

$$f_{0,DL} = f_{0,ULRX} + f_{DL-UL}$$

where: $f_{0,ULRX}$ is the centre frequency of the received radio frame in the base station

f_{DL-UL} is the offset frequency between uplink channel and downlink channel centre frequency.

The TSMA pattern number for downlink transmission to the end-point shall be derived from the header CRC according to clause 6.4.7.1.5.

The same TSMA pattern shall be used for the core frame and each block of the extension frame. The start time of the extension frame may vary and shall be indicated by the TSI field in the core frame.

6.4.7.1.7.2 DL-SB Mode

In DL-SB Mode, no telegram splitting shall be used. Hence for the transmission of a radio-burst the carrier offset $C_{RF}(s = 0)$ from the selected pattern of TSMA pattern group shall be used for core and extension frame.

6.5 Radio Characteristics

6.5.1 Spectrum Use

The TS-UNB protocol may be configured to different spectrum requirements. It may be operated in different SRD sub bands in Europe by adjusting the carrier spacing of the TSMA pattern. When operated in a sub band with a bandwidth of at least 100 kHz the standard TSMA mode with a carrier spacing $B_C = 2\ 380{,}371\ \ Hz$ shall be used. For a wider spectrum bandwidth of at least 750 kHz a carrier spacing $B_C = 28\ 565{,}453\ Hz$ may be used instead. For operation in a sub band with a lower bandwidth of less than 100 kHz, the TSMA mode narrow with a carrier spacing $B_C = 396{,}729\ Hz$ may be used instead.

Table 6-58: Overview of TSMA modes

TSMA Mode	Channel Bandwidth	Carrier Spacing step size B_c	Occupied bandwidth per frame
Narrow	25 kHz	396,729 Hz	12,616 kHz
Standard	100 kHz	2 380,371 Hz	60,223 kHz
Wide	725 kHz	28 564,453 Hz	688,641 kHz

Table 6-58 gives an overview of the different TSMA modes with their carrier spacing step sizes and the occupied bandwidth per frame as well as their required channel bandwidth for single channel operation.

6.5.2 Channel access

The TS-UNB protocol may use random channel access without listen before talk. The relevant radio regulations on duty cycle limit the number of messages and data that can be transmitted. Table 6-59 gives the transmission times for different TS-UNB protocol modes.

Table 6-59: Radio transmission times

	Radio Burst duration	Core Frame on-air time	Extension Frame on-air time
UL-ULP	15,14 ms	362,97 ms	15,14 ms per add. Byte in MPDU
UL-ER	90,74 ms	2 177,81 ms	90,74 ms per add. Byte in MPDU
DL-TS	11,76…21,43 ms	105,87 ms	211,73…383,13 ms per add. Extension frame block

In the TSMA scheme, a radio burst is always followed by a radio transmission pause, thus implementing a certain duty cycle according to the TSMA pattern used. The transmission time of the uplink extension frame is extended by one radio burst per additional byte user data. The transmission time of the downlink extension frame with a fixed number of radio bursts varies depending on the payload to be transmitted.

6.5.3 End-point

6.5.3.1 Carrier Frequency Tolerance

In the end-point symbol time and carrier frequency generation shall be derived from a common reference oscillator (preferable with a frequency of 26 MHz) with a tolerance below ±20 ppm.

6.5.4 Base station

6.5.4.1 Carrier Frequency Tolerance

The base station RF frequency tolerance shall be better than ±5 ppm.

6.5.4.2 Receiver

6.5.4.2.1 Receiver Bandwidth

The receiver bandwidth depends on the system mode of operation and shall be set accordingly.

7 Dynamic Downlink Ultra Narrow Band (DD-UNB) family

7.1 System overview

7.1.1 System elements

7.1.1.1 Architecture

A LTN system running DD-UNB protocol comprises a Service Centre (SC), a number of Base Stations (BS), and many End-points (EP). Some EP may not be in the coverage area of a BS (referred to as Orphaned End-points or OEP). OEP can be connected to the network using a relay link through another EP (called Relay Point or RP).

LTN systems are based on the architecture described in ETSI TS 103 358 [i.9] (Low Throughput Networks (LTN) Architecture). In the case of the DD-UNB system the A-interface protocol supports communication over the A-interface, i.e. between a Base Station (BS) and an End-point (EP); the same protocol provides communication between BS and RP over the A"-interface (typically an EP can be configured to act also as a RP).

The A"-interface is the DD-UNB air interface for the bidirectional relay link between OEP and RP.

The B-interface is the backhaul access network interface (e.g. over cellular) used for communication between BS and SC; backhaul link protocol is out of the scope of the present document.

7.1.1.2 Service Centre

The present document describes a DD-UNB system with a single SC. It is possible to have multiple linked Service Centres to increase capacity for very large systems, but such an arrangement is implementation-specific and out of scope of the present document.

7.1.1.3 Base station

A DD-UNB BS includes a transmitter and a receiver. The receiver typically has an analogue bandwidth greater than 15 kHz and digital signal processing (DSP) which can receive multiple concurrent DD-UNB signals on different frequencies within that bandwidth. The transmitter typically operates at higher power levels (500 mW erp) than EP with a higher gain antenna. The downlink data rate is 8 times that of the uplink.

BSs are connected to the Service Centre using backhaul transmission links (over B interface).

7.1.1.4 End-points

An EP can receive a single DL transmission or transmit a single UL signal on a single frequency at any one time; this can be on the A or A"-interface.

The A"-interface is used by an EP to communicate with a BS via another EP acting as a relay point (RP). The DD-UNB system is not designed to operate as a multi-hop mesh system and allows only one such "extra" hop for each connection.

7.1.2 Protocol Overview

7.1.2.1 Introduction

The DD-UNB protocol is based on the OSI reference model. A typical implementation of DD-UNB is illustrated in Figure 7-1 (for downlink). Physical layer (PHY) and Medium Access Control (part of layer 2 - Data link layer (DLL)) are described in the present document. The remainder of DLL and higher layers are implementation-dependent.

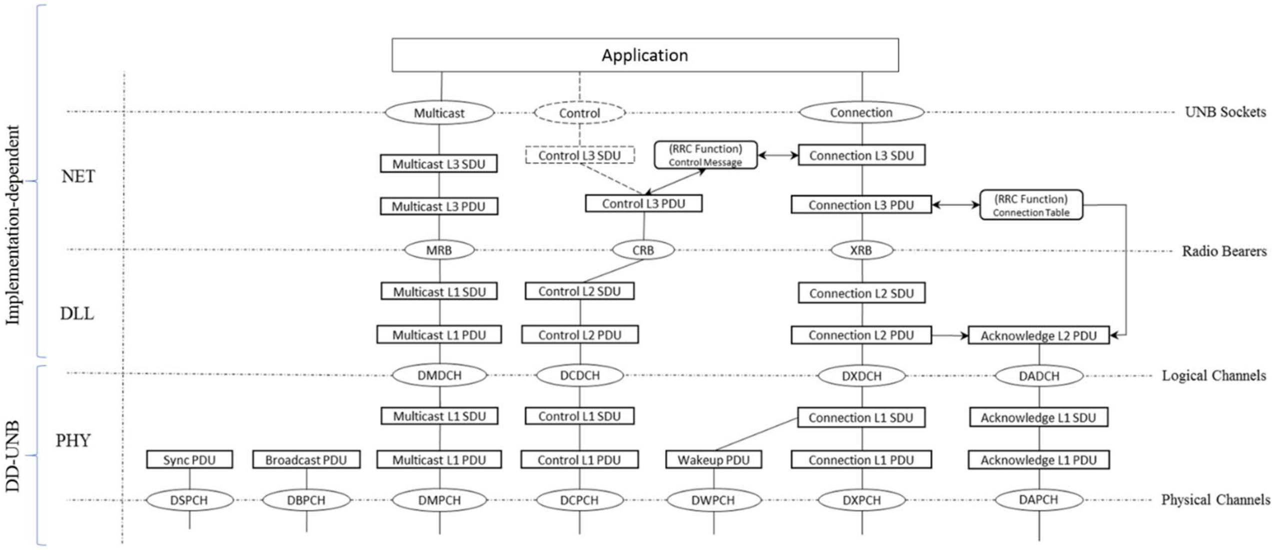

Figure 7-1: DD-UNB Protocol Layers (Downlink) in example implementation

DD-UNB is designed as an efficient means of meeting, within severely constrained resources, the requirements of applications served by LTN systems, and provides a means of transferring 14-byte application messages between a service centre and end-points. While the basic OSI layering model is used, the inherently-limited resources and the benefits of reducing overheads result in the removal of some opacity between the layers of the DD-UNB system. This applies particularly to addressing where a single addressing scheme is assumed at all layers of the DD-UNB protocol. Layers use common sets of parameters as much as possible, for example the "block number" associated with each connection data unit at layer 3 is also used by lower layers to reduce overhead.

The Medium Access Control (MAC) is treated as part of DLL and used only in uplink direction.

7.1.2.2 Protocol Termination Points

The present document specifies behaviour of PHY and MAC. A typical implementation of DD-UNB provides functionality at higher layers and this clause describes how protocols at those layers might be terminated to provide support for typical applications.

Figure 7-2 describes the A-interface protocol DL termination points. Note that all Layer 3 downlink services initiated from SC are supported (Figure 7-2 (a)). In addition, Multicast service may be initiated from BS (Figure 7-2 (b)) where this meets application needs.

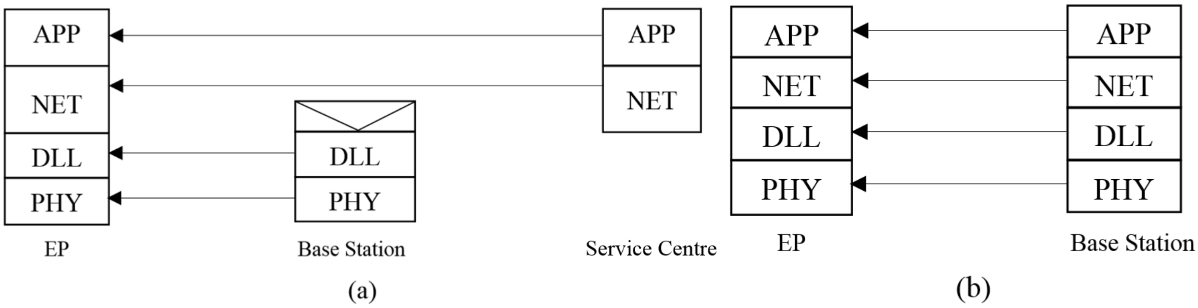

Figure 7-2: Protocol Termination (A-interface Downlink)

A-interface protocol UL termination points are shown in Figure 7-3.

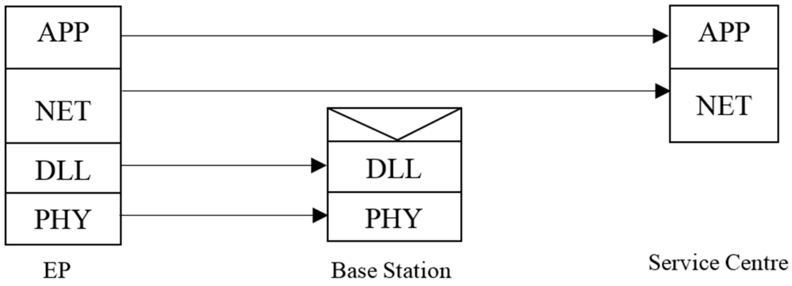

Figure 7-3: Protocol Termination (A-interface Uplink)

In cases where a relay node is used, Figure 7-4 and Figure 7-5 illustrate protocol termination points in A" downlink. All Layer 3 A" downlink services are initiated from SC; Multicast service may also be initiated from BS.

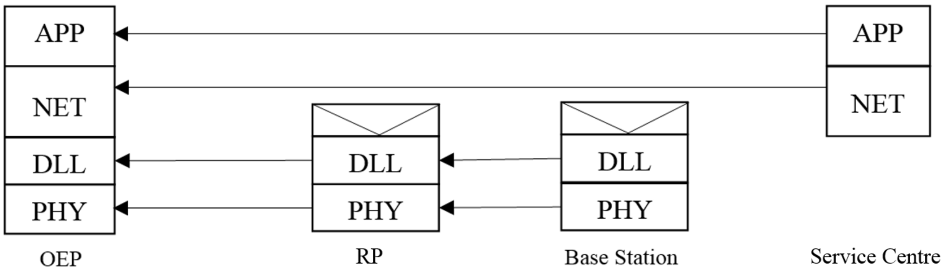

Figure 7-4: Protocol Termination (A" Downlink - SC initiated App)

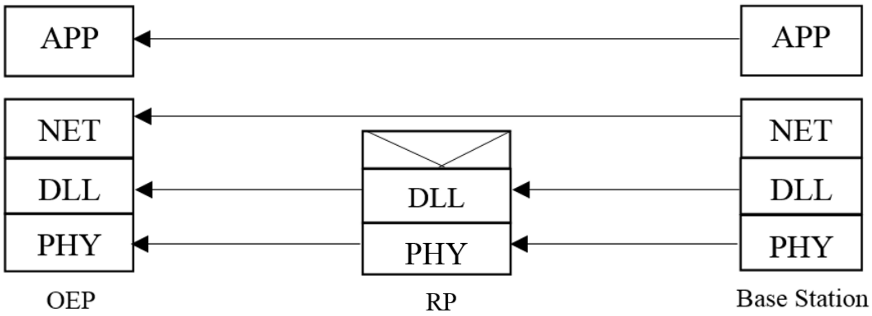

Figure 7-5: Protocol Termination (A" Downlink - BS initiated App)

Figure 7-6 illustrates protocol termination points for A" uplink.

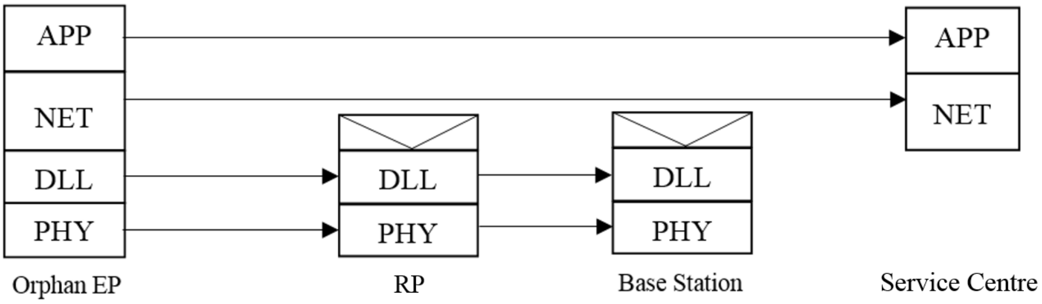

Figure 7-6: Protocol Termination (A"-interface Uplink)

7.1.2.3 System Addressing and Identities

Several address types are used by DD-UNB protocol to address different entities in each system:

- A unique 10 bit Short System ID (SSID) is used to identify the system.
- End-point ID (EPID) is a unique 32 bit BSGP allocated for each EP in the system.
- Base Station ID (BSID) is a unique 13 bit identifier allocated for each BS in the system.
- Connection ID (ConID) is a 14 bit identifier which is unique for each connection within a cell but may be reused in other cells. ConID value 0x0 is reserved for use in A" UL management (see clause 7.3.2.3 and Table 7-6).

In addition a EUI-64 identifier is used for globally-unique identification of End-points.

7.1.3 Upper Layer Principles

DD-UNB provides the L1 / MAC mechanisms to support the implementation of a guaranteed delivery mechanism for streams of Data PDUs (or a definite indication of failure and, in this case, an indication of which blocks have been delivered). Acknowledge PDUs can be used by both L2 and L3 to provide acknowledgement, repetition and flow control for connections on a hop-by-hop and end-to-end basis respectively. Layers above L1 / MAC are implementation-dependent.

Connection-oriented links are anticipated to dominate communications between application entities in a DD-UNB system.

In order to identify each EP uniquely, a 32 bit EP identifier is used (about 4 billion differs). Since a typical system would have a much smaller EP population, DD-UNB uses connection identifiers, reducing overheads.

Connections are made between specific "ports" of application entities. Up to 16 ports can be associated with one EP. A RP can relay as many connections as required although there will typically be implementation restrictions.

Connections are managed with Control PDUs, which can be sent connectionless, and if necessary routed through a multi-hop path using only the information which they themselves contain. Control PDUs are resent if lost.

7.1.4 Layer 3 (NET) Overview

Layer 3 is implementation-dependent. In a DD-UNB implementation many connections are typically "semi-permanent": a connection is set up when an EP begins operation and not removed unless one or both ends of the connection cease operation. However this is not mandated.

7.1.5 Layer 2 (DLL) Overview

7.1.5.1 Overview

DD-UNB Layer 1 is designed to support a range of Layer 2 implementations, but this specification details the MAC sub-layer employed in DD-UNB.

DD-UNB Layer 2 is also designed to support message encryption and authentication of application messages, although other approaches to encryption may be implemented if required for certain applications.

7.1.5.2 MAC Sublayer

Medium Access Control (MAC) is considered as a DLL sublayer.

Medium access in the downlink and A" downlink is based upon the spectrum access rules including regulatory duty cycle limitation. However, in the Uplink and A" Uplink there is potential for multiple EP to transmit simultaneously, therefore MAC is employed to manage UL transmission collision. The MAC procedure (based on slotted ALOHA in time) is described in clause 7.3.2.

7.1.6 Layer 1 (PHY) Overview

7.1.6.1 Frequency use

A-interface Downlink and Uplink frequencies may or may not be the same; regulatory constraints suggest they will typically be different. Frequency planning may be employed to manage interference between cells.

A"-interface Downlink and Uplink transmissions are intended for reception by EP (i.e. by OEP, and by EP configured to act as a RP respectively) and therefore frequencies used should reflect EP receiver implementation. Therefore A"-interface typically uses a frequency close to that of the A-interface Downlink.

Frequency hopping is optional. In a hopping system the BS (and RP on A"-interface) transmissions hop in a pre-determined pattern, with one timeslot per hop.

7.1.6.2 A-interface Downlink and Uplink timing

The UL and DL physical layer operates using TDD with a frame of 60 timeslots, each of length 400 ms. A frame comprises Downlink, Uplink and Uplink Acknowledge subframes, as illustrated in Figure 7-7. The allocation of timeslots to these subframes is variable and is broadcast by the BS for each frame. For relay operation a variable-length A"-interface subframe (during the A-interface UL subframe) is assigned for traffic between the RP and the OEP.

The frame number is a 6-bit number that cycles modulo 64, giving a "superframe" of 64 frames.

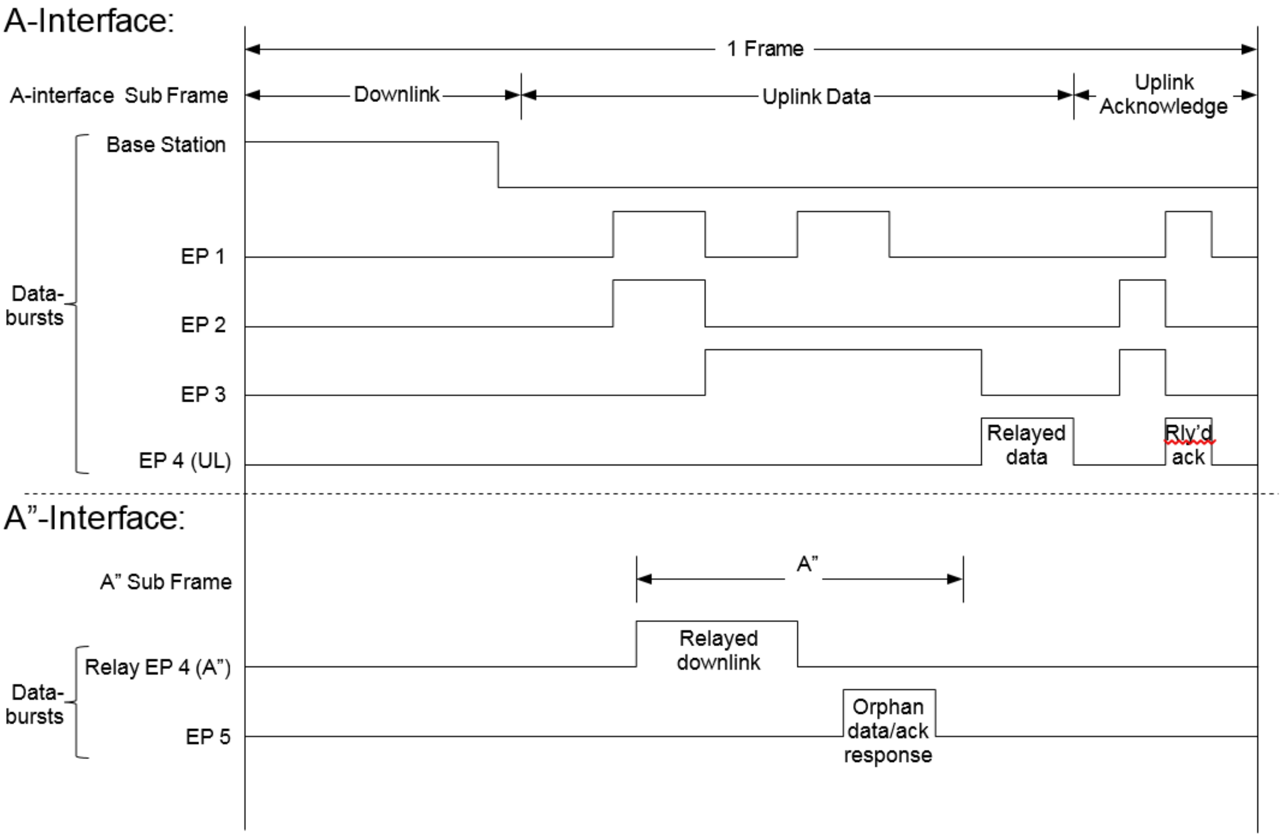

Figure 7-7: Example Frame and Subframe Timings

The downlink data-burst accommodates the L1 PDUs from the following physical channels (if present) in the order listed:

- A "Sync channel" used to synchronize EP with the frame and, if used, the frequency hopping sequence. Sync channel does not carry any upper-layer SDU.
- A "Broadcast channel" defines the format of the downlink data-burst that is to follow. Broadcast channel carries no upper-layer SDU.
- A "Multicast channel" carries Multicast data addressed to all EP in the cell.
- A "Control channel" carries signalling information mainly used in the set-up and control of layer 3 connections and other procedures.
- A "Wakeup channel" carries the connection identifiers for those connections for which Connection PDUs are being sent in the current frame.
- An "Acknowledge channel" carries acknowledgments for the UL Connection (Data) PDUs previously received.
- A "Connection channel" carries Connection (Data) PDUs destined for individual connections, as indicated in the Wakeup channel.

This order allows EP for which there is no connection data to switch off as soon as possible during the data-burst to preserve power.

L1 PDUs are typically BCH codewords of differing strength reflecting differing importance of error-free reception and the use, or not, of acknowledgement.

A-interface UL protocol implements Slotted Aloha MAC: each EP transmits its UL data and UL Acknowledge data-bursts with random (slotted) timing within the appropriate subframes. UL data and UL Acknowledge data-bursts are sent on a random frequency within the allocation.

7.1.6.3 A"-Interface (Relay Operation) timing

An EP which cannot successfully receive a base station is called an Orphan EP (OEP). An OEP may communicate with a BS via a Relay EP (RP) if the radio path permits; EP to RP communication uses the A"-interface. In normal circumstances OEP are avoided by careful deployment planning, however relay operation provides an option in exceptional circumstances. One or more OEP may be served by a RP. Enabling EP to act as RP is part of system planning and configuration activity.

The RP retransmits any required part of a DL data-burst on the A"-interface in a format similar to that of the DL. Transmissions from OEP (i.e. A" Uplink) then follow in the same A" subframe. A MAC procedure is employed in A" uplink which is described in clause 7.3.2.3. Transmissions in both directions on the A"-interface take place at the same data rate as the main downlink.

7.1.6.4 Frequency and Time Synchronization

An EP typically has a low-stability frequency reference. It establishes and maintains frequency and time synchronization by receiving and decoding transmissions from a BS.

7.2 Network Layer

The DD-UNB Layer 3 is implementation-dependent.

7.3 Data Link Layer

7.3.1 DLL introduction

The DD-UNB DLL is implementation-dependent and a range of DLL implementations can be used to take advantage of the features supported by the DD-UNB PHY, in particular the logical channels provided. However MAC sub-layer functionality is closely related to the PHY constraints of UNB (and DD-UNB specifics) and shall be implemented as described in the present document.

7.3.2 MAC sub-layer

7.3.2.1 MAC on A-interface UL - Data Subframe

7.3.2.1.1 General

The A-interface UL protocol MAC procedure is based on the "Aloha" approach randomized in both time (slotted Aloha) and frequency. The MAC procedure randomizes the timing of the transmission of data-bursts subject to avoiding unnecessary delays in sending data and subject to constraints arising from selected frame formats.

7.3.2.1.2 UL throttle

The BS shall transmit (as part of its broadcast channel, see Table 7-7) a number between 0 and 7 related to the degree of overall uplink congestion it is experiencing. This number is called "uplink throttle value". If the uplink throttle value is not zero, then independently for each current or attempted connection (i.e. each active port) an EP shall generate in each frame a random number "Rand" between 1 and 127 (inclusive) and shall only transmit, in that frame, UL data-bursts related to that port if the following condition is met:

$$Rand \geq 128 - 2^{(7-uplink\ throttle\ value)}$$

This allows the BS to influence the population of EPs transmitting, providing a measure of UL medium access control. Any data-bursts not transmitted shall be deferred to the following frame (and the same process repeated if applicable).

7.3.2.1.3 Time domain

The random selection of timing of UL transmissions is strongly influenced by current physical layer configuration (including frame format) and constraints on the handling of data-bursts to be transmitted.

A number of UL transmission time windows are available to an EP in the UL Data subframe, each is of 8 timeslots duration (starting with the first timeslot of the UL Data subframe). UL data-bursts occupy 1 or 2 such windows (see clause 7.4.3.3.3). The number of such windows available in an UL subframe is defined by the selected frame format; however in the case of a RP some of the windows may be assigned to the A" UL subframe and thus be unavailable to the A-interface UL.

UL data-bursts for transmission in a given frame shall be assigned randomly for transmission in available windows (subject also to the constraints of clause 7.4.3.3.3), the seed for the randomization shall be assigned randomly to each EP/RP. Any data-bursts which cannot be accommodated shall be deferred to the following frame.

7.3.2.1.4 Frequency domain

If an EP has one or more data-bursts to send during the UL subframe, MAC shall select, at random and independently for each data-burst, a UL sub-channel on which to transmit the data-burst (a value FMAC is provided to PHY, see clause 7.3.2.2.3); an exception is described in clause 7.4.3.3.3 for strongly-coded PDUs.

7.3.2.2 MAC on A-interface UL - Ack Subframe

7.3.2.2.1 General

The A-interface UL protocol MAC procedure is based on the "Aloha" approach randomized in both time (slotted Aloha) and frequency.

7.3.2.2.2 Time domain

The random selection of timing of UL transmissions is strongly influenced by current physical layer configuration (including frame format) and constraints on the handling of data-bursts to be transmitted.

A number of UL transmission time windows are available to an EP in the UL Ack subframe, each is of 4 timeslots duration (starting with the first timeslot of the UL Ack subframe). Each UL data-burst occupies one such window (see clause 7.4.3.3.4). The number of such windows available in an UL subframe is defined by the selected frame format.

UL data-bursts for transmission in a given frame shall be assigned randomly for transmission in available windows, the seed for the randomization shall be assigned randomly to each EP/RP. Any data-bursts which cannot be accommodated shall be deferred to the following frame.

7.3.2.2.3 Frequency domain

If an EP has one or more data-bursts to send during the UL Ack subframe, MAC shall select, at random and independently for each data-burst, a UL sub-channel on which to transmit the data-burst (a value FMAC is provided to PHY, see clause 7.3.2).

7.3.2.3 MAC on A"-interface UL

7.3.2.3.1 General

The DD-UNB A" UL supports randomization in the time domain but not the frequency domain.

In the A"-interface DL for each frame, an RP shall indicate to attached OEP (see clause 7.4.2.3) that the current A"-interface subframe is either "open" or "closed":

- In an open A"-interface subframe any attached OEP may transmit.
- In a closed A"-interface subframe the RP indicates that a particular OEP, and only that OEP, may transmit during the current subframe. Closed frames are mainly intended for the transmission of data and Ack PDUs, although Control PDUs may also be sent.
- An OEP may request a closed subframe by sending an uplink data-burst to the ROS containing only a Sync PDU (see Table 7-6).

7.3.2.3.2 Time domain

The MAC in an open A" UL subframe is based on slotted Aloha principles in the time domain.

A number of timeslots are available to an OEP in the UL A" subframe (Table 7-3). Transmission of an A" UL data-burst shall start at the beginning of a timeslot, the timeslot shall be chosen randomly from those which permit completion of the transmission of the full data-burst within the current subframe. The seed for the randomization shall be assigned randomly to each EP/RP.

7.3.3 Encryption and Authentication

DD-UNB supports UL and DL encryption of application messages on the A and A"-interfaces.

Encryption is applied between SC and EP (or OEP). Each EP shall be pre-provisioned with a pair of randomly-selected secret 256-bit keys (one for each of UL and DL), the mechanism for this is implementation-dependent; the keys shall be stored with a level of physical security and/or obfuscation appropriate to the application.

Each 14-byte application message (content field in L2 SDU) shall be encrypted before being passed to layer 1 in Connection L1 SDU (Table 7-16). The encryption algorithm used is AES 256 operating in OFB mode (Figure 7-8). Each 14-byte content field presented as a L2 SDU is first encrypted in the SC (for DL data) or the EP (for UL data); decryption is carried out at the corresponding point in the other entity. The key used is the private key stored in both SC and EP for the applicable direction. The initialization vector shall be determined when a L3 connection is established between SC and EP based on parameters related to the connection and known by both ends of the connection (e.g. connection identifiers, connection initialization parameters); choice of specific parameters will depend upon implementation-dependent upper-layer protocol elements and shall provide sufficient entropy to ensure adequate message privacy and an adequately low risk of vulnerability to replay attacks. Output Feedback Mode operation continues for the life of the connection. Note that in both encryption and decryption the block cipher is an encryption operation.

Authentication of application messages is provided by the insertion of implementation- and application-dependent known-text by the application in the originating entity and recovery of that text in the destination application.

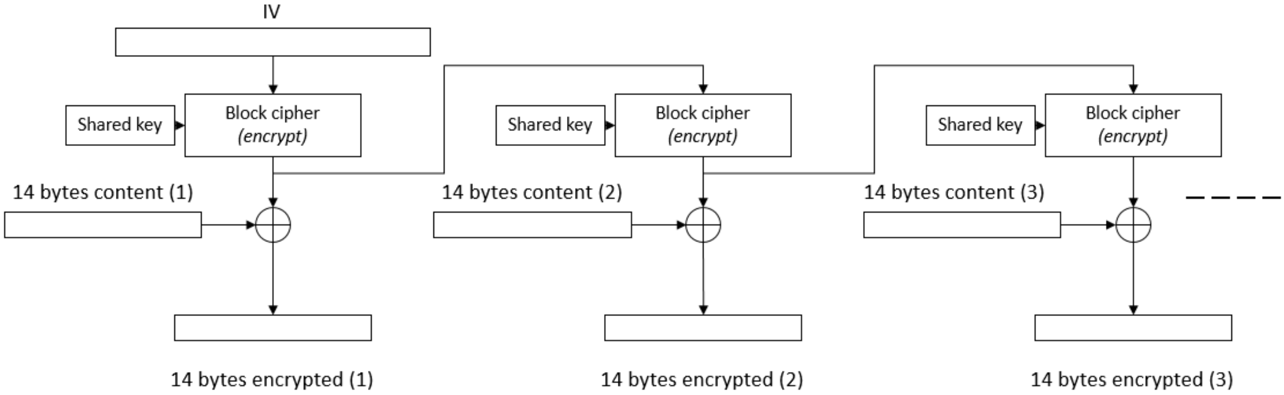

Figure 7-8: Encryption operation

7.4 Physical Layer

7.4.1 PHY Format

7.4.1.1 Timing and Frame Formats

7.4.1.1.1 Introduction

The A-interface and A"-interface PHY use Time Domain Duplex (TDD). The basic element in the time structure of the DD-UNB system is the timeslot, which has a fixed length of 0,4 seconds. A frame comprises 60 timeslots numbered from timeslot number 0. A superframe comprises 64 frames numbered from frame 0.

Each DD-UNB data-burst shall comprise a sequence of (one or more) radio-bursts in consecutive timeslots; its duration is determined by the number and length of the relevant PDUs to be transmitted.

Each radio-burst is divided into an active period (384 ms) and a guard period (16 ms), the latter is provided at the end of each timeslot and is the period during which frequency changes can take place to support optional frequency hopping as described in clause 7.5.1. Transmit power shall be reduced between radio-bursts as described in clause 7.5.3. Data is transmitted during the active part of each timeslot. When all data in a data-burst has been transmitted, transmission of the data-burst shall cease.

Each frame is divided into variable-length subframes allocated to carry specific Physical Channels (see clause 7.4.1.2); the order of subframes is as shown in Table 7-1. Data-bursts shall be transmitted as determined by the MAC layer in the indicated subframe. In the DL a DD-UNB BS shall transmit no more than one data-burst in each subframe of a given frame; transmission of each DL data-burst starts in the first timeslot of the related subframe. In the UL more than one data-burst may be transmitted under the control of the MAC procedure (see clause 7.3.2.3).

If the assigned frame format means a given subframe cannot accommodate all the PDUs to be transmitted, remaining PDUs shall be transmitted in the next such subframe available (i.e. in the next frame).

Table 7-1: Subframe types

	Used for
A-interface	
DL subframe	DL Physical Channels
UL data subframe	Uplink Data Physical Channel (UDPCH)
UL Acknowledge subframe	Uplink Acknowledge Physical Channel (UAPCH)
A"-interface	
A" DL subframe	Local Downlink Physical Channels
A" UL data/ack subframe	Local Uplink Physical Channels

The valid frame formats for the DD-UNB system are listed in Table 7-2 and Table 7-3. Figure 7-9 shows an example frame timing for A-interface format 0 and A"-interface format 1.

The start of the A" subframe within the frame is fixed (starting in timeslot 19) for all frame formats.

Timeslot 55 is reserved (no transmissions shall be made on any interface) in all frame formats.

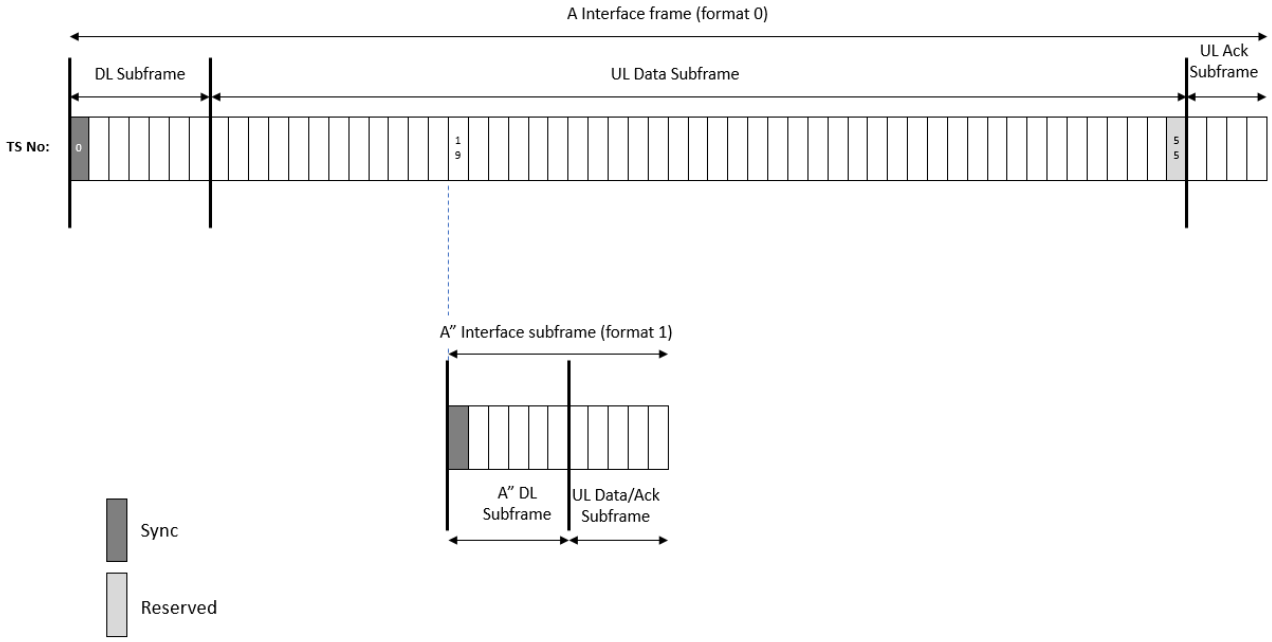

Figure 7-9: Example Frame Structure

7.4.1.1.2 A-interface Frame Formats

There are 8 frame formats defined for the A-interface of a DD-UNB system, the number of timeslots in each subframe are shown in Table 7-2; the timeslots are allocated to subframes within the frame in the order shown. The choice of A-interface frame format shall be made by the BS on a per-frame basis and should take into account the traffic expected by the BS.

The example in Figure 7-9 includes A-interface format 0.

Table 7-2: A-interface Frame Formats - No. of timeslots in each subframe

Frame Format Index	DL		Noise Measurement	UL Data	UL Ack
	Synchronization	Other DL			
0	1	6	0	48	4
1	1	10	0	40	8
2	1	14	0	40	4
3	1	18	0	32	8
4	1	6	12	32	8
5	1	10	8	32	8
6	1	14	4	32	8
7	1	17	1	32	8
8-15	Reserved				

7.4.1.1.3 A"-interface Subframe Formats

There are 5 frame formats defined for the A"-interface of a DD-UNB system, the number of timeslots in each subframe is shown in Table 7-3; timeslots are allocated to subframes within the A"-interface subframe in the order shown. The choice of A"-interface format shall be made by the RP on a per-frame basis and should take into account the traffic expected by the RP.

The example in Figure 7-9 includes A"-interface format 1.

Table 7-3: A"-interface Subframe Formats

Frame Format Index	DL		UL Data/Ack
	Synchronization	Other DL	
0	1	1	5
1	1	5	5
2	1	9	5
3	1	13	5
4	1	17	5
5-14	Reserved		

7.4.1.1.4 Synchronization and Frame Offset

BS in a DD-UNB system may be synchronized to a common timing of timeslot 0 of frame 0 (i.e. start of a superframe) with a maximum error of ±8 ms; such synchronization allows management of inter-BS interference. The method of maintaining synchronization is implementation-dependent.

As described in Table 7-2, the DD-UNB DL is active in the first part of each frame. In order to distribute DL transmissions from multiple synchronized BS more evenly in time, an optional frame offset may be applied to the timing in a specific cell: the value of offset shall be 0, 20 or 40 timeslots. The timing offset used in a cell is signalled in the Downlink Sync pre-coding block as Frame Offset.

7.4.1.1.5 Battery saving

7.4.1.1.5.1 Battery saving in DD-UNB

DD-UNB supports three classes of EP operation. Class(es) supported by a specific EP are implementation-dependent as below. In battery-save mode an EP/RP does not support air-interface activity; it shall exit battery-save mode in time to operate as described below.

Further battery-saving mechanisms are possible, including different EP to be active in different frames / superframes in Class B (to support a greater number of battery-saving EP); these mechanisms are for further study.

All battery-saving classes are applicable only after an EP has established a connection with a BS.

7.4.1.1.5.2 Class C

An EP operating in Class C listens in every frame for BS and/or RP DL transmissions. It may enter battery-save mode (i.e. stop A-interface reception) as soon as it has received any data intended for it or has received an indication that there is no such data in the current frame (clause 7.4.2.4).

A RP may also support Class C, but shall complete any activity required on the A"-interface before entering battery-save mode.

7.4.1.1.5.3 Class B

An EP/RP operating in Class B operates as specified for Class A except that the air interface is only active in frame 0 of each superframe, unless the result of activity in frame 0 indicates a requirement for ongoing activity in subsequent frame(s). As soon as such activity is completed the EP/RP may enter battery-save mode.

Management of Class B battery-saving is implementation-dependent and requires that the associated BS is aware of any EP/RP in Class B operation and schedules DL activity accordingly.

7.4.1.1.5.4 Class A

An EP in Class A operation is normally inactive on the air interface; however it may maintain an implementation-dependent level of synchronization with the DD-UNB network. If the application in the EP determines that an A-interface transmission is required the EP shall re-establish full synchronization with its associated BS and initiate UL communication in the normal way. The EP shall then continue to monitor (and respond to) the A-interface in Class C for one superframe cycle (including the frame corresponding to that in which the EP transmission was initiated) after which it may re-enter battery save mode if such ongoing activity has been completed.

Management of Class A battery-saving is implementation-dependent and requires that the associated BS and/or any application is aware of any EP/RP in Class A operation to ensure DL activity is timed accordingly.

7.4.1.2 Physical Channels

For the Downlink and A" downlink, each logical channel transferring data from higher layers corresponds to a physical channel, with three additional physical channels: the Sync Physical Channel, the Broadcast Physical Channel and the Wakeup Physical Channel.

For the Uplink, two of the logical channels (the Uplink DLL Control channel and the Uplink DLL Connection Channel) are multiplexed into one physical channel (Uplink Physical Data Channel).

DL physical channels are:

- Downlink Sync Physical Channel (DSPCH): carries Sync PDUs that are generated at BS physical layer (i.e. there is no Sync SDU required).
- Downlink Broadcast Physical Channel (DBPCH): carries Broadcast PDUs that are generated at BS physical layer (i.e. there is no Broadcast SDU required).
- Downlink Multicast Physical Channel (DMPCH): carries Multicast L1 PDUs, which BS physical layer has received via Multicast L1 SDUs, to all EP in the cell.

- Downlink Control Physical Channel (DCPCH): carries Control L1 PDUs which BS physical layer has received via Control L1 SDUs, targeted to a specific EP for a specific connection.
- Downlink Wakeup Physical Channel (DWPCH): carries Wakeup PDUs that are generated at BS L1 (i.e. there is no Wakeup SDU required) which it extracts from connection data information.
- Downlink Acknowledge Physical Channel (DAPCH): carries Acknowledge L1 PDUs which BS physical layer has received from upper layers via Acknowledge SDUs, confirming associated uplink Data PDUs sent in previous frame, were received successfully.
- Downlink Connection Physical Channel (DXPCH): carries Connection L1 PDUs which BS physical layer has received via Connection L1 SDUs, targeted to a specific EP for a specific connection, that are being transported along the established connection.

UL physical channels are:

- Uplink Data Physical Channel (UDPCH): carries data PDUs which EP physical layer has received via either Control L1 SDUs or Connection L1 SDUs.
- Uplink Acknowledge Physical Channel (UAPCH): carries Acknowledge L1 PDUs which EP physical layer has received in upper layers' Acknowledge SDUs. These confirm that associated downlink Connection PDUs sent in this frame, and destined to this EP for a specific connection, were received successfully.

A" physical channels are:

- Local Sync Physical Channel (LSPCH) which is the A" equivalent of DSPCH.
- Local Downlink Broadcast Physical Channel (LBPCH) which is the A" equivalent of DBPCH.
- Local Multicast Physical Channel (LMPCH) which is the A"-interface equivalent of DMPCH.
- Local Control Physical Channel (LCPCH) which is the A"-interface equivalent of DCPCH.
- Local Wakeup Physical Channel (LWPCH) which is the A"-interface equivalent of DWPCH.
- Local Acknowledge Physical Channel (LAPCH) which is the A"-interface equivalent of DAPCH.
- Local Connection Physical Channel (LXPCH) which is the A"-interface equivalent of DXPCH.
- Local Uplink Descriptor Physical Channel (LUDSPCH) which is the A"-interface Uplink equivalent of DSPCH and DBPCH combined.
- Local Uplink Control Physical Channel (LUCPCH) which is the A"-interface Uplink equivalent of DCPCH.
- Local Uplink Wakeup Physical Channel (LUWPCH) which is the A"-interface Uplink equivalent of DWPCH.
- Local Uplink Acknowledge Physical Channel (LUAPCH) which is the A"-interface Uplink equivalent of DAPCH.
- Local Uplink Connection Physical Channel (LUXPCH) which is the A"-interface Uplink equivalent of DXPCH.

7.4.2 L1 PDUs and SDUs

7.4.2.1 Overview

Figure 7-10 shows how information is passed to/from Physical layer (downlink example), using L1 PDUs and SDUs.

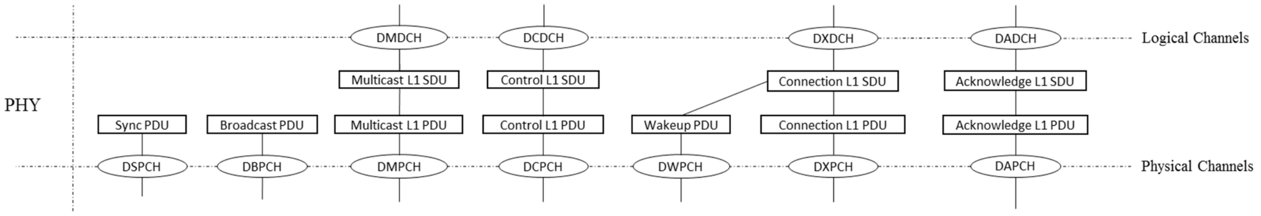

Figure 7-10: PHY PDUs and SDUs (Downlink)

L1 PDUs and SDUs shall be constructed as described below.

7.4.2.2 Sync PDU

Sync PDU is created at L1 and is formed by combining an uncoded Sync Header with a Sync Codeword (i.e. SC codeword, see Table 7-26 and Table 7-28) which is the result of BCH coding of Sync pre-coding block.

Sync Header is defined as follows:

Table 7-4: Sync Header

Type	Preamble Sequence	Sync Word
Downlink / A" Downlink	"0101… 0101" (48 bits) followed by "1010… 1010" (16 bits)	"0xB0E2" (16 bits)
A" Uplink		"0x470D" (16 bits)
Uplink / Uplink Ack	(0 bits)	"0xB8D0" (16 bits) When used for sending normal data/control and Ack
		"0x0B1D" (16 bits) When used for sending strongly-coded (double) data/control

For A-interface downlink and A" downlink, the Sync pre-coding block has a length of 49 bits, see Table 7-5.

Table 7-5: Downlink and A"-interface Downlink Sync pre-coding block

Field	Length (bits)	Notes
SSID	10	Short system ID
BSID	13	Base Station ID
Frame Offset	2	0x0: Frame timing in this cell synchronized with system reference time 0x1: Frame timing in this cell delayed 20 timeslots from system reference time 0x2: Frame timing in this cell delayed 40 timeslots from system reference time
DL Hopping flag	1	0x0 = single DL frequency used 0x1 = DL hopping used
Hop Phase Offset	5	If DL Hopping Flag = 0x0: Reserved (set to 0) If DL Hopping Flag = 0x1: Value to be added to index used to look up centre frequency in each timeslot
Frame Number	6	(0 - 63) frame number
Slot Number	8	Timeslot number of slot in which this PDU is transmitted
Frame Format	4	Frame format index

For A" uplink, the Sync pre-coding block is called "A" UL Descriptor" (and the codeword used is called DC, see Table 7-28). It has a length of 49 bits and contains Sync and other information describing the current A" UL data-burst, see Table 7-6.

Table 7-6: A" Uplink Sync pre-coding block (A" UL Descriptor)

Field	Length (bits)	Notes
Reserved	3	Reserved field (set to 0)
NumStrongCntlCw	2	Number of Strong Control PDUs
SSID	10	Short system ID
BSID	13	Base Station ID
ConID	14	Request closed frame for connection ID (0x0 means no request)
NumCntlCw	3	Number of Control PDUs
NumWakeupCw	2	Number of Wakeup PDUs
NumAckCw	2	Number of Ack PDUs

In A-interface Uplink, Sync PDU does not exist; the Sync header (16 bits, see Table 7-4) is transmitted at the beginning of each UL or UL Acknowledge data-burst and indicates the strength of the coding used for the rest of the data-burst. For other links, length of Sync PDU is 192 bits.

7.4.2.3 Broadcast PDU

Broadcast PDU contains information describing the structure of the DL data-burst. The Broadcast PDU has different formats for the downlink and A" downlink.

The Broadcast PDU is a broadcast codeword of length 175 bits.

For the A-interface downlink, the Broadcast pre-coding block has length 51 bits, see Table 7-7.

Table 7-7: A-interface Downlink Broadcast pre-coding block

Field	Length (bits)	Notes
Reserved	1	Reserved field (set to 0)
Multicast Repeat	1	Multicast repeat flag
NumWeakAckCw	3	Number of Weak Ack PDUs
UL frequency	6	UL_Chan_Freq (note)
Reserved	6	Reserved field (set to 0)
UL throttle	3	UL throttle value
BC BSGP	4	Broadcasted BSGP
Reserved	2	Reserved field (set to 0)
NumStrongCntlCw	5	Number of Strong Control PDUs
NumMulticastCw	4	Number of Multicast PDUs
NumCntlCw	5	Number of Control PDUs
NumWakeupCw	5	Number of Wakeup PDUs
NumAckCw	5	Number of Ack PDUs
Fast reconnect	1	0 = use normal reconnection, 1 = use fast reconnection (see "Fast Find" in clause 7.4.4.1)
NOTE: This field contains the value n which defines the UL_Chan_Freq selected for the cell, see clause 7.5.2.3.		

For A" downlink, the Broadcast pre-coding block is of length 51 bits, see Table 7-8.

Table 7-8: A" Downlink Broadcast pre-coding block

Field	Length (bits)	Notes
Reserved	8	Reserved field (set to 0)
Multicast Repeat	1	Multicast repeat flag
NumStrongCntlCw	5	Number of Strong Control PDUs
Tx Power	2	A" Transmit Power level
Reservation protocol	1	0 = don't use reservation (MAC) protocol
ConID	14	A" reserved connection ID (0x0 means not reserved i.e. "Open")
NumMulticastCw	4	Number of Multicast PDUs
NumCntlCw	5	Number of Control PDUs
NumWakeupCw	5	Number of Wakeup PDUs
NumAckCw	5	Number of Ack PDUs
Fast reconnect	1	0 = use slow reconnection, 1 = use fast reconnection (see "Fast Find" in clause 7.4.4.1)

7.4.2.4 Wakeup PDU

Each Wakeup PDU contains 2 wakeup messages. Each wakeup message is 18 bits long which is evaluated and filled at physical layer, according to what is going to be transmitted on the data channel so that relevant EP stay up and anticipate, whereas others go to sleep and save power.

Each wakeup message contains 14 bits Connection ID which is extracted from Connection L1 SDU. Wakeup PDU is a Codeword which is the result of BCH coding of wakeup pre-coding block (i.e. WU codeword in Table 7-26 and Table 7-28). Wakeup PDU is 175 bits long.

The Wakeup pre-coding block is 51 bits long, see Table 7-9.

Table 7-9: Wakeup pre-coding block

<table>
<tr><th>Field</th><th>Length (bits)</th><th colspan="3">Content</th></tr>
<tr><td>Reserved</td><td>15</td><td colspan="3">Reserved field (set to 0)</td></tr>
<tr><td rowspan="4">Wakeup message 1</td><td rowspan="4">18</td><td>Field</td><td>Length (bits)</td><td>Notes</td></tr>
<tr><td>High Interference</td><td>1</td><td>SFEC Flag
indicating strong coding is used or not</td></tr>
<tr><td>Blkcount</td><td>3</td><td>Number of Connection PDUs to be sent this frame</td></tr>
<tr><td>ConID</td><td>14</td><td>1st Connection ID</td></tr>
<tr><td rowspan="4">Wakeup message 2</td><td rowspan="4">18</td><td>Field</td><td>Length (bits)</td><td>Notes</td></tr>
<tr><td>High Interference</td><td>1</td><td>SFEC Flag
indicating strong coding is used or not</td></tr>
<tr><td>Blkcount</td><td>3</td><td>Number of Connection PDUs to be sent this frame</td></tr>
<tr><td>ConID</td><td>14</td><td>2nd Connection ID or 0x0 if no further messages indicated</td></tr>
</table>

7.4.2.5 Multicast L1 SDU and PDU

Multicast L1 SDU can have two different lengths (51 bits and 139 bits).

The Multicast Short L1 pre-coding block is identical to the Multicast Short L1 SDU and therefore is 51 bits.

The Multicast Long L1 pre-coding block is described in Table 7-10.

Table 7-10: Multicast Long L1 pre-coding block

Field	Length (bits)	Notes
Reserved	4	Reserved field (set to 0)
Content	139	Multicast Long L1 SDU

In both cases, Multicast L1 PDU is a codeword which is the result of BCH coding of that pre-coding block.

In creating Multicast L1 PDU, the BCH code used on Long pre-coding block is WMC codeword (see Table 7-26 and Table 7-28). The stronger MC codeword is used on Short pre-coding block. The resulting Multicast L1 PDU is 175 bits long in both cases.

There is a strong transmission mode for multicast messages, which is activated if the multicast repeat flag (see Table 7-7 and Table 7-8) is set to (1)). If strong transmission mode for multicast is used, once all Multicast PDUs have been transmitted (the "first set") they are transmitted again, in the same order, immediately following the first set and in the same A/A" DL data-burst. The decoding mechanism of such repeated transmissions is implementation-dependent.

7.4.2.6 Control L1 SDU and PDU

7.4.2.6.1 Overview

The Control L1 SDU is always 135 bits long with the format shown in Table 7-11.

Table 7-11: Control L1 SDU

Field	Length (bits)	Notes
SSID	10	Short System ID.
Direction	1	0 = towards Service Centre. 1 = away from Service Centre.
L2 BSID	13	If Direction = 1: L2 BSID identifies the BS sending towards destination EP, or identifies the RP sending towards destination OEP (as applicable). L2 EPID identifies the destination EP, or identifies the receiving RP which will forward the SDU to the destination OEP (as applicable). If Direction = 0: L2 BSID identifies the BS connecting the source EP to SC, or identifies the RP connecting the source OEP towards SC (as applicable). L2 EPID identifies the source EP, or the RP connecting the source OEP (as applicable).
L2 EPID	32	
L3 BSID	13	L3 BSID is typically "0" (i.e. SC). L3 EPID identifies the final source/destination EP (or OEP).
L3 EPID	32	
Control Msg Type	6	Taken from Control L2 SDU. 0 - 63 (note 1).
Port	4	Taken from Control L2 SDU.
Content	24	Control L2 SDU payload (3 bytes) (note 2).
NOTE 1: Control Msg Type is a field which may be used by higher layers to indicate the type of control message conveyed in this SDU (e.g. connect, disconnect). NOTE 2: Content is a field which may be used by higher layers to provide further data associated with the specified type of control message.		

Control L1 PDU is a codeword which is the result of BCH coding of that Control pre-coding block.

7.4.2.6.2 A-interface Downlink and A"-interface

On A-interface DL and A"-interface the pre-coding block is shown in Table 7-12.

Table 7-12: Downlink/A" Control L1 pre-coding block

Field	Length (bits)	Notes
Reserved	1	Reserved field (set to 0)
Content	135	Control L1 SDU

In this case Control L1 PDU is 168 bits if normal coding (i.e. CC codeword, see Table 7-26 and Table 7-28) is used, and 252 bits if strong coding (i.e. SCC codeword, see Table 7-26 and Table 7-28) is used.

7.4.2.6.3 A-interface Uplink

In UL there is only one physical channel (UDPCH) to carry both control and connection data, the corresponding PDU is called Data L1 PDU. For normal coding strength see Table 7-13.

Table 7-13: Uplink Data L1 pre-coding block - normal strength coding

Field	Length (bits)	Notes
Content Type	1	= 0 for Control
Content	135	Control L1 SDU

The resulting Data L1 PDU after coding is 176 bits long (i.e. CC codeword in Table 7-27).

In circumstances where Uplink faces high interference, an entity may use double codeword format Data PDUs see Table 7-14 and Table 7-15.

Table 7-14: Uplink Data L1 pre-coding block, first half

Field	Length (bits)	Notes
Flag	1	= 0 for first half
content	75	First 75 bits out of 136 from Table 7-13

Table 7-15: Uplink Data L1 pre-coding block, second half

Field	Length (bits)	Notes
Flag	1	= 1 for second half
CRC	14	CRC calculated across all data in the Control L1 SDU
content	61	Last 61 bits out of 136 from Table 7-13

The two resulting strongly coded Data L1 PDUs (176 bits each, see SCC codeword in Table 7-27) carrying a single Control L1 SDU shall be transmitted consecutively (sent as one UL data-burst, occupying 16 timeslots).

The CRC shall be the bitwise inverse of that calculated according to the following polynomial:

$$x_{14} + x_{10} + x_6 + x_1 + x_0$$

Initialization value: 0x3fff

7.4.2.7 Connection L1 SDU and PDU

7.4.2.7.1 Connection L1 SDU

Connection L1 SDU is 131 bits long as described in Table 7-16.

Table 7-16: Connection L1 SDU

Field	Length (bits)	Notes
ConID	14	Connection ID
BlkNum	5	PDU block number allocated by layer 3
Content	112	payload (14 bytes)

7.4.2.7.2 A-interface Downlink and A"-interface

PHY extracts Connection ID (14 bits) from the Connection L1 SDU and puts it in Wakeup PDU as explained in clause 7.4.2.4. The Connection L1 pre-coding block is shown in Table 7-17.

Table 7-17: A-interface Downlink/A" Connection L1 pre-coding block

Field	Length (bits)	Notes
Reserved	7	Reserved field (set to 0)
Content	117	Connection L1 SDU without its Connection ID field

PHY creates the Connection L1 PDU which is simply a codeword as the result of BCH coding of the pre-coding block.

Connection L1 PDU can be 168 bits long if normal coding (i.e. XC codeword, see Table 7-26 and Table 7-28) is used, or 252 bits long if strong coding (i.e. SXC codeword, see Table 7-26 and Table 7-28) is used. Connection L1 PDUs for the same connection in the same data-burst shall be transmitted in order and consecutively.

7.4.2.7.3 A-interface Uplink

In this case, the pre-coding block contains Connection L1 SDU (including its ConID field) plus 5 bits header added by PHY, so the pre-coding block is 136 bits:

Table 7-18: Uplink Data L1 pre-coding block - normal strength coding

Field	Length (bits)	Notes
Content Type	1	=1 for Connection (i.e. data)
XC BSGP	4	BSGP used for UL data
Content	131	Connection L1 SDU for uplink

(For details of the XC BSGP field, refer to clause 7.4.4.9.)

The resulting L1 Data PDU after coding is 176 bits long (i.e. XC codeword in Table 7-27).

In a high interference situation an entity may use double codeword format Data PDUs (e.g. SXC codeword, see Table 7-27), in the way described in clause 7.4.3.5. PHY creates two L1 Data PDUs as the result of BCH coding of the first half and second half of the pre-coding block, carrying a single Connection L1 SDU, which shall be transmitted consecutively (in one data-burst, occupying 16 timeslots).

Note that EP may transmit more than one UL data-burst in a single frame.

Data L1 PDUs for the same connection shall be transmitted in order. Received Data L1 PDUs with incorrect (out of sequence) numbers may be discarded.

7.4.2.8 Acknowledge L1 SDU

7.4.2.8.1 Ack Message Format

Acknowledge L1 SDU comprises a number of Ack messages declaring Connection PDUs that are successfully received on the opposite (Up/Down)link, plus some L1-specific control parameters.

The format of an Ack message is described in Table 7-19.

Table 7-19: Ack Message Format

Field	Length (bits)	Notes
ConID	14	Connection ID
Ack type	2	The type of acknowledge, see Table 7-20
BlkNum	5	the block number of acknowledged uplink Data PDU, interpretation depends on the Ack type.

The Ack type field is defined in Table 7-20.

Table 7-20: Ack Types

Type	Value	Interpretation
L2,L3 combined	0	Combined L2 and L3 Acknowledged, hence the same block number
L2 only	1	Acknowledge at L2 only, block number is for L2
L3 only	2	Acknowledge at L3 only, block number is for L3
L3 ack confirm	3	Confirmation of L3 acknowledge, block number is for the last correctly received L3 Ack block number

7.4.2.8.2 Acknowledge on A"-interface and A-interface DL

For downlink, A" downlink and A" uplink, Acknowledge L1 SDU can have two different lengths, see Table 7-21 and Table 7-22. PHY adds some L1 control fields and creates long Ack L1 pre-coding block (143 bits) or short Ack L1 pre-coding block (51 bits), which are then coded using the WAC or AC codeword respectively. The resulting Acknowledge L1 PDU is always 175 bits long.

Long Acknowledge L1 SDU is 126 bits long, and has the format described in Table 7-21.

Table 7-21: Long Acknowledge L1 SDU (Downlink)

Field	Number of fields	Length of each field (bits)	Notes
Ack messages	6	21	6 Ack messages, see Table 7-19

Short Acknowledge L1 SDU is 42 bits long, and has the format described in Table 7-22.

Table 7-22: Short Acknowledge L1 SDU (A-interface Downlink/A")

Field	Number of fields	Length of each field (bits)	Notes
Ack messages	2	21	2 Ack messages, see Table 7-19

Long Acknowledge L1 pre-coding block is described in Table 7-23.

Table 7-23: Long Ack L1 pre-coding block (A-interface Downlink/A"-interface)

<table>
<tr><th>Field</th><th>Number of fields</th><th>Length of each field (bits)</th><th colspan="3">Content of each field</th></tr>
<tr><td>Reserved</td><td>1</td><td>5</td><td colspan="3">Reserved field (set to 0)</td></tr>
<tr><td rowspan="4">Ack messages
+
L1 Control parameters</td><td rowspan="4">6</td><td rowspan="4">23</td><td>Field</td><td>Length (bits)</td><td>Notes</td></tr>
<tr><td>One Ack message (extracted from Ack L1 SDU)</td><td>21</td><td>See Table 7-19</td></tr>
<tr><td>Too Loud
Note 1</td><td>1</td><td>UL power control flag (significant on A-interface DL only).
=1 EP should lower its transmit power.
=0 EP should increase its transmit power.
Reserved on A" (set to 0)</td></tr>
<tr><td>High Interference
Note 2</td><td>1</td><td>UL high interference flag (significant on A-interface DL only).
=1 means the EP should transmit (or continue to) in High Interference mode (i.e. using double codewords).
=0 means it should transmit in Normal mode.
Reserved on A" (set to 0)</td></tr>
<tr><td colspan="6">NOTE 1: Setting of Too Loud flag is implementation-dependent and typically reflects RSSI at BS. Power limits shall be observed.
NOTE 2: Decision to set High Interference flag is implementation-dependent.</td></tr>
</table>

Short Acknowledge L1 pre-coding block is 51 bits long, see Table 7-24.

Table 7-24: Short Ack L1 pre-coding block (Downlink/A")

<table>
<tr><th>Field</th><th>Number of fields</th><th>Length of each field (bits)</th><th colspan="3">Content of each field</th></tr>
<tr><td>Reserved</td><td>1</td><td>5</td><td colspan="3">Reserved field (set to 0)</td></tr>
<tr><td rowspan="4">Ack message
+
L1 Control parameters</td><td rowspan="4">2</td><td rowspan="4">23</td><td>Field</td><td>Length (bits)</td><td>Notes</td></tr>
<tr><td>One Ack message (extracted from Ack L1 SDU)</td><td>21</td><td rowspan="3">As indicated in Table 7-23</td></tr>
<tr><td>Too Loud</td><td>1</td></tr>
<tr><td>High Interference</td><td>1</td></tr>
</table>

7.4.2.8.3 Acknowledge on A-interface UL

For A-interface uplink, Acknowledge L1 SDU is always 21 bits long. PHY creates Uplink Ack L1 pre-coding block which is 31 bits long as Table 7-25.

Table 7-25: Uplink Ack L1 pre-coding block

Field	Length (bits)	Notes
Reserved	1	Reserved field (set to (0))
AC BSGP	4	BSGP used for UL Ack
Reserved	4	Reserved field (set to (0))
High Interference	1	DL high interference flag (significant on A-interface UL only). =1 means the BS should transmit (or continue to) in High Interference mode (i.e. using double codewords). =0 means BS should transmit in Normal mode. Reserved on A" (set to (0))
Ack message	21	See Table 7-19

The BCH code used on uplink Ack L1 pre-coding block is AC codeword which results in Acknowledge L1 PDU which is 80 bits long.

7.4.3 PHY Functions

7.4.3.1 Channel Processing

Figure 7-11 illustrates the channel processing applied in the physical layer for the A-interface Downlink transmission.

L2 PDUs are passed to the PHY through logical channels (which is then called L1 SDU). L1 SDUs are passed as described in clause 7.4.2 as pre-coding blocks to PHY channel coding function which performs BCH coding on them according to the information type, pre-coding block size and coding strength (see Figure 7-11 for downlink example).

The resulting BCH codewords are named as Sync Codeword (SC), Broadcast Codeword (BC), Multicast Codeword (MC), Weak Multicast Codeword (WMC), Control Codeword (CC), Strong Control Codeword (SCC), Wake Up (WU), Acknowledge Codeword (AC), Weak Acknowledge Codeword (WAC), Connection data Codeword (XC), and Strong Connection data Codeword (SXC). Details of each BCH codeword format is provided in clause 7.4.3.2.

PHY shall treat these BCH codewords as L1 PDUs without any modification (except Sync PDU as below) and pass them through relevant physical channels.

The Sync PDU shall be formed by concatenating the uncoded Sync header with the Sync Codeword (SC).

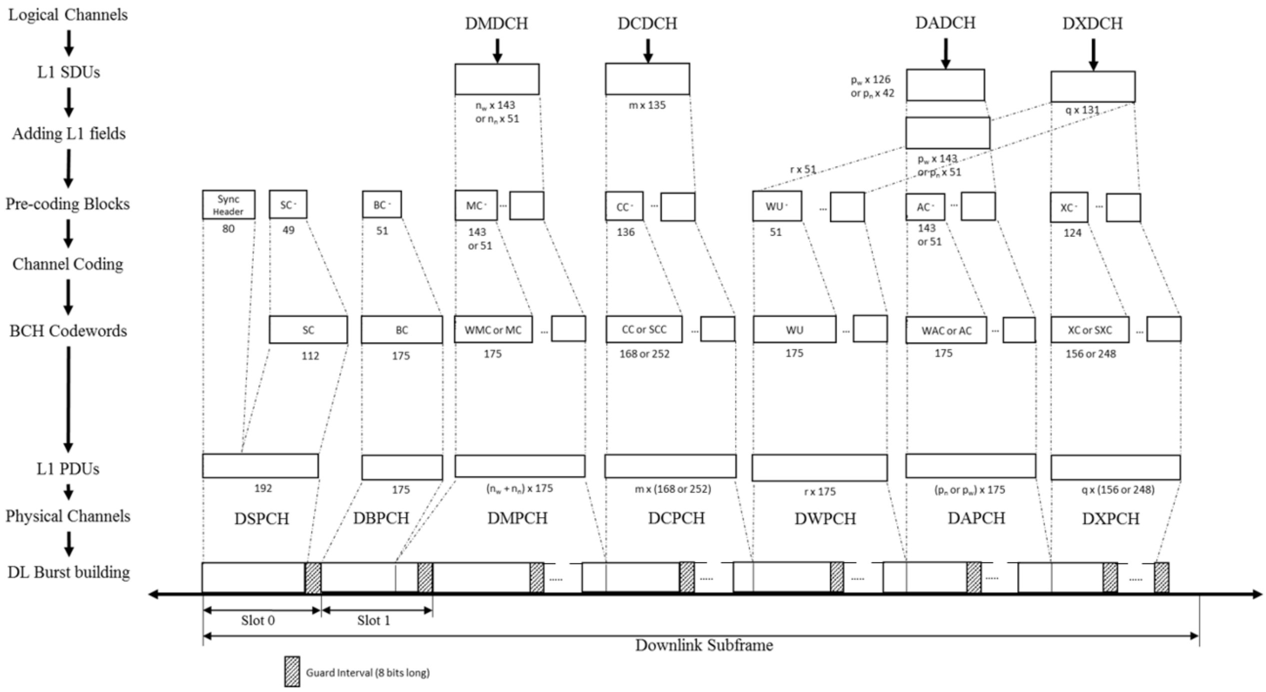

Figure 7-11: PHY Channel Processing in A-interface Downlink

Figure 7-12 illustrates the channel processing applied in the physical layer for the A-interface Uplink transmission. Selection of the slot "U" in which transmission of the burst starts is described in clause 7.4.4.6.

Normal or strong coding may be used as shown in Figure 7-12.

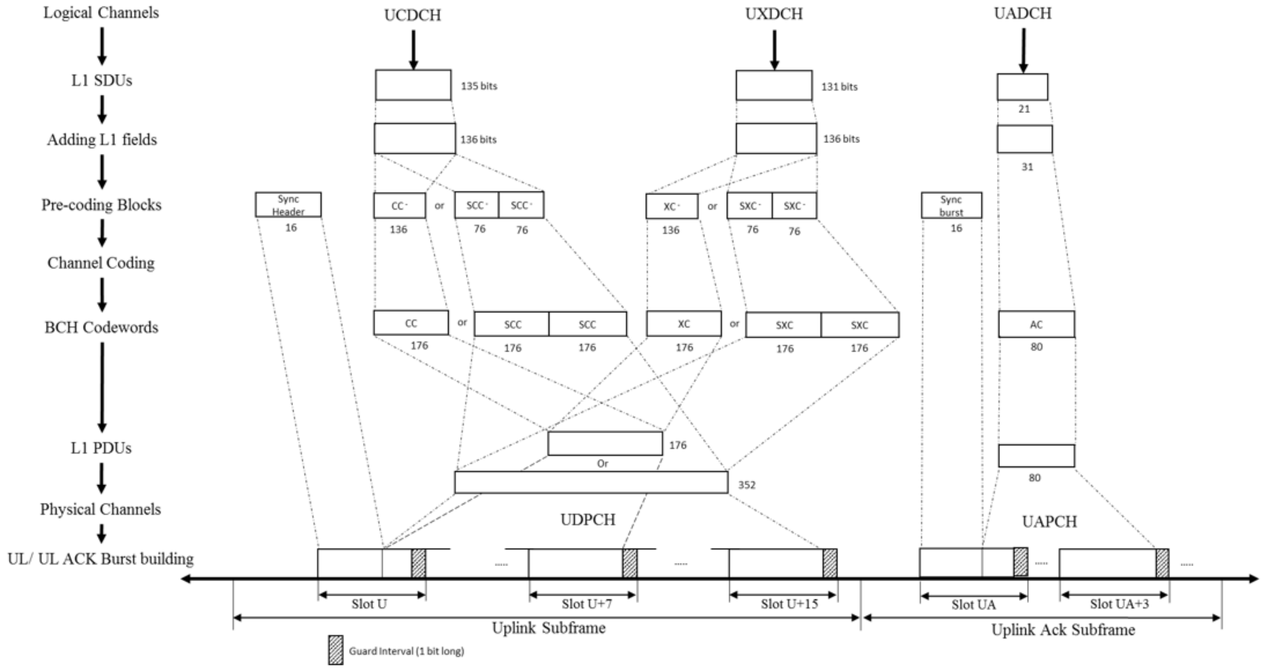

Figure 7-12: Channel processing and example scheduling in A-interface Uplink / Uplink Ack

Figure 7-13 and Figure 7-14 illustrate the channel processing applied in the physical layer for the A" Downlink and Uplink transmission respectively.

A" channel processing for both uplink and downlink is similar to that of normal downlink but with the introduction of Descriptor Codeword (DC) replacing SC and BC.

Selection of the slot "LU" or "LA" in which transmission of the A" UL data-burst starts is described in clause 7.4.4.6.

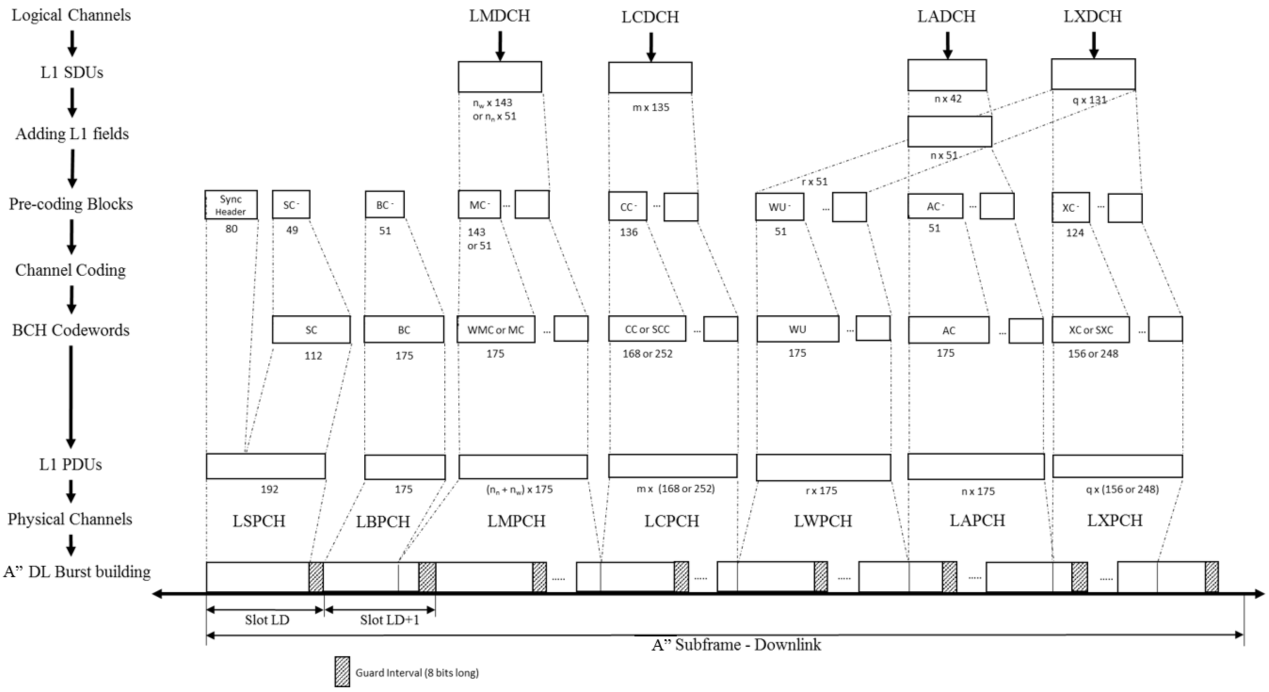

Figure 7-13: Channel processing in A" Downlink

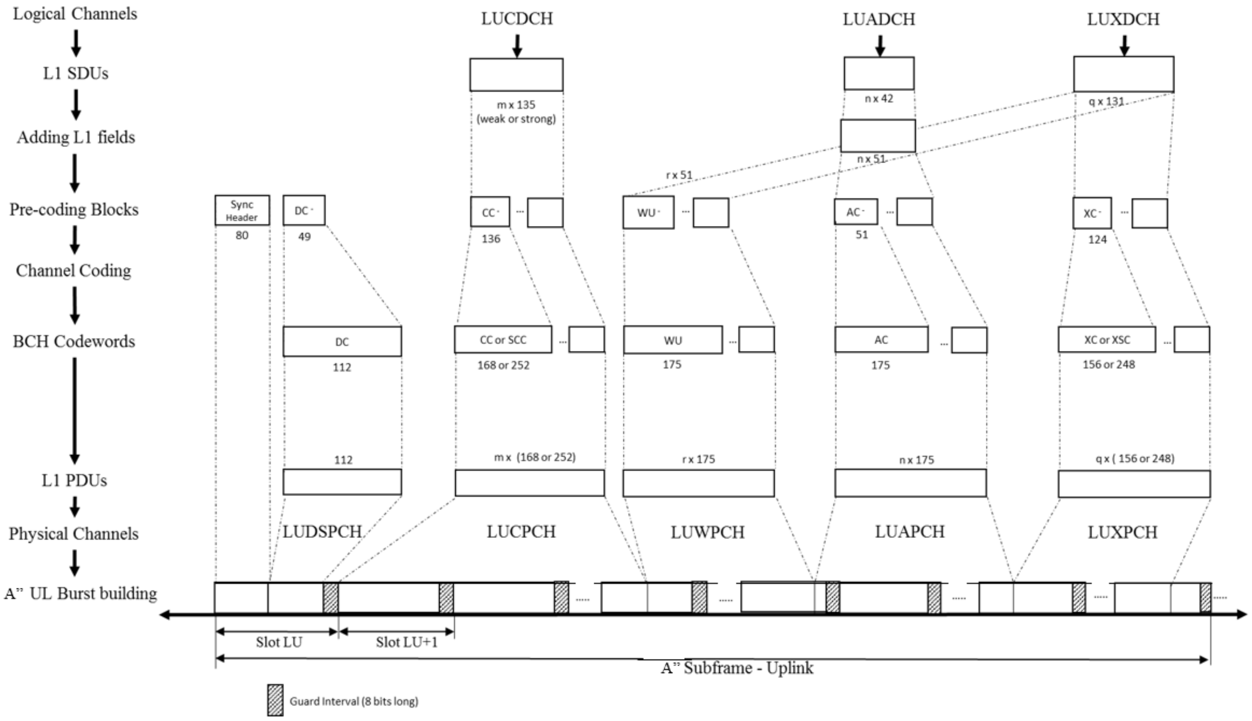

Figure 7-14: Channel processing in A" Uplink

7.4.3.2 Channel Coding

All data transmitted by either Base Station or End-point shall be encoded using shortened BCH cyclic codes as described in Table 7-26, Table 7-27 and Table 7-28.

Table 7-26: Downlink Codewords

Code Type	Base Code		Shortened Form		Properties		DL BCH Codewords
	n	k	n'	k'	rate	t (used)	
DL Strong 2	127	64	112	49	49/112	10(10)	SC
DL Strong 1	255	131	175	51	51/175	18(18)	BC MC WU AC
DL Strong 3	255	139	252	136	136/252	15(10)	SCC
DL Strong 4	255	131	248	124	124/248	18(13)	XSC
DL Weak 1	255	223	168	136	136/168	4(2)	CC
DL Weak 3	255	223	175	143	143/175	4(2)	WAC WMC
DL Weak 2	255	223	156	124	124/156	4(2)	XC

Table 7-27: Uplink Codewords

Code Type	Base Code		Shortened Form		Properties		UL BCH Codewords
	n	k	n'	k'	rate	t (used)	
UL Short	127	78	80	31	31/80	7(6)	AC
UL Long	255	215	176	136	136/176	5(3)	CC XC
DL Long Strong	255	155	176	76	76/176	13(13)	SCC SXC

Table 7-28: A" Codewords

Code Type	Base Code		Shortened Form		Properties		A" BCH Codewords
	n	k	n'	k'	rate	t (used)	
DL Strong 2	127	64	112	49	49/112	10(10)	SC DC
DL Strong 1	255	131	175	51	51/175	18(18)	BC MC WU AC
DL Strong 3	255	139	252	136	136/252	15(10)	SCC
DL Strong 4	255	131	248	124	124/248	18(13)	SXC
DL Weak 1	255	223	168	136	136/168	4(2)	CC
DL Weak 3	255	223	175	143	143/175	4(2)	WMC
DL Weak 2	255	223	156	124	124/156	4(2)	XC

7.4.3.3 Data-Burst Building

7.4.3.3.1 Introduction

In the DD-UNB system, a data-burst typically occupies multiple timeslots. Data-bursts of different types are used for A-interface (Downlink, Uplink and Uplink Ack) and A"-interface (Downlink and Uplink). The transmission of data-bursts is generally determined by application requirements and those of other protocol layers.

7.4.3.3.2 A-interface DL

Each A-interface DL data-burst shall comprise, in the order shown, a concatenation of:

- A Sync PDU (a Sync header of 80 bits followed by 112 bits SC codeword and then a guard period) which fits exactly into one timeslot (0,4 second).
- A single BC which carries the details of the sequence of codewords that follows it.
- Zero or more WMC/MC codewords.

- Zero or more CC/SCC codewords.
- Zero or more WU codewords.
- Zero or more WAC/AC codewords.
- Zero or more XC/SXC codewords, in the order indicated by the contents of WU PDU transmitted in the current frame.
- The content of the data-burst shall be consistent with the DL subframe duration as indicated by the current frame format.
- A BS shall transmit a single such data-burst in each frame, see Figure 7-11.

7.4.3.3.3 A-interface UL Data

Each A-interface UL Data data-burst shall comprise a Sync header of 16 bits (see Table 7-4) followed by a CC/XC codeword (176 bits) or a double SCC/XCC codeword (352 bits), occupying 8 or 16 timeslots. A resulting 16-slot data-burst shall be divided into a first and second sequential (but not necessarily contiguous) 8-slot data-bursts for separate scheduling by MAC for the purpose of fitting it into timeslots available (given the constraints of the current frame and subframe formats).

Zero or more UL Data data-bursts may be transmitted by an EP/RP in each UL subframe, see Figure 7-12, subject to frame and subframe format constraints.

7.4.3.3.4 A-interface UL Ack

Each A-interface Uplink Ack data-burst shall comprise a Sync header of 16 bits (see Table 7-4) followed by a single AC codeword (80 bits), occupying 4 timeslots.

Zero or more UL Ack data-bursts may be transmitted by an EP/RP in each UL subframe, see Figure 7-12, subject to frame and subframe format constraints. Timing is determined by MAC.

7.4.3.3.5 A"-interface DL

Each A"-interface DL data-burst shall comprise, in the order shown, a concatenation of:

- A Sync PDU (a Sync header of 80 bits followed by 112 bits SC codeword and then a guard period) which fits exactly into one timeslot (0,4 second).
- A single BC which carries the details of the sequence of codewords that follows it.
- Zero or more WMC/MC codewords.
- Zero or more CC/SCC codewords.
- Zero or more WU codewords.
- Zero or more WAC/AC codewords.
- Zero or more XC/SXC codewords, in the order indicated by the contents of WU PDU transmitted in the current frame.
- The content of the data-burst shall be consistent with the current A"-interface subframe format.
- A RP shall transmit a single such data-burst in each A"-interface DL subframe, see Figure 7-13.

7.4.3.3.6 A"-interface UL Data data-burst

Each A"-interface UL data-burst shall comprise, in the order shown, a concatenation of:

- A Sync PDU (a Sync header of 80 bits followed by 112 bits DC codeword and then a guard period) which fits exactly into one timeslot (0,4 second).

- Zero or more CC/SCC codewords.
- Zero or more WU codewords.
- Zero or more WAC/AC codewords.
- Zero or more XC/SXC codewords, in the order indicated by the contents of WU PDU transmitted in the current frame.
- The content of the data-burst shall be consistent with the current A"-interface subframe format.

An OEP shall transmit no more than one such data-burst in each A"-interface UL subframe, see Figure 7-14, subject to frame and subframe format constraints.

In a closed A" UL subframe, transmission starts in the first available timeslot.

In an open A" UL subframe, timing is determined by MAC.

7.4.3.3.7 A"-interface UL Ack data-burst

A"-interface Uplink Ack data-burst shall always start with a specific Sync header of 16 bits (as in Table 7-4). The remainder of the data-burst consists of a single AC codeword (80 bits).

A RP shall transmit no more than one such data-burst in each A"-interface UL subframe, subject to frame and subframe format constraints.

In a closed A" UL subframe, transmission shall start in the first available timeslot.

In an open A" UL subframe, timing is determined by MAC.

7.4.3.3.8 Bit order

Each pre-coding block shall be packed with the last entry in its pre-coding block table in the least significant location of the PDU (without changing bit order) and then each preceding entry shall be added in more significant locations (in the same bit order). The packed and coded PDU is transmitted least significant bit, of least significant byte, first.

Figure 7-15 is an example for the Sync PDU (clause 7.4.2.2).

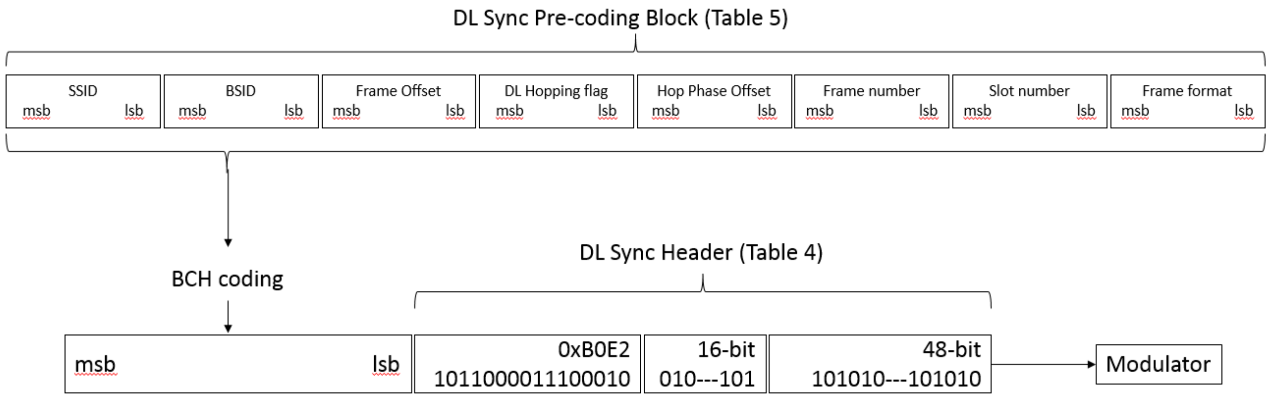

Figure 7-15: Example bit order - Sync PDU

7.4.3.4 Power Control

Power control is used in A-interface Uplink transmission by EP. Provision is made in PHY to control transmit power level using "Too Loud" flag. When the received RSSI at the BS is higher than an implementation-dependent defined threshold, BS may indicate "Too Loud" (see Table 7-23) in which case the EP shall reduce its transmit power by 2 dB from its current level when it next transmits. If "Too Loud" is not indicated, the EP shall increase its transmit power by 2 dB from its current level when it next transmits (up to its maximum level).

If the EP is in high interference mode (and is therefore sending double codeword format Data PDUs) (see clause 7.4.2.6), it shall ignore the "Too Loud" flag and set the transmit power level to its maximum level.

7.4.3.5 High Interference Mode

As described in this specification, strong and weak coding is available for a range of PDUs. The choice of coding scheme shall be made by the related entity and shall be signalled as described (e.g. Table 7-9). Choice of algorithm by which to determine whether to use High Interference Mode is implementation dependent, however specified control mechanisms shall be supported (see Table 7-23, Table 7-24, Table 7-25 and clause 7.4.3.4).

7.4.4 PHY Procedures

7.4.4.1 Synchronization and Frequency Scanning

Layer 1 supports frequency scanning and synchronization processes to detect available BS and RP. This process is implementation-dependent.

7.4.4.2 Base Selection

The process by which an EP selects a BS / RP with which to attempt connection is implementation-dependent.

7.4.4.3 Transmit Duty-Cycle Control

DD-UNB implementations are typically subject to regulatory limits on transmitter duty cycle. It is an implementation issue to ensure such limits are not exceeded.

7.4.4.4 A-interface Downlink Transmission Control - Frame Structure

Before the start of each frame, BS shall determine the frame format to use for that frame as described in clause 7.4.1.1. This process is implementation-dependent. Transmission of DL data-bursts shall commence in the first timeslot allocated to the related subframe, see Table 7-1.

7.4.4.5 A"-interface Downlink Transmission Control - Subframe Structure

Before the start of each A"-interface subframe, RP shall determine the format to use for that subframe as described in clause 7.4.1.1. This process is implementation-dependent.

7.4.4.6 Uplink Transmission Control

BS transmissions are the reference for both the time and the frequency of EP and RP transmissions. No allowance for propagation delays is required in the timing of uplink transmissions.

7.4.4.7 PHY Measurements

PHY measurements are implementation-dependent and may include:

- the average power (RSSI) of the Sync Word in a data-burst;
- the number of corrected bits in each received codeword;

or other measurements.

Such measurements may be used to support "too loud" indication (clause 7.4.3.4).

7.4.4.8 Noise Measurement

Some A-interface frame formats allocate "noise measurement" timeslots during which no system elements transmit. These may be used to measure noise and/or interference levels; such measurements, and the use of the results, are implementation-dependent.

7.4.4.9 Base-System Group (BSGP)

To enable the BS to distinguish reception of a local EP's (intended) transmissions from distant EP's (unintended) transmissions (in the case that block numbers coincide), "Uplink Connection Base-System Group" (XC BSGP) is included in each Data L1 PDU on the A-interface UL, see Table 7-18.

XC BSGP (see Table 7-18) has the same value as BC BSGP (see Table 7-7) which is broadcast in every frame. Received Uplink Data PDUs at the BS side with incorrect XC BSGP shall be ignored.

Similarly, AC BSGP (see Table 7-25) is used to prevent the same problem happening for Uplink Acknowledgements. AC BSGP has the same value as BC BSGP which is broadcast in every frame. Received Uplink Ack PDUs at the BS side with incorrect AC BSGP shall be ignored.

7.5 Radio characteristics

7.5.1 Frequency Structure - Radio Mode 0

Clause 7.5.1 and any subclauses describe DD-UNB operation in Radio Mode 0; other modes are for further study.

Table 7-29: Radio Mode definition

Radio Mode	**Downlink / A"**			**Uplink**		
	Bit-rate (bps)	Symbol-rate (Hz)	Deviation Δf (Hz)	Bit-rate (bps)	Symbol-rate (Hz)	Deviation Δf (Hz)
0	500	500	±250	62,5	62,5	±250
Other	Reserved					

Frequency domain separation of uplink and downlink transmissions may be used for network planning purposes and/or to reflect regulatory constraints, but this is not essential to achieve full-duplex operation.

The operating frequency band(s) to be used for DL and UL, and whether to use frequency hopping for the DL and A"-interface, are selected when a system is planned and shall be known to all entities; the selection is applicable to both A and A"-interfaces. The spectrum used for each interface in a given direction shall be contiguous. In a non-hopping system each cell operates on one of N planned DL and UL channels (UL/DL_Chan_Freq(n), n $\in$ {0, … , N-1}; the spacing of the centre frequencies of these channels within the respective operating band is 15 kHz in the UL and 25 kHz in the DL (Figure 7-16).

If DL hopping, the frequencies in the hop set (selected within the DL band as described above for a non-hopping system) shall be arranged in pseudorandom order in a Frequency Hopping Sequence, each element of which defines a DL centre frequency. The Physical Layer maintains a Frequency Hopping Index that shall be initialized (see below) for timeslot 0 of each frame and incremented for each subsequent timeslot within the frame, modulo the size of the table, and used to look up the DL frequency to be used in the timeslot. The initial value in each frame shall be determined by the Hop Phase Offset selected when a system is planned and allows nearby cells to reduce or avoid the simultaneous use of the same DL frequency by the use of different Hop Phase Offset values. The Hop Phase Offset shall be signalled in the DL Sync PDU to enable an EP to ascertain system time (see Table 7-5).

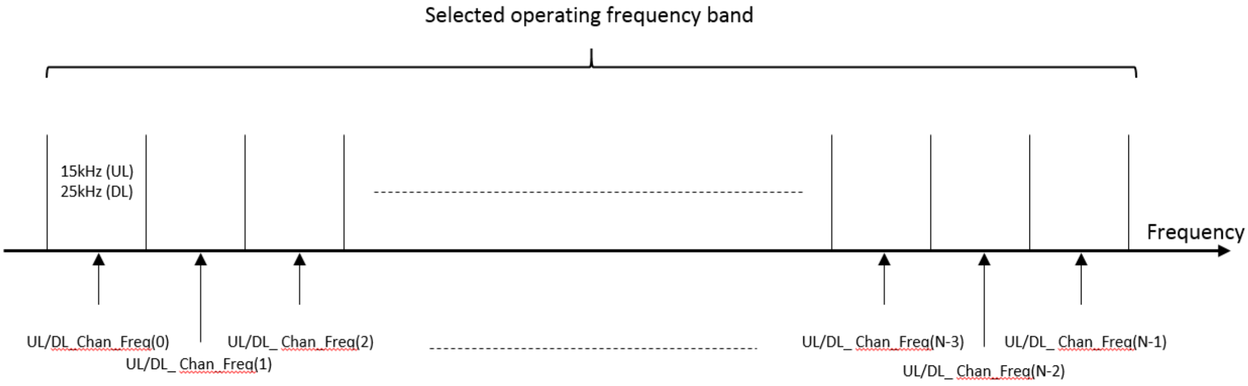

Figure 7-16: Channel numbering

7.5.2 Modulation - Radio Mode 0

7.5.2.1 General

Clause 7.5.2 and subclauses describe DD-UNB operation in Radio Mode 0; other modes are for further study and may, for example, include the generation of more than one modulated carrier within the identified channel on one or more interfaces or alternative modulation schemes.

The DD-UNB modulation uses Binary Frequency Shift Keying (BFSK) for UL on A"-interface and for DL on both A-interface and A"-interface. It uses a combination of BFSK and Random Frequency Selection (RFS) for UL on A-interface. Use of Continuous Phase FSK is mandatory for the base station but optional for the End-point. BS transmit frequencies are determined in network planning.

In Radio Mode 0, in all interfaces, the information bits are represented by two tones offset in frequency by $\Delta f = 250$ Hz from a selected carrier frequency. A "1" corresponds to transmission of the higher frequency tone (f_h).

7.5.2.2 A-interface DL and A"-interface (UL and DL) modulation

Within the selected 25 kHz channel a number of nominal carrier frequencies spaced at 500 Hz intervals are identified (as FDM_f_c(n)) as depicted in Figure 7-17. For Radio Mode 0 A-interface DL a modulated carrier is generated at FDM_f_c(10) or FDM_f_c(40); the choice between these values of FDM_f_c is made in network planning.

For A"-interface (UL and DL) FDM_f_c(25) is used.

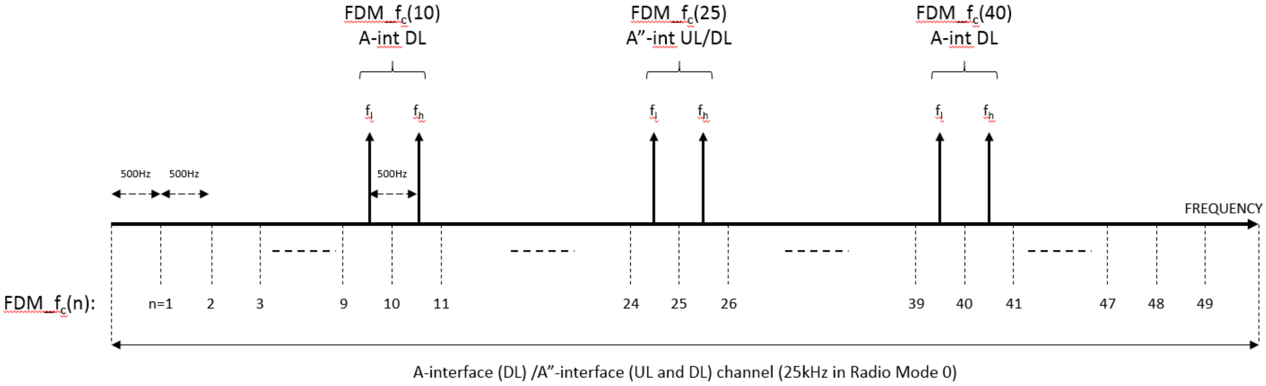

Figure 7-17: A-interface (DL) and A"-interface (UL and DL) frequencies

In Radio Mode 0 a DL (A and A") receiver shall receive any signal or signals within the selected 25 kHz channel. Such a receiver typically employs digital techniques to filter and demodulate those signals.

7.5.2.3 A-interface UL modulation

Uplink modulation is implemented based on a combination of BFSK and Random Frequency Selection (RFS).

In Radio Mode 0 the UL operating channel width is 15 kHz. Each EP/RP shall perform RFS independently for each data-burst (except as described in clause 7.4.3.3.3 for strongly-coded PDUs where each pair of data-bursts shall be transmitted on the same frequency) and shall choose its BFSK centre frequency (RFS_f_c) within the UL channel (see Figure 7-18) as determined by MAC, such that:

$$\text{RFS\_f}_c = \text{UL\_Chan\_Freq} - (\text{RFS\_range} / 2) + (F_{MAC} \times F_{gran})$$

and where:

- UL_Chan_Freq is the centre frequency of the UL channel (see Table 7-7).
- RFS_range is the difference between the lowest and highest permitted values of RFS_f_c (14 kHz for Radio Mode 0).

- F_{MAC} is an integer value generated by MAC (value from 0 to (RFS_range/ F_{gran})).
- F_{gran} is the granularity of RFS selection (implementation dependent).

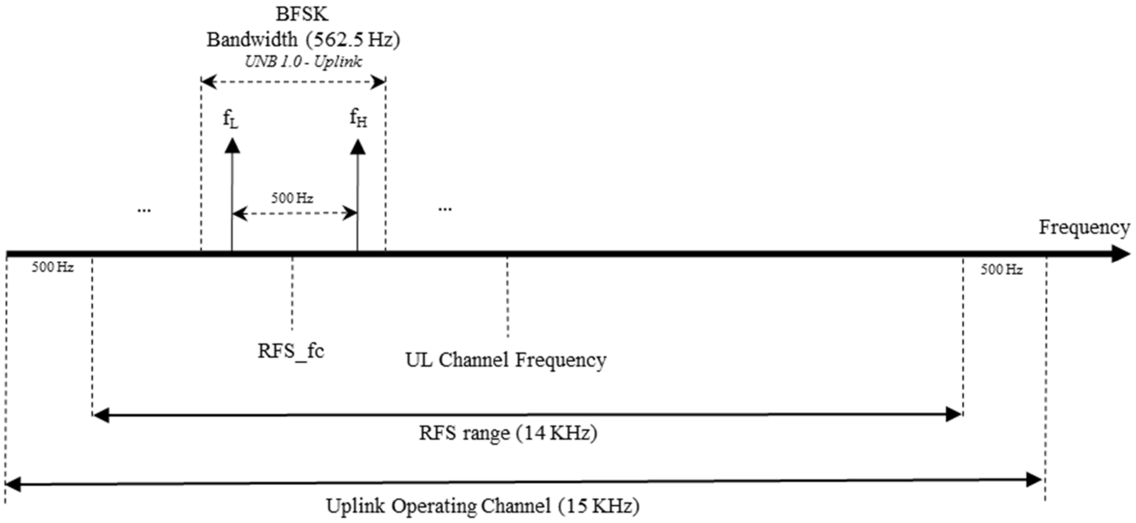

Figure 7-18: A-interface UL modulation

7.5.3 Radio-Burst Power Ramping

A guard period of 16 ms is provided for power-ramping and optional frequency hopping between radio-bursts; when transmitting, transmit power shall be reduced during the guard period in all entities (whether or not frequency-hopping). Transmit power shall rise or fall by ≥60 dB within 500 µs of the start or end (respectively) of the radio-burst, any frequency changes shall take place when the power is at that reduced level. The power shall be within ±1 dB of the average radio-burst transmit power for the active part of the radio-burst (see Figure 7-19). Any emissions arising from such ramping and frequency changes shall be within regulatory limits.

During the guard period a sequence of alternating "1"s and "0"s at the bit rate, beginning with a "1", is inserted in the modulation bit-stream.

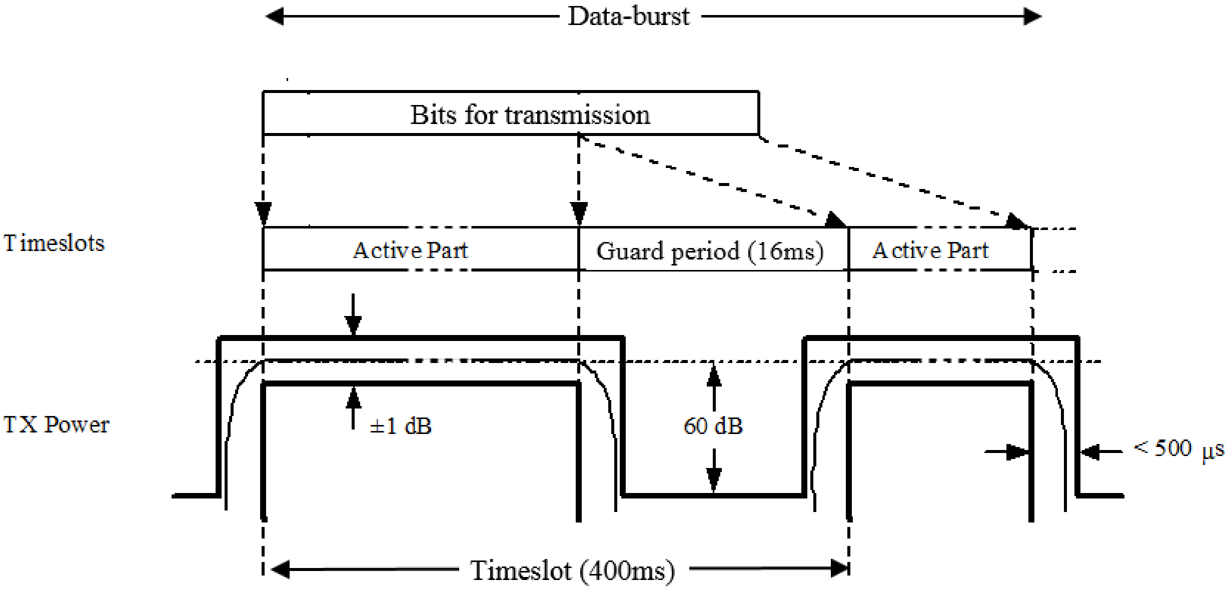

Figure 7-19: Power Ramping and Frequency Switching

Annex A (informative): Generic end-point system block diagram

A.1 Overview

The BS and the RP are network elements that are specific to each family.

To maximize the economy of scale, this section proposes an example of a generic EP transceiver implementation that supports all LTN families.

Figure A-1 shows an example implementation of an EP.

The EP can be designed with sensors and/or control/data ports for external sensors.

The EP can be designed with or without a host CPU - for instance, the microcontroller embedded in the transceiver may have sufficient functionality and performance to undertake the role of host CPU for some applications.

The EP can additionally have a Secure Element (SE) to hold secret data for payload encryption for example. While it is possible to embed the SE into the transceiver IC, an external SE is likely to provide more flexibility and potentially offers a more future-proof design.

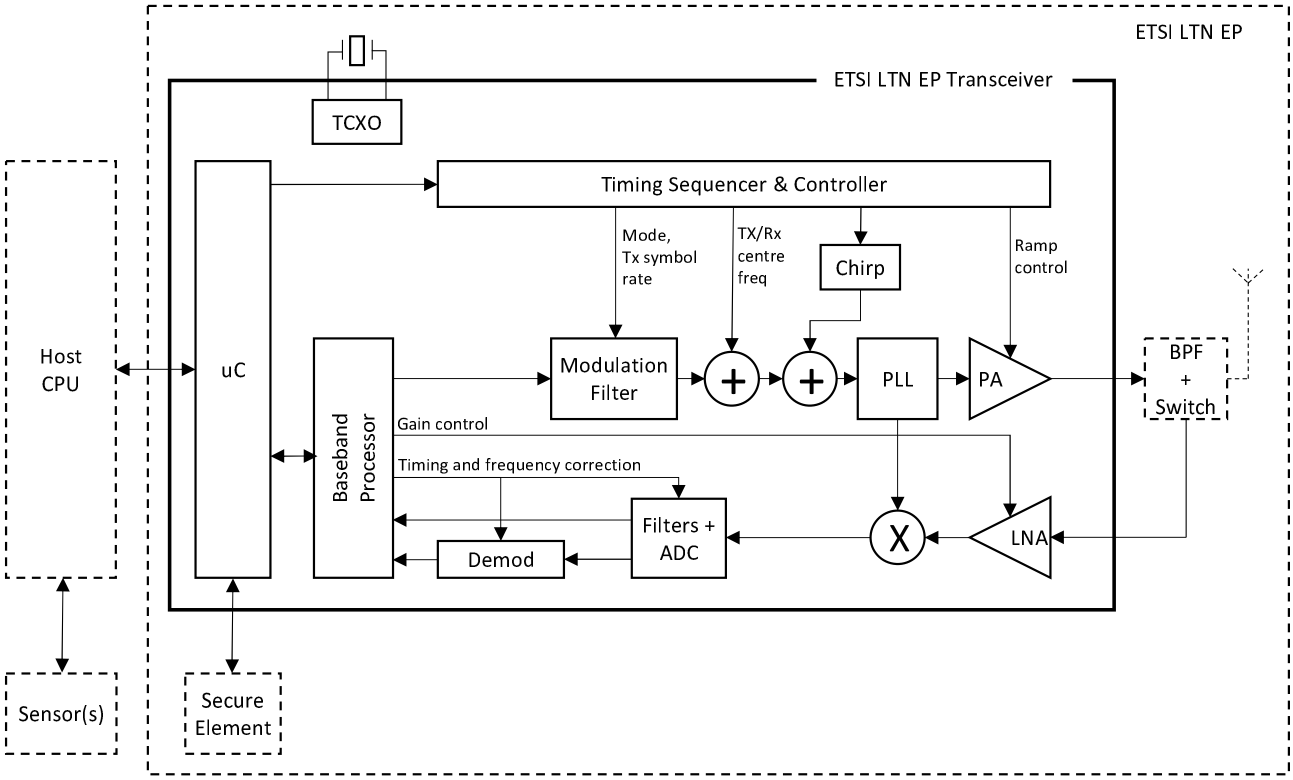

Figure A-1: System overview of EP

The following clauses provide some implementation detail about some of the key blocks within the EP transceiver.

A.2 uC

A microcontroller that is optimized for small size and low-power consumption while being able to handle functions such as; manipulation of payload data, communication with the SE and the set up the Timing Sequencer & Controller.

A.3 Baseband Processor

The uplink functions are; CRC calculation, FEC, Interleaving, Encryption.

The downlink functions are; Decryption, de-interleaving, error correction (convolutional, LDPC), CRC check.

A hardware DSP function is likely to provide the optimal trade-off of size, power consumption and cost.

A.4 TCXO

It is possible to use a 26 MHz reference clock for all families. However, with detailed analysis, a more suitable clock frequency may be found that will ease the design of the sequencers, state machines, modulator and demodulator.

The TCXO is likely to be a function integrated into the transceiver IC.

A.5 Timing Sequencer & Controller

This block is likely to be a collection of Finite State Machines and sequencers implemented in hardware. The configuration will be undertaken by software running on the microcontroller. Functions will include; set modulation/demodulation mode, set the Tx and Rx symbol rate, set the Tx and Rx centre frequency, chirp control and PA ramp control.

A.6 Modulation Filter

Modulation function is provided by a configurable filter supporting the following modulations; BPSK, Pi/2 BPSK, BFSK and GMSK.

A.7 PLL

A fractional-N type PLL with performance to meet the local RF requirements is used.

A single PLL design is shown in Figure A-1, however a dual-PLL design (one for Tx and one for Rx) may offer performance advantages.

A.8 Power Amplifier

A suitable Power Amplifier (PA) is provided for the desired frequency band of operation and the regulations that are in force locally.

A.9 Demodulator

The demodulator could be implemented using a matched filter.

A.10 Summary

An implementation example has been shown for a generic EP transceiver that can support all three families that make up LTN. Based on knowledge of the requirements of the families and the use-cases for LTN, some high-level guidance has been included for some of the blocks to aid the design trade-offs, particularly between performance and cost. Other approaches can be followed in implementing each of these functional blocks.

Annex B (informative): TS-UNB Profiles

B.1 Overview

The TS-UNB profiles define standard TS-UNB protocol settings for interoperability of end-points and base stations operating in a TS-UNB based LTN network. The profiles are a recommendation and can be extended in the future.

B.2 EU0 Profile

B.2.1 Spectrum Use

Table B-1: UL channel Frequencies

	Channel Centre Frequency f_c	**Channel Bandwidth**
Primary Channel A	868,180 MHz	100 kHz

Table B-2: DL channel Frequencies

	Channel Centre Frequency f_c	**Channel Bandwidth**
Primary Channel A	869,575 MHz	100 kHz

The frequency offset between uplink and downlink is $f_{DL-UL} = 1{,}395\ MHz$.

B.2.2 Mode of operation

Table B-3: Mode of operation of EU0 profile

	Uplink	**Downlink (Optional)**
PHY Mode	Telegram Splitting (TS)	
Modulation	(G)MSK	(G)MSK
Symbolrate	ULP: 2 380,371 Sym/s	ULP: 2 380,371 Sym/s
TSMA Mode	Wide (Carrier spacing: 2 380,371 Hz)	
Sync Burst	off	
Repetition	off	
Channels	Single Channel	

B.3 EU1 Profile

B.3.1 Spectrum Use

Table B-4: UL channel frequencies

	Channel Centre Frequency f_c	Channel Bandwidth
Primary Channel A	868,180 MHz	100 kHz
Secondary Channel B	868,080 MHz	100 kHz

Table B-5: DL channel frequencies

	Channel Centre Frequency f_c	Channel Bandwidth
Primary Channel A	869,575 MHz	100 kHz
Secondary Channel B	869,475 MHz	100 kHz

The frequency offset between uplink and downlink is $f_{DL-UL} = 1{,}395\ MHz$. For frame repetition in dual channel mode a carrier frequency offset step $N_{re} = 42$ is used.

B.3.2 Mode of operation

Table B-6: Mode of operation of EU1 profile

	Uplink	Downlink (Optional)
PHY Mode	Telegram Splitting (TS)	
Modulation	(G)MSK	(G)MSK
Symbolrate	ULP: 2 380,371 Sym/s	ULP: 2 380,371 Sym/s
TSMA Mode	Wide (Carrier spacing: 2 380,371 Hz)	
Sync Burst	off	
Repetition	off/on	
Channels	Dual Channel	

B.4 EU2 Profile

B.4.1 Spectrum Use

Table B-7: Channel Frequencies

	Channel Centre Frequency f_c	Channel Bandwidth
Primary Channel A	867,625 MHz	750 kHz
Secondary Channel B	866,911 MHz	750 kHz

Both channels are overlapping resulting in an overall channel bandwidth of 1,46 MHz. For frame repetition in dual channel mode a carrier frequency offset step $N_{re} = 25$ is used.

The same channel is used in uplink and downlink. The frequency offset between uplink and downlink is $f_{DL-UL} = 0\ Hz$.

B.4.2 Mode of operation

Table B-8: Mode of operation of EU2 profile

	Uplink	Downlink (Optional)
PHY Mode	Telegram Splitting (TS)	
Modulation	(G)MSK	(G)MSK
Symbolrate	ULP: 2 380,371 Sym/s	ULP: 2 380,371 Sym/s
TSMA Mode	Wide (Carrier spacing: 28 564,453 Hz)	
Sync Burst	on/off	
Repetition	on/off	
Channels	Dual Channel	

B.5 US0 Profile

B.5.1 Spectrum Use

Table B-9: UL channel Frequencies

	Channel Centre Frequency f_c	Channel Bandwidth
Primary Channel A	916,357 MHz	750 kHz
Secondary Channel B	915,643 MHz	750 kHz

Both channels are overlapping resulting in an overall channel bandwidth of 1,46 MHz. For frame repetition in dual channel mode a carrier frequency offset step $N_{re} = 25$ is used.

The same channel is used for uplink and downlink. The frequency offset between uplink and downlink is $f_{DL-UL} = 0\ Hz$.

B.5.2 Mode of operation

Table B-10: Mode of operation of US0 profile

	Uplink	Downlink (Optional)
PHY Mode	Telegram Splitting (TS)	
Modulation	(G)MSK	(G)MSK
Symbolrate	ULP: 2 380,371 Sym/s	ULP: 2 380,371 Sym/s
TSMA Mode	Wide (Carrier spacing: 28 564,453 Hz)	
Sync Burst	on	
Repetition	on/off	
Channels	Dual Channel	

History

Document history		
V1.1.1	June 2018	Publication