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Information technology — Real-time locating systems (RTLS) —

Part 5: Chirp spread spectrum (CSS) at 2,4 GHz air interface

Technologies de l'information — Systèmes de localisation en temps réel (RTLS) —

Partie 5: Spectre étalé de compression d'impulsions (CSS) à une interface d'air de 2,4 GHz

Reference number
ISO/IEC 24730-5:2010(E)

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Foreword

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The main task of the joint technical committee is to prepare International Standards. Draft International Standards adopted by the joint technical committee are circulated to national bodies for voting. Publication as an International Standard requires approval by at least 75 % of the national bodies casting a vote.

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ISO/IEC 24730-5 was prepared by Joint Technical Committee ISO/IEC JTC 1, *Information technology*, Subcommittee SC 31, *Automatic identification and data capture techniques*.

ISO/IEC 24730 consists of the following parts, under the general title *Information technology — Real-time locating systems (RTLS)*:

— *Part 1: Application program interface (API)*

— *Part 2: 2,4 GHz air interface protocol*

— *Part 5: Chirp spread spectrum at 2,4 GHz air interface*

Introduction

CSS is a technique for spreading the bandwidth of a digital signal by using chirp pulses. Chirp pulses are pulses with a monotonically increasing or decreasing instantaneous frequency. Chirp pulses were originally used for radar applications. Recently, systems and standards have been developed which use chirp pulses also for communication applications. This part of ISO/IEC 24730 includes ranging and bidirectional communication between tags and infrastructure. Bidirectional communication enables the infrastructure to control the behaviour of tags in a timely manner.

Information technology — Real-time locating systems (RTLS) —

Part 5: Chirp spread spectrum (CSS) at 2,4 GHz air interface

1 Scope

ISO/IEC 24730 defines air interface protocols and an application programming interface (API) for real-time locating systems (RTLS). This part of ISO/IEC 24730 defines an air interface protocol which utilizes chirp spread spectrum (CSS) at frequencies from 2,4 GHz to 2,483 GHz. This protocol supports bidirectional communication and two-way ranging between the readers and tags of an RTLS. The mandatory default mode ensures interoperability between tags and infrastructure from various manufacturers, while the availability of several options offers flexibility to the developer of the infrastructure to adapt the behaviour of the overall system to the specific needs of his application.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 15963, *Information technology — Radio frequency identification for item management — Unique identification for RF tags*

ISO/IEC 19762-1, *Information technology — Automatic identification and data capture (AIDC) techniques — Harmonized vocabulary — Part 1: General terms relating to AIDC*

ISO/IEC 19762-3, *Information technology — Automatic identification and data capture (AIDC) techniques — Harmonized vocabulary — Part 3: Radio frequency identification (RFID)*

ISO/IEC 19762-4, *Information technology — Automatic identification and data capture (AIDC) techniques — Harmonized vocabulary — Part 4: General terms relating to radio communications*

ISO/IEC 19762-5, *Information technology — Automatic identification and data capture (AIDC) techniques — Harmonized vocabulary — Part 5: Locating systems*

ISO/IEC 24730-1, *Information technology — Real-time locating systems (RTLS) — Part 1: Application program interface (API)*

Guidelines on Limiting Exposure to Non-Ionizing Radiation, International Commission on Non-Ionizing Radiation Protection (ICNIRP), Munich, 1999

IEC 62369-1 ed1.0, *Evaluation of human exposure to electromagnetic fields from short range devices (SRDs) in various applications over the frequency range 0 GHz to 300 GHz — Part 1: Fields produced by devices used for electronic article surveillance, radio frequency identification and similar systems*

IEEE Std C95.1-2005, *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/IEC 19762-1, ISO/IEC 19762-3, ISO/IEC 19762-4, ISO/IEC 19762-5 and the following apply.

3.1
chirp spread spectrum
technique for spreading the bandwidth of a digital signal using linear frequency sweep signals

3.2
Class I
system that operates at a radiated power of up to 10 mW EIRP

3.3
Class II
system that operates at a radiated power higher than 10 mW up to the maximum defined by local regulations

3.4
ranging
process of determining the distance between two RTLS transceivers through the exchange of a specific set of messages

3.5
ranging peer
RTLS transceiver with which to perform ranging

3.6
RF channel
combination of a centre frequency value and bandwidth value

3.7
RTLS tag
RTLS transceiver that accepts commands from RTLS readers and sends blinks and/or reports to the RTLS readers

3.8
RTLS transmitter
part of an RTLS transceiver which is capable of sending messages

3.9
demultiplexer
equipment for reversing the process of multiplexing

3.10
medium
wireless channel

3.11
trilateration
method of determining the relative positions of objects using the known locations of three reference points and the measured distance between the object to be located and each reference point

3.12
interleaving
rearrangement or transposition of data to enhance the effectiveness of error control schemes

3.13
interleaver
unit that performs interleaving (3.12)

3.14
baseband
frequency band occupied by the aggregate of the signals used to modulate a carrier before they combine with the carrier in the modulation process

3.15
orthogonal
inner product being close to zero

3.16
peer X
x'th peer in a description of a situation with multiple peers

4 Symbols and abbreviated terms

ACK	acknowledge
ARQ	Automatic Repeat Query
BTS	Backoff Time Slot
CIFS	Carrier sense Inter Frame Space
CTS	Clear To Send
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CSS	Chirp Spread Spectrum
dBr	decibel relative
DEMUX	demultiplexer
DQPSK	Differential Quadrature Phase Shift Keying
DQPSK-CSS	Differential Quadrature Phase Shift Keying over Chirp Spread Spectrum
Dst	Destination address
EIRP	Equivalent Isotropical Radiated Power
LFSR	Linear Feedback Shift Register
LSB	Least Significant Bit
MMSE	Minimum Mean Square Error
MAC	Medium Access Control
NAV	Network Allocation Vector
PHR	PHY header
PHY	physical layer
PPDU	PHY Protocol Data Unit

PSDU	PHY Service Data Unit
QPSK	Quadrature Phase Shift Keying
RTS	Request To Send
RTLS	Real Time Locating System
SFD	Start of Frame Delimiter
SHR	synchronization header
SIFS	Short Inter Frame Space
Src	source address
TWR	Two Way Ranging
SDS-TWR	Symmetric Double Sided Two Way Ranging
e	Euler constant
j	imaginary unit
$\tilde{s}^{M_0}(t)$	continuous time baseband representation of 2-ary orthogonal CSS signal
$\tilde{r}^{M_0}(t)$	implemented version of $\tilde{s}^{M_0}(t)$
$\tilde{s}_m^{M_1}(t)$	continuous time baseband representation of DQPSK-CSS signal
$\tilde{r}_m^{M_1}(t)$	implemented version of $\tilde{s}_m^{M_1}(t)$
m	configuration constant determining the type (one our of four possibilities) of sub-chirp sequence used
M_0	superscript indicating that 2-ary orthogonal CSS is described
M_1	superscript indicating that DQPSK-CSS is described
k	index variable
n	index variable
b_n	n'th symbol to be transmitted
$c_b(t)$	continuous time baseband representation of chirp pulse b for 2-ary orthogonal CSS
μ_0	configuration constant determining the chirp rate for 2-ary orthogonal CSS
μ_1	constant determining the chirp rate for DQPSK-CSS
T_{base}	timebase

T_{SBIFS}	time in between two sub blinks
T_{Blink}	average blink repetition time
T_{Rand}	random time
T_{Rxon}	duration of time interval for during which the receiver of a tag is activated
$T_{Contact}$	maximum expected duration between a tag receiving any packets from infrastructure if such is present
$T_{TimeoutApplication}$	duration of time interval during which a tag application shall respond to certain requests
$T_{WaitAfterRange}$	duration of time for which a tag shall go to Wait state after leaving Range state
T_0	configuration constant determining the duration of a chirp pulse for 2-ary orthogonal CSS
T_1	duration of sub-chirp sequence
T_{sub}	duration of sub-chirp
$T_{n,k,m}$	time position of k'th sub-chirp of n'th sub-chirp sequence of type m
$W_T(t)$	raised cosine window of duration T
α	roll of factor of the raised cosine window
A	amplitude variable which is minimized in minimum mean square error computation
τ_d	time delay variable that is minimized in minimum mean square error computation
φ	phase variable that is minimized in minimum mean square error computation
$d_{n,k}$	information sample of k'th sub-chirp in n'th sub-chirp sequence
$C_{k,m}^{sub}(t)$	continuous time baseband representation of k' sub-chirp of sub-chirp sequence type m
τ_m	timing constant that determines the time-gap between subsequent sub-chirp sequences for the sub-chirp sequence type m
$f_{k,m}$	offset centre frequency of k'th sub-chirp in sub-chirp sequence type m
$\zeta_{k,m}$	chirp direction of k'th sub-chirp in sub-chirp sequence type m
$S_m^{sub}(t)$	continuous time baseband representation of sub-chirp sequence of type m

5 Overview

5.1 Components

The major components of a real-time locating system (RTLS) and the relationship of those components are shown in Figure 1. As shown in this Figure the tags communicate with an infrastructure. The infrastructure provides an application program interface (API) through which an application can control the RTLS and retrieve information about location and state of tags.

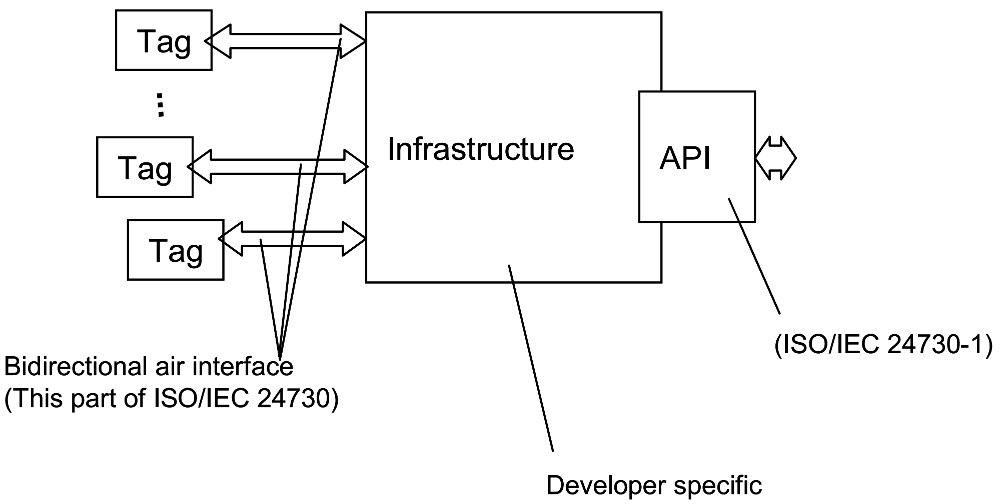

Figure 1 – RTLS components

As indicated in Figure 1 tags communicate with infrastructure over an air interface. Generally the air interface includes the definition of waveforms, formats of packets as well as commands and reports to be exchanged between tags and infrastructure. This can be depicted in a layered approach as shown in Figure 2. Similar interpretations can be found in other standards e.g. in ISO/IEC 18000-1[1].

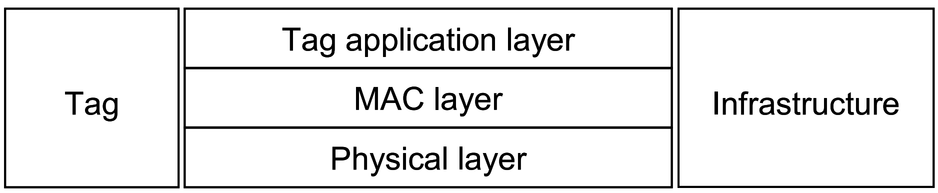

Figure 2 – Air interface layers

5.2 Purpose

This part of ISO/IEC 24730 defines an air interface protocol that optimizes small scale RTLS with an installation that enables simple, and also handheld, RTLS readers. Although the infrastructure itself is not defined in this part of ISO/IEC 24730, it is anticipated that the air interface protocol has a strong impact on the realization of the infrastructure and the related installation effort.

The key condition for simple installation is the possibility of 'autonomous' infrastructure nodes. In this part of ISO/IEC 24730, "autonomous" means there is not a requirement for these nodes to be synchronized with other infrastructure nodes. After being placed at a fixed location, an autonomous node simply responds to requests from RTLS tags.

This condition is achieved by specifying bidirectional communication and two-way ranging. As a consequence, the tag must also support bidirectional communication. Although this requirement increases the complexity of the tag in one area, it also decreases the complexity in other areas, as additional interfaces for programming and conditioning the tag are not required. Thus bidirectional communication with the tag is seen as beneficial for many applications. Finally in order to utilize existing state of the art communication technology this part of ISO/IEC 24730 includes parts that correspond with IEEE 802.15.4a[5], which is a PHY amendment of IEEE 802.15.4[4], a successful standard for low power, low data rate wireless communication.

5.3 Not covered by the standard

The design of the infrastructure is left completely to the developer, e.g. the density of RTLS reader nodes, how the RTLS readers are controlled and communicate with each other, how the infrastructure is set up, etc. may be different in various scenarios and for systems from different vendors. For typical RTLS applications, at least three RTLS readers will communicate with each tag, measuring time of flight in order to locate the tag. For more details on this interaction, see Clause 9, Tag application layer specification.

5.4 System

After power on, a tag uses a default profile in which it blinks periodically. With each blink the tag signals its physical address, its capabilities and information about when it will be ready to receive commands from the infrastructure.

The infrastructure decides whether it needs to send commands to the tag while the tag is listening. By sending commands to the tag, the infrastructure controls which RTLS readers are part of the infrastructure the tag performs ranging with. Furthermore the infrastructure can adapt the behaviour of the tags to the actual conditions such as the number of tags in range, number of infrastructure nodes available, etc. For example, the infrastructure is able to instruct the tag to change to another mode (bandwidth, centre frequency, data rate) according to the actual environment or to perform ranging with a specific set of RTLS readers.

When the tag assumes that it has lost connection to the infrastructure e.g. because it doesn't receive any commands for a certain time, it reverts to the default profile. A more detailed description of complete system behaviour can be found in Annex D.

5.5 Document structure

The remainder of this part of ISO/IEC 24730 follows the "layered structure" mentioned above. This means that after the Requirements clause the three layers that form an air interface protocol (the Physical Layer [PHY], Media Access Control [MAC] and the Tag application layer) are addressed and specified separately. Additional information for the user of this part of ISO/IEC 24730 is provided in the informative annexes.

6 Requirements

6.1 Frequency range

This part of ISO/IEC 24730 addresses real-time locating systems (RTLS) operating in the 2,400 to 2,4835 GHz frequencies.

6.2 2,4 GHz spread spectrum air interface specifications

The minimum requirements shall include:

– RTLS transceivers shall autonomously generate a chirp spread spectrum frequency beacon indicating when the receiver will be activated.

– RTLS transceivers shall be able to perform two-way ranging when the receiver is activated.

– RTLS transmitters shall be fully compliant with local regulatory requirements.

– Class I RF transmissions shall not exceed 10 mW EIRP

– Class II RF transmissions shall not exceed 100 mW EIRP or the maximum EIRP according to the local radio regulations.

6.3 Compliance requirements

To be fully compliant with this part of ISO/IEC 24730, real-time locating systems (RTLS) shall also comply with ISO/IEC 24730-1.

Device manufacturers claiming conformance to this part of ISO/IEC 24730 shall self-certify RF emissions do not exceed the maximum permitted exposure limits recommended by either IEEE C95.1: 2005 or ICNIRP according to IEC 62369-1. If a device manufacturer is unsure as to which recommendation to be cited for compliance the manufacturer shall self-certify to ICNIRP limits.

6.4 Manufacturer tag ID

The manufacturer's tag identification number identifies a particular manufacturer and consists of 16 bits. A manufacturer may have more than one ID number. The frame format used in this part of ISO/IEC 24730 mandates a MAC address of at least 48 bits for each device. The first 16 bits of the MAC address are designated for the manufacturer's identification number and shall be assigned according to ISO/IEC 15963 Annex D, under Allocation Class 0000 0000.

6.5 Physical layer parameters

For the purposes of this part of ISO/IEC 24730, the following parameter definitions apply in Table 1. These parameters are referenced by parameter name. These operating parameters are to be defined for the temperature range of minus 30 degrees Celsius to 50 degrees Celsius.

Table 1 – 2,4 GHz CSS link parameters

Parameter name	Description
Operating frequency range	As permitted by local radio regulations in the band from 2400 to 2483,5 MHz.
Operating frequency accuracy	± 70 ppm (2-ary orthogonal CSS) ± 40 ppm (DQPSK –CSS)
Maximum phase noise	-85 dBc/Hz @ 1 MHz
Occupied 20 dB channel bandwidth	80 MHz (Default value) 22 MHz (Configuration option)
Centre frequency, bandwidth combination	According to Table 2 and Table 6
Time base, T_{base}	31,25 ns
Time base accuracy	± 40 ppm
Transmit power	Class 1: 10 dBm EIRP. max. Class 2: Maximum in accordance to local regulations.
Transmitter spectrum mask	According to Table 3 and Figure 13
Spurious emission, out of band	The device shall transmit in conformance with spurious emissions requirements defined by the country's regulatory authority within which the system is operated.
Modulation	2-ary orthogonal CSS DQPSK-CSS (optional)

Parameter name	Description
Data bit rates	1 Mbit/s 250 kbit/s
Symbol rates	10^6 symbols/s, 250000 symbols/s 166667 symbols/s (with DQPSK-CSS)

7 Physical (PHY) layer specification

7.1 Modulations

The PHY layer specification shall contain two modulations (2-ary orthogonal CSS and DQPSK-CSS). The support of 2-ary orthogonal shall be mandatory while the support of DQPSK-CSS is optional.

7.2 Data rates

2-ary orthogonal CSS shall support data rates of 1 Mbits/s and 250 kbit/s.

DQPSK-CSS, when implemented, shall support data rates of 1 Mbits/s and 250 kbit/s.

7.2.1 General PHY packet format

A PHY packet shall consist of a synchronization header and a PHY protocol data unit as shown in Figure 3.

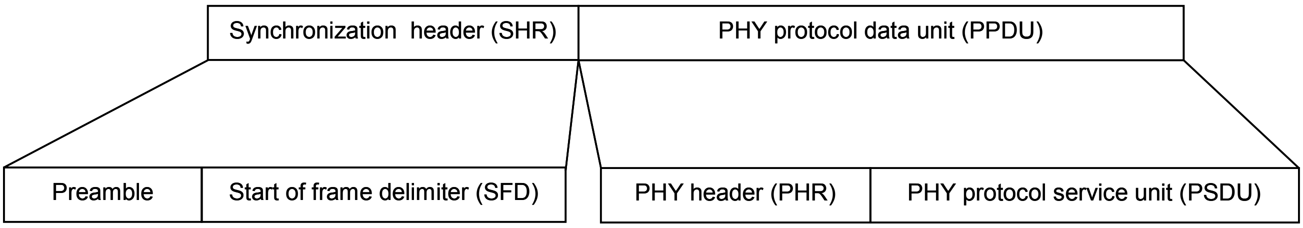

Figure 3 – General PHY packet structure

The definitions of preamble, SFD and PHY are given in 7.3.7, 7.3.8, 7.3.10 and 7.4.14, 7.4.15, 7.4.16.

The PSDU shall contain the MAC a frame defined Clause 8.

7.3 2-ary orthogonal CSS

2-ary orthogonal CSS shall be the mandatory PHY mode. A combination of centre frequency and bandwidth shall called "RF channel". The possible RF channels are defined in Table 2.

Table 2 – Possible combinations of centre frequency and bandwidth for 2-ary orthogonal CSS

RF channel number	Centre frequency	Bandwidth
0	2441,75 MHz	80 MHz
1	2441,75 MHz	22 MHz
2	2412 MHz	22 MHz
3	2417 MHz	22 MHz
4	2422 MHz	22 MHz
5	2427 MHz	22 MHz
6	2432 MHz	22 MHz
7	2437 MHz	22 MHz
8	2442 MHz	22 MHz
9	2447 MHz	22 MHz
10	2452 MHz	22 MHz
11	2457 MHz	22 MHz
12	2462 MHz	22 MHz
13	2467 MHz	22 MHz
14	2472 MHz	22 MHz
15	2484 MHz	22 MHz

7.3.1 Reference modulator diagram

The functional block diagram in Figure 4 is provided as a reference for specifying 2-ary orthogonal CSS for both data rates 1 Mbits/s and 250 kbit/s. The functionality of the Bit scrambler block is specified in 7.3.9. The functionality of the Bit to symbol mapping block is specified in 7.3.5. The functionality of the chirp generator block is specified in 7.3.6.

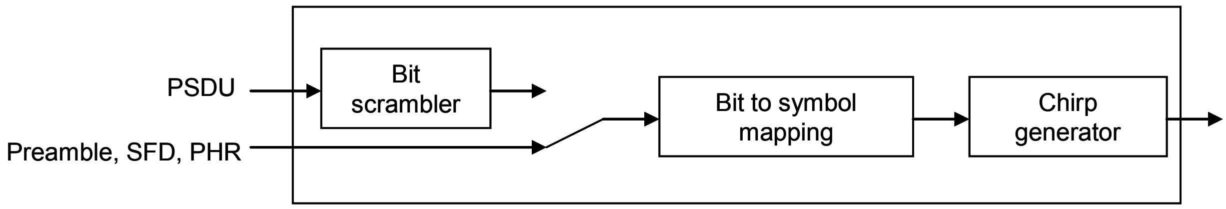

Figure 4 – Reference modulator for 2-ary orthogonal CSS

7.3.2 Bandwidths and Transmit power spectral density (PSD) mask

The supported bandwidth values shall be 80 MHz and 22 MHz. The transmitted spectral products shall be less than the limits specified in Table 3, Figure 5 and Figure 6. For both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ± Bandwith/2 of the centre frequency, fc. For testing the transmitted spectral power density a pseudo-random binary sequence shall be used as input data.

Table 3 – Transmit PSD limits for 2-ary CSS

Frequency	Relative limit	Absolute limit
|f-fc| >Bandwith/2	-20 dBr	-30 dBm

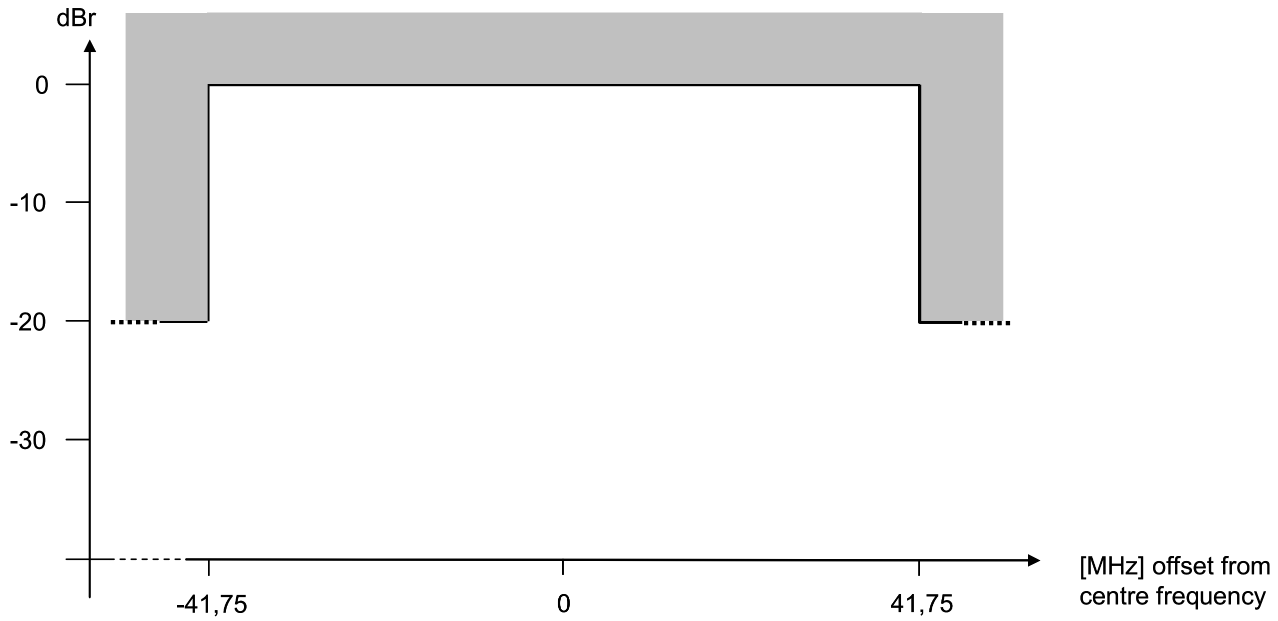

Figure 5 – Transmit PSD limits for 2-ary orthogonal CSS at 80 MHz bandwidth

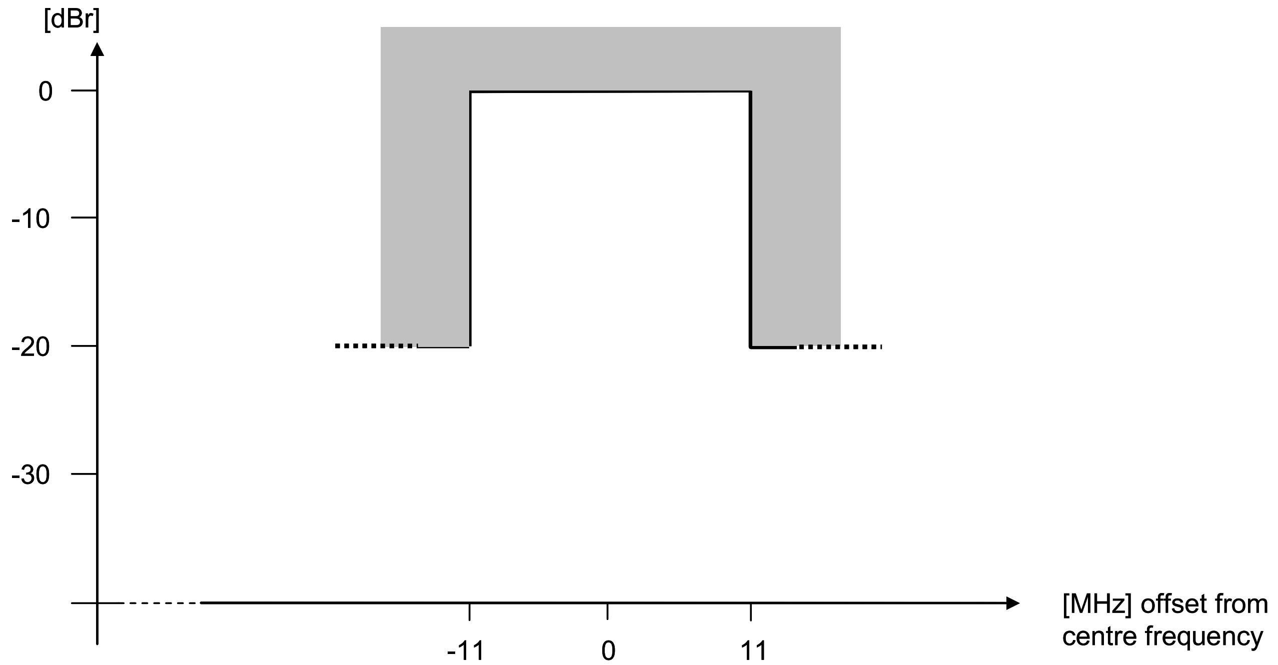

Figure 6 – Transmit PSD limits for 2-ary orthogonal CSS at 22 MHz bandwidth

7.3.3 Equivalent baseband representation of the continuous time 2-ary orthogonal CSS signal

The mathematical representation of the continuous time-domain baseband signal $\tilde{s}^{M_0}(t)$ for 2-ary orthogonal CSS shall be given by Equation (1).

$$\tilde{s}^{M_0}(t) = \sum_{n=0}^{\infty} c_{b_n}\left(t - nT_0 - \frac{T_0}{2}\right) \tag{1}$$

Where

M_0 is indicating that 2-ary orthogonal CSS is described,

n is the index of the symbol,

b_n are symbols to be transmitted, which can take the values from [1, -1] and determine which of the two possible pulses is actually realized.

$c_b(t)$ are the continuous time-domain baseband versions of the two possible pulses, which are required for 2-ary orthogonal modulation and which shall be chirp pulses as described by Equation (2).

$$c_b(t) = \begin{cases} \exp\left[j \cdot b \cdot \frac{\mu_0}{2} \cdot t^2\right] \cdot W_{T_0}(t) & for\ |t| \le \frac{T_0}{2} \\ 0 & otherwise \end{cases} \tag{2}$$

Where

μ_0 is a constant which either takes the value $2\pi \cdot \frac{80MHz}{T_0}$ or $2\pi \cdot \frac{22MHz}{T_0}$ depending on the bandwidth selected.

T_0 is the duration of the chirp pulse which can take a value of 1 μs or 4 μs, depending on the data rate,

$j = \sqrt{-1}$

and

$W_T(t)$ is the raised cosine window as described in Equation (3).

$$W_T(t) = \begin{cases} 1 & \text{for } |t| \le \dfrac{(1-\alpha)}{(1+\alpha)}\dfrac{T}{2} \\ \dfrac{1}{2}\left[1+\cos\left(\dfrac{(1+\alpha)\pi}{\alpha T}\left(|t| - \dfrac{(1-\alpha)}{(1+\alpha)}\dfrac{T}{2}\right)\right)\right] & \text{for } \dfrac{(1-\alpha)}{(1+\alpha)}\dfrac{T}{2} < |t| \le \dfrac{T}{2} \\ 0 & \text{for } |t| > \dfrac{T}{2} \end{cases} \quad (3)$$

$$with \quad \alpha = 0.25$$

Where

T is the duration of the raised cosine window.

α is the roll off factor of the raised cosine window.

7.3.4 Signal tolerance

In addition to the limits specified in Table 3, the Minimum Mean Square Error, MMSE, shall be used as criterion for the compliance of the signal. Let $\tilde{s}^{M_0}(t)$ be the signal that is defined by (1). Then $\tilde{r}^{M_0}(t)$, the implemented version of $\tilde{s}^{M_0}(t)$, shall satisfy (4) for b_0=+1 and b_0=-1.

$$MMSE = \min_{A,\tau_d,\varphi}\left[\frac{\int_0^{T_0}\left|\tilde{s}^{M_0}(t) - A\cdot\tilde{r}^{M_0}(t-\tau_d)\cdot e^{j\varphi}\right|^2 dt}{\int_0^{T_0}\left|\tilde{s}^{M_0}(t)\right|^2 dt}\right] \le 0.005 \quad (4)$$

where the variables A, τ_d, and φ are used to minimize the mean squared error.

7.3.5 Bit to symbol mapping

A bit value of 0 shall be mapped to b=-1.

A bit value of 1 shall be mapped to b=1.

7.3.6 Chirp generator

The chirp generator shall generate subsequent pulses as defined in Equation (2).

7.3.7 Preamble

The preamble for 2-ary orthogonal CSS shall consist of 30 alternating bits starting with bit 0 as shown in Table 4.

Table 4 – Preamble bit sequence for 2-ary orthogonal CSS

Bit 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	15	17	18	19	20	21	22	23	24	25	26	27	28	29
1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

7.3.8 Start of frame delimiter

The start of frame delimiter (SFD) for 2-ary orthogonal CSS shall consist of 64 bits that correspond to 8 octets as specified in Table 5. The SFD shall start with the least significant bit of octet 0 and end with the most significant bit of octet 7.

Table 5 – Start of frame delimiter for 2-ary orthogonal CSS

Octet 0	Octet 1	Octet 2	Octet 3	Octet 4	Octet 5	Octet 6	Octet 7
64h	52h	52h	9Ah	5Ah	4Bh	DBh	54h

7.3.9 Bit scrambler

Before transmission, the bit sequence shall be scrambled with a pseudo-random noise (PRN) sequence. The PRN-sequence shall be generated with the polynomial g(D)= D7+D4+D0 (221 in octal representation) and is subsequently EXORed with the bit stream. The 127-bit-length PRN-sequence shall be generated with the linear feedback shift register, as illustrated in Figure 7.

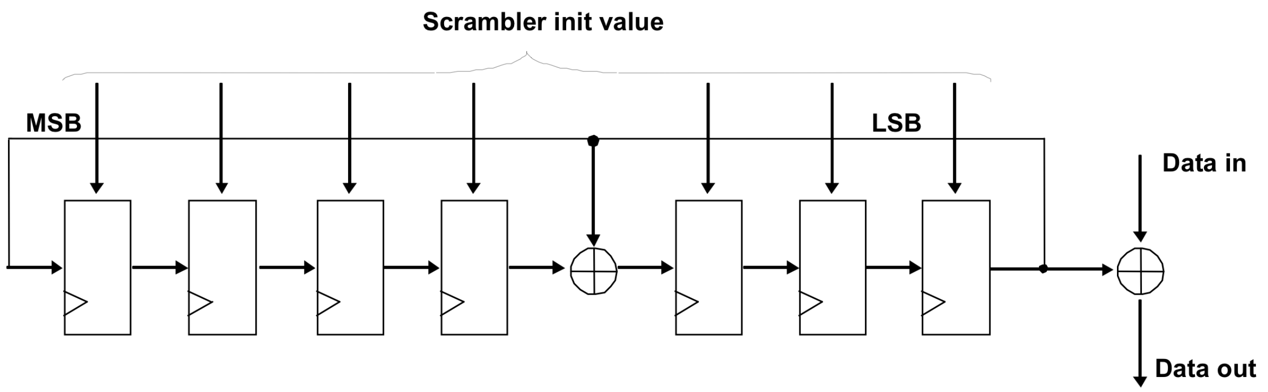

Figure 7 – Bit scrambler

7.3.10 PHY Header

The PHY Header for 2-ary orthogonal CSS shall consist of 8 bits. The first bit shall be reserved. The subsequent 7 bits shall contain the Scrambler init value as depicted in Figure 7 starting with the MSB.

7.3.11 Overview (informative)

For illustrative purposes Figure 8 shows an up chirp pulse and a down chirp pulse in passband domain, while Figure 9 shows the same pulses in time frequency domain. A bit sequence modulated with 2-ary orthogonal CSS is depicted in Figure 10 and Figure 11.

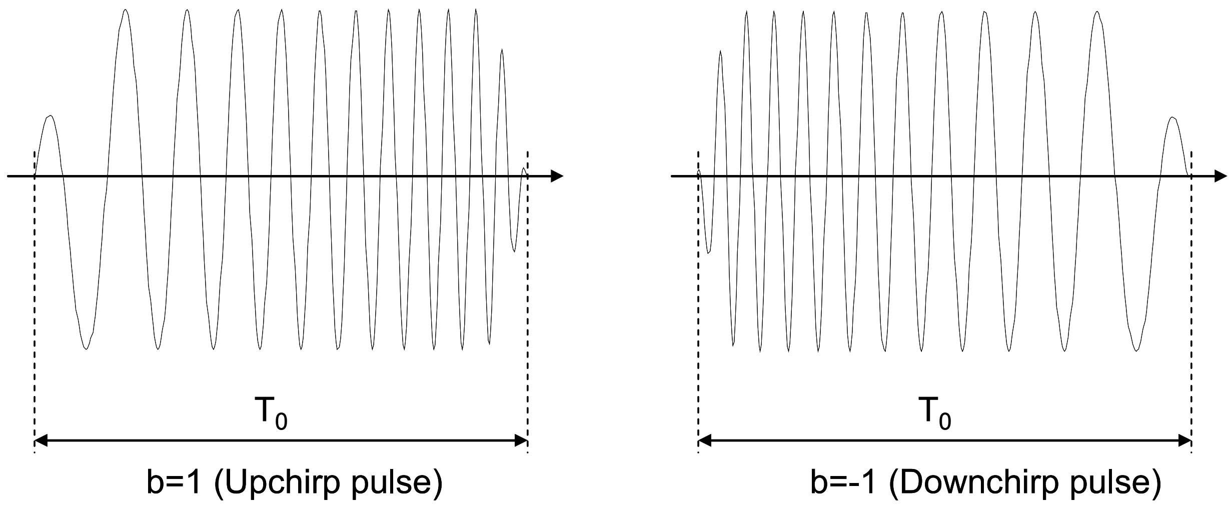

Figure 8 – Chirp pulses in passband domain

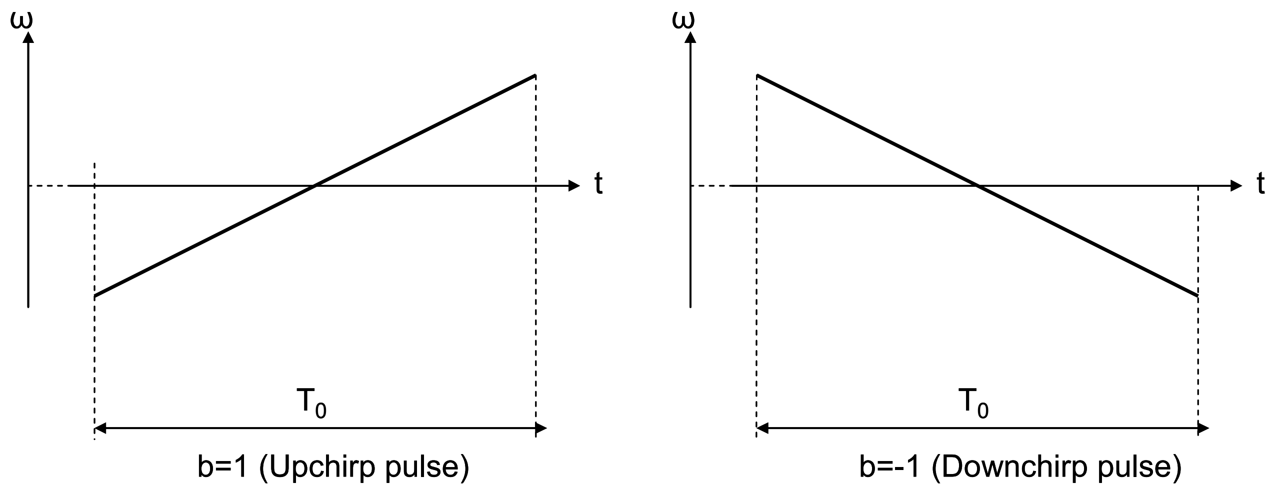

Figure 9 – Chirp pulses in time frequency domain

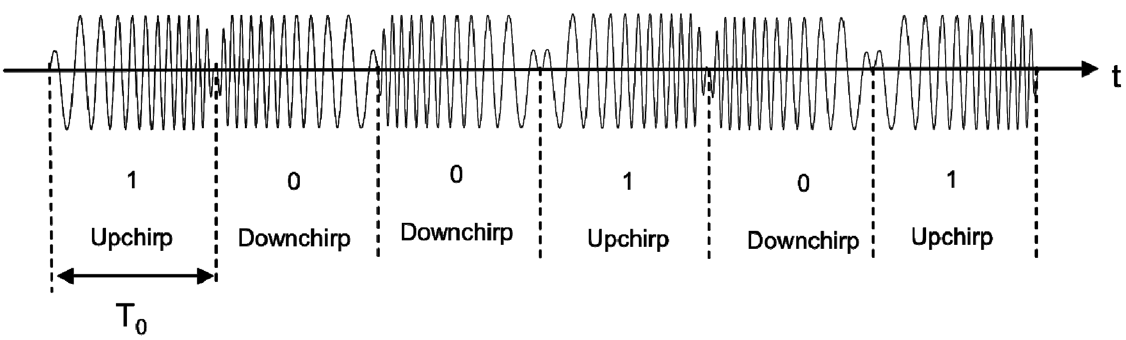

Figure 10 – 2-ary orthogonal CSS modulated bit sequence in passband domain

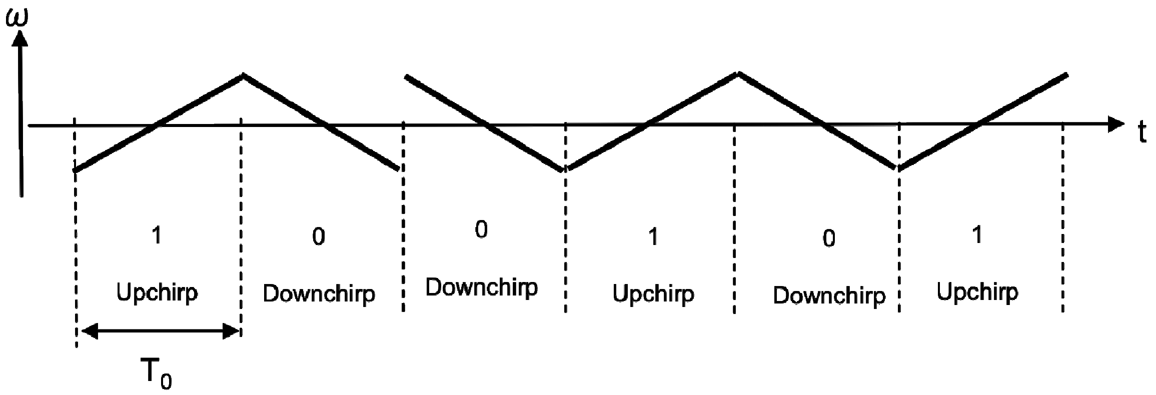

Figure 11 – 2-ary orthogonal CSS modulated bit sequence in time frequency domain

7.4 DQPSK-CSS

Differential Quadrature Phase Shift Keying, in combination with chirp spread spectrum, is an optional PHY mode. The possible combinations of centre frequencies and bandwidths are defined in Table 6.

Table 6 – Possible combinations of centre frequency and bandwidth for DQPSK-CSS

Centre frequency	Bandwidth
2412 MHz	22 MHz
2417 MHz	22 MHz
2422 MHz	22 MHz
2427 MHz	22 MHz
2432 MHz	22 MHz
2437 MHz	22 MHz
2442 MHz	22 MHz
2447 MHz	22 MHz
2452 MHz	22 MHz
2457 MHz	22 MHz
2462 MHz	22 MHz
2467 MHz	22 MHz
2472 MHz	22 MHz
2484 MHz	22 MHz

7.4.1 Reference modulator diagram

The functional block diagram in Figure 12 is provided as a reference for specifying the DQPSK CSS mode for both data rates 1 Mbit/s and 250 kbit/s. The functionality of the 1:2 DEMUX block is specified in 7.4.6. The functionality of the S/P block is specified in 7.4.7. The functionality of the Symbol Mapper block is specified in 7.4.8. The functionality of the Interleaver block is specified in 7.4.13. The functionality of the P/S block is specified in 7.4.9. The functionality of the QPSK mapper is specified in 7.4.9. The functionality of the chirp generator block mapper is specified in 7.4.12.

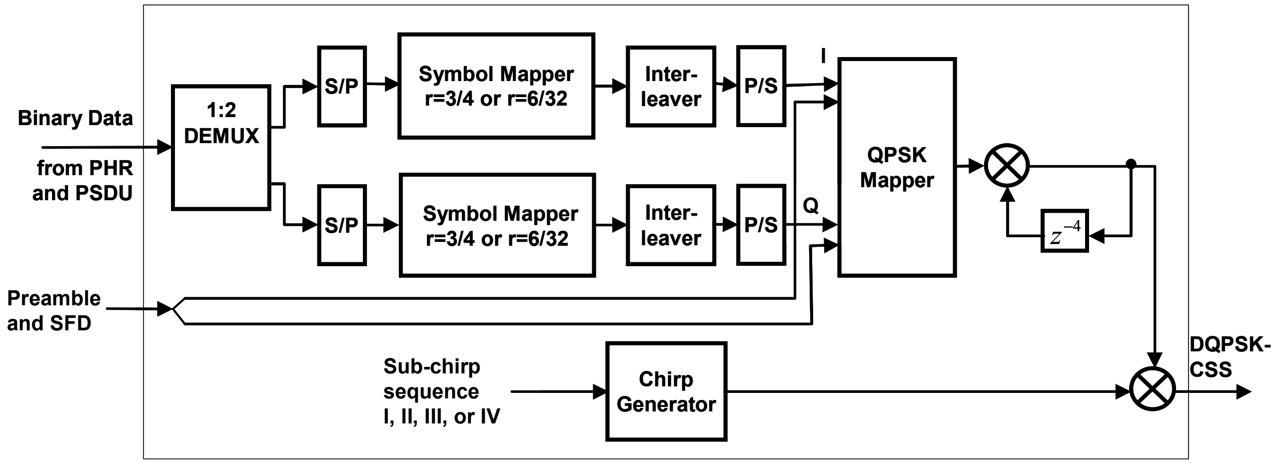

Figure 12 – DQPSK CSS reference modulator

7.4.2 Bandwidth and transmit Power Spectral Density (PSD) mask

The supported bandwidth value shall be 22 MHz. The transmitted spectral products shall be less than the limits specified in Figure 13. The average spectral power shall be measured using a 100 kHz resolution bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ±11 MHz of the centre frequency. For testing the transmitted spectral power density, a pseudo-random binary sequence shall be used as input data.

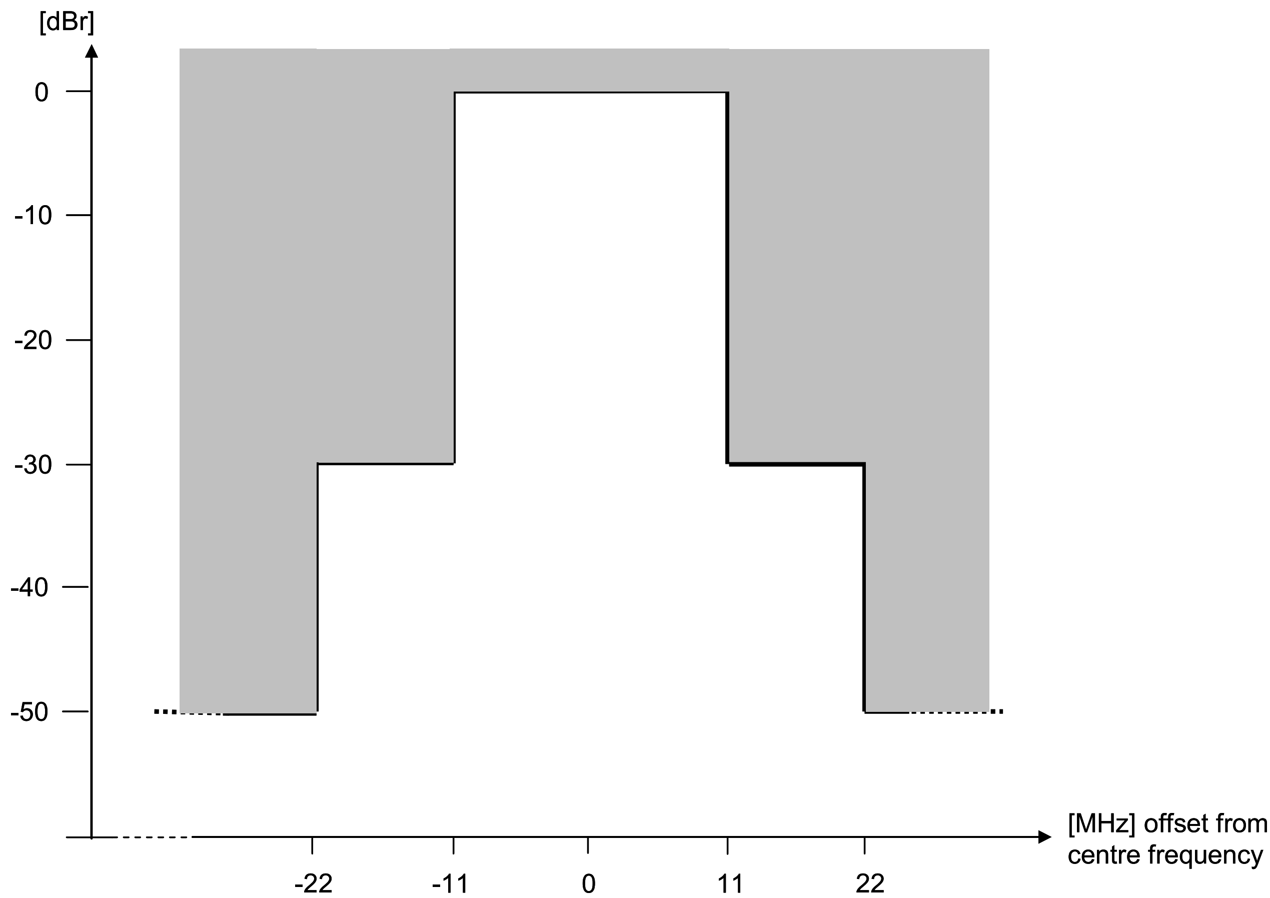

Figure 13 – Transmit PSD limits for DQPSK-CSS

7.4.3 Equivalent baseband representation of the continuous time DQPSK-CSS signal

The equivalent baseband representation of the continuous time DQPSK-CSS signal, $\tilde{s}_m^{M_1}(t)$, shall be defined by Equation (5)

$$\tilde{s}_m^{M_1}(t) = \sum_{n=0}^{\infty}\sum_{k=1}^{4} d_{n,k} C_{k,m}^{sub}(t - T_{n,k,m}) \qquad (5)$$

Where

M_1 is indicating that DQPSK-CSS is described.

m is a configuration constant from [1,2,3,4] (corresponding to [I, II, III, IV] in Figure 14) that defines which of the four possible sub-chirp sequences has been selected.

n is the index of the sub-chirp sequence.

k is the index of the sub-chirp (see 7.4.3.1)

$d_{n,k}$ is the stream of DQPSK samples which can take values from [1+j ,1-j, -1+j, -1-j] with $j = \sqrt{-1}$.

$C_{k,m}^{sub}(t)$ is a sub-chirp as defined in 7.4.3.1

$T_{n,k,m}$ is the time position of the sub-chirp as defined by Equation (6).

$$T_{n.k,m} = (k-1)T_{sub} + nT_1 - \left(1-(-1)^n\right)\tau_m \qquad (6)$$

Where

T_{sub} is the duration of the sub-chirp as defined in Table 9.

T_1 is the duration of the sub-chirp sequence as defined in Table 9.

τ_m is a constant as defined in Table 9 that determines which time-gap is applied between the previous and the actual sub-chirp sequence (see Figure 15).

7.4.3.1 Sub-chirp

A sub-chirp shall be defined by (7)

$$C_{k,m}^{sub}(t) = \exp\left[j\left(2\pi \cdot f_{k,m} + \frac{\mu_1}{2}\zeta_{k,m}\left(t - \frac{T_{sub}}{2}\right)\right)\left(t - \frac{T_{sub}}{2}\right)\right] \cdot W_{T_{sub}}\left(t - \frac{T_{sub}}{2}\right) \qquad (7)$$

Where

$f_{k,m}$ is a constant that defines the offset centre frequency of the sub-chirp as defined in Table 7.

$\zeta_{k,m}$ is a constant that defines direction of the sub-chirp as defined in Table 8.

T_{sub} is the duration of the sub-chirp as defined in Table 9.

μ_1 is a constant that takes the value $2\pi \cdot \dfrac{8.6875125MHz}{T_{sub}}$.

$W_{T_{sub}}$ is the raised cosine window with a duration of T_{sub} as defined in Equation (3).

7.4.3.2 Sub-chirp sequence

A sub-chirp sequence shall be defined by (8)

$$S_m^{sub}(t) = \sum_{k=1}^{4} C_{k,m}^{sub}\left(t-(k-1)T_{sub}\right) \qquad (8)$$

Where

m is a configuration constant that defines which of the four possible sub-chirp sequences has been selected.

$C_{k,m}^{sub}(t)$ is a sub-chirp as defined in 7.4.3.1

T_{sub} is the duration of the sub-chirp as defined in Table 9.

7.4.3.3 Parameters

Table 7 defines the offset centre frequencies of the sub-chirps.

Table 8 defines the chirp directions of the sub-chirps.

Table 9 defines the timing parameters of the sub-chirps.

Table 7 – Offset centre frequencies of sub-chirps

$f_{k,m}$ [MHz]				
m\k	**1**	**2**	**3**	**4**
1	-3,15	+3,15	+3,15	-3,15
2	+3,15	-3,15	-3,15	+3,15
3	-3,15	+3,15	+3,15	-3,15
4	+3,15	-3,15	-3,15	+3,15

Table 8 – Sub-chirp directions

$\xi_{k,m}$				
m\k	**1**	**2**	**3**	**4**
1	+1	+1	-1	-1
2	+1	-1	+1	-1
3	-1	-1	+1	+1
4	-1	+1	-1	+1

Table 9 – Timing parameters

Name	Value
T_1	192 T_{base}
T_{sub}	38 T_{base}
τ_1	15 T_{base}
τ_2	10 T_{base}
τ_3	5 T_{base}
τ_4	0

7.4.4 Signal tolerance

In addition to the limits specified in Figure 13, the minimum mean square error shall be used as criterion for the compliance of the signal. Let $\tilde{s}_m^{M_1}(t)$ be the signal that is defined by Equation (5). Then $\tilde{r}_m^{M_1}(t)$, the implemented version of $\tilde{s}_m^{M_1}(t)$, shall satisfy Equation (9).

$$MMSE = \min_{A,\tau_d,\varphi}\left[\frac{\int_0^{T_0}\left|\tilde{s}_m^{M_1}(t) - A\cdot\tilde{r}_m^{M_1}(t-\tau_d)\cdot e^{j\varphi}\right|^2 dt}{\int_0^{T_0}\left|\tilde{s}_m^{M_1}(t)\right|^2 dt}\right] \le 0.005 \text{ for m=1,2,3,4} \quad (9)$$

where the constants A, τ_d, and φ are used to minimize the mean squared error.

The $d_{n,k}$ in $\tilde{s}_m^{M_1}(t)$ in Equation (5) are constantly equal (1+j) for the measurement for all n and k.

7.4.5 Overview (informative)

DQPSK-CSS uses chirp spread spectrum (CSS) techniques in combination with Differential Quadrature Phase Shift Keying (DQPSK) and 8-ary or 64-ary Bi-Orthogonal Coding for 1 Mbit/s data rate or 250 kbit/s data rate, respectively.

7.4.5.1 Waveform and sub-chirp sequences

Four individual chirp pulses, here called *sub-chirps*, shall be concatenated to form a sub-chirp sequence that occupies two adjacent frequency sub-bands. Each sub-chirp is weighted with a raised cosine window in the time domain.

By using alternating time-gaps in conjunction with sub-chirp sequences, this DQPSK-CSS provides sub-chirp sequence division as well as frequency division. Four different sub-chirp sequences are defined. Figure 14 shows the four different sub-chirp sequences in time frequency domain. It can be seen that four sub-chirps that have either a linear down-chirp characteristic or a linear up-chirp characteristic and a centre frequency which has either a positive or a negative frequency offset against the centre frequency of the signal are concatenated. The frequency discontinuities between subsequent chirps will not impact the spectrum because the signal amplitude will be zero at these points due to the raised cosine window applied to each sub-chirp.

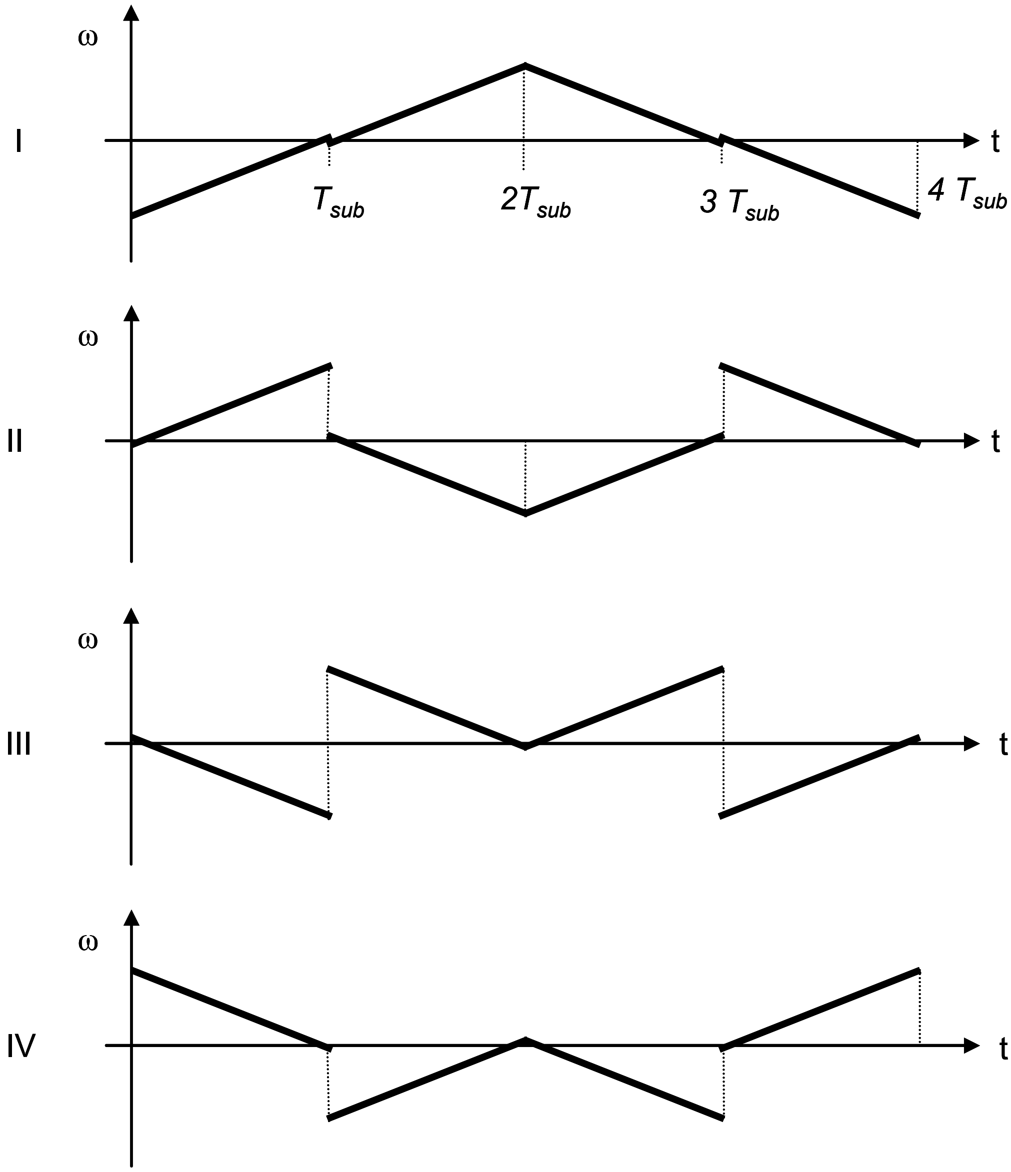

Figure 14 – The four defined sub-chirp sequences

7.4.5.2 Active usage of time gaps

In conjunction with the sub-chirp sequences, pairs of time-gaps are defined. The time-gaps are chosen to apply a sharper orthogonality to the four sub-chirp sequences. The time-gaps are applied alternatively between subsequent chirp symbols as shown in Figure 15.

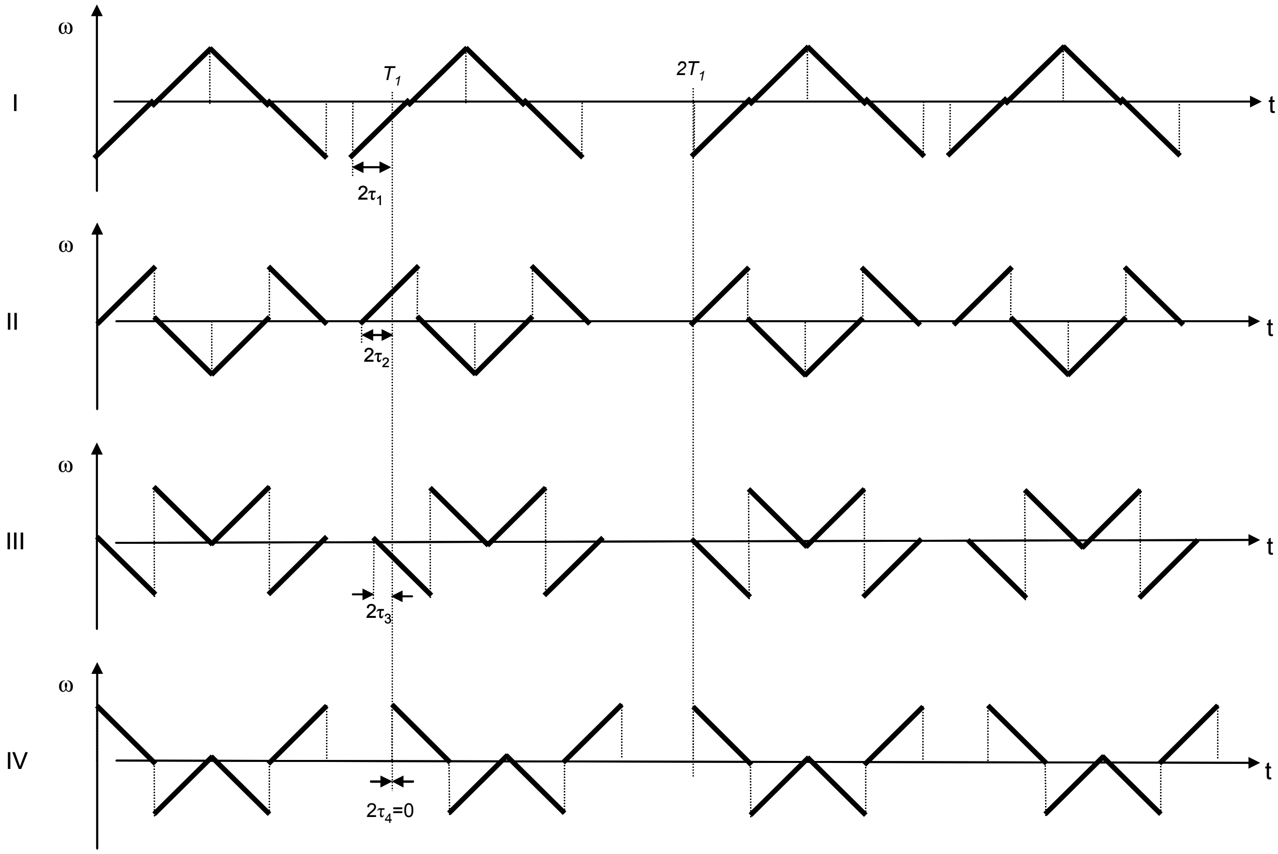

Figure 15 – The four time-gap pairs for the four defined sub-chirp sequences

7.4.6 Demultiplexer (DEMUX)

For each packet the initial position of the DEMUX shown in Figure 12 shall be set to serve the I path (upper path). Thus, the first bit of the incoming stream of information bits of a packet shall be switched to the I path and the second bit shall be switched to the Q path.

7.4.7 Serial to Parallel mapping (S/P)

By using two serial to parallel converters, the sub-streams are independently partitioned into sets of bits to form data symbols. For the data rate of 1 Mbit/s a data symbol shall consist of three bits. Within the binary data symbol (b_0, b_1, b_2), the first input data bit for each of I and Q is assigned b_0 and the third input data bit is assigned b_2. For the data rate of 250 kbit/s a data symbol shall consist of 6 bits, within the binary data symbol (b_0, b_1, b_2, b_3, b_4, b_5), the first input data bit for each of I and Q is assigned b_0 and the 6th input data bit is assigned b_5.

7.4.8 Data Symbol - to - Bi-Orthogonal code word mapping

Each 3-bit data symbol shall be mapped onto a 4-chip Bi-Orthogonal code word *(c0, c1, c2, c3)* for the data rate of 1 Mbit/s as specified in Table 10. Each 6-bit data symbol shall be mapped onto a 32-chip Bi-Orthogonal code word *(c0, c1, c2, ... , c31)* for the data rate 250 kbit/s, as specified in Table 11.

Table 10 – 8-ary Bi-Orthogonal Mapping Table (r = 3/4)

8-ary Bi-Orthogonal r = 3/4, 1Mbit/s		
Data Symbol (Decimal)	**Data Symbol (Binary) (b_0 b_1 b_2)**	**Code Word (c_0 c_1 c_2 c_3)**
0	000	1 1 1 1
1	001	1 -1 1 -1
2	010	1 1 -1 -1
3	011	1 -1 -1 1
4	100	-1 -1 -1 -1
5	101	-1 1 -1 1
6	110	-1 -1 1 1
7	111	-1 1 1 -1

Table 11 – 64-ary Bi-Orthogonal mapping table (r = 6/32) (Optional)

64-ary Bi-Orthogonal r = 6/32, 250kbit/s		
Data Symbol (Decimal)	**Data Symbol (Binary) (b0 b1 b2 b3 b4 b5)**	**Code Word (co c1 c2 ... c31)**
0	000000	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1	000001	1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
2	000010	1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1
3	000011	1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1
4	000100	1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1
5	000101	1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1
6	000110	1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1
7	000111	1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1
8	001000	1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1
9	001001	1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1
10	001010	1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1
11	001011	1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1
12	001100	1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1
13	001101	1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1
14	001110	1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1
15	001111	1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1
16	010000	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1

64-ary Bi-Orthogonal r = 6/32, 250kbit/s		
Data Symbol (Decimal)	**Data Symbol (Binary) (b0 b1 b2 b3 b4 b5)**	**Code Word (co c1 c2 ... c31)**
17	010001	1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1
18	010010	1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1
19	010011	1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1
20	010100	1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1
21	010101	1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1
22	010110	1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1
23	010111	1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1
24	011000	1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1
25	011001	1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1
26	011010	1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1
27	011011	1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1
28	011100	1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1
29	011101	1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1
30	011110	1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1
31	011111	1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1
32	100000	-1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1
33	100001	-1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1
34	100010	-1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1
35	100011	-1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1
36	100100	-1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1
37	100101	-1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1
38	100110	-1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1
39	100111	-1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1
40	101000	-1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1
41	101001	-1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1
42	101010	-1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1
43	101011	-1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1
44	101100	-1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1
45	101101	-1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1
46	101110	-1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1
47	101111	-1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1
48	110000	-1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
49	110001	-1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
50	110010	-1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1

64-ary Bi-Orthogonal r = 6/32, 250kbit/s		
Data Symbol (Decimal)	Data Symbol (Binary) (b0 b1 b2 b3 b4 b5)	Code Word (co c1 c2 ... c31)
51	110011	-1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1
52	110100	-1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1
53	110101	-1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1
54	110110	-1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1
55	110111	-1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1
56	111000	-1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1
57	111001	-1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1
58	111010	-1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1
59	111011	-1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1
60	111100	-1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1
61	111101	-1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1
62	111110	-1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1
63	111111	-1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1

7.4.9 Parallel - to - Serial converter (P/S) and QPSK symbol mapping

Each Bi-Orthogonal code word shall be converted to a serial chip sequence. Within each 4-chip code word (c0, c1, c2, c3) for the data rate of 1 Mbit/s, the least significant chip c0 is processed first and the most significant chip c3 is processed last for I and Q, respectively. Within each 32-chip code word (c0, c1, c2, ... , c31) for the data rate of 250 kbit/s, the least significant chip c0 is processed first and the most significant chip c31 is processed last for I and Q, respectively. Each pair of I and Q chips shall be mapped onto a QPSK symbol as specified in Table 12.

Table 12 – QPSK Mapping Table

QPSK Symbol Mapping		
Input chips ($I_{n,k}$ $Q_{n,k}$)	Magnitude	Output Phase $\varphi_{n,k}$ [rad]
1, 1	1	0
-1, 1	1	π/2
1, -1	1	-π/2
-1, -1	1	π

7.4.10 Differential-QPSK (DQPSK) coding

The stream of QPSK symbols shall be differentially encoded by using a differential encoder with a QPSK symbol feedback memory of length 4. (This means that the phase differences between QPSK symbol 1 and 5, 2 and 6, 3 and 7, 4 and 8 and so on are computed.)

DQPSK Output: $e^{j\theta_{n,k}} = e^{j\theta_{n-1,k}} \times e^{j\varphi_{n,k}}$

where $e^{j\varphi_{n,k}}$ is the QPSK input,

$e^{j\theta_{n-1,k}}$ is stored in feedback memory.

For every packet, the initial values of all 4 feedback memory stages of the differential encoder shall be set $e^{j\pi/4}$ or equivalently $\theta_{0,k} = \pi/4\ [rad]$.

7.4.11 DQPSK to DQPSK-CSS modulation

The stream of DQPSK symbols shall be modulated onto the stream of sub-chirps generated by the chirp generator. One DQPSK symbol shall be multiplied with one sub-chirp.

7.4.12 Chirp generator

The chirp generator shall periodically generate the one of the four defined sub-chirp sequences as specified in 7.4.3.2, which has been configured.

7.4.13 Bit interleaver

The bit interleaver shall be applied only for the data rate of 250 kbit/s. The 32 chip Bi-Orthogonal code words shall be interleaved prior to the parallel to serial converter. The input-output relationship of this interleaver shall be given by:

Input:

even-symbol (c0, c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15,

c16, c17, c18, c19, c20, c21, c22, c23, c24, c25, c26, c27, c28, c29, c30, c31)

odd-symbol (d0, d1, d2, d3, d4, d5, d6, d7, d8, d9, d10, d11, d12, d13, d14, d15,

d16, d17, d18, d19, d20, d21, d22, d23, d24, d25, d26, d27, d28, d29, d30, d31)

Output:

even-symbol (c0, c1, c2, c3, d20, d21, d22, d23, c8, c9, c10, c11, d28, d29, d30, d31,

c16, c17, c18, c19, d4, d5, d6, d7, c24, c25, c26, c27, d12, d13, d14, d15)

odd-symbol (d0, d1, d2, d3, c20, c21, c22, c23, d8, d9, d10, d11, c28, c29, c30, c31,

d16, d17, d18, d19, c4, c5, c6, c7, d24, d25, d26, d27, c12, c13, c14, c15)

As shown in Figure 12, coding (symbol mapping) is applied to every bit following the SFD. The first codeword generated shall be counted as zero, and thus is even.

7.4.14 Preamble

The preamble for 1Mbit/s shall consist of 32 bits as specified in Table 13. The preamble for 250 kbit/s shall consist of 80 bits as specified in Table 13. The preamble sequence from Table 13 shall be applied directly and in parallel to the I input and the Q input of QPSK Mapper, as indicated in Figure 12.

Table 13 – Preamble Sequence

Data rate	Preamble Sequence
1 Mbit/s	ones(0:31)
250 kbit/s	ones(0:79)

where ones(0:N) for integer number N shall define a 1-by-N matrix of ones.

7.4.15 Start of frame delimiter

A different start of frame delimiter (SFD) shall be used for each of the two data rates. According to the data rate, the SFD sequences as specified in Table 14 shall be applied starting with bit 0 directly and in parallel to the I input and the Q input in of QPSK Mapper, as indicated in Figure 12.

Table 14 – SFDs for DQPSK-CSS

Data rate	Bit 0	Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit 7	Bit 8	Bit 9	Bit 10	Bit 11	Bit 12	Bit 13	Bit 14	Bit 15
1 Mbit/s	-1	1	1	1	-1	1	-1	-1	1	-1	-1	1	1	1	-1	-1
250 kbit/s	-1	1	1	1	1	-1	1	-1	-1	-1	1	-1	-1	-1	1	1

7.4.16 PHY Header

The PHY Header for QPSK CSS shall be empty (consist of 0 bits).

8 MAC sub-layer specification

8.1 Overview

As generally described in literature, e.g. Tanenbaum[6], the MAC sub-layer is the layer above the PHY layer. The MAC sub-layer controls access to the Medium (wireless channel) using methods such as ALOHA or CSMA/CA. The MAC sub-layer performs operations like address filtering, checksum generation and evaluation. Furthermore, the MAC sub-layer processes handshake packets for 2-way handshake and 3-way handshake e.g. IEEE 802.11[3]. In this part of ISO/IEC 24730 the process of ranging (determining the distance between two RTLS transceivers) is realized using handshake packets. Thus ranging-related time measurements are specified inside the MAC sub-layer specification.

8.2 General packet format

The PHY protocol service unit shown in Figure 3 shall also be called “MAC frame”.

8.3 Packet types

The RTLS transceiver shall support the packet types shown in Table 15.

Table 15 – Packet types

Type	Name	Description	Format
Data	Data	The MAC frame of a Data packet can contain up to 8192 octets of data payload.	Figure 16
Acknowledgement	ACK	Acknowledges the successful reception of a Data packet.	Figure 17
Broadcast	Broadcast	Transmits information to all stations in range	Figure 18
Request to Send	RTS	Requests a frame transmission	Figure 19
Clear to Send	CTS	Confirms a requested frame transmission and indicates that a Data packet can be transmitted.	Figure 20

8.4 MAC frame formats

8.4.1 MAC frame format for Data packet

The Data packet shall use the MAC frame format defined in Figure 16.

Reserved	Type	Dst	Src	Length	Ctrl	CRC1	MAC payload	CRC2
4	4	48	48	13	3	16	8…8*8192	16

Figure 16 – MAC frame format for Data packet

8.4.2 MAC frame format for ACK packet

The ACK packet shall use the MAC frame format defined in Figure 17.

Reserved	Type	Dst	CRC1
4	4	48	16

Figure 17 – MAC frame format for ACK packet

8.4.3 MAC frame format for Broadcast packet

The Broadcast packet shall use the MAC frame format defined in Figure 18.

Reserved	Type	Blink info	Src	Length	Ctrl	CRC1	MAC payload	CRC2
4	4	48	48	13	3	16	8…8*8192	16

Figure 18 – MAC frame format for Broadcast packet

8.4.4 MAC frame format for RTS packet

The RTS packet shall use the MAC frame format defined in Figure 19.

Reserved	Type	Dst	Src	Length	Ctrl	CRC1
4	4	48	48	13	3	16

Figure 19 – RTS packet

8.4.5 MAC frame format for CTS packet

The CTS packet shall use the MAC frame format defined in Figure 20.

Reserved	Type	Dst	Length	Ctrl	CRC1
4	4	48	13	3	16

Figure 20 – CTS packet

8.4.6 MAC frame fields

8.4.6.1 Reserved field

The reserved bit field shall be reserved for future enhancements. The bits of the reserved field shall be written as specified in Table 16.

Table 16 – Reserved field definitions

Bit 0	Bit 1	Bit 2	Bit 3
0	0	0	0

8.4.6.2 Type field

The Type field shall contain a code that identifies the actual packet type as specified in Table 17.

Table 17 – Type field definitions

Packet type	Bit 0	Bit 1	Bit 2	Bit 3
Data	0	0	0	0
ACK	1	0	0	0
Broadcast	1	1	0	0
RTS	0	0	1	0
CTS	1	0	1	0

8.4.6.3 Blink info

The Blink info field shall be used by the upper layer according to the specification in Figure 40.

8.4.6.4 Dst field

The Dst field shall contain the 48-bit destination address starting with bit 0.

8.4.6.5 Src field

The Src field shall contain the 48-bit source MAC address starting with bit 0. The MAC address shall be the Tag ID described in 6.4.

8.4.6.6 Length field

In a Data or Broadcast packet, the Length field shall contain the number of octets of MAC payload. The minimum size of the MAC payload is one octet. A value 0 of the Length field shall indicate that the MAC payload contains 8192 octets.

In a RTS or CTS packet, the Length field shall contain the number of octets that the initiating RTLS transceiver intends to transmit in the MAC payload of the subsequent Data packet.

8.4.6.7 Ctrl field

The Ctrl field shall be used by the upper layer according to the specification in Clause 9.

8.4.6.8 CRC calculation

CRC1, as well as CRC2, shall be calculated using the polynomial $X^{16}+X^{12}+X^5+1$. For reference purposes, a structure for CRC calculation using a Linear Feedback Shift Register (LFSR) is depicted in Figure 21 and Table 18.

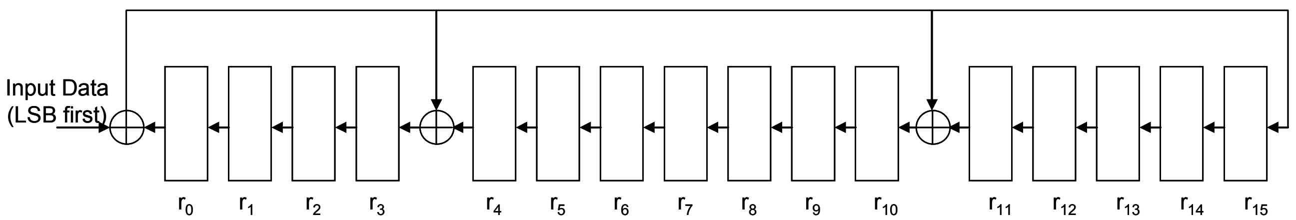

Figure 21 – CRC calculation with LFSR

Table 18 – Steps for CRC calculation with LFSR

Step	Operation
1	Initialize all registers (r_0 through r_{15}) to one
2	Shift data portion for which CRC is to be calculated into the LFSR
3	After the data portion has been shifted in, invert bits r_0 through r_{15}.
4	Bits r_0 through r_{15} contain the CRC value

8.4.6.9 CRC1 field

The CRC1 field shall contain the CRC1 checksum starting with bit r_{15}. CRC1 shall be calculated starting with the first bit of the MAC frame until the bit just before the CRC1 field.

8.4.6.10 MAC payload field

The MAC payload field shall be used by the upper layer according to the specification in Clause 9.

8.4.6.11 CRC2 field

The CRC2 field shall contain the CRC2 checksum starting with bit r_{15}. CRC2 shall be calculated starting with the first bit following the CRC1 field until the last bit of the MAC payload.

8.5 MAC Timing

Table 19 specifies timing values which shall be used by the MAC sub-layer as specified in the subsequent sub clauses.

Table 19 – Basic MAC timing parameters

Parameter name	Value	Tolerance
AirInterface PropagationTimeMax	8 µs	Relative timebase tolerance as specified in Clause 6
SIFS (Short Inter Frame Space)	8 µs	Relative timebase tolerance as specified in Clause 6.
CIFS (Carrier sense Inter Frame Space)	SIFS +2 AirInterface PropagationTimeMax	Relative timebase tolerance as specified in Clause 6.
BTS (Backoff Time Slot)	24 µs	Relative timebase tolerance as specified in Clause 6

8.5.1 2-way handshake

2-way handshake shall consist of acknowledging a received Data packet by transmitting an ACK packet back to the RTLS transmitter that sent the Data packet. Upon reception of a Data packet, the MAC sub-layer of the responding RTLS transceiver shall start its ACK packet after SIFS time, as depicted in Figure 22.

An RTLS transceiver shall be capable of performing a 2-way handshake as initiating RTLS transceiver.

An RTLS transceiver shall be capable of performing a 2-way handshake as responding RTLS transceiver.

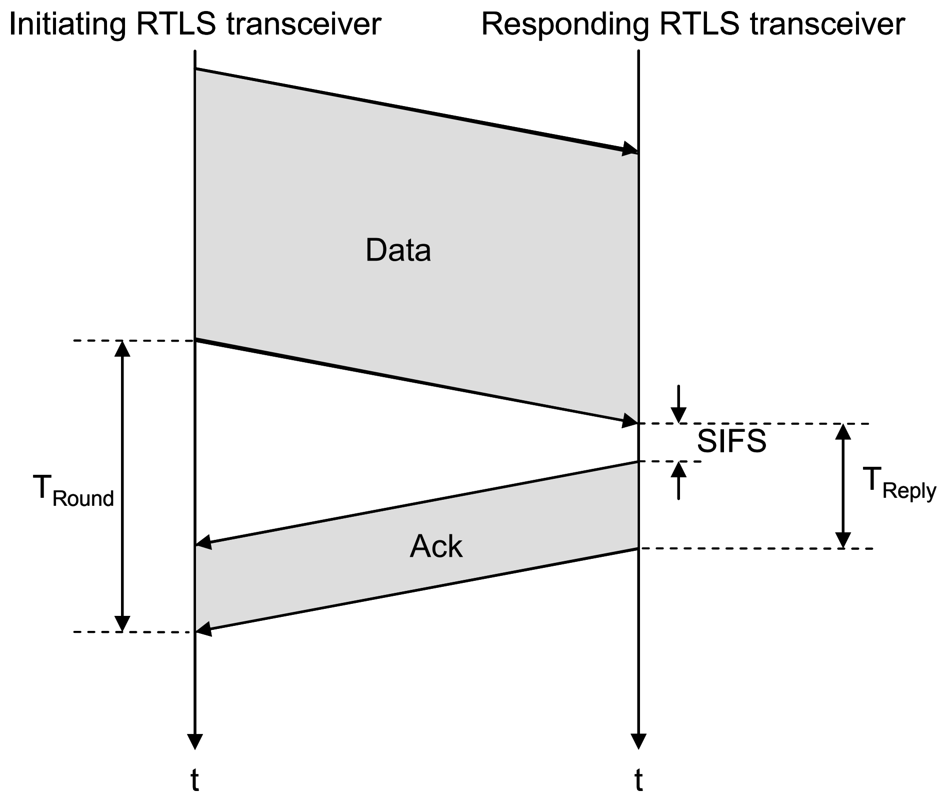

Figure 22 – Data ACK timing

8.5.2 3-way handshake

An RTLS transceiver shall be capable of performing 3-way handshake. 3-way handshake shall consist of the steps specified in Table 20 and depicted in Figure 23.

Table 20 – 3-way handshake procedure

Step	
1	The initiating RTLS transceiver sends the RTS packet to the responding RTLS transceiver
2	If the responding RTLS transceiver has received the RTS, the responding RTLS transceiver sends the CTS packet to the initiating RTLS transceiver
3	If the initiating RTLS transceiver has received the CTS packet, the initiating RTLS transceiver sends the Data packet to the responding transceiver.
4	If the responding RTLS transceiver has received the Data packet, the responding RTLS transceiver sends an ACK packet to the initiating RTLS transceiver

3-way handshake shall be performed according to the timing specified in Figure 23.

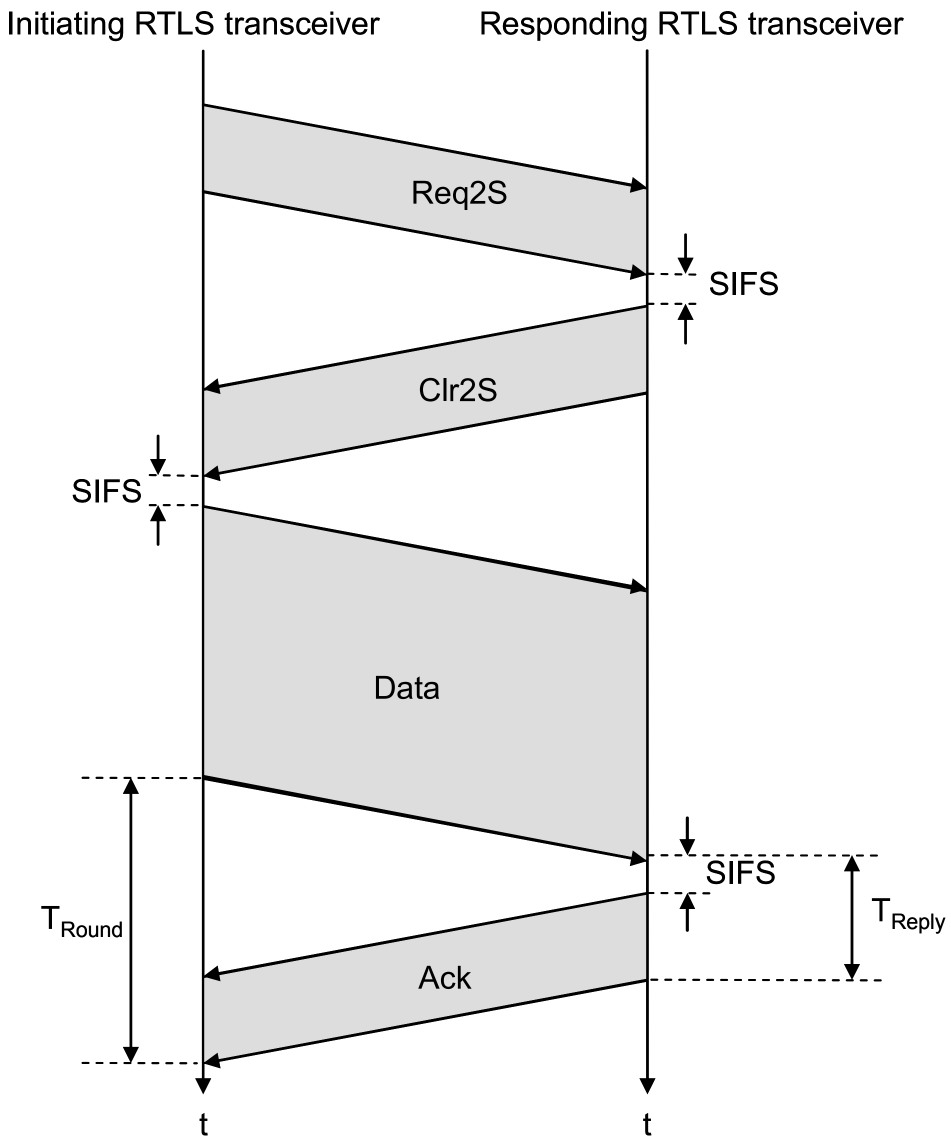

Figure 23 – RTS-CTS timing

8.5.3 Ranging-related time measurements

An RTLS transceiver shall be capable of measuring T_{Reply} and T_{Round} as depicted in Figure 22 and Figure 23 within the time base accuracy specified in Clause 6.

8.5.4 Media access

An RTLS transceiver shall support ALOHA as specified below.

An RTLS transceiver shall support CSMA/CA (Carrier Sense Multiple Access/Collision avoidance) as specified below.

8.5.4.1 ALOHA

When using the ALOHA protocol, an RTLS transceiver shall immediately access the Medium without prior listening for any activity.

8.5.4.2 CSMA/CA

When using CSMA/CA, an RTLS transceiver shall be able to sense whether the Medium is busy by using one or more of the following methods:

Energy detect

Physical carrier sense

Virtual carrier sense

When the Medium is busy, the RTLS transceiver shall back-off, as specified in 8.5.4.2.5.

8.5.4.2.1 Usage of CSMA/CA

CSMA/CA shall be applicable only for 2 way handshake and 3-way handshake.

In case of 2-way handshake CSMA/CA shall be used only for the data packets.

In case of 3-way handshake CSMA/CA shall be used only for the RTS packets.

CSMA/CA shall be used on request of the upper layer.

8.5.4.2.2 Energy detect

When using energy detect, the RTLS transceiver shall sense the average power during a CIFS period. If the average power is above a threshold of ED_{thres} the Medium shall be assumed busy. ED_{thres} shall be selectable by the upper layer from [-30 dBm, -50 dBm, -70 dBm,- 90 dBm].

8.5.4.2.3 Physical carrier sense

When using physical carrier sense, an RTLS transceiver shall sense for CIFS duration before transmission. When chirp symbols are detected, the Medium shall be assumed busy.

8.5.4.2.4 Virtual carrier sense

When using virtual carrier sense, an RTLS transceiver shall maintain a network allocation vector (NAV) by evaluating the type field and the length field of any incoming traffic. Thus, the NAV contains the information related to how long the Medium will be kept busy by the ongoing packet exchange as specified in Figure 24, Figure 25 and Figure 26.

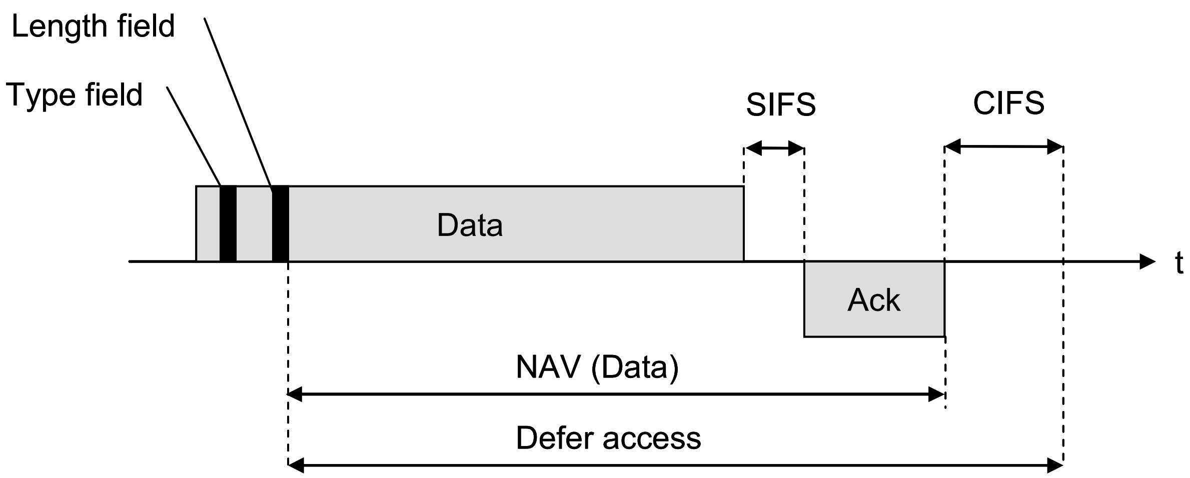

Figure 24 – NAV for Data packet

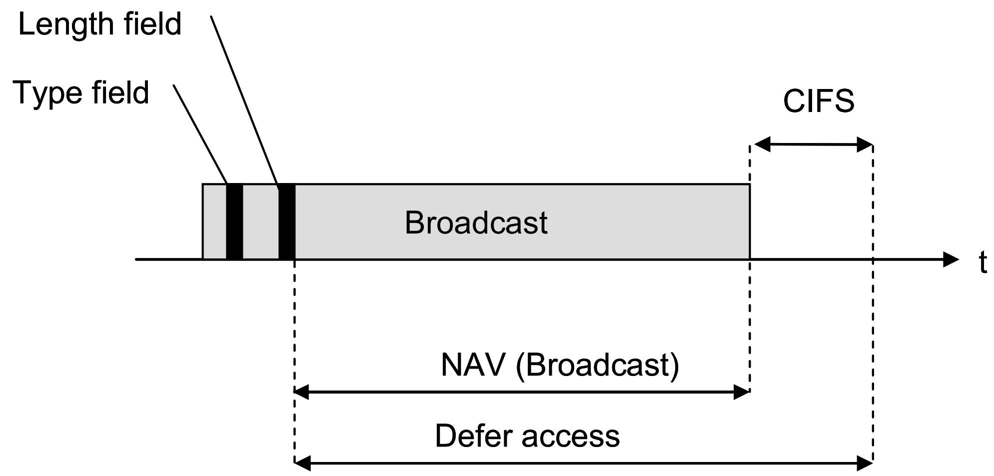

Figure 25 – NAV for Broadcast packet

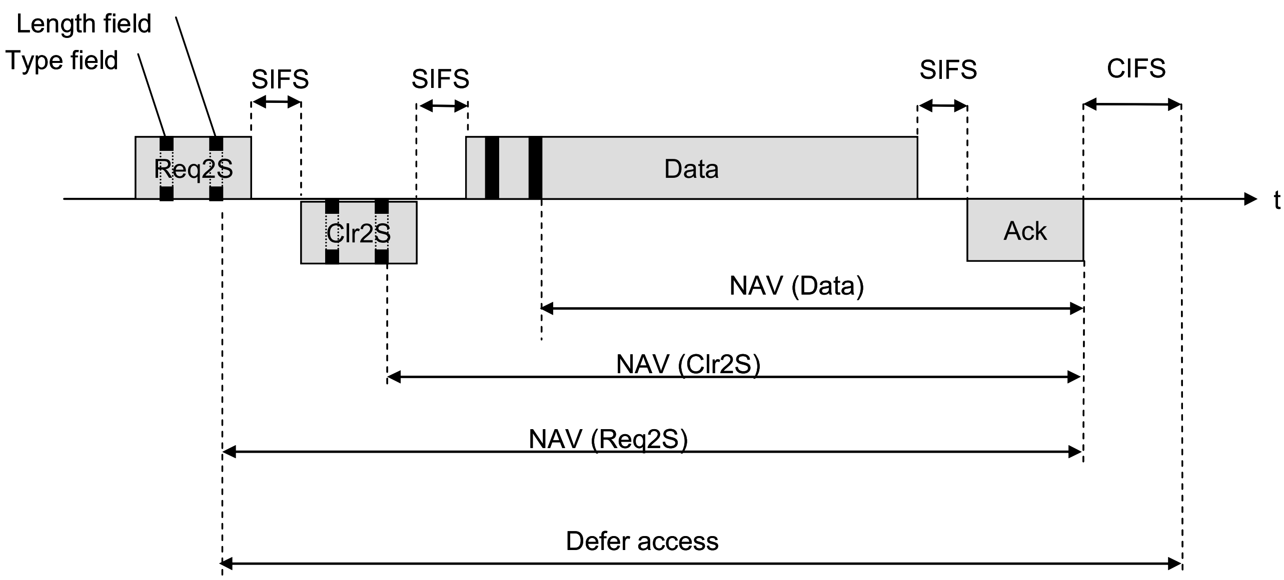

Figure 26 – NAV for 3 way handshake

8.5.4.2.5 Back-off

Back-off shall be applied in combination with CSMA/CA in order to reduce the probability of collisions between transceivers that try to access the Medium when it becomes idle.

8.5.4.2.5.1 Back-off procedure

If the Medium is idle, the RTLS transmitter shall wait a specific period of time of CIFS before it attempts or reattempts a transmission. This time period is the contention window and is determined by a back-off counter that counts defined time slots, each of which is a back-off time slot (BTS). This procedure is illustrated in Figure 27 and specified as follows.

While the Medium is idle, the RTLS transmitter shall decrement the back-off counter using physical carrier sensing and/or energy detect as configured by the upper layer until either the Medium again becomes busy or the back-off counter reaches 0. While the Medium is busy, the back-off counter shall be frozen until the Medium is detected idle again.

An RTLS transmitter shall access the Medium and transmit a packet only when the back-off counter has reached “0” and the Medium is idle.

When a station makes the first transmission attempt, the back-off counter shall be initialized with a pseudo-random integer in the range of 0 to 7. For every new reattempt, this range shall be doubled. For the second transmission attempt, the back-off counter shall be initialized with a pseudorandom integer in the range of 0 to 15; for the third attempt, it shall be initialized in the range of 0 to 31. If the third attempt (second retransmission) also no ACK is received, the transaction shall considered to have failed.

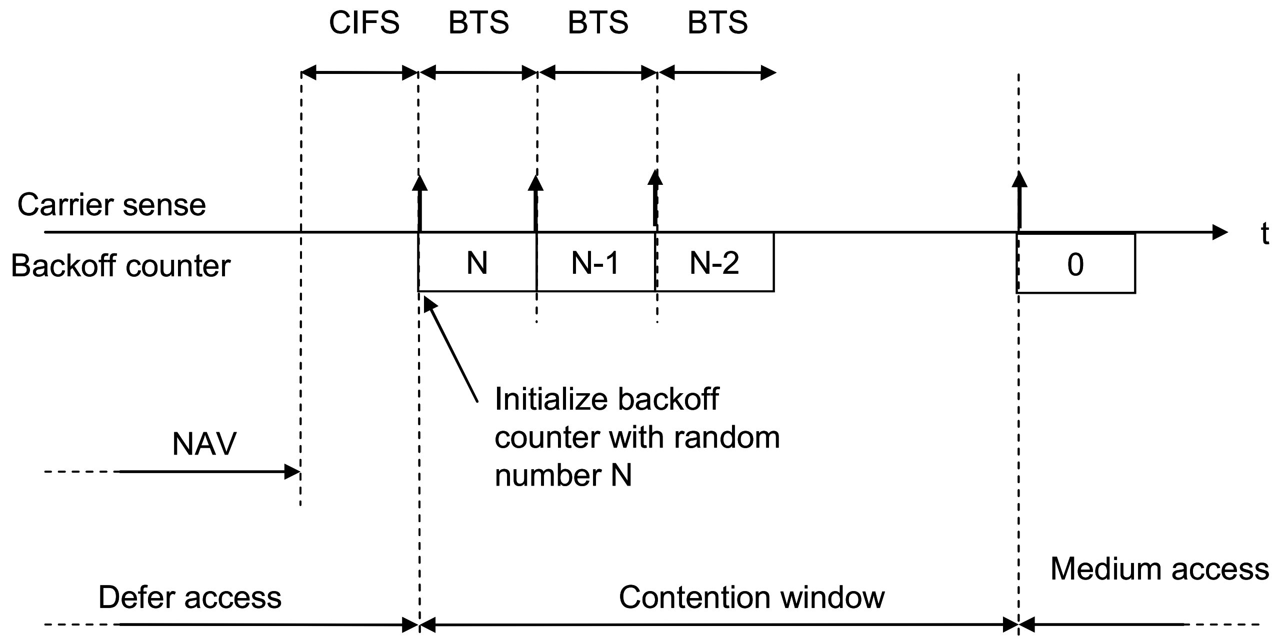

Figure 27 – CSMA/CA Back-off procedure

9 Tag application layer specification

9.1 Overview

The tag application layer is the layer above the MAC sub-layer. The tag application layers of an RTLS transceiver in a system communicate through application packets. Four types of application packets are defined:

1) Command packets are used by the infrastructure to transmit instructions to tags.

2) Report packets are used by tags to transmit any kind of information or notification to the infrastructure.

3) Ranging packets are used for ranging packet exchanges.

4) Blink packets are Broadcast packets transmitted by tags.

The tag application can be switched between certain states, as illustrated in Figure 28. A set of commands is defined through which the infrastructure can instruct the tag application to go to desired states or to go through sequences of states. Details on states and state transitions are specified in 9.2 and 9.2.6 respectively.

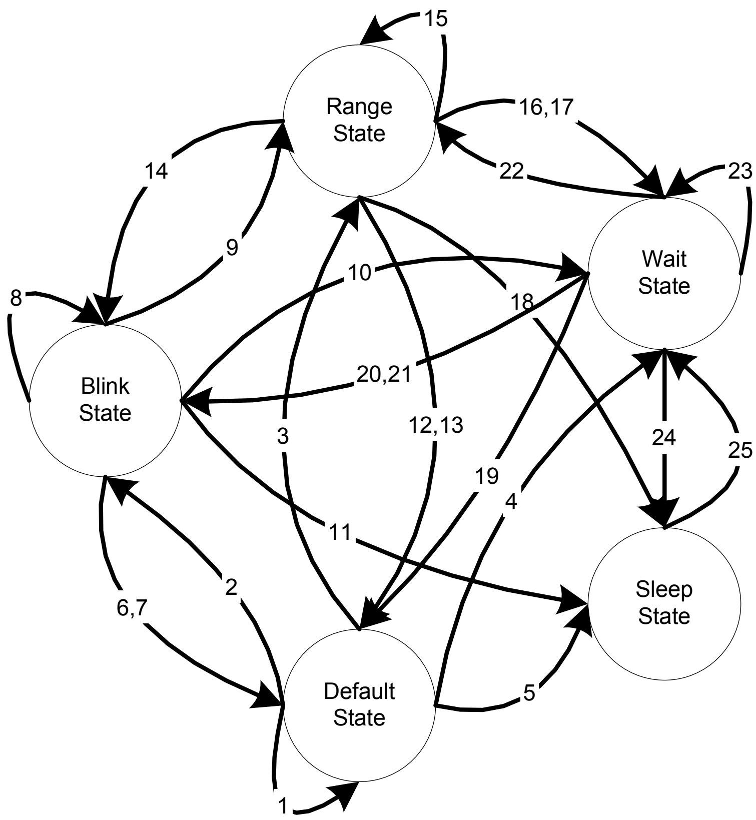

Figure 28 – Tag application states

9.1.1 Example scenario

The following example scenario is for illustrative purposes:

A tag is travelling through the world. Since most of the world is not equipped with any wireless infrastructure, the tag will be in the default state, which means the tag sends out broadcast packets (blinks)) on a regular basis.

When the tag enters an area equipped with an infrastructure which is compliant with this part of ISO/IEC 24730, the infrastructure will receive one or several broadcast packets (blinks). The infrastructure then instructs the tag how it should behave by sending one or several application packets, each containing one or several commands. One of these commands will be the SetRangingPeers command by which the infrastructure tells the tag which of the readers the tag should use as ranging peers. Subsequently, by sending the command SwitchState with “Ranging” as argument, the infrastructure instructs the tag to perform ranging with these peers. The tag now cyclically ranges with the peers. The number of cycles, as well as the time between these cycles, is determined by the parameters of the previous SwitchState(Ranging) command. Another parameter of the previous SwitchState(Ranging) command controls if and how the tag sends out an application report packet containing a ranging report. When the tag travels through the area covered by the infrastructure, the readers to range with might change. Thus the infrastructure will update the list of readers to range with (the list of ranging peers) using the commands SetRangingPeers and/or AddRangingPeers.

It should be noted that in order to accommodate varying numbers of tags inside the infrastructure area, the infrastructure can individually instruct each tag how often per time unit the tag shall range with its peers through the SwitchState(Ranging) command.

When the infrastructure recognizes from position changes of the tag, that the tag is about to leave the infrastructure area, a reader will instruct the tag to switch to the default state.

If the instruction to switch to the default state is missed, the tag itself will decide to switch to default state after not having received any commands for a certain time.

9.2 Tag application states

An RTLS tag application shall support the states listed in Table 21.

Table 21 – Tag application states

Name	State code
Default state	0
Blink state	1
Wait state	2
Range state	3
Sleep state	4

Reserved and user-defined tag application state codes shall be the ones defined in Table 22.

Table 22 – Reserved and user-defined tag application states

Status	State code
Reserved	5..8
User defined	9..15

9.2.1 Default state

A tag shall enter the Default state either upon receiving a SwitchState(Default) command from the infrastructure or upon having detected the "Out of infrastructure area condition" defined 9.2.1.1. Upon entering the default state, the tag shall select the default profile as specified in 9.7 and shall blink periodically as defined in 9.2.5. For parameters in the default state, see Table 42.

9.2.1.1 Out of infrastructure area condition

If the tag receives no Command or ACK packets from an RTLS transceiver for a duration of $T_{Contact}$ the tag shall assume that it has left the infrastructure area.

9.2.2 Wait state

A tag shall enter the Wait state upon receiving a SwitchState(Wait) command or upon waking up from Sleep state. Upon entering the Wait state the tag application shall check the latest Command packet received for any pending commands. If pending commands are found, these are executed. If, after executing the last command, no command has altered the state of the tag, the tag shall activate its receiver and listen for further instruction(s).

A tag shall leave the Wait state upon receiving a state changing command or, if after WaitMaxDuration the tag has not received any state changing command, the tag shall switch from Wait state to Blink state.

9.2.3 Range state

A tag shall enter the Range state upon receiving a SwitchState(Range state) command. In this state, the tag shall range X times with the RTLS transceivers specified to the tag by a previous SetRangingPeers command. For details of the parameter X, see 9.3.1.6.3.

A tag shall leave the Range state upon any state changing command.

A tag shall switch from Range state to Wait state with WaitMaxDuration =$T_{WaitAfterRange}$ after the number of ranging cycles X is complete

9.2.4 Sleep state

A tag shall enter the Sleep state for a duration of X ms upon receiving the corresponding command. During the Sleep state, the tag shall deactivate its receiver and transmitter.

Upon completion of the sleep duration, the tag shall enter the Wait state for WaitMaxDuration=$T_{Waitdefault}$. For details of the parameter X see 9.3.1.7.1.

9.2.5 Blink state

A tag shall enter the Blink state upon receiving a SwitchState(Blink) command or upon detecting a timeout condition in Wait state. In blink state, a tag shall periodically transmit a burst of packets (one blink) consisting of N_{sub} identical Broadcast packets (sub blinks) as specified in Figure 29. Each M_{Blink}th blink shall consist of only one sub-blink followed by a receive window during which the receiver of the RTLS transceiver shall be activated for at least T_{Rxon}. During the receive window the tag listens for commands from any infrastructure RTLS transceiver. Any commands shall be executed immediately after the receive window has closed. In case of having received inconsistent commands from different infrastructure RTLS transceivers the commands shall be prioritized as defined in 9.3.8.

A tag shall leave the Blink state upon receiving a SwitchState command or upon detecting the “Out of infrastructure area condition” specified in 9.2.1.1.

9.2.5.1 Randomization of blink time interval

The time interval between the start of subsequent blinks shall be randomized by a random offset T_{Rand}, which is added to the constant T_{Blink}.

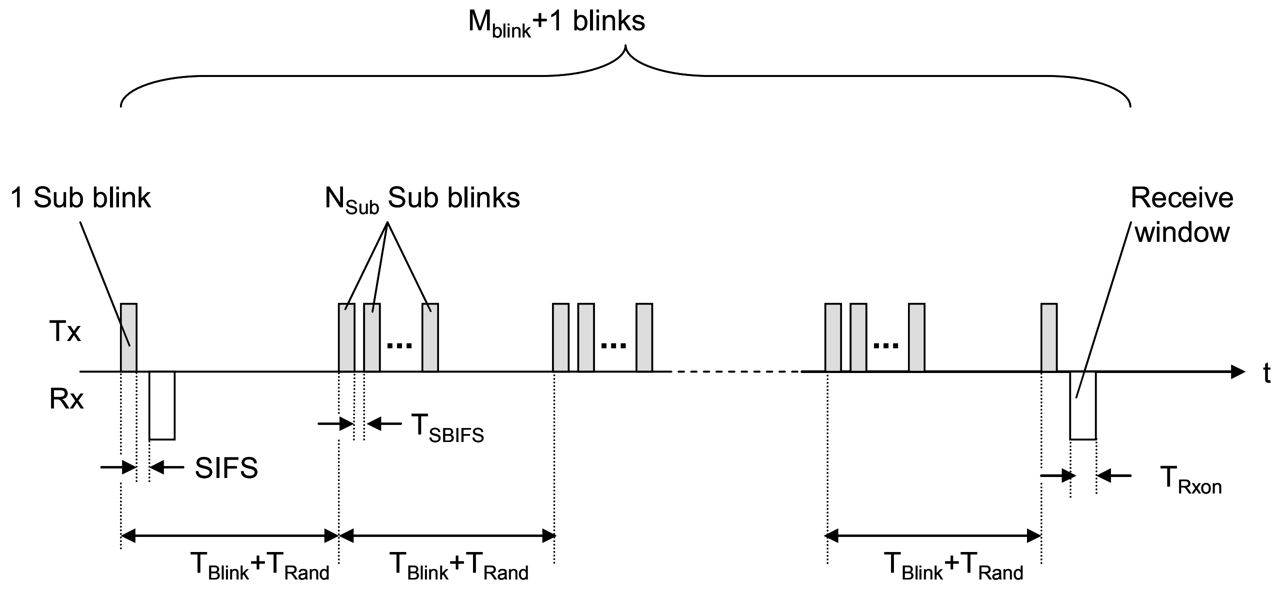

Figure 29 – Blink mode

For timing values see Table 41.

9.2.6 State transitions

The possible transitions among the states defined above are summarized in Table 23. In most cases a SwitchState command will be the trigger for a state change.

Besides the SwitchState command, the following events may trigger state transitions:

1. Detection of the "Out of infrastructure area" condition: Upon this event a tag shall switch to Default state.

2. WaitMaxDuration timeout: Upon this event a tag shall switch to Blink state.

3. Sleep duration over: Upon this event a tag shall switch to Wait state

4. Ranging cycles complete: Upon this event a tag shall switch to Wait state.

Table 23 – Application layer state transitions

<table>
<tr><th>Previous\new</th><th>Default</th><th>Blink</th><th>Range</th><th>Wait</th><th>Sleep</th></tr>
<tr><td>Default</td><td>1
SwitchState(Default)</td><td>2
SwitchState(Blink)</td><td>3
SwitchState(Range)</td><td>4
SwitchState(Wait)</td><td>5
SwitchState(Sleep)</td></tr>
<tr><td rowspan="2">Blink</td><td>6
SwitchState(Default)</td><td rowspan="2">8
SwitchState(Blink)</td><td rowspan="2">9
SwitchState(Range)</td><td rowspan="2">10
SwitchState(Wait)</td><td rowspan="2">11
SwitchState(Sleep)</td></tr>
<tr><td>7
Out of infrastructure area</td></tr>
<tr><td rowspan="2">Range</td><td>12
SwitchState(Default)</td><td rowspan="2">14
SwitchState(Blink)</td><td rowspan="2">15
SwitchState(Range)</td><td>16
SwitchState(Wait)</td><td rowspan="2">18
SwitchState(Sleep)</td></tr>
<tr><td>13
Out of infrastructure area</td><td>17
Ranging cycles complete</td></tr>
<tr><td rowspan="2">Wait</td><td rowspan="2">19
SwitchState(Default)</td><td>20
SwitchState(Blink)</td><td rowspan="2">22
SwitchState(Range)</td><td rowspan="2">23
SwitchState(Wait)</td><td rowspan="2">24
SwitchState(Sleep)</td></tr>
<tr><td>21
WaitMaxDuration timeout</td></tr>
<tr><td>Sleep</td><td></td><td></td><td></td><td>25
After sleep duration is over</td><td></td></tr>
</table>

9.3 Commands

Commands shall start with a command code field containing the command code as specified in Table 24.

Table 24 – Tag application commands

Command name	Command code
SwitchState	01h
SetConfigVector	02h
GetConfigVector	82h
SetRangingPeers	03h
AddRangingPeers	04h
GetRangingPeers	83h

Command codes reserved or user defined shall be the codes defined in Table 25.

Table 25 – Reserved and user-defined tag application command codes

Status	Command code range
Reserved	0
Reserved	05...40h
User defined	41h...7Fh
Reserved	80h
Reserved	84h…C0h
User defined	C1...FFh

9.3.1 SwitchState command

The SwitchState(New state) command shall be formatted as specified in Figure 30.

Command code	Reserved	New state code	Parameters
8	4	4	Format depends on New state code

Figure 30 – SwitchState command format

9.3.1.1 New state code field

The State code field shall switch to the new state code as specified in Table 21.

9.3.1.2 Parameters field

The Parameters field shall contain parameters for the new state as specified in Table 26.

Table 26 – Switch state parameters

New state	Parameter
Default state	-
Blink state	T_{Blink}, M_{Blink}, T_{Rxon}
Wait state	$T_{WaitMaxDuration}$
Range state	Type, report, repetition
Sleep state	Duration

9.3.1.3 SwitchState(Default)

The SwitchState command with Default as argument shall be formatted as specified in Figure 31.

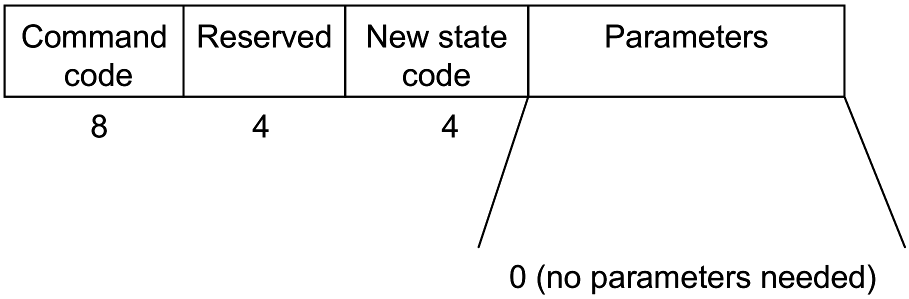

Figure 31 – SwitchState(Default)

9.3.1.4 SwitchState(Blink)

The SwitchState command with Blink as argument shall be formatted as specified in Figure 32.

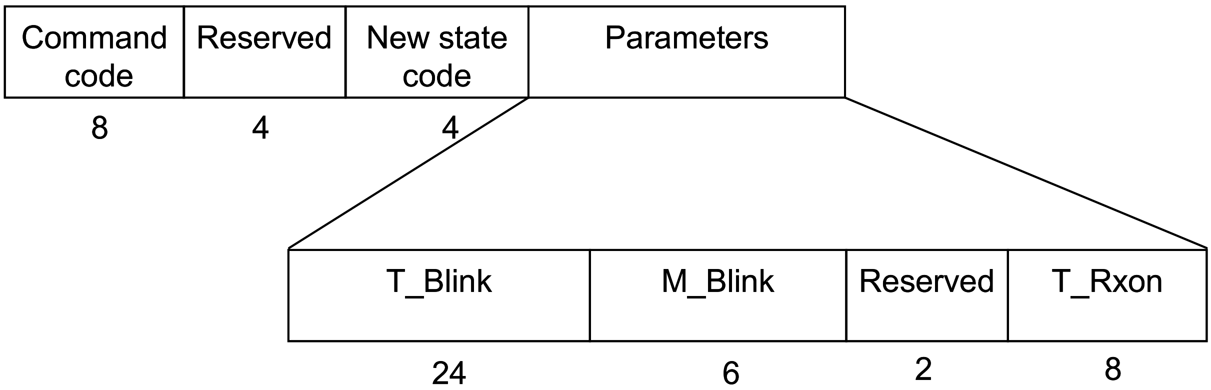

Figure 32 – SwitchState(Blink)

9.3.1.4.1 T_Blink subfield

The T_Blink subfield shall be an unsigned 24-bit integer. It shall contain the duration parameter T_{Blink} in ms, as specified in Figure 29.

9.3.1.4.2 M_Blink subfield

The M_Blink subfield shall be an unsigned 6-bit integer starting with the LSB. It shall contain the dimensionless parameter M_{blink} defined in 9.2.5.

9.3.1.4.3 T_Rxon subfield

The T_Rxon subfield shall be an unsigned 8-bit integer starting with the LSB. It shall contain the duration of the receive window in ms, as described in Figure 29.

9.3.1.5 SwitchState(Wait)

The SwitchState to Wait state command with Wait as argument shall be formatted as specified in Figure 33.

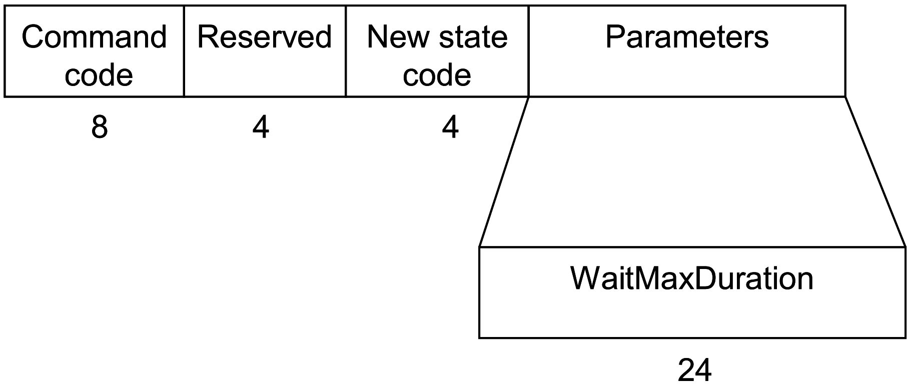

Figure 33 – SwitchState(Wait)

9.3.1.5.1 WaitMaxDuration subfield

The WaitMaxDuration subfield shall be an unsigned 24-bit integer starting with the LSB. The WaitMaxDuration subfield shall contain the maximum time in ms for which the tag application layer stays in Wait state after having received the SwitchState to Wait state command. If no state changing command is received during this time, the tag application layer shall switch to default state.

9.3.1.6 SwitchState(Range)

The SwitchState to Range state command with Range as argument shall be formatted as specified in Figure 34.

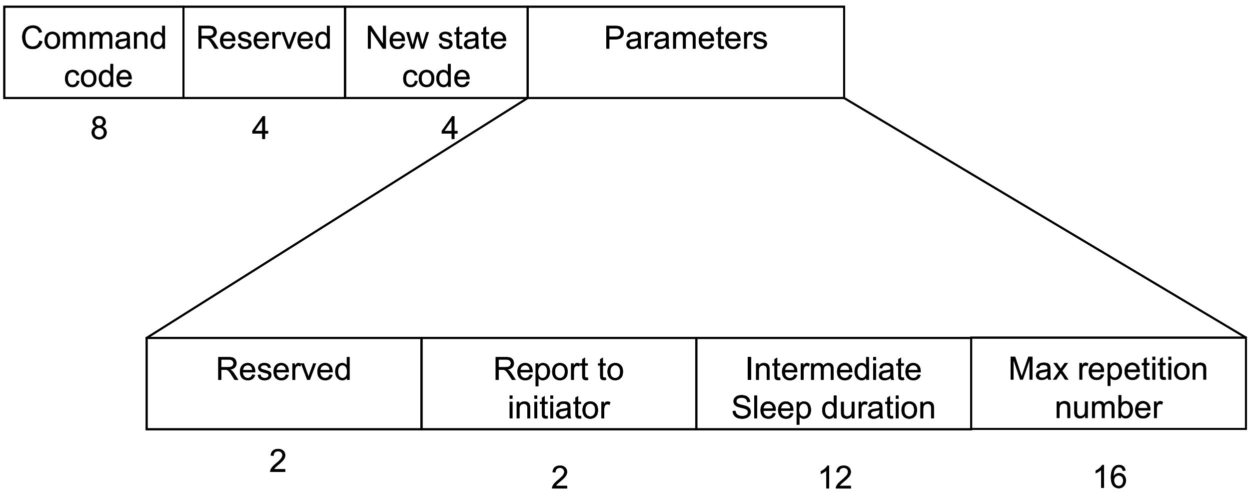

Figure 34 – SwitchState(Range)

Upon receiving the SwitchState to Range state command, the RTLS transceiver shall start ranging with the ranging peers as specified by a previous SetRangingPeers command.

9.3.1.6.1 Report to initiator subfield

The Report to initiator subfield shall be a 2-bit unsigned integer starting with the LSB.

The value of 0h shall define that no ranging report will be sent.

The value 1h shall define that the RTLS transceiver sends a Ranging report to the reader that sent the last SwitchState(Range) command after performing a ranging packet exchange with each ranging peer.

The value of 2h shall identify that the RTLS transceiver sent the Ranging report as broadcast.

The value of 3h shall be reserved.

9.3.1.6.2 Intermediate sleep duration subfield

The Intermediate sleep duration subfield shall be a 12-bit unsigned integer starting with the LSB.

The Intermediate sleep duration subfield shall define a time duration in ms for which the RTLS transceiver goes to sleep state after having performed a ranging packet exchange with each ranging peer and having sent its Ranging report (if requested).

9.3.1.6.3 Max repetition number subfield

The Max repetition number subfield shall be a 16 bit unsigned integer starting with the LSB.

After the having stayed in Sleep state the RTLS transceiver starts again to range with all ranging peers. This process is performed as often as specified in the Max repetition number subfield.

9.3.1.7 SwitchState(Sleep)

The SwitchState command with Sleep as argument shall be formatted as specified in Figure 35.

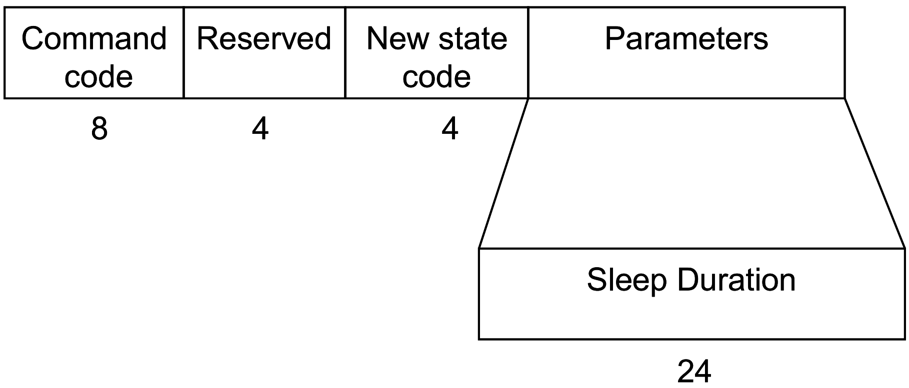

Figure 35 – SwitchState(Sleep)

9.3.1.7.1 Sleep Duration subfield

The Sleep Duration subfield shall be an unsigned 24-bit integer starting with the LSB. The Sleep Duration subfield shall specify the duration in ms for which the RTLS transceiver is instructed to stay in sleep state.

9.3.2 SetConfigVector command

The SetConfigVector command shall be formatted as specified in Figure 36.

Command code	Configuration vector
8	48

Figure 36 – SetConfigVector command format

The Configuration vector shall be defined by Table 27.

Table 27 – Configuration vector

Parameter	Bit width	Possible valued
Modulation	1	0= 2-ary orthogonal CSS 1= DQPSK CSS
Bandwidth/centre frequency combination	4	0..15, according to Table 2
Data rate	1	0= 1 Mbit/s 1= 250 kbit/s
Default T_{Blink}	24	Unsigned integer from [0..2^24-1]
Default M_{Blink}	6	Unsigned integer from [0..2^6-1]
CSMA/CA	1	0= CSMA/CA off 1= CSMA/CA on
Carrier sense criteria: Energy detect	1	0= off 1= on
Energy detect threshold	2	Unsigned integer from [0..3] 0h= -30dBm 1h= -50dBm 2h= -70dBm 3h= -90dBm
Carrier sense criteria: Physical carrier sense	1	0= off 1= on
Carrier sense criteria: Virtual carrier sense	1	0= off 1= on
3 way handshake	1	0= 3 way handshake off 1= 3 way handshake on
Reserved	1	
$T_{WaitAfterRange}$	4	Unsigned integer from [0..15]
Sub-chirp sequence for DQPSK-CSS	2	Unsigned integer from [0..3] 0= sub-chirp sequence I 1= sub-chirp sequence II 2= sub-chirp sequence III 3= sub-chirp sequence IV
Reserved	6	

After start of execution of a SetConfigVector command, the RTLS transceiver shall have updated the configuration within 25 ms.

9.3.3 GetConfigVector command

The GetConfigVector command shall be formatted as specified in Figure 37.

Command code
8

Figure 37 – GetConfigVector command format and GetRangingPeers command format

Upon receiving a GetConfigVector command, the RTLS transceiver shall respond with the corresponding report packet within $T_{TimeoutApplication}$.

9.3.4 SetRangingPeers command

The SetRangingPeers command shall be formatted as specified in Figure 38.

Command code	Reserved	Number of peers	MAC address of peer 1	Ranging packet exchange type for peer 1	Application ID of peer 1		MAC address of peer N	Ranging packet exchange type for peer N	Application ID of peer N
8	4	4	48	2	14		48	2	14

Figure 38 – SetRangingPeers command format, AddRangingPeers command format

The SetRangingPeers shall be used by the infrastructure to instruct a tag with which peers to exchange ranging packets upon subsequent “SwitchState to Range state commands”.

Upon reception of the SetRangingPeers command, a tag shall overwrite the internal list of ranging peers.

9.3.5 AddRangingPeers command

The AddRangingPeers command shall be formatted as specified in Figure 38.

The AddRangingPeers command shall be used by the infrastructure to instruct a tag to add peers to the list of peers to exchange ranging packets upon subsequent “SwitchState to Range state commands”.

Upon reception of the AddRangingPeers command, a tag shall add the peers to its internal list of peers to range with (ranging peer list). If the size of the ranging peer list, which a tag can support is exceeded, the first entry of the list shall be removed and a new entry shall be appended. A tag shall support a list of up to 15 ranging peers.

9.3.5.1 MAC address of peer X subfield

The MAC address of peer X subfield shall contain the 48-bit address of peer X.

9.3.5.2 Ranging packet exchange type for peer X

The "Ranging packet exchange type for peer X" subfield shall be a 2 bit unsigned integer starting with the LSB. As specified in Table 28, its value plus one shall determine which of the four defined ranging packet exchanges shall be used with this ranging peer.

Table 28 – Ranging packet exchange type subfield values

Value of Ranging packet exchange type subfield	Ranging packet exchange type
0h	1
1h	2
2h	3
3h	4

9.3.5.3 Application ID of peer X subfield

The Application ID of the peer X subfield shall contain a 14-bit ID of the peer which has been determined by the infrastructure.

NOTE The purpose of the ID is to identify the ranging peer in the ranging report (see 9.4.6),

9.3.6 GetRangingPeers command

The GetRangingPeers command shall be formatted as specified in Figure 37.

Upon receiving a GetConfigVector command, the RTLS transceiver shall respond with the corresponding report packet within $T_{TimeoutApplication}$.

9.3.7 User defined command

Any user-defined command shall be formatted as specified in Figure 39.

Command code	Number of octets	User defined
8	8	8 * Number of octets

Figure 39 – User defined command

9.3.7.1 Number of octets subfield

The Number_of_octets subfield shall contain the remaining number of octets of the command.

9.3.8 Command prioritization

In case that a tag while it has activated its receiver, receives different commands from different infrastructure RTLS transceivers the following rules shall apply.

1) Any commands that do not change the configuration vector or the state of the tag application (e.g. SetRangingPeers, AddRangingPeers) shall be executed upon reception.

2) Any commands that might change the configuration vector or the state of the tag application shall only be executed from the RTLS transceiver which sent the command with the highest priority according to Table 29. The commands shall be executed following the order in which the commands are given in the selected application command packet.

Table 29 – Application command priorities

Command	Priority
SetConfig	7
GetConfig	6
Get RangingPeers	5
SwitchState(Sleep)	4
SwitchState (Wait)	3
SwitchState (Range)	2
SwitchState (Blink or Default)	1

3) In the case that a tag, while it has activated its receiver, receives commands with identical priorities from different infrastructure RTLS transceivers, the tag shall consider only the latest received command packet.

9.4 Tag application packet formats

The tag application layer shall support the four application packet types listed in Table 30.

Table 30 – Tag application packet types

Application ranging packet type	Application control code
Ranging	1h
Command	2h
Report	3h
Blink	4h

Reserved and user-defined tag application packet type codes shall be those specified in Table 31.

Table 31 – Reserved and user defined tag application packet types

Status	Application control code
Reserved	0h
User defined	5h…7h

The type of a tag application packet shall be indicated by the application control code placed in the Ctrl field of the MAC frame.

9.4.1 Application blink packet

The application blink packet shall be a Broadcast packet formatted as specified in Figure 40.

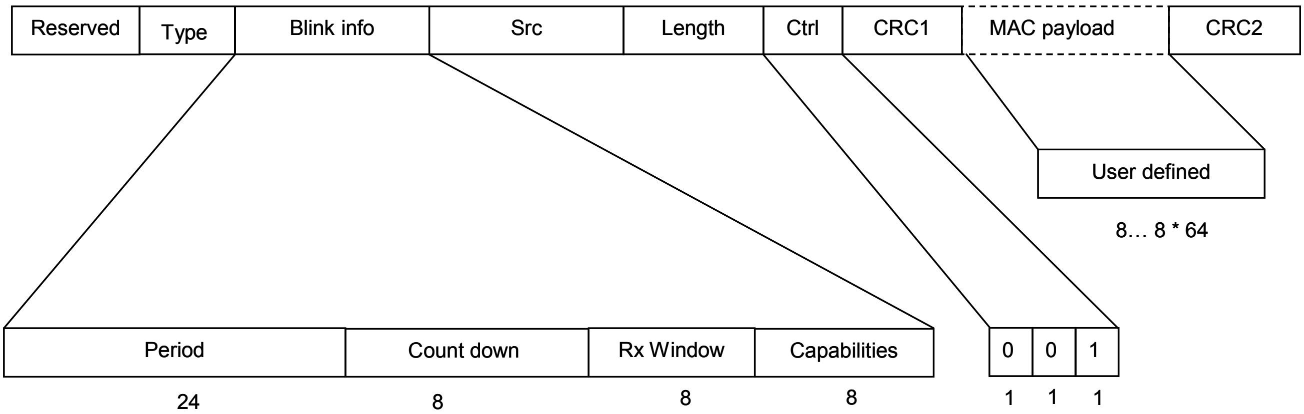

Figure 40 – Blink packet

9.4.1.1 Period subfield

The Period subfield shall contain the value of T_{blink} in ms, as an unsigned integer starting with the LSB.

9.4.1.2 Count down subfield

The Count down subfield shall contain the remaining number of blinks after which the tag will turn on its receiver. A value of zero shall indicate that immediately after this sub blink the RTLS transceiver will activate its receiver for a duration of at least T_{Rxon}. This subfield shall be an unsigned integer, starting with the LSB.

9.4.1.3 Rx Window subfield

The Rx Window subfield shall contain the width of the receive window in ms as an unsigned integer starting with the LSB.

9.4.1.4 Capabilities subfield

The Capabilities subfield shall contain a bit field starting with bit 0, indicating the capabilities of the tag as specified in Table 32.

Table 32 – Capabilities subfield

Bit number	Capability	Usage
0	DQPSK-CSS for communication	1 = capability available 0 = capability **not** available
1	DQPSK-CSS for ranging	1 = capability available 0 = capability **not** available
2	T_{Blink} overwritable	1 = capability available 0 = capability **not** available 0
3	M_{Blink} overwritable	1 = capability available 0 = capability **not** available 0
4,5,6,7	Reserved	0

9.4.2 Application command packet

An application command packet shall be formatted as specified in Figure 41.

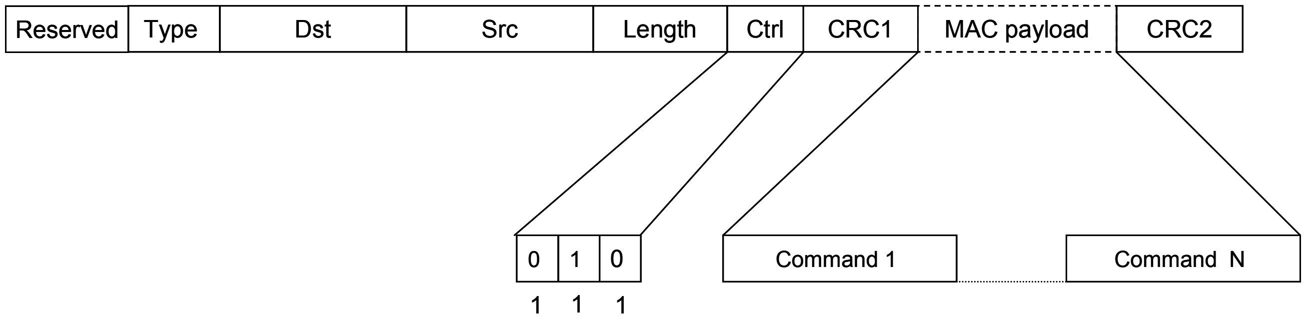

Figure 41 – Command packet format

It shall be possible to place one or several commands in the MAC payload of a Data packet. Commands shall be executed by the tag application layer strictly in the order in which they are received.

The length of the MAC payload of an application command packet shall not exceed 128 octets.

NOTE As mentioned in 9.1, it is anticipated that command packets are transmitted from infrastructure stations to tags. Thus, it is the responsibility of the developer of the infrastructure to choose commands or sequences of commands appropriate for his purpose.

9.4.3 Application report packet

Application report packets shall be transmitted by tags in response to Get commands.

A report packet shall be formatted as specified in Figure 42.

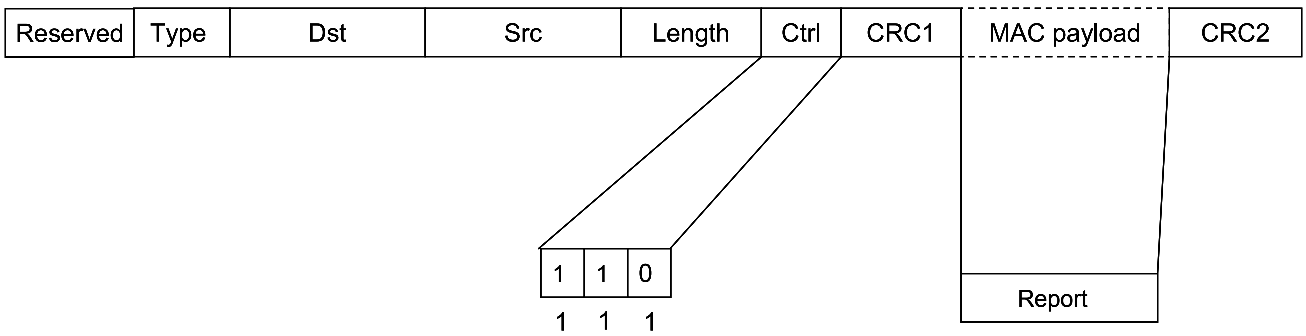

Figure 42 – Report packet format

The tag application reports listed in Table 33 shall be supported.

Table 33 – Application report codes

Report name	Report code
Ranging report	81h
GetConfigVector report	82h
GetRangingPeers report	83h

Reserved and user-defined application report codes shall be those specified in Table 34

Table 34 – Reserved and user defined application report codes

Status	Report code
Reserved	80h
Reserved	84h…FFh
User defined	0h…7Fh

9.4.4 GetConfigVector report

The GetConfigVector report shall be formatted as specified in Figure 43.

Report code	Configuration vector
8	48

Figure 43 – GetConfigVector report

The Configuration vector shall be defined by Table 27.

9.4.5 GetRangingPeers report

The GetRangingPeers report shall be formatted as specified in Figure 44. The subfields MAC address of peer,Ranging packet exchange type for peer and Application ID of peer shall correspond with the subfields defined in 9.3.4.

Report code	Reserved	Number of peers	MAC address of peer 1	Ranging packet exchange type for peer 1	Application ID of peer 1		MAC address of peer N	Ranging packet exchange type for peer N	Application ID of peer N
8	4	4	48	2	14		48	2	14

Figure 44 – GetRangingPeers report format

9.4.6 Ranging report

The Ranging report shall be formatted as specified in Figure 45. The subfields Ranging packet exchange type for peer and Application ID of peer shall correspond with the subfields defined in 9.3.4.

Report code	Reserved	Number of peers	Ranging packet exchange type for peer 1	Application ID of peer 1	Distance to peer 1	RSSI of peer 1		Ranging packet exchange type for peer n	Application ID of peer n	Distance to peer n	RSSI of peer n
8	4	4	2	14	16	8		2	14	16	8

Figure 45 – Ranging report format

9.4.6.1 Distance to peer subfield

The Distance to peer subfield shall be a 16-bit signed integer starting with the LSB. Values equal or greater than 0 shall contain an estimate of the distance to the peer in decimetres. This means that one integer unit corresponds to 1E-1 meters. Any negative value shall indicate that no ranging result is available. Negative values shall be available for user-defined error codes.

9.4.6.2 RSSI of peer subfield

The RSSI of peer subfield shall be an 8-bit signed integer starting with the LSB. Values equal or smaller than zero shall be a measurement in dBm within +-6 dBm of the signal strength with which packets of the peer have been received. Values larger than zero shall be user-defined.

9.4.7 Application ranging packet

An application ranging packet shall contain an RTLS code and a ranging packet code as specified in Table 35.

Table 35 – Ranging packet codes

Application ranging packet type	RTLS control code	Ranging packet code
T1R1	1h	1h
T1R2	1h	2h
T1R3	1h	3h
T2R1	1h	4h
T2R2	1h	5h
T2R3	1h	6h
T3R1	1h	7h
T3R2	1h	8h
T4R1	1h	9h
T4R2	1h	Ah

Reserved and user-defined ranging packet codes shall be those specified in Table 36.

Table 36 – Reserved and user defined ranging packet codes

Status	RTLS control code	Ranging packet code
Reserved	1h	0h
User defined	1h	80h…FFh

9.4.7.1 Application ranging packet fields

An application ranging packet may contain one or more of the following fields.

9.4.7.2 Ranging packet code field

The ranging packet code field shall be an unsigned 8-bit integer value as specified in Table 35, starting with the LSB.

9.4.7.3 Treply field

The Treply field shall be an unsigned 24-bit integer value starting with the LSB. It shall contain a time value in units of 0.1 ns, meaning that one integer unit corresponds to 1E-10 seconds.

9.4.7.4 Tround field

The Tround field shall be an unsigned 24-bit integer value starting with the LSB. It shall contain a time value in units of [0.1 ns].

9.4.7.4.1 Type 1, ranging 1 (T1R1)

The T1R1 packet shall be formatted as specified in Figure 46.

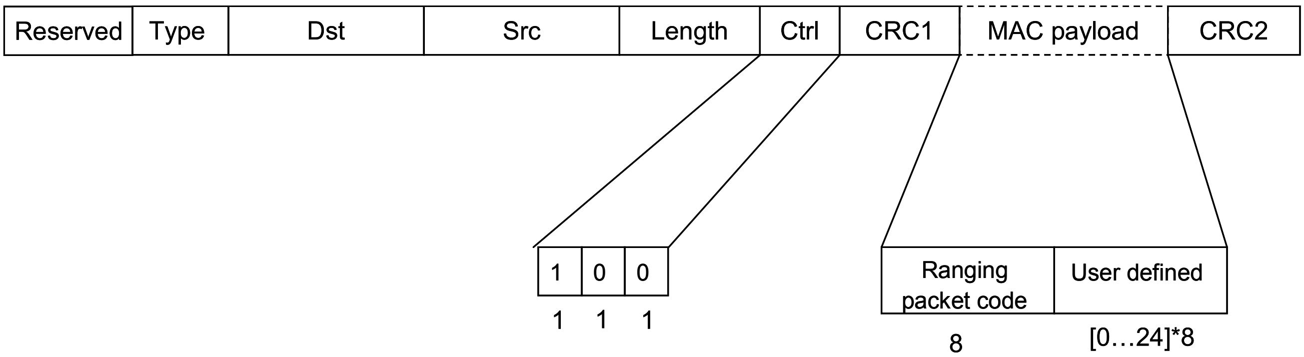

Figure 46 – Ranging packet T1R1

9.4.7.4.2 Type 1, ranging 2 (T1R2)

The T1R2 packet shall be formatted as specified in Figure 47.

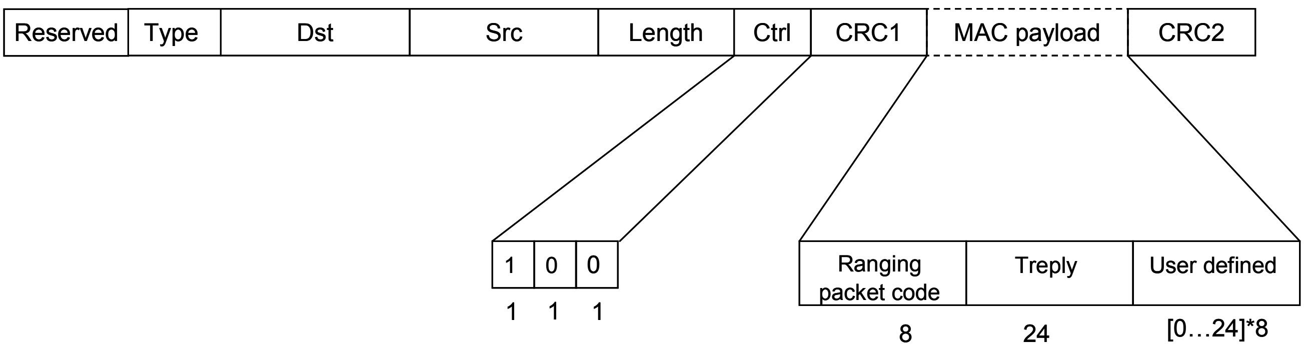

Figure 47 – Ranging packet T1R2

9.4.7.4.3 Type 1, ranging 3 (T1R3)

The T1R3 packet shall be formatted as specified in Figure 48.

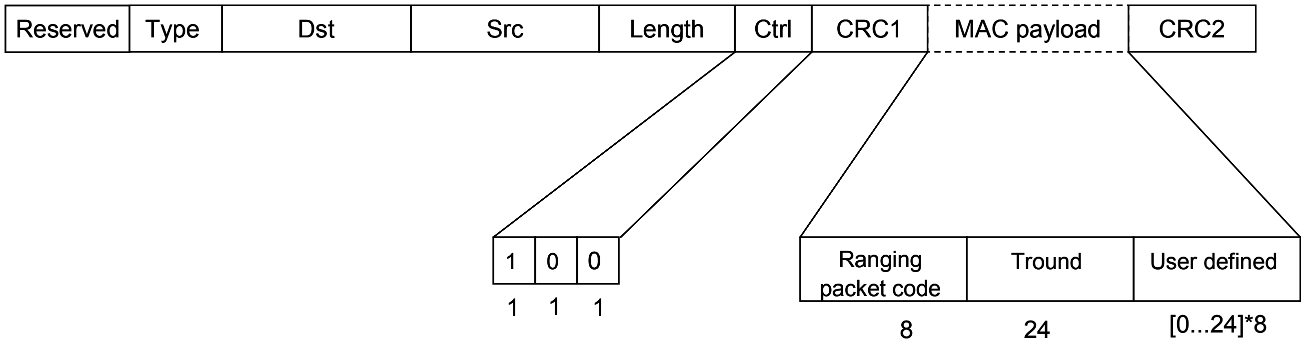

Figure 48 – Ranging packet T1R3

9.4.7.4.4 Type 2, ranging 1 (T2R1)

The T2R1 packet shall be formatted as specified in Figure 49.

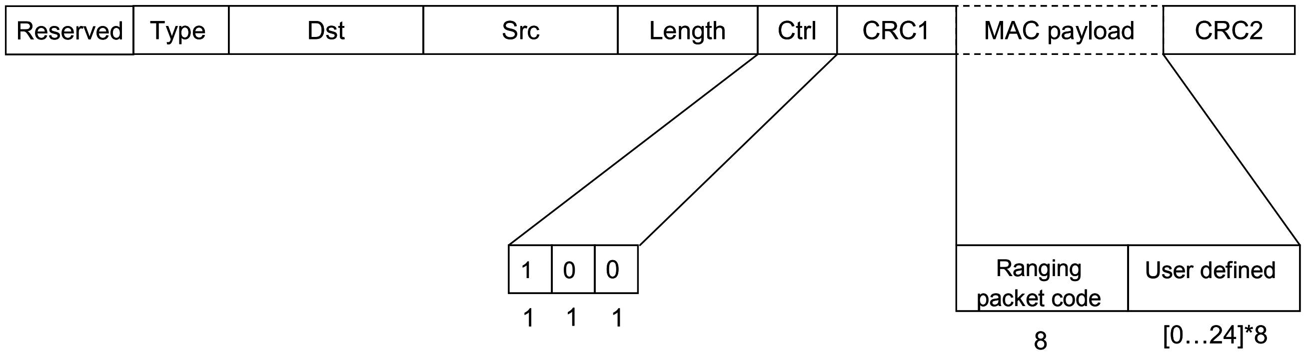

Figure 49 – Ranging packet T2R1

9.4.7.4.5 Type 2, ranging 2 (T2R2)

The T2R2 packet shall be formatted as specified in Figure 50.

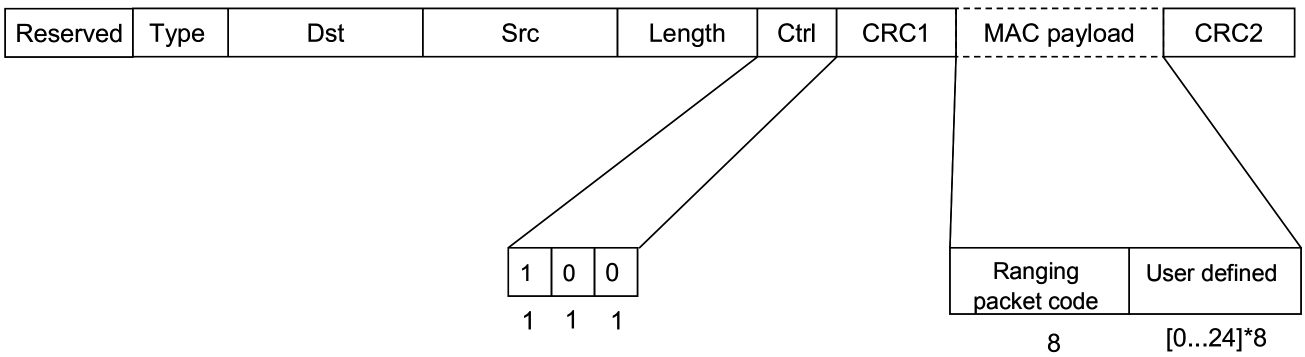

Figure 50 – Ranging packet T2R2

9.4.7.4.6 Type 2, ranging 3 (T2R3)

The T2R3 packet shall be formatted as specified in Figure 51.

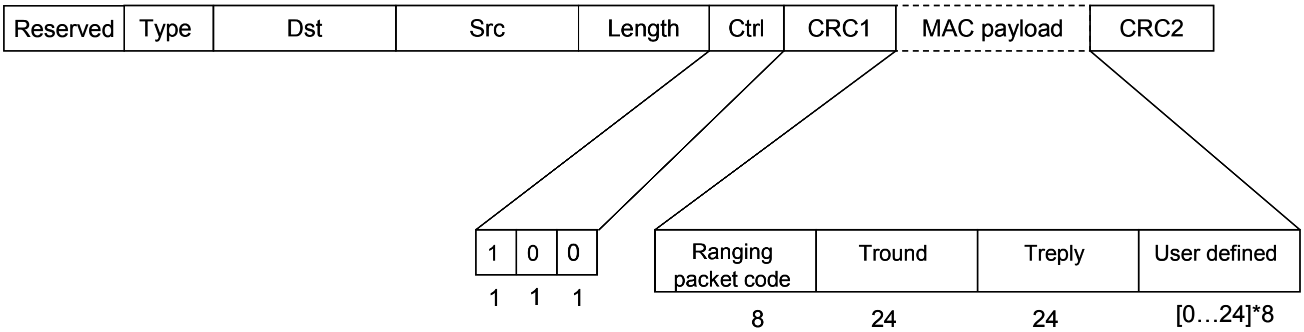

Figure 51 – Ranging packet T2R3

9.4.7.4.7 Type 3, ranging 1 (T3R1)

The T3R1 packet shall be formatted as specified in Figure 52.

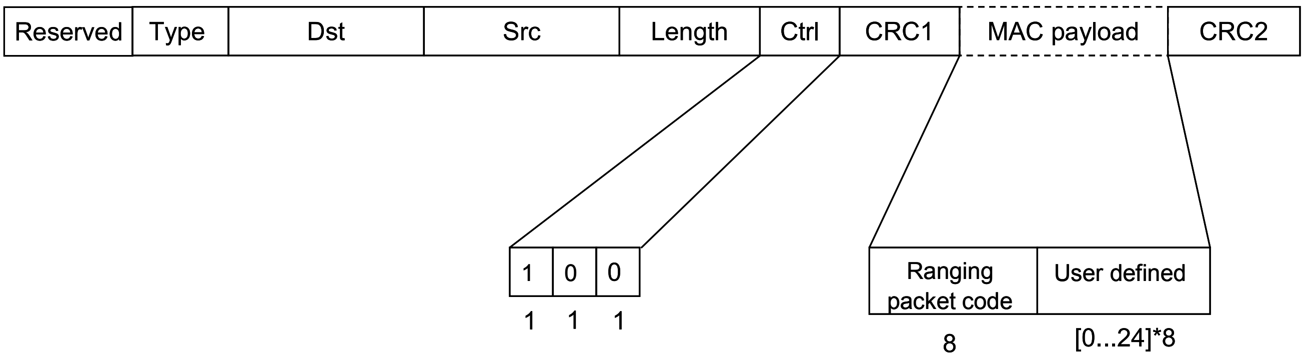

Figure 52 – Ranging packet T3R1

9.4.7.4.8 Type 3, ranging 2 (T3R2)

The T3R2 packet shall be formatted as specified in Figure 53.

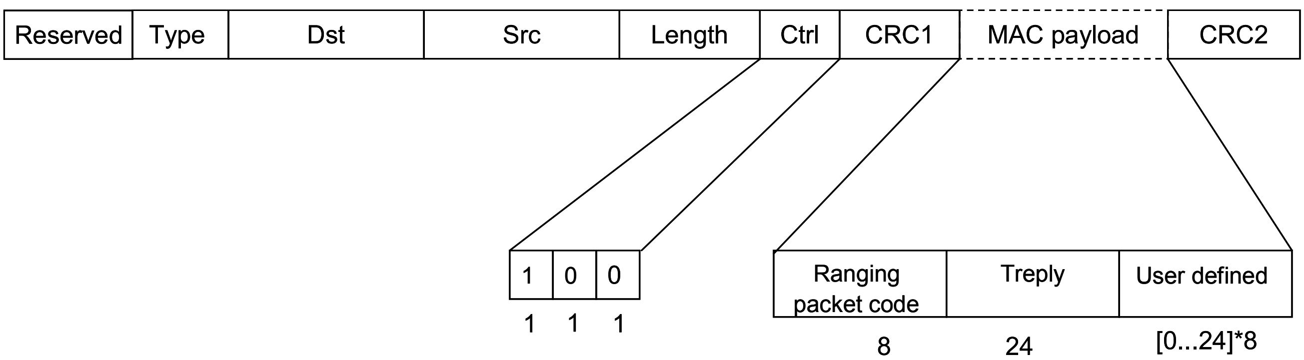

Figure 53 – Ranging packet T3R2

9.4.7.4.9 Type 4, ranging 1 (T4R1)

The T4R1 packet shall be formatted as specified in Figure 54.

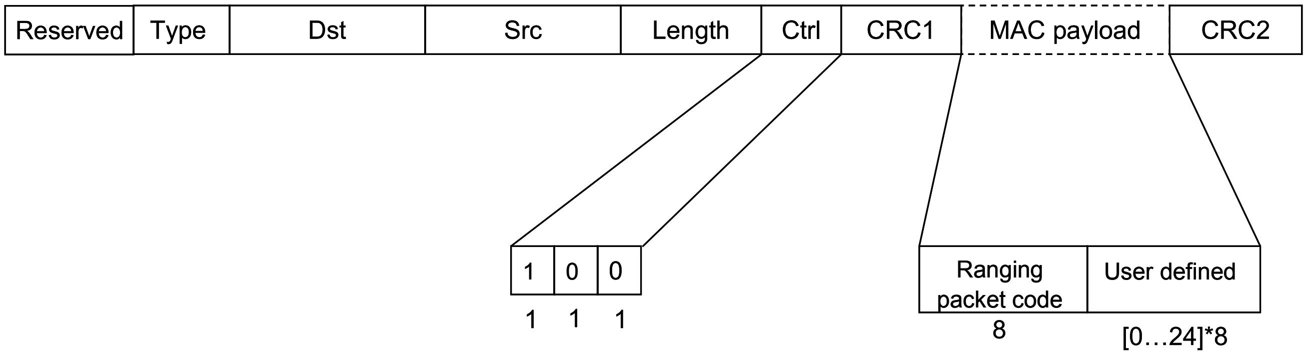

Figure 54 – Ranging Packet T4R1

9.4.7.4.10 Type 4, ranging 2 (T4R2)

The T4R2 packet shall be formatted as specified in Figure 55.

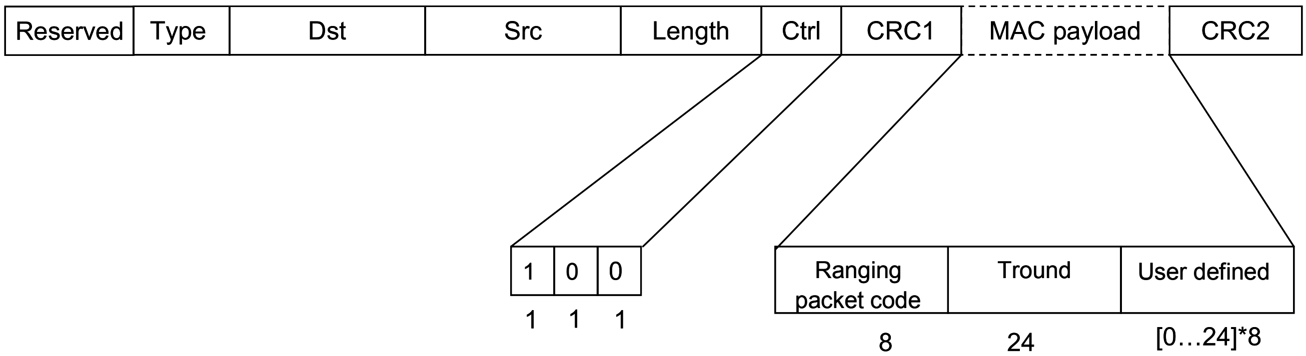

Figure 55 – Ranging packet T4R2

9.5 Ranging packet exchanges

Four types of ranging packet exchanges between two RTLS transceivers shall be supported. The four types differ in the number of packets exchanged and in which of the two RTLS transceivers have all information required to calculate the distance between the RTLS transceivers after completion of the ranging packet exchange.

9.5.1 Ranging packet exchange type 1

Ranging packet exchange type 1 shall consist of the three steps specified in Table 37 and depicted in Figure 56. After completion of this ranging packet exchange, RTLS transceiver A has all of he information required to calculate the distance between the two RTLS transceivers.

Table 37 – Ranging packet exchange type 1

Step	Description
1	RTLS transceiver A transmits a MAC Data packet containing a tag application layer T1R1 packet in its payload to RTLS transceiver B and receives an ACK packet.
2	RTLS transceiver B transmits a MAC Data packet containing a tag application layer T1R2 packet in its payload to RTLS transceiver A and receives an ACK packet.
3	RTLS transceiver B transmits a MAC Data packet containing a tag application layer T1R3 packet in its payload to RTLS transceiver A and receives an ACK packet.

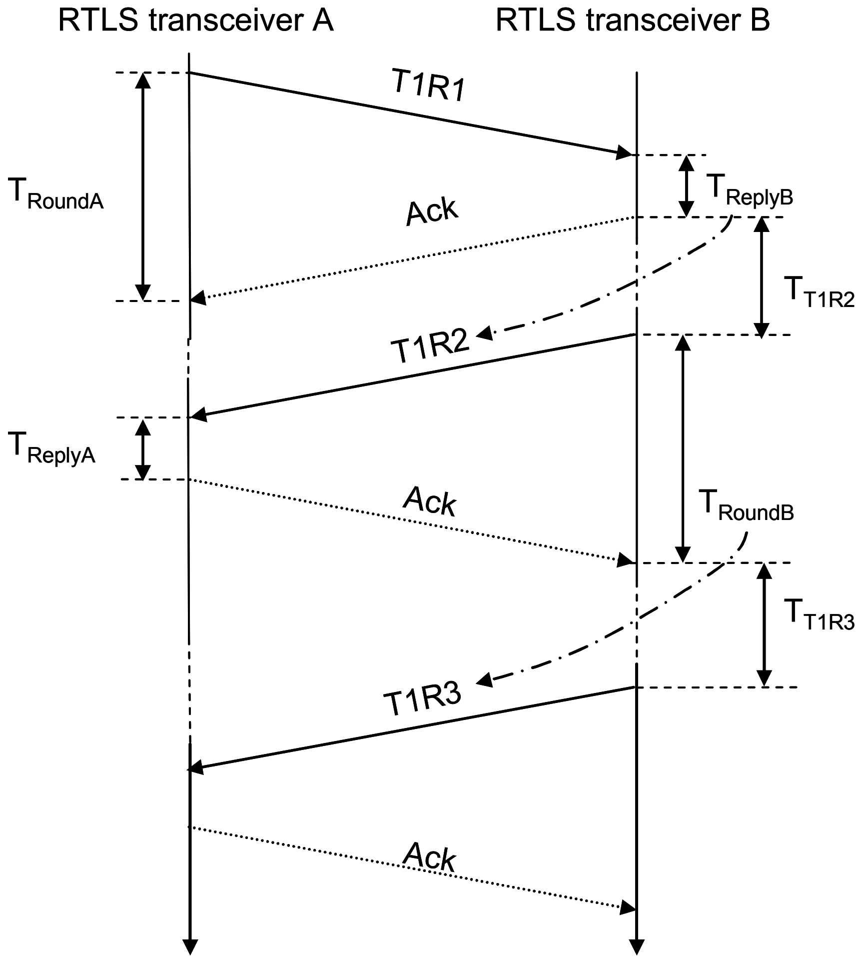

Figure 56 – Ranging packet exchange type 1

9.5.2 Ranging packet exchange type 2

Ranging packet exchange type 2 shall consist of the three steps specified in Table 38 and depicted in Figure 57. After completion of this ranging packet exchange, RTLS transceiver B has all of the information required to calculate the distance between the two RTLS transceivers.

Table 38 – Ranging packet exchange type 2

Step	Description
1	RTLS transceiver A transmits a MAC Data packet containing a tag application layer T2R1 packet in its payload to RTLS transceiver B and receives an ACK packet.
2	RTLS transceiver B transmits a MAC Data packet containing a tag application layer T2R2 packet in its payload to RTLS transceiver A and receives an ACK packet.
3	RTLS transceiver A transmits a MAC Data packet containing a tag application layer T2R3 packet in its payload to RTLS transceiver B and receives an ACK packet.

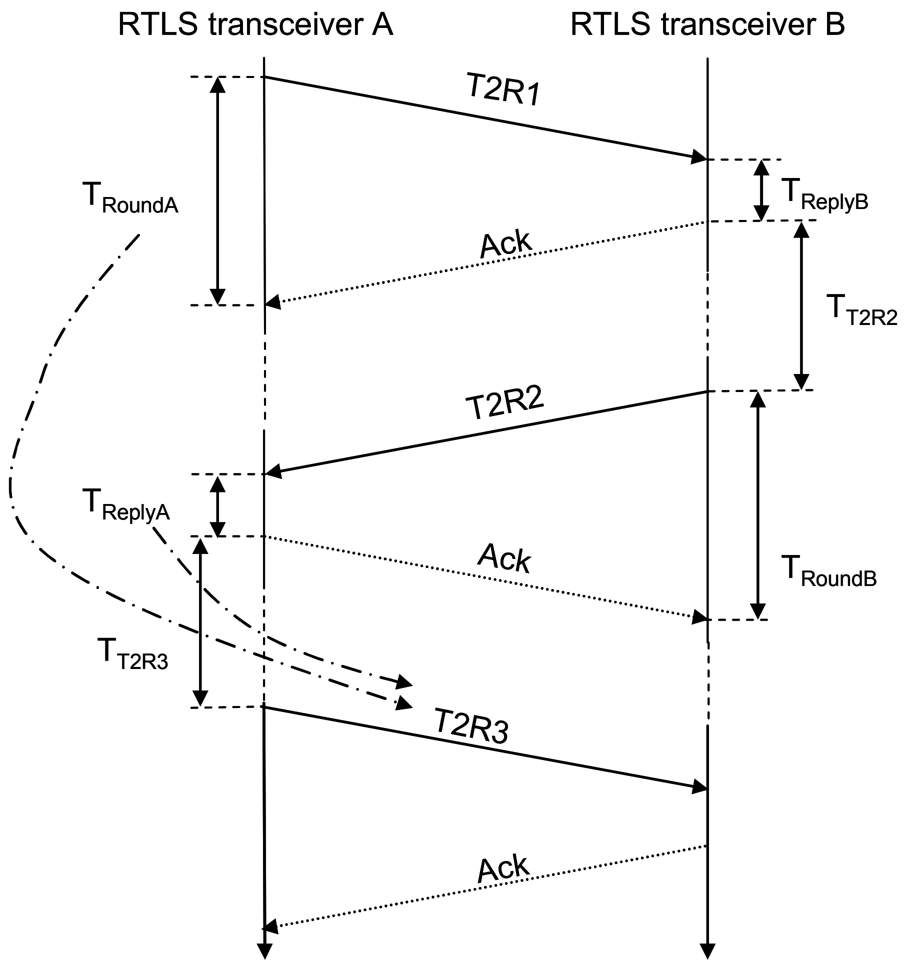

Figure 57 – Ranging packet exchange type 2

9.5.3 Ranging packet exchange type 3

Ranging packet exchange type 3 shall consist of the two steps specified in Table 39 and depicted in Figure 58. After completion of this ranging packet exchange, RTLS transceiver A has all of the information required to calculate the distance between the two RTLS transceivers.

Table 39 – Ranging packet exchange type 3

Step	Description
1	RTLS transceiver A transmits a MAC Data packet containing a tag application layer T3R1 packet in its payload to RTLS transceiver B and receives an ACK packet.
2	RTLS transceiver B transmits a MAC Data packet containing a tag application layer T3R2 packet in its payload to RTLS transceiver A and receives an ACK packet.

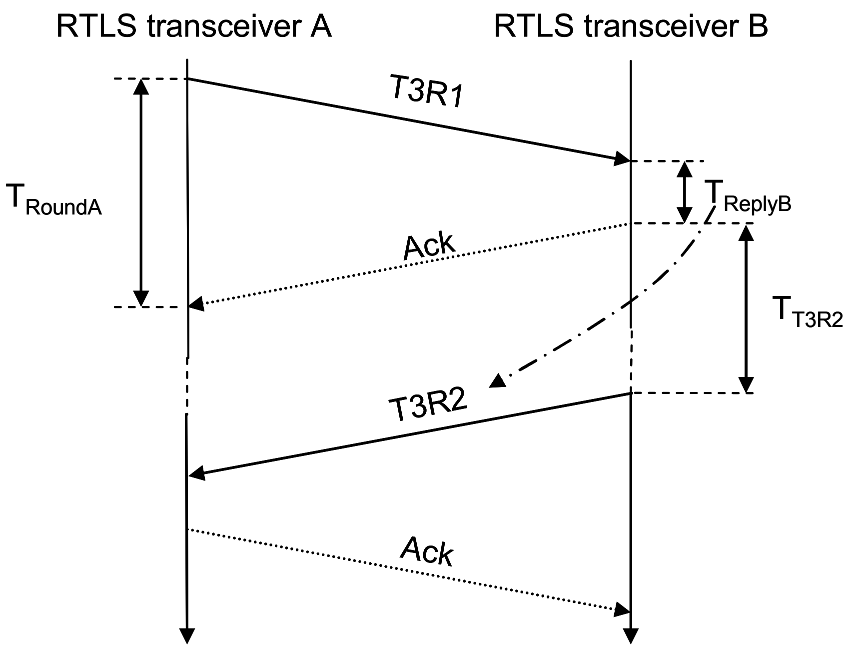

Figure 58 – Ranging packet exchange type 3

9.5.4 Ranging packet exchange type 4

Ranging packet exchange type 4 shall consist of the two steps specified in Table 40 and depicted in Figure 59. After completion of this ranging packet exchange, RTLS transceiver B has all of the information required to calculate the distance between the two RTLS transceivers.

Table 40 – Ranging packet exchange type 4

Step	Description
1	RTLS transceiver A transmits a MAC Data packet containing a tag application layer T4R1 packet in its payload to RTLS transceiver B and receives an ACK packet.
2	RTLS transceiver A transmits a MAC Data packet containing a tag application layer T4R2 packet in its payload to RTLS transceiver B and receives an ACK packet.

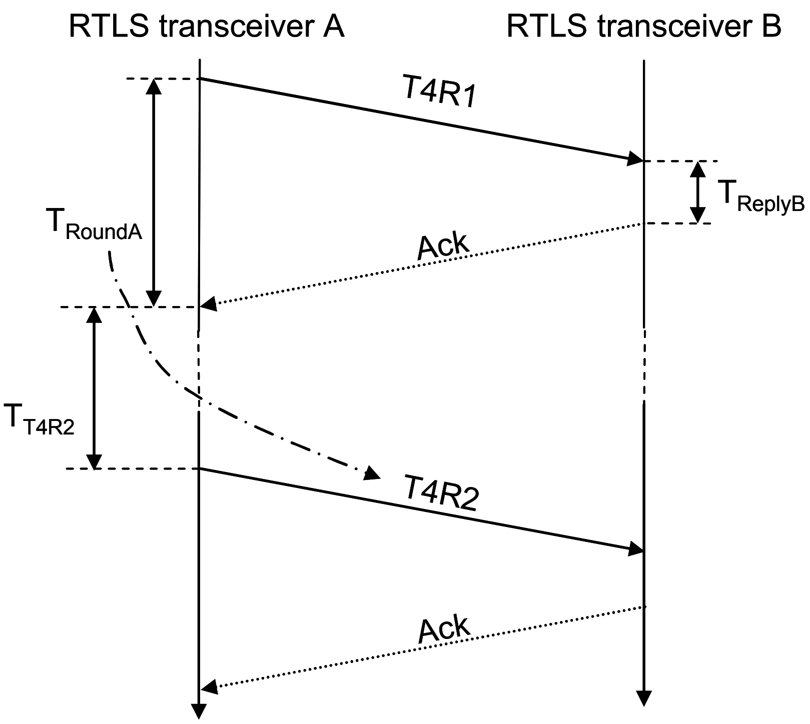

Figure 59 – Ranging packet exchange type 4

9.6 Timing values

The timing values defined in Table 41 shall apply.

Table 41 – Application layer timing values

Timing parameter	Value
SIFS	Specified in Clause 8
T_{SBIFS} (Sub blink inter frame space)	200 μs < TSBIFS <500 μs
T_{Blink}	Programmable in steps of 1 ms between 1 ms and (2^24-1) ms
T_{Rand}	Random number in from [-500us to 500 us] with granularity of equal or smaller 250 us
T_{Rxon}	Programmable in steps of 1 ms between 1 ms and (2^8-1) ms
$T_{Contact}$	5 T_{Blink}
$T_{TimeoutApplication}$	5 ms
$T_{WaitAfterRange}$	Configurable through configuration vector

9.7 Default profile

The default profile shall be determined by the parameters specified in Table 42.

Table 42 – Default profile parameters

Parameter	Value
Modulation	2-ary orthogonal CSS
Bandwidth	80 MHz
Centre frequency	2441.75 MHz
Data rate	1 Mb/s
T_{Blink}	Programmable by user from [50…2^24-1] ms
T_{Blink} overwritable	Programmable by user
T_{Rxon}	5 ms
M_{Blink}	Programmable by user from [0,1,2,…63]
M_{Blink} overwritable	Programmable by user
N_{sub}	Programmable by user from [1,2,…8]
CSMA/CA for Data packets	Off

9.8 Error handling

If an RTLS receiver receives a packet containing code values or parameter values which are out of range or cannot be processed for any reason, the complete packet shall be silently discarded unless specified otherwise.

Annex A
(informative)

Time base tolerances in two-way ranging

A.1 Two way ranging

One approach to perform ranging between two devices communicating with each other is Two-Way Ranging (TWR) as shown in Figure A.1. Device A sends a message to device B, starting an internal stopwatch. Device B receives the message, starting its internal stopwatch. After processing the received message, device B sends a reply message to device A, stopping its internal stopwatch, which then shows the reply time of device B measured by device B. Device A receives the reply message and stops its internal stopwatch, which then shows the round trip time measured by device B.

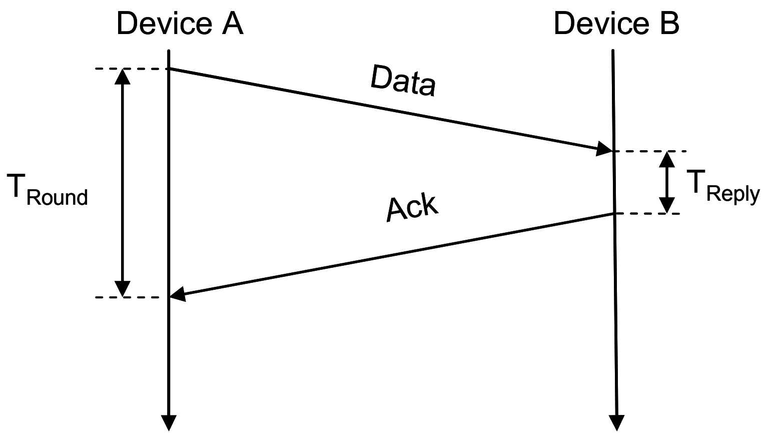

Figure A.1 – Two-way ranging

The propagation time can be computed according to Equation (A.1).

$$T_p = \frac{T_{Round} - T_{Reply}}{2} \quad \text{(A.1)}$$

A detailed error analysis can be found in Annex D 1.2.1 of IEEE 802.15.4a[5]. This analysis reveals that time-based tolerances of 40 ppm in combination with packet durations in the range of more than 100 µs yield an unacceptable estimation error.

Two methods for mitigating that problem are proposed in IEEE 802.15.4a[5].

The first method is referred to as “Characterizing crystal offsets with digital tracking loops” and it is described in of 5.5.7.5.1 of IEEE 802.15.4a[5]. Basically, this method means that a device that receives a packet from a peer device estimates the time base offset between its own time base and the peer device's time base by precisely tracking the symbol timing during the reception. If this method is used, two-way ranging yields good ranging performance despite the unsynchronized time bases subject to tolerances.

The second method is referred to as “Symmetric double-sided two-way ranging” (SDS-TWR) and it is described in Annex D1.3.2 of IEEE 802.15.4a[5]. A description of SDS-TWR, which has been accommodated to the nomenclature of this part of ISO/IEC 24730, is provided below.

A.2 Symmetric Double Sided Two Way Ranging (SDS-TWR)

In this approach, each device measures a round trip and a reply time. Figure A.2 depicts how the SDS TWR is applied over a Data-ACK packet exchange.

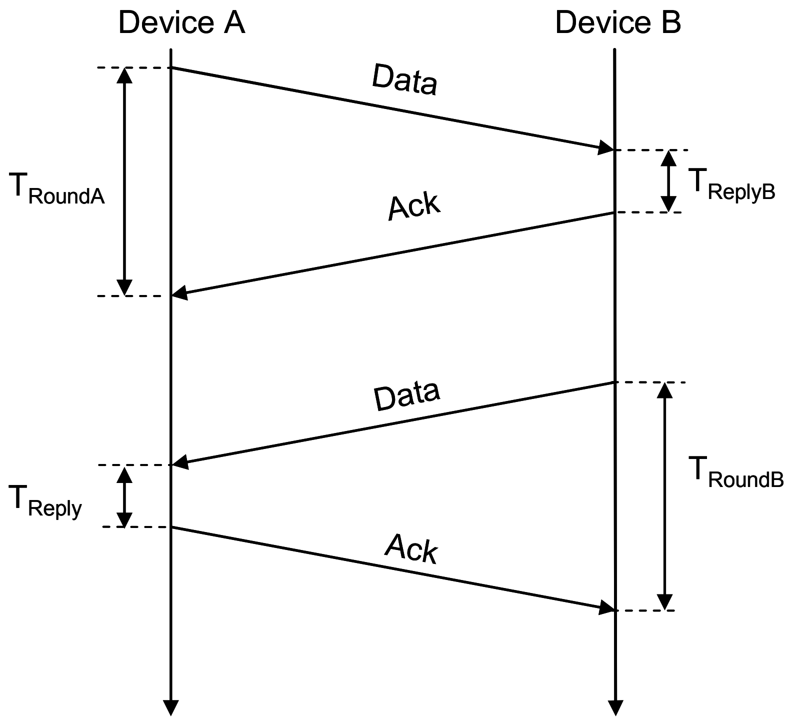

Figure A.2 – SDS-TWR over Data-ACK packet exchange

The estimated propagation delay will be computed according to Equation (A.2)

$$\hat{T}_{p} = \frac{\hat{T}_{RoundA} - \hat{T}_{ReplyA} + \hat{T}_{RoundB} - \hat{T}_{ReplyB}}{4} \qquad \text{(A.2)}$$

Where the subscript " ^ " denotes an estimate which is subject to time base tolerances.

The effect of time base tolerances e_A, e_B leads to the relationship between the true value and the estimated value given in Equations (A.3), (A.4), (A.5) and (A.6).

$$\hat{T}_{RoundA} = T_{RoundA}(1 + e_A) \qquad \text{(A.3)}$$

$$\hat{T}_{RoundB} = T_{RoundB}(1 + e_A) \qquad \text{(A.4)}$$

$$\hat{T}_{ReplyA} = T_{ReplyA}(1 + e_B) \qquad \text{(A.5)}$$

$$\hat{T}_{ReplyB} = T_{ReplyB}(1 + e_B) \qquad \text{(A.6)}$$

The detailed analysis of the estimation error (see Annex D1.3.2 of IEEE 802.15.4a[5]) yields Equation (A.7).

$$(\hat{T}_p - T_p) \approx \frac{1}{4}(T_{ReplyB} - T_{ReplyA})(e_A - e_B) \qquad \text{(A.7)}$$

If the maximum magnitude of e_A and e_B is specified to be e_{max} Equation (A.8) follows immediately.

$$\left|\hat{T}_p - T_p\right| < \frac{1}{2} \cdot \left|T_{ReplyB} - T_{ReplyA}\right| \cdot e_{max} \qquad \text{(A.8)}$$

Since in a Data-ACK as described in Clause 8, the reply time of a device is a known, fixed value, the tolerance of which is determined by the specification given in Clause 6, the difference of the reply times can be expected to be significantly below 1 µs. This results in an estimation error for the propagation delay significantly below 100 ps.

Annex B
(informative)

Coexistence

B.1 Considering coexistence

The operation of various wireless systems in the same frequency band leads to the question of how these systems affect each other (how they coexist). Since the 2,4 GHz band is an unlicensed band it is used by various radio systems. Currently IEEE 802.11[3] WLAN systems can be assumed as the most dominant systems in the 2,4 GHz band, but many others are also in existence. Any user who operates a system in an unlicensed band should be aware of potential interference from other systems and any developer who develops a system to operate in an unlicensed band should make use of the options he has to improve the coexistence of his system with other known or even unknown, future systems.

B.2 Determining coexistence behaviour

Most RF interference between systems occupying the same band is the equivalent to the interfering system raising the RF noise floor for the other occupants. The amount of frequency overlap, the level of RF power density (dBm per MHz) and the frequency profile power density shape of the interferer all contribute to the net degradation of the other band occupants. The amount of power level suppression of the interferer outside of its designated portion of the shared band is also very important, especially in near-far situations.

Obviously power density, and thus power levels and frequency bandwidth values, are key parameters in determining coexistence behaviour.

B.3 Other systems with comparable bandwidth values

This part of ISO/IEC 24730 defines two bandwidths. These bandwidth values are 80 MHz and 22 MHz. To assess the coexistence behaviour of a system implementation according to this part of ISO/IEC 24730, it is helpful for the user to consider the coexistence behaviour of systems with comparable bandwidth parameters. Another system that uses a bandwidth of 80 MHz is ISO/IEC 24730-2[2]. Other systems with a 22 MHz bandwidth are 802.11b, 802.11g and 802.15.4a, which includes the 2-ary orthogonal CSS option defined in this part of ISO/IEC 24730 in 7.3. It should be noted that the process for 802 standards for wireless communication explicitly requires a detailed coexistence analysis. The results for 802.15.4a CSS, which follows the approach of analyzing power densities as mentioned in B.2 and which confirms good coexistence performance between 802.15.4a CSS and other occupants of the 2,4 band can be found in Annex E of 802.15.4a.

B.4 General techniques

The following mechanisms are known for sharing the Medium among multiple users and/or different systems.

B.4.1 Frequency Division

Different frequency channels are used by different users and/or systems. This technique is supported through the definition of in total 16 centre frequencies.

B.4.2 Time Division

Different users and/or channels access the wireless channel at varying times. This technique is supported through the possibility of activating CSMA/CA.

B.4.3 Code Division

Systems using more bandwidth than the actual data rate requires, provide coding gain (sometimes called spreading gain) because data symbols are spread with a band spread code sequence. The chirp waveforms used in this part of ISO/IEC 24730 can be interpreted as specific band spread code sequences, which are different from the sequences used in other well known systems such as WLAN or ISO/IEC 24730-2[2]. Thus, this technique is supported through the usage of chirp signals.

B.5 This part of ISO/IEC 24730 specific

For coexistence considerations it should be considered whether the tag which is compliant with this part of ISO/IEC 24730 is controlled by the infrastructure.

B.5.1 This part of ISO/IEC 24730 compliant tag not under infrastructure control

While a tag is not under control of a corresponding infrastructure, the tag is in default state. In default state, the tag from time to time transmits broadcast packets using the full 2,4 band. From a coexistence point of view, this part of ISO/IEC 24730 is comparable to ISO/IEC 24730-2[2] in this phase. Although the time between blinks is programmable, for the obvious reason of battery lifetime, it is anticipated that the user will program this time during which no signal will be emitted as long as the application can tolerate. Thus, the occupancy of air-time is minimized.

B.5.2 This part of ISO/IEC 24730 compliant tag under infrastructure control

When an infrastructure is in place, additional traffic between the tag and the infrastructure will increase the occupancy of airtime. On the other hand, since the infrastructure is able to talk to the tag, it should make use of the options provided in order to achieve acceptable coexistence performance. For example:

B.5.2.1 Using frequency division

The infrastructure could identify or it could be instructed which WLAN channel shows the least power level of activity. This WLAN channel would be an obvious choice for the operation of the RTLS which is compliant with this part of ISO/IEC 24730. Since this part of ISO/IEC 24730 supports the WLAN band plan, the infrastructure could configure incoming tags to switch to the desired WLAN channel.

NOTE Extensive coexistence simulations on CSS using the WLAN band plan are provided in Annex E of 802.15.4a.

B.5.2.2 Using time division

If the infrastructure has detected any activity in the band it could configure incoming tags to use CSMA/CA. Since it is common practice, e.g. 802.11 to use energy detection as criterion for carrier sense, the probability of collisions between the this part of ISO/IEC 24730 system and the coexisting system will be reduced.

B.5.3 This part of ISO/IEC 24730 with ISO/IEC 24730-2

Since this part of ISO/IEC 24730 and ISO/IEC 24730-2[2] are RTLS standards that are based on their differing feature sets, target separate application spaces, it is anticipated that only one will fit the needs of a specific customer and that Ithis part of SO/IEC 24730 and ISO/IEC 24730-2[2] will not operate simultaneously at the same location. In order to avoid a potentially misleading situation, it is recommended not to operate ISO/IEC 24730-2[2] and infrastructure according to this part of ISO/IEC 24730 with high density of tags at the same location. However, if the situation of simultaneous operation is required for some reason, ISO/IEC 24730-5 could be configured to use one WLAN channel.

B.5.3.1 Bandwidth

From a bandwidth point of view, the coexistence behaviour of this part of ISO/IEC 24730 using a WLAN channel would be comparable to the coexistence behaviour between ISO/IEC 24730-2[2] and WLAN.

B.5.3.2 Power level

From a power level point of view, the coexistence behaviour of this part of ISO/IEC 24730 using a WLAN channel is similar or even more relaxed since this part of ISO/IEC 24730 nodes use less (Class I) or similar (Class II) transmit power.

B.5.3.3 Time profile

From a time profile point of view, the coexistence behaviour of this part of ISO/IEC 24730 using a WLAN channel is relaxed since WLAN is optimized for TCP/IP throughput (e.g. in Annex E of 802.15.4a typical WLAN packets are assumed to have a size of 1500 octets), while the traffic generated by this part of ISO/IEC 24730 consists mainly of ranging packets carrying only a few octets of payload. Even if the higher data rate of WLAN is taken into account, this part of ISO/IEC 24730 can be expected to use shorter segments of air-time in comparison with WLAN.

Annex C
(informative)

Computing location values from range values

Given that an infrastructure has collected the distance values between a tag and a set of readers with known positions, the position of the tag can be computed by means of trilateration, as illustrated in Figure C.1 It is well known that the position of the tag relative to the readers can be calculated based on the position of the readers and the distance values between readers and tag. In the example given in Figure C.1 these distance values are name d1, d2, d3.

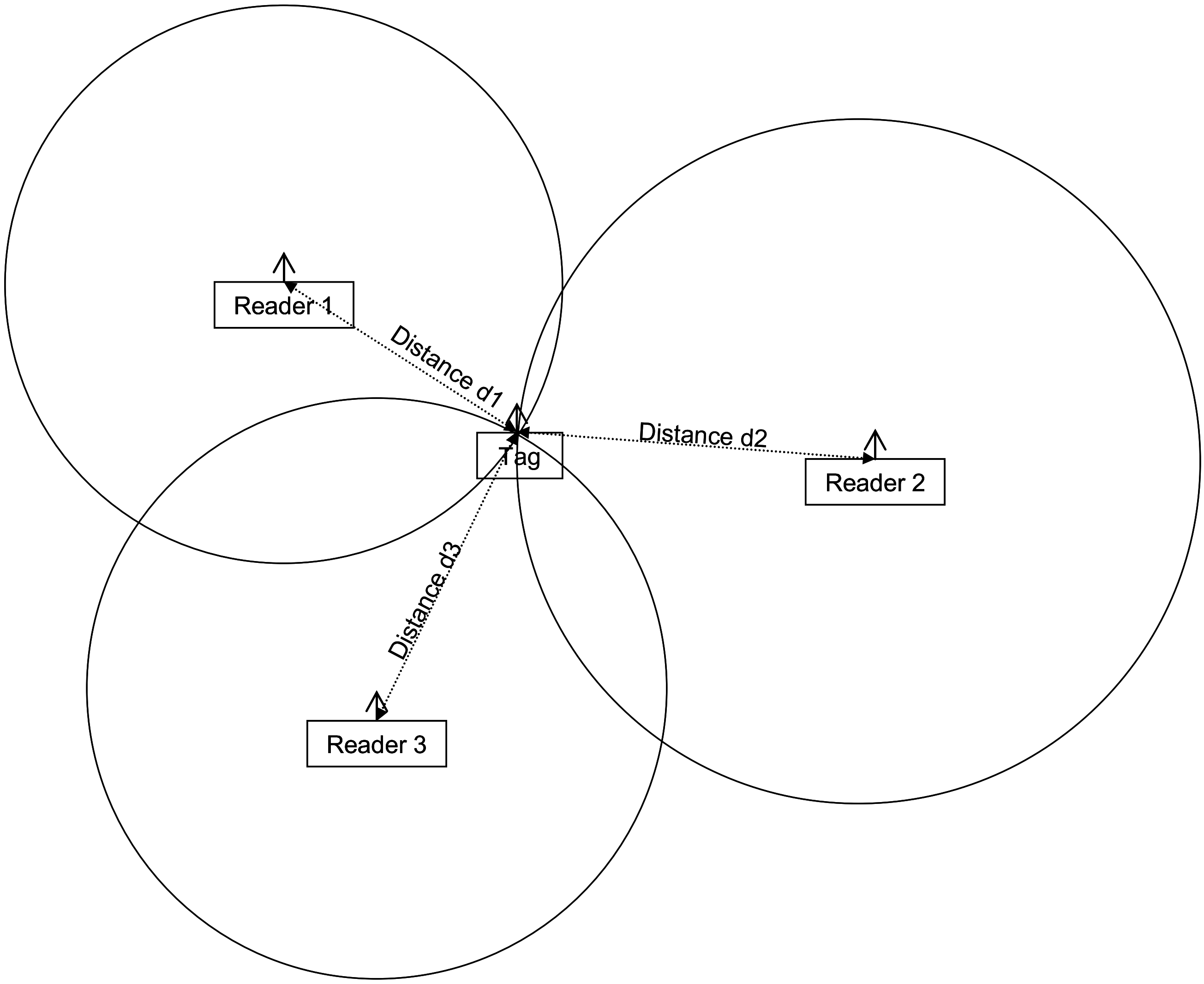

Figure C.1 – Localization of a tag through trilateration

For a mathematical description of trilateration see Annex D.1 of 802.15.4a and Annex A of ISO/IEC 24730-2[2] It should be noted that the implementation of a solver for trilateration problem will highly depend on parameters like target precision, tolerance to range estimation errors and available computation power.

Annex D
(informative)

Location and roaming of tags

D.1 Overview

Tags are designed to work in conjunction with an infrastructure comprising one or more base stations. The minimum number of base stations required depends on the location problem to be solved. For example in case of a hallway of limited length, one base station at the beginning or the end of the hallway can be sufficient.

Two or more infrastructures may be connected together to form a wider area network of location systems.

In the absence of an infrastructure, tags operate in a default state. In this state, tags transmit a blink periodically. The blink is a broadcast message to signal the presence of a tag to any infrastructure that is within communication range of the tag.

When an infrastructure receives a tag blink, the infrastructure can establish communication with the tag to instruct it how to communicate and to provide it a list of base stations with which to range. One command indicates to the tag how frequently it should blink or range. If the number of tags present is large, the tag ranging interval can be increased, i.e. cause the tag to transmit less often. If the number or tags present is small, the tag ranging interval can be reduced in order to report the tag position more frequently.

When the infrastructure detects that a tag may be moving out of the area, the infrastructure may command the tag to switch back to default state. If for any reason the tag loses contact with the infrastructure, then it will revert to the default state after a time of 5 blink periods. The default state is the mode used by the tag for roaming between infrastructures and for searching infrastructures.

D.2 Functional description

When a base station detects a tag the infrastructure transmits a SetRangingPeers or a AddRangingPeers command containing a list of RTLS transceivers to use as ranging peers. These RTLS transceivers are identified by their MAC address in the appropriate field of the command. The receipt by the tag of the SetRangingPeers or AddRangingPeers command does not cause a tag to perform ranging.

When the infrastructure transmits a SwitchState command with “Ranging” as the argument, the tag will then try to perform ranging with the base station previously identified in the SetRangingPeers or AddRangingPeers command. Parameters in the SwitchState(Ranging) command set the number of cycles, inter-cycle interval and define if and how the tag should transmit its ranging report. The ranging report contains the range values (distances) measured to all the ranging peers with which ranging was successful.

As the tag moves within the infrastructure coverage area, the tag may move out of range of some base stations and into range of others. The Infrastructure will update the base station ranging list on the tag by means of the SetRangingPeers and/or AddRangingPeers commands.

D.3 Communicating ranging results

If the tag has been instructed to transmit a ranging report, it will send out a list of ranging peers and the corresponding range values that it has measured. Based on the measurement data received, the infrastructure is able to calculate the tag position.

Alternatively if the tag is operating according to an embedded user defined application and has some knowledge of the location of the ranging peers, e.g. through user defined fields in previous commands, the tag is able to compute its location directly.

D.4 Hybrid nodes

This part of ISO/IEC 24730 does not provide implementation information for an RTLS infrastructure. However, the standard does not forbid a tag from acting as both a tag and as an infrastructure node. Where a tag performs both functions it is known as a “hybrid node”. Manufacturers of tags or infrastructure my define user fields to control the behaviour of hybrid nodes and so design solutions to satisfy specific applications. One such application may require the use of so called “mobile base stations”. To act as a mobile base station a tag would determine its own location using the infrastructure and an embedded application. Once it knows its own location a tag can then act as a base station.

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