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Information technology — Real time locating systems (RTLS) —

Part 62: High rate pulse repetition frequency Ultra Wide Band (UWB) air interface

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

Partie 62: Interface aérienne ultra large bande (UWB) à impulsions haute fréquence de répétition

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Foreword

ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission) form the specialized system for worldwide standardization. National bodies that are members of ISO or IEC participate in the development of International Standards through technical committees established by the respective organization to deal with particular fields of technical activity. ISO and IEC technical committees collaborate in fields of mutual interest. Other international organizations, governmental and non-governmental, in liaison with ISO and IEC, also take part in the work. In the field of information technology, ISO and IEC have established a joint technical committee, ISO/IEC JTC 1.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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 24730-62 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: Direct Sequence Spread Spectrum (DSSS) 2,4 GHz air interface protocol*

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

— *Part 21: Direct Sequence Spread Spectrum (DSSS) 2,4 GHz air interface protocol: Transmitters operating with a single spread code and employing a DBPSK data encoding and BPSK spreading scheme*

— *Part 22: Direct Sequence Spread Spectrum (DSSS) 2,4 GHz air interface protocol: Transmitters operating with multiple spread codes and employing a QPSK data encoding and Walsh offset QPSK (WOQPSK) spreading scheme*

— *Part 61: Low rate pulse repetition frequency Ultra Wide Band (UWB) air interface*

— *Part 62: High rate pulse repetition frequency Ultra Wide Band (UWB) air interface*

Introduction

This series of standards defines one Air Interface Protocol for Real Time Locating Systems (RTLS) for use in asset management and is intended to allow for compatibility and to encourage interoperability of products for the growing RTLS market.

This document, the high rate pulse repetition frequency (HRP) UWB Air Interface Protocol, establishes a technical standard for Real Time Locating Systems that operate at an internationally available UWB frequency bands and that are intended to provide accurate location (e.g. within some tens of centimetres) with frequent updates (for example, every second).

Real Time Locating Systems are wireless systems with the ability to locate the position of an item anywhere in a defined space (local/campus, wide area/regional, global) at a point in time that is, or is close to, real time. Position is derived by measurements of the physical properties of the radio link.

Conceptually there are four classifications of RTLS:

- Locating an asset via satellite - requires line-of-sight - accuracy to 10 meters
- Locating an asset in a controlled area, e.g., warehouse, campus, airport - area of interest is instrumented - accuracy to 3 meters
- Locating an asset in a more confined area - area of interest is instrumented - accuracy to tens of centimetres
- Locating an asset over a terrestrial area using a terrestrial mounted receivers over a wide area, cell phone towers for example – accuracy 200 meters

With a further two methods of locating an object which are really RFID rather than RTLS:

- Locating an asset by virtue of the fact that the asset has passed point A at a certain time and has not passed point B
- Locating an asset by virtue of providing a homing signal whereby a person with a handheld can find an asset

Method of location is through identification and location, generally through multilateration

- Types
  - Time of Flight Ranging Systems
  - Amplitude Triangulation
  - Time Difference of Arrival (TDOA)
  - Cellular Triangulation
  - Satellite multilateration
  - Angle of Arrival

This standard defines the air interface protocol needed for the creation of an RTLS system using HRP UWB which is a physical layer UWB signalling mechanism (based on standard IEEE 802.15.4a UWB) and employing high rate pulse repetition frequencies (PRF) 16 MHz or 64 MHz, and a combination of burst position modulation (BPM) and binary phase-shift keying (BPSK.

Information technology — Real time locating systems (RTLS) —

Part 62: High rate pulse repetition frequency Ultra Wide Band (UWB) air interface

1 Scope

This part of ISO/IEC 24730 defines the air-interface for real time locating systems (RTLS) using a physical layer Ultra Wide Band (UWB) signalling mechanism (based on IEEE 802.15.4a UWB). This modulation scheme employs high rate pulse repetition frequencies (PRF) 16 MHz or 64 MHz, and a combination of burst position modulation (BPM) and binary phase-shift keying (BPSK) giving an extremely high level of performance with a fully coherent receiver.

In addition to defining the air interface protocol (AIP) in terms of the physical layer modulation, this part of ISO/IEC 24730 also defines the AIP in terms of the messages sent over the air. This AIP supports simple one-way communication of a basic blink that may be used for a one-way Time Difference of Arrival (TDOA) based RTLS, where mobile tags periodically transmit the blink message which is received by an infrastructure consisting of a number of fixed reader nodes.

This AIP also optionally supports bidirectional communication and two-way ranging between the readers and tags of an RTLS. The support of two-way ranging depends on additionally including a UWB receiver in the tag and UWB transmitters in the reader infrastructure.

The mandatory default operational 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/IEEE 8802-15-4, *Information technology — Telecommunications and information exchange between systems — Local and metropolitan area networks — Specific requirements Part 15-4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)*

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

ISO/IEC 19762, *Information technology AIDC techniques — Harmonized vocabulary — (all parts)*

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/IEC/IEEE 8802-15-4, ISO/IEC 19762 (all parts), and the following apply.

3.1.1
burst
group of ultra wide band (UWB) pulses occurring at consecutive chip periods

3.1.2
complex channel
combination of a channel [radio frequency (RF) center frequency] and a ternary code sequence

3.1.3
frame
format of aggregated bits that are transmitted together in time

3.1.4
hybrid modulation
modulation used in the ultra wide band (UWB) physical layer (PHY) that combines both binary phase-shift keying (BPSK) and burst position modulation (BPM) so that both coherent and non-coherent receivers can be used to demodulate the signal

3.1.5
idle period
duration of time where no transceiver activity is scheduled to take place

3.1.6
local clock
symbol clock internal to a device

3.1.7
mean pulse repetition frequency (PRF)
total number of pulses within a symbol divided by the symbol duration

3.1.8
payload data
contents of a data message that is being transmitted

3.1.9
peak pulse repetition frequency (PRF)
maximum rate at which an ultra wide band (UWB) physical layer (PHY) emits pulses

3.1.10
ranging frame (RFRAME)
ultra wide band (UWB) frame having the ranging bit set in the physical layer (PHY) header (PHR)

3.1.11
ranging marker (RMARKER)
first ultra wide band (UWB) pulse of the first bit of the physical layer (PHY) header (PHR) of a ranging frame (RFRAME)

3.1.12
symbol
period of time and a portion of the transmitted signal that is logically considered to be a unit signaling event conveying some defined number of data bits or repeated portion of the synchronization signal

3.2 Abbreviated terms

AGC	automatic gain control
API	application program interface
BPM	burst position modulation
BPSK	binary phase-shift keying
CRC	cyclic redundancy check
DPS	dynamic preamble selection
DSN	data sequence number
FCS	frame check sequence
FEC	forward error correction
HRP	high rate PRF
LFSR	linear feedback shift register
LRP	low rate PRF
LSB	least significant bit
MAC	medium access control
MSB	most significant bit
PHR	PHY header
PHY	physical layer
PPDU	PHY protocol data unit
PRBS	pseudo-random binary sequence
PRF	pulse repetition frequency
PSD	power spectral density
PSDU	PHY service data unit
RF	radio frequency
RFID	Radio Frequency Identification
RFRAME	ranging frame
RMARKER	ranging marker
RTLS	Real Time Locating System
RX	receive or receiver
SFD	start-of-frame delimiter
SHR	synchronization header
SNR	signal-to-noise ratio
SYNC	synchronization
TDOA	time difference of arrival
TOF	time of flight

TX	transmit or transmitter
UWB	ultra wide band

4 Overview

4.1 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.

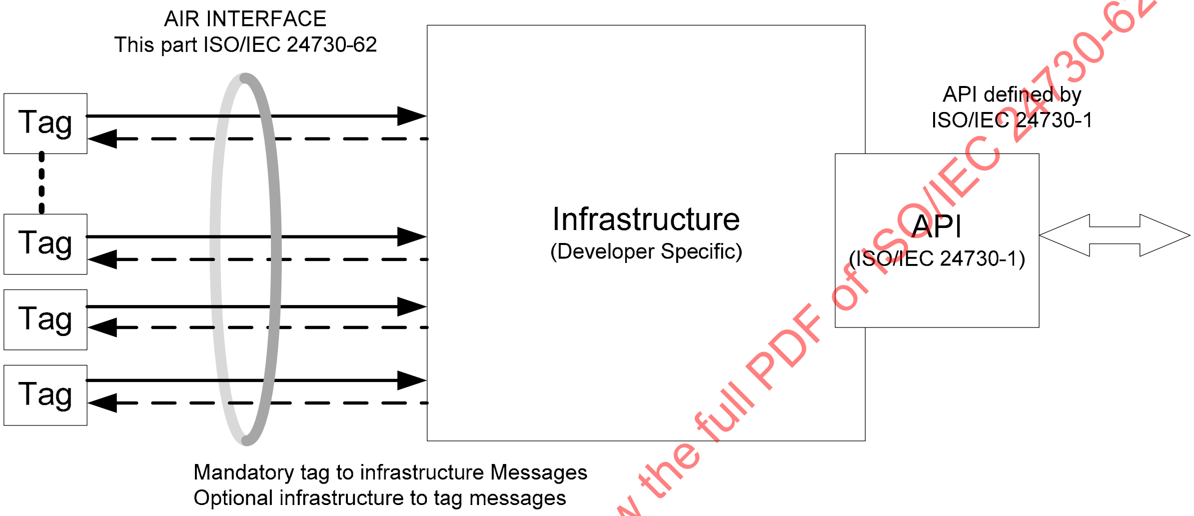


Figure 1 — RTLS components

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].

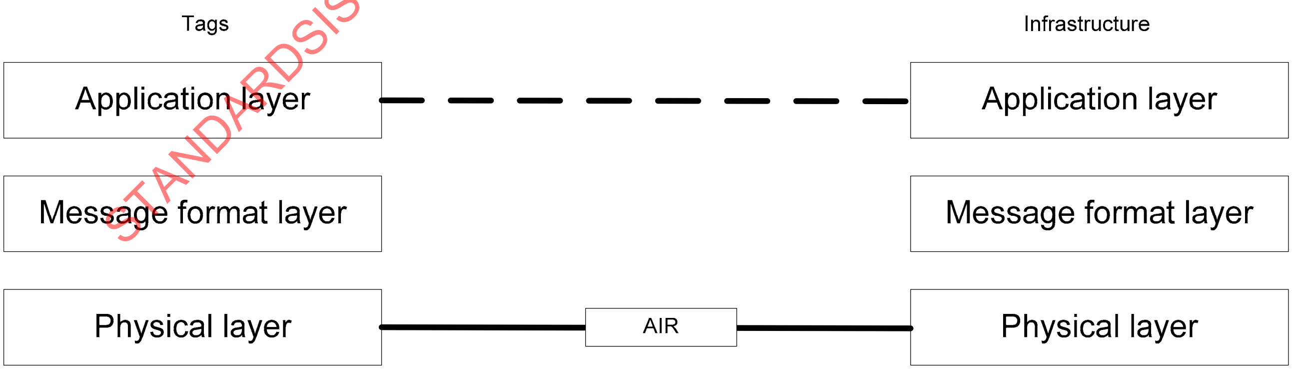


Figure 2 — air interface layers

4.2 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 reader nodes 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 need to receive the blink message from a tag, measuring its time of arrival, in order to locate the tag.

4.3 System

After power on, a tag uses a default profile in which it blinks periodically. With each blink the tag signals its physical address and optional information about whether and when it can receive commands from the infrastructure.

The infrastructure may use the arrival times of the blink at a number of time synchronised readers to compute the tag location using TDOA mechanisms.

The infrastructure may decide (for two-way capable tags) to command the tag to perform two-way ranging to a number of similarly capable reader nodes in the vicinity. By sending commands to the tag while the tag is listening, the infrastructure may select the reader nodes with which the tag performs two-way ranging. 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.

When a two-way tag loses connection to the infrastructure, i.e. doesn't receive any commands for a certain time, it reverts to its default blink activity.

4.4 Document structure

The remainder of this part of ISO/IEC 24730 firstly defines and specifies the Physical Layer (PHY) layer modulation and then defines the basic message format before separately detailing the messages of the default one-way communications mode of operation and the messages of the optional two-way communications mode of operation.

5 Physical (PHY) layer specification

5.1 General

The High Rate PRF (HRP) UWB physical layer herein called the UWB PHY, employs a mean PRF that is nominally 16 MHz or optionally nominally 64 MHz. The UWB PHY waveform is based upon an impulse radio signaling scheme using band-limited data pulses. The UWB PHY supports two independent bands of operation:

— The low band, which consists of four channels and occupies the spectrum from 3.1 GHz to 4.8 GHz

— The high band, which consists of eleven channels and occupies the spectrum from 6.0 GHz to 10.6 GHz

Within each channel, there is support for at least two complex channels that have unique length 31 SHR preamble codes. The combination of a channel and a preamble code is termed a *complex channel*.

A combination of burst position modulation (BPM) and binary phase-shift keying (BPSK) is used to support both coherent and non-coherent receivers using a common signaling scheme. The combined BPM-BPSK is used to modulate the symbols, with each symbol being composed of an active burst of UWB pulses. The various data rates are supported through the use of variable-length bursts.

Figure 3 shows the sequence of processing steps used to create and modulate a packet. The sequence of steps indicated here for the transmitter is used as a basis for explaining the creation of the UWB waveform. Note that the receiver portion of Figure 3 is informative and meant only as a guide to the essential steps that any compliant UWB receiver needs to implement in order to successfully decode the transmitted signal.

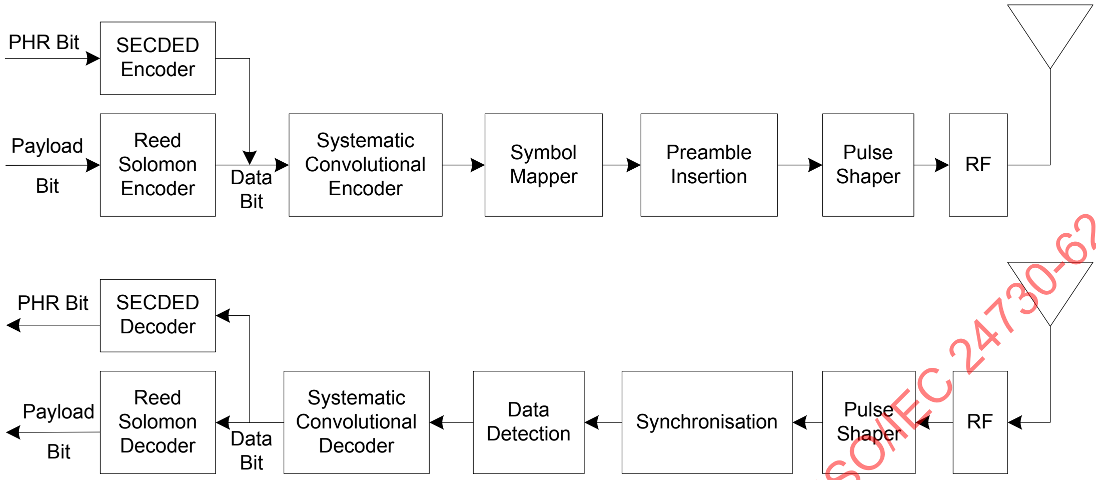


Figure 3 — signal flow

5.2 Default operating mode for a HRP UWB tag

The default operating parameters for the tag shall be as follows:

- Default band used by the tag shall be channel 5. This has centre frequency of 6489.6 MHz. This band is widely acceptable and suitable for use in many regions around the world.
    - Where national regulations prohibit transmission within this default band, another UWB channel may be used as an alternative along with an associated preamble code, as per Table 6.
- The nominal PRF employed by the tag shall be 16 MHz.
- The default preamble code employed by the tag for the transmitting the blink message shall be preamble code 3.
- The default preamble length shall be 256 symbols. Where this preamble length is not supported by the tag a preamble length of 1024 symbols may be used as an alternative.
- The default data rate shall be 850 kb/s.
- The default blink period shall be 3 seconds.
    - A random dither should be applied to this value so that tags with closely aligned crystal frequency do not stay in lock-step with long periods where their transmissions collide.

5.3 PPDU format

Figure 4 shows the format for the UWB frame, which is composed of three major components: the SHR preamble, the PHR, and the PSDU. For convenience, the PPDU packet structure is presented so that the leftmost field as written in this standard shall be transmitted or received first. All multiple octet fields shall be transmitted or received least significant octet first, and each octet shall be transmitted or received LSB first. The same transmission order should apply to data fields.

The SHR preamble is first, followed by the PHR, and finally the PSDU. The SHR preamble is always sent at the base rate for the preamble code. The PHR is sent at a nominal rate of 850 kb/s for all data rates above 850 kb/s and at a nominal of 110 kb/s for the nominal data rate of 110 kb/s. The PSDU is sent at the desired information data rate as defined in Table 3 — Rate-dependent and timing dependent parameters.

5.3.1 PPDU encoding process

The encoding process is composed of many steps as illustrated in Figure 4. The details of these steps are fully described in later sub-clauses, as noted in the following list, which is intended to facilitate an understanding of those details:

a) Perform Reed-Solomon encoding on PSDU as described in 5.4.3.1.

b) Produce the PHR as described in 5.3.6.1.

c) Add SECDED check bits to PHR as described in 5.3.6.2 and prepend to the PSDU.

d) Perform further convolutional coding as described in 5.4.3.2. Note that in some instances at the 27 Mb/s data rate, the convolutional encoding of the data field is effectively bypassed and two data bits are encoded per BPM-BPSK symbol.

e) Modulate and spread PSDU according to the method described in 5.4.1 and 5.4.2. The PHR is modulated using BPM-BPSK at 850 kb/s or at 110 kb/s (for the 110 kb/s data rate) and the data field is modulated at the rate specified in the PHR.

f) Produce the SHR preamble field from the SYNC field (used for AGC convergence, diversity selection, timing acquisition, and coarse frequency acquisition) and the SFD field (used to indicate the start of frame). The SYNC and SFD fields are described in 5.3.5.1 and 5.3.5.2, respectively.

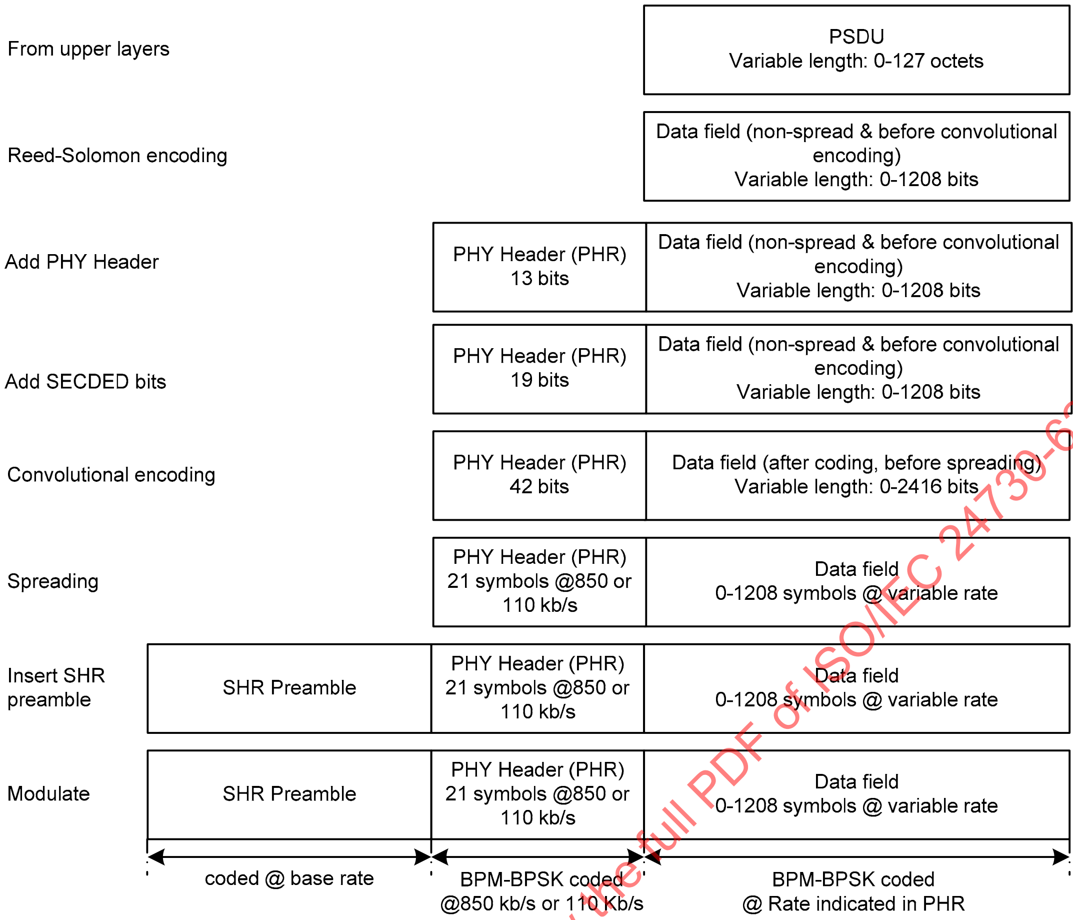


Figure 4 — PPDU encoding process

Table 1 and Table 2 show how the 19 header bits (H_0-H_{18}), N data bits (D_0-D_{N-1}), and two tail bits (T_0-T_1) are mapped onto the symbols. In these tables, the polarity bit column operation is an XOR. The tables also show when the transition from the header bit rate to the data bit rate takes place. Note that the delay line of the convolutional code is initialized to zero. For this reason, the position bit of Symbol 0 shall always be zero. This means that Symbol 0 is always transmitted in the first half of the first header symbol.

Table 1 — Mapping of header bits, data bits and tail bits onto symbols with Viterbi rate 0.5

Symbol #	Input data	Position bit	Polarity bit	
0	H_0	0	H_0	21 symbols of header at 850 kb/s
1	H_1	H_0	H_1	
2	H_2	H_1	$H_0 \oplus H_2$	
3	H_3	H_2	$H_1 \oplus H_3$	
…	…	…	…	
16	H_{16}	H_{15}	$H_{14} \oplus H_{16}$	
17	H_{17}	H_{16}	$H_{15} \oplus H_{17}$	
18	H_{18}	H_{17}	$H_{16} \oplus H_{17}$	
19	D_0	H_{18}	$H_{17} \oplus D_0$	
20	D_1	D_0	$H_{18} \oplus D_1$	
21	D_2	D_1	$D_0 \oplus D_2$	N symbols of data at data rate, e.g., 6.8 Mb/s
…	…	…	…	
N+17	D_{N-2}	D_{N-3}	$D_{N-4} \oplus D_{N-2}$	
N+18	D_{N-1}	D_{N-2}	$D_{N-3} \oplus D_{N-1}$	
N+19	T_0	D_{N-1}	$D_{N-2} \oplus T_0$	
N+20	T_1	T_0	$D_{N-1} \oplus T_1$	

5.3.2 Symbol structure

In the BPM-BPSK modulation scheme, a symbol is capable of carrying two bits of information: one bit is used to determine the position of a burst of pulses while an additional bit is used to modulate the phase (polarity) of this same burst.

The structure and timing of a symbol is illustrated in Figure 5. Each symbol shall consist of an integer number of possible chip positions, N_c, each with duration T_c. The overall symbol duration denoted by T_{dsym} is given by $T_{dsym} = N_c T_c$. Furthermore, each symbol is divided into two BPM intervals each with duration $T_{BPM} = T_{dsym}/2$, which enables binary position modulation.

A burst is formed by grouping N_{cpb} consecutive chips and has duration $T_{burst} = N_{cpb} T_c$. The location of the burst in either the first half or second half of the symbol indicates one bit of information. Additionally, the phase of the burst (either –1 or +1) is used to indicate a second bit of information.

In each symbol interval, a single burst event shall be transmitted. The fact that burst duration is typically much shorter than the BPM duration, i.e., $T_{burst} << T_{BPM}$, provides for some multi-user access interference rejection in the form of time hopping. The total number of burst durations per symbol, N_{burst}, is given by $N_{burst} = T_{dsym} / T_{burst}$. In order to limit the amount of inter-symbol interference caused by multipath, only the first half of each T_{BPM} period shall contain a burst. Therefore, only the first $N_{hop} = N_{burst}/4$ possible burst positions are candidate hopping burst positions within each BPM interval. Each burst position can be varied on a symbol-to-symbol basis according to a time hopping code as described in 5.4.

Table 2 — Mapping of header bits, data bits and tail bits onto symbols with Viterbi rate 1

Symbol #	Input data	Position bit	Polarity bit	
0	H_0	0	H_0	21 symbols of header at 850 kb/s
1	H_1	H_0	H_1	
2	H_2	H_1	$H_0 \oplus H_2$	
3	H_3	H_2	$H_1 \oplus H_3$	
…	…	…	…	
16	H_{16}	H_{15}	$H_{14} \oplus H_{16}$	
17	H_{17}	H_{16}	$H_{15} \oplus H_{17}$	
18	H_{18}	H_{17}	$H_{16} \oplus H_{17}$	
19	T_0	H_{18}	$H_{17} \oplus T_0$	
20	T_1	T_0	$H_{18} \oplus T_1$	
21	D_0, D_1	D_0	D_1	1/2 N symbols of data at data rate, e.g., 6.8 Mb/s
…	D_2, D_3	D_2	D_3	
…	…	…	…	
1/2 N+19	D_{N-6}, D_{N-5}	D_{N-6}	D_{N-5}	
1/2 N+20	D_{N-4}, D_{N-3}	D_{N-4}	D_{N-3}	
1/2 N+21	D_{N-2}, D_{N-1}	D_{N-2}	D_{N-1}	

5.3.3 PSDU timing parameters

The PSDU rate-dependent parameters and timing-related parameters are summarized in Table 3. Within each channel {0:15}, the peak PRF shall be 499.2 MHz. This rate corresponds to the highest frequency at which a compliant transmitter shall emit pulses. Additionally, the mean PRF is defined as the total number of pulses emitted during a symbol period divided by the length of the symbol duration. During the SHR preamble portion of a UWB frame, the peak and mean PRFs are essentially the same since pulses are emitted uniformly during each preamble symbol. During the data portion of a PPDU, however, the peak and mean PRFs differ due to the grouping of pulses into consecutive chip durations.

There are two possible preamble code lengths (31 or 127) and two mean PRFs (15.6 MHz or 62.4 MHz). A compliant device shall implement support for the preamble code length of 31 and the 15.6 MHz mean PRFs for the PSDU as depicted in Table 3. The use of the length 127 code is optional; when implemented, the mean PRF of the PSDU shall be 62.4 MHz.

UWB channels {4, 7, 11, and 15} are all optional channels and are differentiated from other UWB channels by the larger bandwidth (> 500 MHz) of the transmitted signals. These channels overlap the lower bandwidth channels. The larger bandwidth enables devices operating in these channels to transmit at a higher power (for fixed PSD constraints), and thus they may achieve longer communication range. The larger bandwidth pulses offer enhanced multipath resistance. Additionally, larger bandwidth leads to more accurate range estimates. The admissible data rates, preamble code lengths, PRFs, and modulation timing parameters are listed in Table 3. Each UWB channel allows for several data rates that are obtained by modifying the number of chips within a burst while the total number of possible burst positions remains constant. Therefore, the symbol duration, T_{dsym}, changes to obtain the stated symbol rate and bit rates.

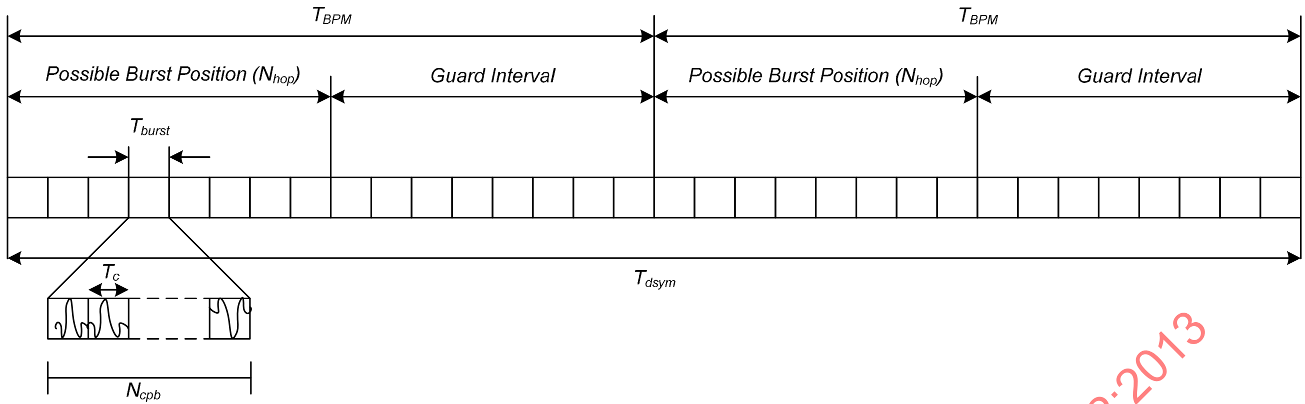


Figure 5 — symbol structure

Table 3 — Rate-dependent and timing dependent parameters

Preamble Code Length	Modulation & Coding			Data Symbol Structure						Data		
	Viterbi Rate	RS Rate	Overall FEC Rate	#Burst Positions per Symbol Nburst	# Hop Bursts Nhop	# Chips Per Burst Ncpb	#Chips Per Symbol	Burst Duration T burst (ns	Symbol Duration Tdsym (ns)	Symbol Rate (MHz)	Bit Rate Mb/s	Mean PRF (MHz)
31	0.5	0.87	0.44	32	8	128	4096	256.41	8205.13	0.12	0.11	15.60
31	0.5	0.87	0.44	32	8	16	512	32.05	1025.64	0.98	0.85	15.60
31	0.5	0.87	0.44	32	8	2	64	4.01	128.21	7.80	6.81	15.60
31	1.0	0.87	0.87	32	8	1	32	2.00	64.10	15.60	27.24	15.60
127	0.5	0.87	0.44	8	2	512	4096	1025.64	8205.13	0.12	0.11	62.40
127	0.5	0.87	0.44	8	2	64	512	128.21	1025.64	0.98	0.85	62.40
127	0.5	0.87	0.44	8	2	8	64	16.03	128.21	7.80	6.81	62.40
127	0.5	0.87	0.44	8	2	2	16	4.01	32.05	31.20	27.24	62.40

The peak PRF is 499.2 MHz. This is the highest frequency in megahertz at which a compliant transmitter shall emit pulses. The peak PRF is also used to derive the chip duration T_c by the formula $T_c = {}^{1}/_{\text{peakPRF}}$. The value of T_c is approximately 2 ns. The channel center frequencies and bandwidths are given in Table 11. Note that the bandwidth is not necessarily the inverse of the chip duration T_c. Pulse shape and bandwidth are further defined in 5.5.3.1.

The UWB PHY contains several optional data rates, preamble code lengths, and PRF. Table 3 describes the remaining timing parameters of Figure 5 for each permitted combination of preamble code length and PRF.

The preamble code length parameter denotes the length of the preamble code to be used during the SHR portion of a data frame. The code together with the channel number defines a complex channel. Individual codes to be used on each channel are given in Table 6 (length 31) and Table 7 (length 127).

The Viterbi rate parameter determines the rate of the convolutional code applied to the PSDU data bits. A value of 1 indicates that no convolutional coding is applied while a value of 0.5 indicates that a rate 1/2 code as described in 5.4.3.2 is applied to the PSDU data bits.

The RS rate parameters indicates the (63, 55) Reed-Solomon code rate, which is approximately 0.87. The Reed-Solomon code is applied to all the PSDU data bits that are transmitted by the UWB PHY. Reed-Solomon encoding is further described in 5.4.3.1.

The overall FEC rate is determine by the product of the Viterbi rate and the Reed-Solomon rate and has either a value of 0.44 or 0.87.

The burst-positions-per-symbol parameter is the total number of possible burst positions within the data symbol duration. N_{burst} has been chosen so that for each mean PRF a data symbol consists of a fixed number of burst durations.

The hop bursts parameter is the number of burst positions that may contain an active burst, that is, a burst containing UWB pulses. The value is computed as $N_{hop} = N_{burst}/4$.

The chips per burst parameter is the number of chip T_c durations within each burst period T_{burst}. Each burst consists of a multiple number of consecutive chips, as illustrated in Figure 5. Depending on the data rate to be used in the transmission of the PSDU, the number of chips in a burst varies, e.g., for low data rates, the burst consists of more chip periods than for high data rates. Particular, values of N_{cpb} have been selected so that the following is a valid data rate: (2 × Overall FEC rate)/(N_{cpb} × N_{burst} × T_c).

The burst duration is computed as $T_{burst} = N_{cpb} \times T_c$.

The symbol duration is the duration of a modulated and coded PSDU symbol on the air and is computed as follows: $T_{dsym} = N_{burst} \times T_{burst}$.

The symbol rate is the inverse of the PSDU symbol duration $1/T_{dsym}$.

The bit rate is the user information rate considering FEC and is computed as follows:

$$Bit\ Rate = 2 \times (Overall\ FEC\ Rate)/T_{dsym}$$

The mean PRF is the average PRF during the PSDU portion of a PHY frame and is computed as follows:

$$Mean\ PRF = N_{cpb}/T_{dsym}$$

5.3.4 Preamble timing parameters

Due to the variability in the preamble code length and the PRF, there are several admissible values for the timing parameters of a preamble symbol. These values are summarized in Table 4. In this subclause, a preamble symbol is defined as the waveform consisting of one whole repetition of the modulated preamble code (either length 31 or 127). Details on the construction of the preamble symbol for various code lengths and PRFs are given in 5.3.5. For each target PRF, the preamble is constructed from a preamble code, C_i, by inserting a number of chip durations between code symbols. The number of chip durations to insert is denoted by δ_L, values for each code length and PRF are given in Table 4, and the chip insertion is detailed in 5.3.5.1.

Table 4 presents the timing parameters during the SHR portion of a UWB PHY frame while Table 3 presents the timing parameters for the PSDU portion of the frame. First, note that the preamble is sent at a slightly higher mean PRF than the data as defined in Table 3. This is due to the fact that length 31 or 127 ternary codes are being used within the SHR, and the number of chips within the SHR is no longer a power of 2. For example, for the 16 MHz PRF in channels {0:3, 5:6, 8:10, 12:14), the peak PRF during the preamble is 31.2 MHz, and the corresponding mean PRF during the preamble is 16.10 MHz. The mean PRF during the data (PSDU) is 15.60 MHz. The remaining peak and mean PRF values for other optional UWB channels and the optional length 127 code are listed in Table 4.

Table 4 — Preamble parameters

C_i Code Length	Peak PRF (MHz)	Mean PRF (MHz)	Delta Length δ_L	#Chips Per Symbol	Symbol Duration T_{psym}(ns)	Base Rate Msymbol/s
31	31.20	16.10	16	496	993.59	1.01
127	124.80	62.89	4	508	1017.63	0.98

The base symbol rate is defined as the rate at which the preamble symbols are sent. The base rate corresponding to the (default) mean PRF of 16.10 MHz is 1 Msymbol/s. This symbol rate corresponds to preamble symbol duration, T_{psym}, of 993.59 ns.

Table 5 — Frame-dependent parameters

Parameter	Description	Value	
Channel	UWB PHY channel number	{1:15}	
PRF_{mean}	Mean PRF (MHz)	16.10	62.89
N_c	Number of chips per preamble symbol	496	508
T_{psym}	Preamble symbol duration (ns)	993.6	1017.6
N_{sync}	Number of symbols in the packet sync sequence.	64 to 4096	
T_{sync}	Duration of the packet sync sequence (µs)	63.6 to 4069.7	65.1 to 4168.2
N_{sfd}	Number of symbols in the SFD	8 (or 64)	
T_{sfd}	Duration of the SFD (µs)	7.9 (or 63.6)	8.1 (or 65.1)
N_{pre}	Number of symbols in the SHR preamble	72 to 4104 (or 128 to 4160)	
T_{pre}	Duration of the SHR preamble (µs)	71.5 to 4077.7 (or 127.2 to 4133.3)	73.3 to 4176.3 (or 319.5 to 4422.6)
N_{CCA_PHR}	Number of multiplexed preamble symbols in PHR	4 or 32	
N_{CCA_data}	Number of multiplexed preamble symbols in the data field	$T_{pre}/(4 \times T_{dsym/M})$	

Note: the values in brackets apply to the 110 Kb/s data rate.

Finally, for each UWB frame consisting of the SHR, SFD, PHR, and a data field, there are four possible durations of the SHR. This is due to the four possible lengths of SYNC field in the SHR, as described in 5.3.5. The SYNC field consists of repetitions of the preamble symbol. The number of preamble symbol repetitions may be 64, 1024, or 4096, with additional optional values of 128, 256, 512, 1536 and 2048. These different SYNC field lengths yield different time durations of the UWB frame. The relationship between SYNC field length and frame duration is shown in Table 5. After the insertion of the SFD (the SFD may be either 8 or 64 preamble symbols long), the total length (in preamble symbols) of the SHR is N_{pre} as shown in Table 5, and this in turn leads to the possible SHR durations denoted as T_{pre}. After creation of the SHR, the frame is appended with the PHR whose length, N_{hdr}, is 16 symbols and duration is denoted as T_{hdr}. The values of the frame duration parameters are shown in Table 5.

5.3.5 SHR preamble

A SHR preamble shall be added prior to the PHR to aid receiver algorithms related to AGC setting, antenna diversity selection, timing acquisition, coarse and fine frequency recovery, packet and frame synchronization, channel estimation, and leading edge signal tracking for ranging.

In this subclause, four different mandatory preambles are defined: a default preamble, a short preamble, a medium preamble, and a long preamble. The preamble to be used in the transmission of a frame is decided by the application layer.

Figure 6 shows the structure of the SHR preamble. The preamble can be subdivided into two distinct portions: SYNC (packet synchronization, channel estimation, and ranging sequence) and SFD (frame delimiter sequence). The duration of these portions are provided in Table 5. Subclauses 5.3.5.1 and 5.3.5.2 detail the different portions of the preamble.

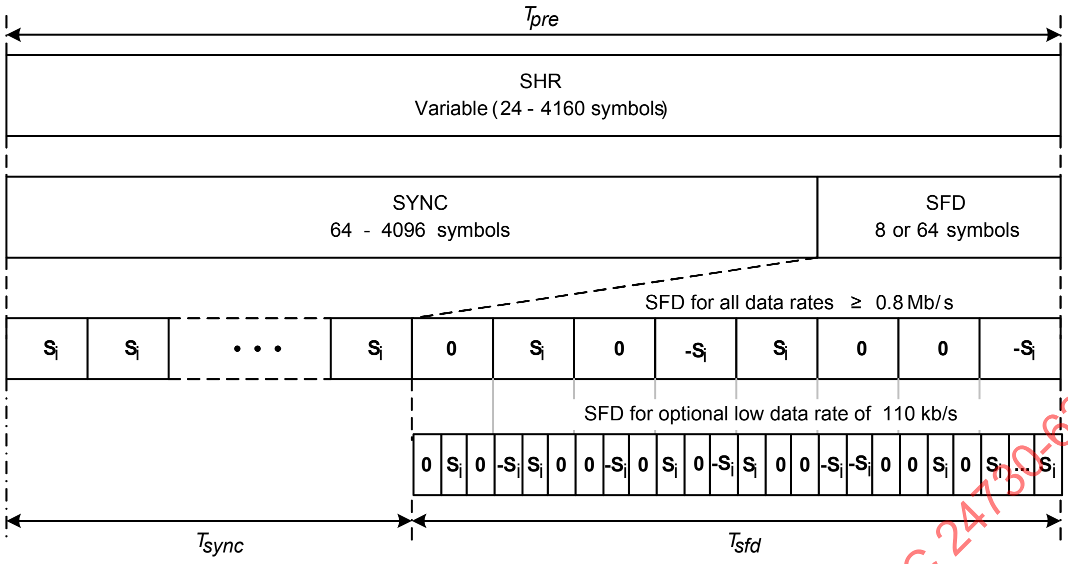


Figure 6 — SHR preamble structure

5.3.5.1 SHR SYNC field

Each network operating on one of the UWB PHY channels {1–15} is also identified by a preamble code. The preamble code is used to construct symbols that constitute the SYNC portion of the SHR preamble as shown in Figure 6.

The UWB PHY supports two lengths of preamble code: a length 31 code and an optional length 127 code. Each preamble code is a sequence of code symbols drawn from a ternary alphabet {-1,0,1} and selected for use in the UWB PHY because of their perfect periodic autocorrelation properties. The length 31 code sequences are shown in Table 6 while the length 127 code sequences are shown in Table 7 where they are indexed from 1–24 (Ci i = 1,2,...24). The first 8 codes (index 1–8) are length 31 while the remaining 16 (index 9–24) are length 127. Which codes may be used in each of the channels is restricted, and the particular code assignments are made in Table 6 and Table 7. Specifically, the last column in each table indicates the set of channel numbers that permit use of the code. This restriction of codes is to ensure that codes with the lowest cross-correlation are used in the same channel. Additionally, 8 of the length 127 codes are reserved for use with the private ranging protocol only and are not used during normal operation. This restriction is indicated in the third column of Table 7 as well.

Table 6 — Length 31 ternary codes

Code index	Code sequence	Channel number[a]
1	-0000+0-0+++0+-000+-+++00-+0-00	1, 8, 12
2	0+0+-0+0+000-++0-+---00+00++000	1, 8, 12
3	-+0++000-+-++00++0+00-0000-0+0-	2, 5, 9, 13
4	0000+-00-00-++++0+-+000+0-0++0-	2, 5, 9, 13
5	-0+-00+++-+000-+0+++0-0+0000-00	3, 6, 10, 14
6	++00+00---+-0++-000+0+0-+0+0000	3, 6, 10, 14
7	+0000+-0+0+00+000+0++---0-+00-+	4, 7, 11, 15
8	0+00-0-0++0000--+00-+0++-++0+00	4, 7, 11, 15

[a] Note code indices 1 through 6 may also be used for channels 4, 7, 11, and 15 (i.e., channels with bandwidth wider than 500 MHz) if interchannel communication is desired.

Table 7 — Length 127 ternary codes

Code index	Code sequence	Channel number[a]
9	+00+000-0--00--+0+0+00-+-++0+0000++-000+00-00--0-+0+0--0-+++0++000+-0+00-0++-0+++00-+00+0+0-0++-+--+000000+00000-+0000-0-000--+	1–3, 5, 6, 8–10, 12–14
10	++00+0-+00+00+000000-000-00--000-0+-+0-0+-0-+00000+-00++0-0+00--+00++-+0+-0+0000-0-0-0-++-+0+00+0+000-+0+++000----+++0000+++0--	1–3, 5, 6, 8–10, 12–14
11	-+-0000+00--00000-0+0+0+-0+00+00+0-00-+++00+000-+0+0-0000+++++-+0+--0+-0++--0-000+0-+00+0+----000-000000-+00+-0++000++-00++-0-0	1–3, 5, 6, 8–10, 12–14
12	-+0++000000-0+0-+0---+-++00-+0++0+0+0+000-00-00-+00+-++000-+-0-++0-0++++0-00-0++00+0+00++-00+000+-000-0--+0000-0000--0+00000+--	1–3, 5, 6, 8–10, 12–14
13	+000--0000--++0-++++0-0++0+0-00-+0++00++-0++0+-+0-00+00-0--000-+-00+0000-0++-00000+-0-000000-00-+-++-+000-0+0+0+++-00--00+0+000	1–15; DPS only
14	+000++0-0+0-00+-0-+0-00+0+0000+0+-0000++00+0+++++-+0-0+-0--+0++--000---0+000+0+0-+-000000+-+-0--00++000-00+00++-00--++-00-00000	1–15; DPS only
15	0+-00+0-000-++0000---++000+0+-0-+00-+000--0-00--0--+++-+0-++00+-++0+00000+0-0+++-00+00+000-0000+00--+0++0+0+0-00-0-+-0+0++00000	1–15; DPS only
16	++0000+000+00+--0+-++0-000--00+-0+00++000+++00+0+0-0-+-0-0+00+00+0++----+00++--+0+-0--+000000-0-0000-+0--00+00000+-++000-0-+0+0	1–15; DPS only
17	+--000-0-0000+-00000+000000+--+-++0-0+0+00+-00+++0-++0-00+0-+000++0+++-0--0+0+-0--00-00+000-++0000+0++-+-00+0+0+--00--0-000+00+	4, 7, 11, 15
18	--0+++0000+++----000+++0+-000+0+00+0+-++-0-0-0-0000+0-+0+-++00+--00+0-0++00-+00000+-0-+0-0+-+0-000--00-000-000000+00+00+-0+00++	4, 7, 11, 15
19	-0-++00-++000++0-+00+-000000-000----+0+00+-0+000-0--++0-+0--+0+-+++++0000-0+0+-000+00+++-00-0+00+00+0-+0+0+0-00000--00+0000-+-0	4, 7, 11, 15
20	--+00000+0--0000-0000+--0-000-+000+00-++00+0+00++0-00-0++++0-0++-0-+-000++-+00+-00-00-000+0+0+0++0+-00++-+---0+-0+0-000000++0+-	4, 7, 11, 15
21	+0+00--00-+++0+0+0-000+-++-+-00-000000-0-+00000-++0-0000+00-+-000--0-00+00-0+-+0++0-++00++0+-00-0+0++0-0++++-0++--0000--000+000	1–15; DPS only
22	0-00-++--00-++00+00-000++00--0-+-+000000-+-0+0+000+0---000--++0+--0-+0-0+-+++++0+00++0000-+0+0000+0+00-0+-0-+00-0+0-0++000+0000	1–15; DPS only
23	000++0+0-+-0-00-0+0+0++0+--00+0000-000+00+00-+++0-0+00000+0++-+00++-0+-+++--0--00-0--000+-00+-0-+0+000++---0000++-000-0+00-+000	1–15; DPS only
24	+0+-0-000++-+00000+00--0+-0000-0-000000+--0-+0+--++00+----++0+00+00+0-0-+-0-0+0+00+++000++00+0-+00--000-0++-+0--+00+000+0000++0	1–15; DPS only

[a] Note code indices 9 through 13 may also be used for UWB channels 4, 7, 11, and 15 (i.e., channels with bandwidth wider than 500 MHz) if interchannel communication is desired.

Note that the assignment of preamble codes to channels has been done to enable interchannel communication. In other words, it is possible that a device operating on a wideband channel {4, 7, 11 or 15} may communicate with a device on a channel with which it overlaps.

When using the ternary code indexed by i, the SYNC field shall consist of N_{sync} repetitions of the symbol $\boldsymbol{S}_i$, where $\boldsymbol{S}_i$ is the code $\boldsymbol{C}_i$ spread by the delta function δ_L of length L as shown in Table 4. The spreading operation, where code $\boldsymbol{C}_i$ is extended to the preamble symbol duration indicated in Table 4, is described mathematically by

$$\boldsymbol{S}_i = \boldsymbol{C}_i \otimes \mathbf{d}_L(n)$$

$$\delta_L(n) = \begin{cases} 1 & n = 0 \\ 0 & n = 1, 2\ldots, L-1 \end{cases}$$

where the operator $\otimes$ indicates a Kronecker product. After the Kronecker operation, a preamble symbol is formed as depicted in Figure 7, where $L - 1$ zeros have been inserted between each ternary element of $\boldsymbol{C}_i$.

The spreading factor L, number of chips per symbol, preamble symbol duration T_{psym}, and base symbol rate for different channels are given in Table 4.

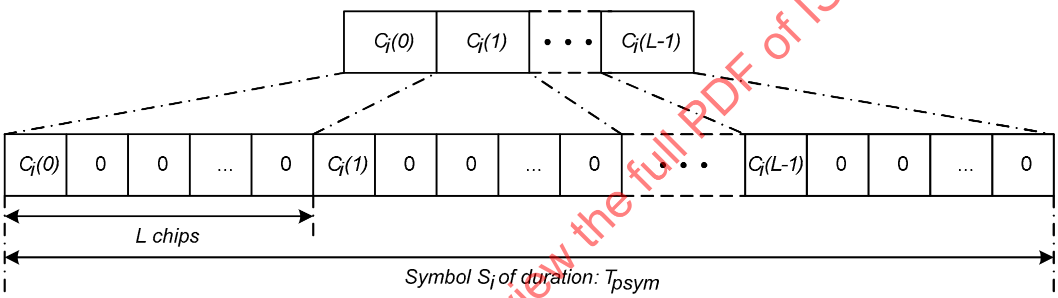


Figure 7 — Construction of symbol S_i from code C_i

5.3.5.2 SHR SFD

An SFD shall be added to establish frame timing. The UWB PHY uses a short SFD for default and medium data rates and a long SFD for the optional low data rate of 110 kb/s as shown in Figure 6. The short SFD shall be [0 +1 0 -1 +1 0 0 -1] spread by the preamble symbol S_i, where the leftmost bit shall be transmitted first in time. The optional long SFD shall be obtained by spreading the sequence [0 +1 0 -1 +1 0 0 -1 0 +1 0 -1 +1 0 0 -1 -1 0 0 +1 0 -1 0 +1 0 +1 0 0 0 -1 0 -1 0 -1 0 0 +1 0 -1 -1 0 -1 +1 0 0 0 0 +1 +1 0 0 -1 -1 -1 +1 -1 +1 +1 0 0 0 0 +1 +1] by the preamble sequence S_i. Note that the long SFD is eight times longer than the short SFD and consists of 64 preamble symbols, only 32 of which are active, and the other 32 are zeros. The structure of the SHR preamble and the two possible SFDs are shown in Figure 6.

5.3.6 PHY header (PHR)

A PHR, as shown in Figure 8, shall be added after the SHR preamble. The PHR consists of 19 bits and conveys information necessary for a successful decoding of the packet to the receiver. The PHR contains information about the data rate used to transmit the PSDU, the duration of the current frame's preamble, and the length of the frame payload. Additionally, six parity check bits are used to further protect the PHR against channel errors.

Bit 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14	16	17	18
R1	R0	L6	L5	L4	L3	L2	L1	L0	RNG	EXT	P1	P0	C5	C4	C3	C2	C1	C0
Data Rate		Frame Length							Ranging Packet	Header Extension	Preamble Duration		SECDED Check Bits					

Figure 8 — PHR bit assignment

The PHR shall be transmitted using the BPM-BPSK modulation outlined in 5.4. The PHR shall be transmitted at the nominal rate of 850 kb/s for all data rates above 850 kb/s and at the nominal rate of 110 kb/s for the nominal low data rates of 110 kb/s.

5.3.6.1 PHR rate, length, ranging, extension, preamble duration fields

The Data Rate field shall consist of two bits (R1, R0) that indicate the data rate of the received PSDU. The bits R1–R0 shall be set according to Table 9. The default value of the bits R1–R0 shall be set to 01 as this is the only mandatory data rate that is supported by a UWB-compliant PHY implementation. Support for other data rates listed in Table 9 is optional.

The Frame Length field, L6–L0, shall be an unsigned 7-bit integer number that indicates the number of octets in the PSDU that the MAC sublayer is currently requesting the PHY to transmit.

The Ranging Packet bit, RNG, indicates that the current frame is an RFRAME if it is set to 1; otherwise, it is set to 0.

The Header Extension bit, EXT, is reserved for future extension of the PHR. This bit shall be set to 0.

The Preamble Duration field, P1–P0, represents the length (in preamble symbols) of the SYNC portion of the SHR. P1–P0 shall be set according to Table 8. The default Preamble Duration setting is 01, which corresponds to a SYNC field of length 64 preamble symbols.

Table 8 — Preamble Duration field values

P1–P0	SYNC length (symbols) (Si)
01	64
10	1024
11	4096

The Preamble Duration field is intended for use during ranging operations and is used by a receiver of the PHY frame to help determine at which preamble symbol the UWB PHY acquired and began tracking the preamble. A receiver may use the Preamble Duration field to set the value of its own preamble duration based upon the received value when communicating a ranging ACK packet. The optional values of 128, 256, 512, 1536 and 2048 cannot be encoded within the PHY header (PHR), but may be ascertained in the receiver by counting the number of preamble symbols received. Where one of these optional values is used the PHR encoding shall be the nearest smaller length value.

Table 9 — Nominal data rates

R1–R0	Data rate Mb/s
00	0.11
01	0.85
10	6.81
11	27.24

5.3.6.2 PHR SECDED check bits

The SECDED (single error correct, double error detect) field, C5–C0, is a set of six parity check bits that are used to protect the PHR from errors caused by noise and channel impairments. The SECDED bits are a simple Hamming block code that enables the correction of a single error and the detection of two errors at the receiver. The SECDED bit values depend on PHR bits 0–12 and are computed as follows:

C0 = *XOR* (R0, R1, L0, L2, L4, L5, EXT, P1)

C1 = *XOR* (R1, L2, L3, L5, L6, RNG, EXT, P0)

C2 = *XOR* (R0, L0, L1, L5, L6, RNG, EXT)

C3 = *XOR* (L0, L1, L2, L3, L4, RNG, EXT)

C4 = *XOR* (P0, P1)

C5 = *XOR* (R1, R0, L6, L5, L4, L3, L2, L1, L0, RNG, EXT, P1, P0, C4, C3, C2, C1, C0)

5.3.7 Data field

The Data field is the last component of the PPDU and is encoded as shown in Figure 9.

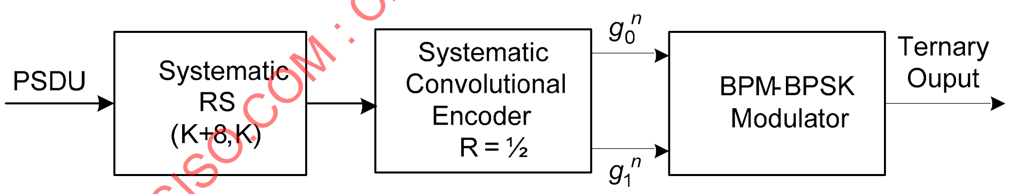


Figure 9 — Data field encoding process

The data field shall be formed as follows:

— Encode the PSDU using systematic Reed-Solomon block code, which adds 48 parity bits as described in 5.4.3.1.

— Encode the output of the Reed-Solomon block code using a systematic convolutional encoder as described in 5.4.3.2, except in the cases where the Viterbi rate for the modulation is 1.0 in Table 3. In these cases the convolutional encoder is bypassed.

— Spread and modulate the encoded block using BPM-BPSK modulation as described in 5.4.

5.4 UWB PHY modulation

5.4.1 Modulation mathematical framework

The transmit waveform during the k^{th} symbol interval may be expressed as

$$x^{(k)}(t) = [1-2g_1^{(k)}]\sum_{n=1}^{N_{cpb}}[1-2s_{n+kN_{cpb}}]\times p(t-g_0^{(k)}T_{BPM}-h^{(k)}T_{burst}-nT_c)$$

This equation describes the time hopping with polarity scrambling, which improves interference rejection capabilities of the UWB PHY. The k^{th} symbol interval carries two information bits $g_0^{(k)}$ and $g_1^{(k)} \in \{0, 1\}$. Bit $g_0^{(k)}$ is encoded into the burst position whereas bit $g_1^{(k)}$ is encoded into the burst polarity. The sequence $s_{n+kN_{cpb}} \in \{0, 1\}, n = 0, 1, \ldots, N_{cpb}-1$ is the scrambling code used during the k^{th} symbol interval, $h^{(k)} \in \{0, 1-N_{hop}-1\}$ is the k^{th} burst hopping position, and $p(t)$ is the transmitted pulse shape at the antenna input. The burst hopping sequence $h^{(k)}$ provides for multiuser interference rejection. The chip scrambling sequence $s_{n+kN_{cpb}}$ provides additional interference suppression among coherent receivers as well as spectral smoothing of the transmitted waveform. Note that equation defines the transmitted signal during the valid burst interval; at all other possible burst positions, no signal shall be transmitted. A reference modulator illustrating the BPM-BPSK modulation is shown in Figure 10.

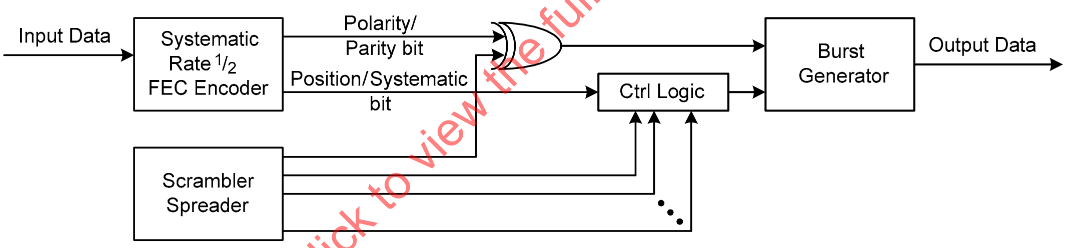


Figure 10 — Reference symbol modulator

Note here that the FEC Encoder is not included if the modulation Viterbi rate is 1.0, as described in 5.3.7. In this case, the FEC encoder is replaced by a multiplexer which shall apply even bits to the position input and odd bits to the polarity input.

5.4.2 Spreading

The time-varying spreader sequence $s_{n+kN_{cpb}}$ and the time-varying burst hopping sequence $h^{(k)}$ shall be generated from a common PRBS scrambler.

The polynomial for the scrambler generator shall be $g(D) = 1 + D^{14} + D^{15}$

where D is a single chip delay, T_c, element. This polynomial forms not only a maximal length sequence, but also is a primitive polynomial. By the given generator polynomial, the corresponding scrambler output is generated as

$$s_n = s_{n-14} \oplus s_{n-15} \qquad n = 0, 1, 2, \ldots$$

where $\oplus$ denotes modulo-2 addition.

A linear feedback shift register (LFSR) realization of the scrambler is shown in Figure 11. The LFSR shall be initialized upon the transmission of bit 0 of the PHR. Note that N_{cpb} may change depending on the data rate and PRF in use during the PSDU. The LFSR shall not be reset after transmission of the PHR.

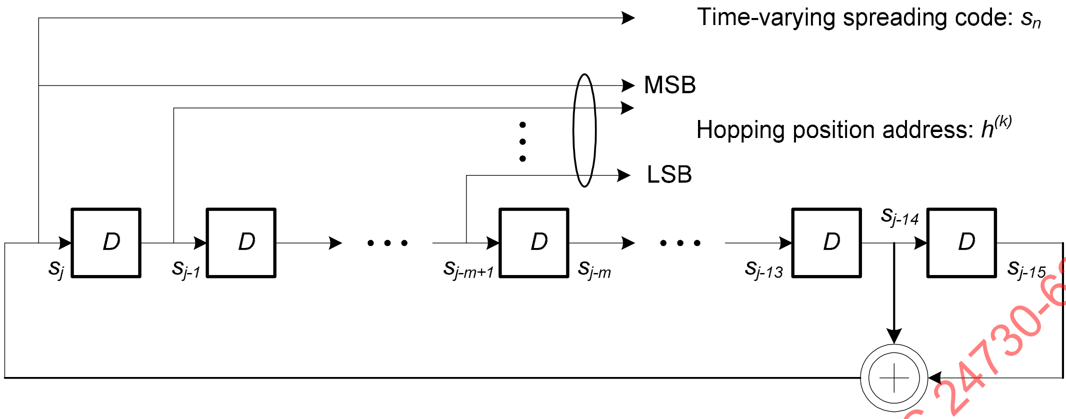


Figure 11 — LFSR implementation of the scrambler

The initial state of the LFSR shall be determined from the preamble code by first removing all the 0s in the ternary code and then replacing all the –1s with a zero. The first 15 bits of the resulting binary state shall be loaded into the LFSR. Table 10 shows an example of the above procedure for preamble code, C_6 (length 31, preamble code index 6, see Table 6). Table 10 shows the initial state as well as the first 16 output bits from the scrambler.

Table 10 — Example LFSR initial state for preamble code 6

Initial state ($s_{-15}, s_{-14}, \ldots, s_{-1}$)	**LFSR output: First 16 bits** $s_0, s_1, \ldots, s_{15}$ (s_0 first in time)
111000101101101	0010011101101110

Note that even though each device within a network use the same initial LFSR setting, the communication is asynchronous so that the hopping and scrambling provides interference rejection.

The LFSR shall be clocked at the peak PRF of 499.2 MHz as specified in Table 3. During the k^{th} symbol interval, the LFSR shall be clocked N_{cpb} times, and the scrambler output shall be the k^{th} scrambling code $s_{n+kN_{cpb}}, n = 0, 1, \ldots, N_{cpb} - 1$. Furthermore, the k^{th} burst hopping position, shall be computed as follows:

$$h^{(k)} = 2^0 s_{kN_{cpb}} + 2^1 s_{1+kN_{cpb}} + \cdots + 2^{m-1} s_{m-1+kN_{cpb}}$$

where

$$m = \log_2(N_{hop})$$

As shown in Table 3, the number of hopping burst N_{hop} is always a power of two, and consequently m is always an integer. Note that for $N_{cpb} < m$, the LFSR is clocked N_{cpb} times, not m times.

For the mandatory mode with mean data PRF of 15.60 MHz, the numbers of hopping bursts is 8, as indicated in Table 3, and consequently m takes on the values 3 and the corresponding hopping sequence is as follows:

$$h^{(k)} = s_{kN_{cpb}} + 2s_{1+kN_{cpb}} + 4s_{2+kN_{cpb}}$$

5.4.3 Forward error correction (FEC)

The FEC used by the UWB PHY is a concatenated code consisting of an outer Reed-Solomon systematic block code and an inner half-rate systematic convolutional code. The inner convolutional code is not necessarily enabled at all data rates; the rows of Table 3 that have a Viterbi rate of 1 indicate that the inner convolutional code is disabled for the PSDU part of the PHY frame.

The FEC encoding of a block of M PSDU bits, $b_0, b_1, \ldots, b_{M-1}$, is shown in Figure 12. The Reed-Solomon encoder shall append 48 parity bits, $p_0, p_1, \ldots, p_{47}$, to the original block. This results in a Reed-Solomon encoded block of length M + 48. Where the Viterbi rate is 0.5, a half-rate systematic convolutional encoder shall encode the Reed-Solomon encoded block into a systematic coded block of length $2M$ + 96 bits. The convolutional systematic bits shall be used to encode the position of the burst whereas the convolutional parity bits shall be used to encode the polarity of the pulses within a burst. Where the Viterbi rate is 1.0, even outputs of the Reed-Solomon encoder $(b_0, b_2, \ldots, b_{M-2}, p_0, p_2, \ldots, p_{46})$ shall be used to encode the position of the burst, and odd outputs $(b_1, b_3, \ldots, b_{M-1}, p_1, p_3, \ldots, p_{47})$ shall be used to encode the polarity of the pulses. Note here that M is always an even number.

A noncoherent receiver cannot see the convolutional parity bits (parity bits), and consequently a noncoherent receiver may use only a Reed-Solomon decoder to improve its performance. A coherent receiver may use either or both Reed-Solomon and convolutional decoding algorithms. Note here that since both the Reed-Solomon and the convolutional codes are both systematic, a receiver (either coherent or noncoherent) may be implemented without an FEC decoder. In this case, the information bits are simply recovered by demodulating the position of the burst. There will be additional parity check bits as a result of the Reed-Solomon encoding, but these may be simply ignored.

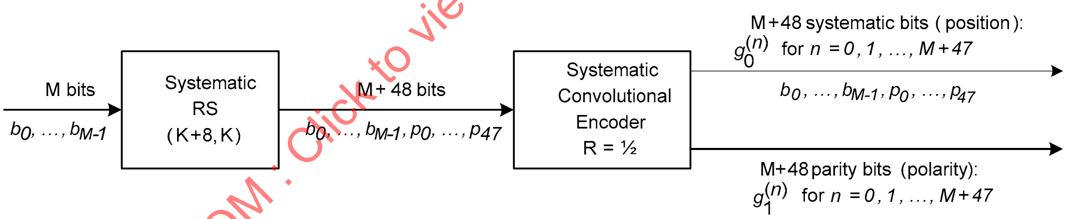


Figure 12 — FEC encoding process

5.4.3.1 Reed-Solomon encoding

The systematic Reed-Solomon code is over Galois field, GF(2^6), which is built as an extension of GF(2). The systematic Reed-Solomon code shall use the generator polynomial

$$g(x) = \prod_{k=1}^{8}(x+\alpha^k) = x^8 + 55x^7 + 61x^6 + 37x^5 + 48x^4 + 47x^3 + 20x^2 + 6x^1 + 22$$

where α = 010000 is a root of the binary primitive polynomial $1 + x + x^6$ in GF(2^6).

In Reed-Solomon encoding $RS_6(K + 8, K)$, a block of I bits (with $K = \lceil I/6 \rceil$) is encoded into a codeword of I + 48 bits. The Reed-Solomon encoding procedure is performed in the following five steps:

a) *Addition of dummy bits*. The block of I information bits is expanded to 330 bits by adding 330 – I dummy (zero) bits to the beginning of the block. The expanded block is denoted as $\{d_0, d_1, \ldots, d_{329}\}$ where d_0 is the first in time.

b) *Bit-to-symbol conversion*. The 330 bits $\{d_0, d_1, \ldots, d_{329}\}$ are converted into 55 Reed-Solomon symbols $\{D_0, D_1, \ldots, D_{54}\}$ having the following polynomial representation:

$$D_k = \alpha^5 d_{6k+5} + \alpha^4 d_{6k+4} + \alpha^3 d_{6k+3} + \alpha^2 d_{6k+2} + \alpha d_{6k+1} + d_{6k}, \qquad k = 0{:}54$$

Resulting 6-bit symbols are presented as $D_k = \{d_{6k+5}, d_{6k+4}, d_{6k+3}, d_{6k+2}, d_{6k+1}, d_{6k}\}$, where d_{6k+5} is the MSB and d_{6k} is the LSB.

c) *Encoding*. The information symbols $\{D_0, D_1, \ldots, D_{54}\}$ are encoded by systematic $RS_6(63,55)$ code with output symbols $\{U_0, U_1, \ldots, U_{62}\}$ ordered as follows:

$$U_k = \begin{cases} D_k & (k = 0, 1, \ldots, 54) \\ P_k & (k = 55, 56, \ldots, 62) \end{cases}$$

where P_k are parity check symbols added by $RS_6(63,55)$ encoder.

The information polynomial associated with the information symbols $\{D_0, D_1, \ldots, D_{54}\}$ is denoted as $D(x) = x^{54}D_0 + x^{53}D_1 + \ldots + xD_{53} + 54$. The parity check polynomial associated with the parity check symbols is denoted as $P(x) = x^7 P_{55} + x^6 P_{56} + \ldots + xP_{61} + P_{62}$. The parity check symbols are calculated as:

$$P(x) = \text{remainder}[x^8 D(x)/g(x)]$$

$$U(x) = x^8 D(x) + P(x)$$

d) *Symbol-to-bit conversion*. The output symbols $\{U_0, U_1, \ldots, U_{62}\}$ are converted into binary form with LSB coming out first, resulting in a block of 378 bits $\{u_0, u_1, \ldots, u_{377}\}$.

e) *Removal of dummy bits*. The 330 – I dummy bits added in the first step are removed. Only the last I + 48 bits are transmitted, i.e., $\{u_{330-I}, u_{331-I}, \ldots, u_{377}\}$ with u_{330-I} being first in time.

5.4.3.2 Systematic convolutional encoding

The inner convolutional encoder shall use the rate R = ½ code with generator polynomials $g_0 = [010]_2$ and $g_1 = [101]_2$ as shown in Figure 13. Upon transmission of each PPDU, the encoder shall be initialized to the all zero state. Additionally, the encoder shall be returned to the all zero state by appending two zero bits to the PPDU. Note that since the generator polynomials are systematic, they are also noncatastrophic.

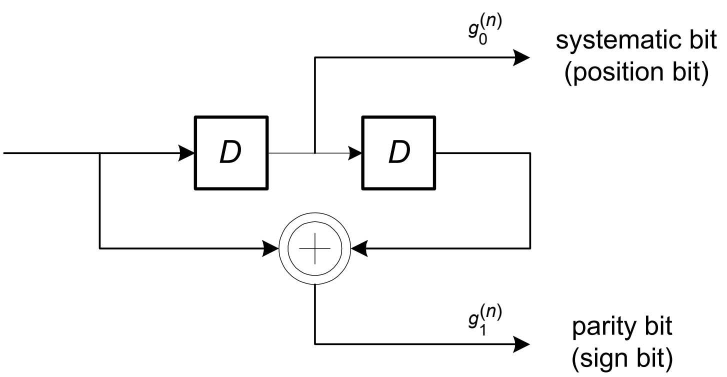


Figure 13 — Systematic convolutional encoder

5.5 UWB PHY RF requirements

5.5.1 Operating frequency bands

The set of operating frequency bands are as defined in Table 11. Default channel is channel 5.

5.5.2 Channel assignments

For each of the 15 operating frequency bands defined in Table 11, at the nominal 16 MHz PRF, two preamble codes are assigned, as per Table 6, giving a total of 30 complex channels. At the optional nominal 64 MHz PRF, an additional 60 complex channels are available by employing the four preamble codes assigned for each channel as per Table 7.

Table 11 — Band allocation

Channel number (decimal)	Center frequency, f_c (MHz)	Band width (MHz)
1	3494.4	499.2
2	3993.6	499.2
3	4492.8	499.2
4	3993.6	1331.2
5	6489.6	499.2
6	6988.8	499.2
7	6489.6	1081.6
8	7488.0	499.2
9	7987.2	499.2
10	8486.4	499.2
11	7987.2	1331.2
12	8985.6	499.2
13	9484.8	499.2
14	9984.0	499.2
15	9484.8	1354.97

5.5.3 Transmitter specification

5.5.3.1 Baseband impulse response

The transmitted pulse shape *p*(*t*) of the UWB PHY shall be constrained by the shape of its cross-correlation function with a standard reference pulse, *r*(*t*). The normalized cross-correlation between two waveforms is defined as

$$\phi(\tau) = \frac{1}{\sqrt{E_r E_p}} \mathrm{Re} \int_{-\infty}^{\infty} r(t) p^*(t+\tau) dt$$

In the above, E_r and E_p are the energies of $r(t)$ and $p(t)$, respectively. The reference $r(t)$ pulse used in the calculation of $\phi(\tau)$ is a root raised cosine pulse with roll-off factor of β = 0.5. Mathematically this is

$$r(t) = \frac{4\beta}{\pi\sqrt{T_p}} \frac{\cos[(1+\beta)\pi t/T_p] + \dfrac{\sin[(1-\beta)\pi t/T_p]}{4\beta(t/T_p)}}{1-(4\beta t/T_p)^2}$$

In the above equation, T_p is the reciprocal of the chip frequency. Table 12 shows the required pulse duration for each channel.

Table 12 — Required reference pulse durations in each channel

Channel number	Pulse duration, T_p (ns)	Main lobe width, T_w (ns)
{1:3, 5:6, 8:10, 12:14}	2.00	0.5
7	0.92	0.2
{4, 11}	0.75	0.2
15	0.74	0.2

In order for a UWB PHY transmitter to be compliant with this standard, the transmitted pulse $p(t)$ shall have a magnitude of the cross-correlation function $|\phi(\tau)|$ whose main lobe is greater or equal to 0.8 for a duration of at least T_w (see Table 12), and any sidelobe shall be no greater than 0.3. For the purposes of testing a pulse for compliance, the following are defined: Let $|\phi(\tau)|$ be the magnitude of the cross-correlation of $p(t)$ and $r(t)$, and let τ_i i = 1,2,... be a set of critical points, i.e. points at which $\frac{d}{d\tau}|\phi(\tau)|\big|_{\tau = \tau_i} = 0$. The maximum of the function occurs at one of these critical points, τ_{max} where $|\phi(\tau_{max})| \geq |\phi(\tau)|$ for all values of τ. The requirement above thus states that for some continuous set of values that contain the point τ_{max} the function $|\phi(\tau)|$ is greater than 0.8. In addition, the second constraint on the value of sidelobes may be stated mathematically as $|\phi(\tau_i)| \leq 0.3$ for all τ_i.

Figure 14 shows an example UWB-compliant pulse, $p(t)$ (left plot), along with the root raised cosine reference pulse $r(t)$ (middle plot) with T_p = 2.0 ns and the magnitude of the cross-correlation $|\phi(\tau)|$ (right plot). The pulse $p(t)$ is an 8 order butterworth pulse with a 3 dB bandwidth of 500 MHz. The figure is intended to show that this example pulse meets the requirements for compliance. Specifically, the main lobe is above 0.8 for nearly 1 ns, and no sidelobe is greater than 0.3 (in this case, the largest sidelobe peak is 0.2). The pulse $p(t)$ is a compliant pulse for channels {1:3, 5:6, 8:10, 12:14}.

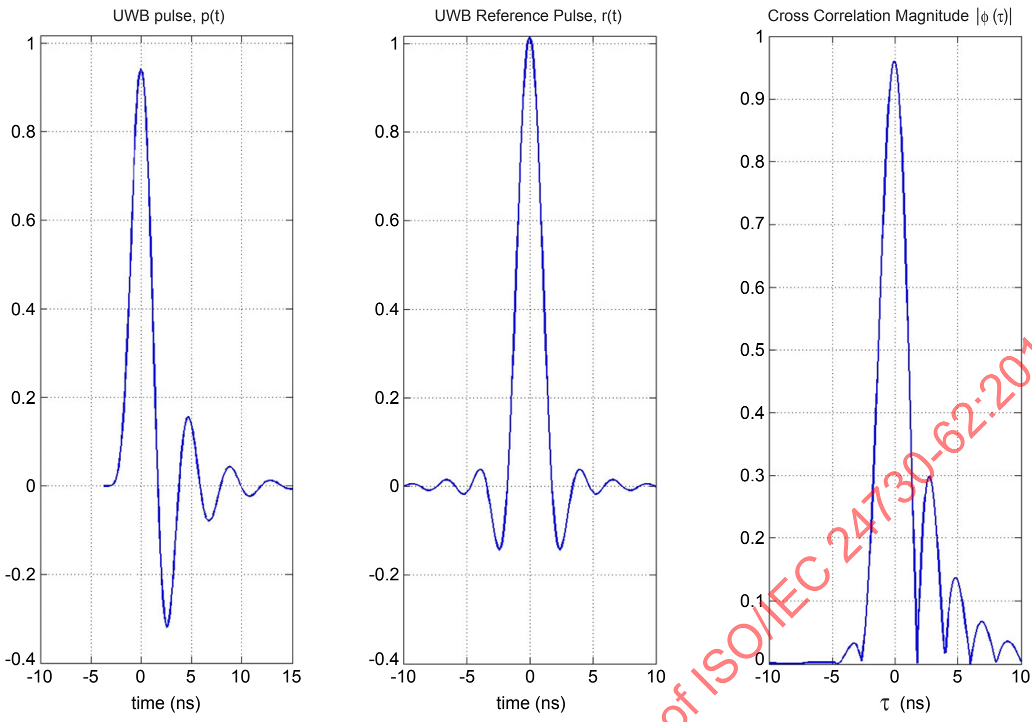


Figure 14 — Compliant pulse example

Note that it is not the intention of this standard to imply that pulse shaping shall occur at baseband, only that the measurements described here occur on the pulse envelope if shaping is done at passband.

5.5.3.2 Transmit PSD mask

The transmitted spectrum shall be less than –10 dBr (dB relative to the maximum spectral density of the signal) for $0.65 / T_p < |f - f_c| < 0.8 / T_p$ and –18 dBr for $|f - f_c| > 0.8 / T_p$. For example, the transmit spectrum mask for channel 4 is shown in Figure 15. The measurements shall be made using 1 MHz resolution bandwidth and a 1 kHz video bandwidth.

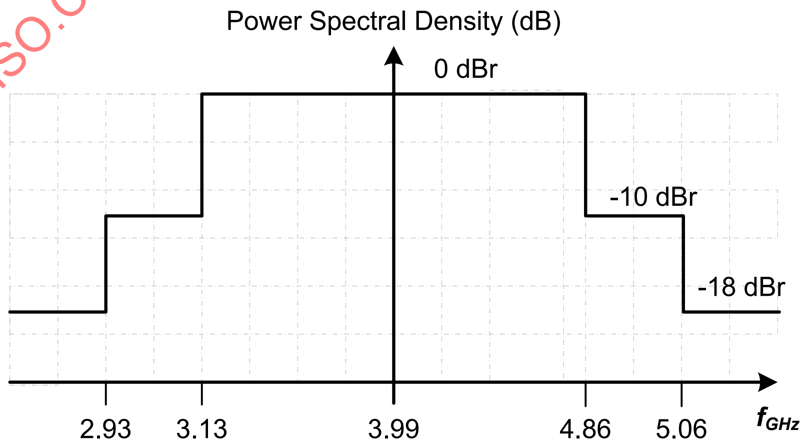


Figure 15 — Transmit spectrum mask for band 4

5.5.3.3 Chip rate clock and chip carrier alignment

A UWB transmitter shall be capable of chipping at the peak PRF given in Table 3 with an accuracy of ± 20 parts per million. In addition, for each UWB PHY channel, the center of transmitted energy shall be at the values listed in Table 11 also with an accuracy of ± 20 parts per million. The measurements shall be made using 1 MHz resolution bandwidth and a 1 kHz video bandwidth.

5.6 Timestamps and time units

At a fundamental level, the RTLS and ranging described in this standard is enabled by the capability of assigning timestamp (ranging counter) values to the precise instant that RMARKERS are received (and transmitted). Once that counter and the ability for it to precisely timestamp are in place, then conceptually, the computation of the time of flight is simple. The ranging counter values timestamp RMARKER events at the device antenna.

5.6.1 Time units

The time units used for ranging counter timestamps is defined by the least significant bit (LSB) of the time values which represents $^{1}/_{128}$ of a chip time at the mandatory chipping rate of 499.2 MHz.

Note: The LSB of the ranging counter represents a time interval so small that an actual physical counter would have to run at a nominal 64 GHz to produce values with this resolution. An actual physical realization is not expected. Instead it is assumed that computational techniques will be used to generate sufficient of the less significant bits to yield the desired operational precision.

5.6.2 Antenna delays

The time of arrival and time of sending events relate to the RMARKER being at the antenna.

The receive timestamp will naturally occur in the digital domain of the receiver some time after the RMARKER arrives at the antenna. To calculate when the RMARKER was at the antenna, and generate an accurate time of arrival, all the system delays between the antenna and the internal digital receive timestamp need to be accounted for. This receive antenna delay then needs to be subtracted from the internal digital receive timestamp to give the time of arrival value.

Similarly in the transmitter all the system delays between the internal digital transmit timestamp and the antenna need to be accounted. This transmit antenna delay then needs to be added to the internal digital transmit timestamp to give the time of sending value, when the transmit RMARKER is at the antenna.

The mechanisms for determining these antenna delays are beyond the scope of this standard.

6 Basic message format

This clause describes the basic format used for over the air messages between tag and infrastructure. The same basic message formatting rules apply to the messages used for both the one-way communication defined in Clause 7 and for the two-way communication defined in Clause 8.

6.1 Message structure and processing rules

Every message begins with one or two Frame Control octets and every message ends with a two-octet frame check sequence, FCS. The message length defined in the PHY header (see 5.3.6) is used to find and check the FCS as described in 6.2.

Each message carries a sequence number (DSN) incremented for by 1 (modulo 256) for every new frame transmitted. The initial value of the DSN may be randomly determined.

For each frame received the FCS is validated. Where the FCS is not correct the frame is considered to be errored and it is discarded. Only frames with the correct FCS are processed further.

Where a received frame has a destination address it shall be discarded if the destination address does not match the receiving node's address.

6.1.1 Time of arrival / Time of sending

The times of arrival and times of sending of frames may be used to do localization. The one-way communication blink messages (as defined in Clause 7) are alone sufficient to do one-way localization using the TDOA method. Two-way ranging based localization is possible where tags are capable of the optional two-way communications (as defined in Clause 8) and also additionally capable of accurate transmit and receive time stamping.

6.2 Frame Check Sequence (FCS)

The FCS comes at the end of all frames. The FCS is 2 octets in length and contains a 16-bit ITU-T CRC. The FCS is calculated over the complete frame beginning with the Frame Control (FC) octet(s). The FCS shall be calculated using the following standard generator polynomial of degree 16:

$$G_{16}(x) = x^{16}+x^{12}+x^{5}+1$$

The FCS shall be calculated for transmission using the following algorithm:

— Let $M(x) = b_0x^{k-1} + b_1x^{k-2} + \ldots + b_{k-2}x + b_{k-1}$ be the polynomial representing the sequence of bits for which the checksum is to be computed.

— Multiply $M(x)$ by x^{16}, giving the polynomial $x^{16} \times M(x)$.

— Divide $x^{16} \times M(x)$ modulo 2 by the generator polynomial, $G_{16}(x)$, to obtain the remainder polynomial, $R(x) = r_0x^{15} + r_1x^{14} + \ldots + r_{14}x + r_{15}$.

— The FCS field is given by the coefficients of the remainder polynomial, $R(x)$.

Here, binary polynomials are represented as bit strings, in highest polynomial degree first order.

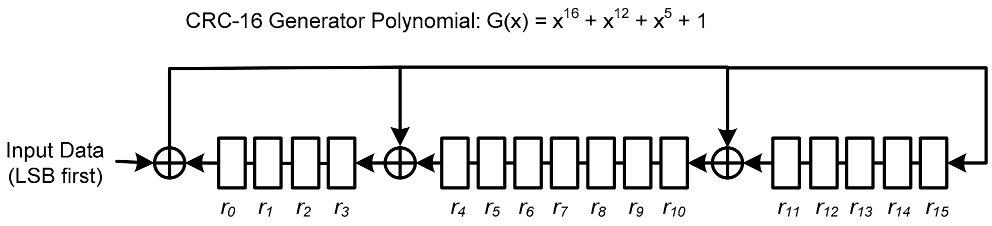
As an example, consider an acknowledgment frame with no payload and the following 3 byte header:

0100 0000 0000 0000 0101 0110 [leftmost bit (b_0) transmitted first in time]
b_0..b_{23}

The FCS for this case would be the following:

0010 0111 1001 1110 [leftmost bit (r_0) transmitted first in time]
r_0.......................................r_{15}

A typical implementation is depicted in Figure 16.



1. Initialize the remainder register (r0 through r15) to zero.
2. Shift header and payload into the divider in the order of transmission (LSB first).
3. After the last bit of the data field is shifted into the divider, the remainder register contains the FCS.
4. The FCS is appended to the data field so that r0 is transmitted first.

Figure 16 — Typical FCS implementation

7 One-way communication – blink message

The basic mode of operation is simple one-way communication of a blink message conveying the tag's ID to the infrastructure.

The blink frame length is minimized to save power and air-time, thus maximizing battery life and tag density. The blink at this level is sufficient to identify the sending tag and, if received at a number of time-synchronized infrastructure nodes, is also sufficient to locate the sending tag.

Two encoding options are allowed, one employing an ISO/IEC 15963 type of ID, and the other employing an IEEE EUI-64 ID. The tag may use either option. The infrastructure should be capable of decoding both options. The encodings are defined in the sub-clauses below.

The blink is a periodically transmitted message. Typically after sending a blink message the tag will enter a lower power sleeping state counting off the period until the next blink is due for sending. A random dither should be applied to the blink period so that tags with closely aligned crystal frequency do not stay in lock-step where their transmissions collide for long periods.

7.1 Encoding of blink frames with ISO/IEC 15963 tag ID

This encoding carries an ISO/IEC 15963 ID and employs an encoding header octet defining the remaining fields of the frame. Figure 17 shows the fields within the frame.

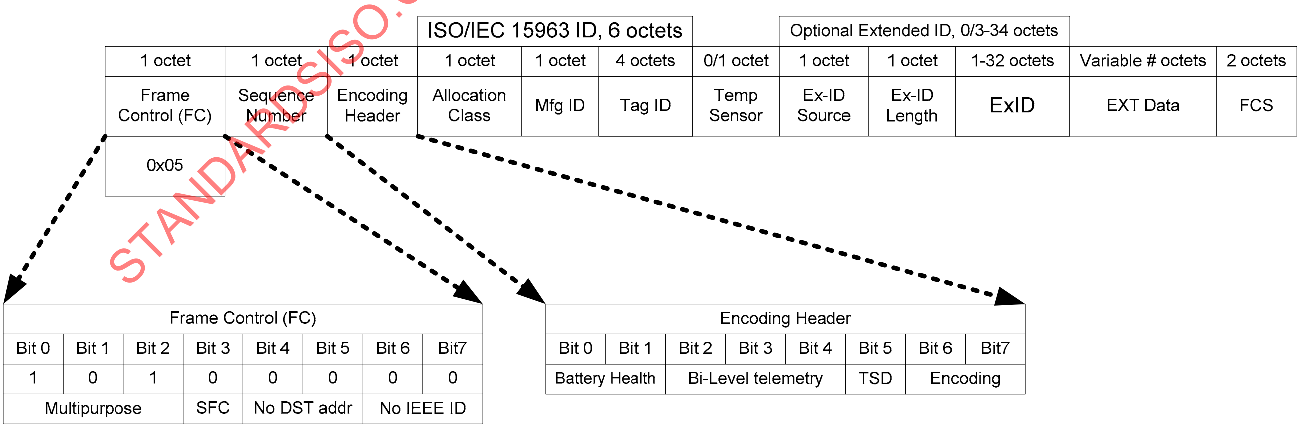


Figure 17 — Blink frame encoding with an ISO/IEC 15963 ID

7.1.1 Sub-fields of the blink frame with ISO ID

The individual sub-fields, shown in Figure 17, are described in the sub-clauses below.

7.1.1.1 Frame control (FC)

The FC (octet) of the blink frame that carries an ISO/IEC 15963 ID has fixed value of 0x05, indicating the multipurpose data frame with: a short 1-octet frame control, no destination address and a no IEEE source address, indicating that the tag ID is an ISO/IEC 15963 ID carried later in the frame. A destination address is unnecessary as the blink message is a broadcast frame.

7.1.1.2 Sequence Number

The sequence number octet contains the current value of the Data Sequence Number (DSN). The DSN is inserted into the outgoing blink frame, after which the DSN is incremented by 1 (modulo 256).

7.1.1.3 Encoding Header

The encoding header octet has a number of sub-fields defining the remaining contents of the frame. These are defined in Table 13.

Table 13 — Encoding header sub-fields in the blink frame that carries an ISO ID

Field	Bit number(s)	Meaning
Encoding Mode	7, 6	This two-bit field defines the encoding mode of the frame with the following meanings: 0, 0 – Reserved. 0, 1 – The blink frame has no optional extended ID 1, 0 – The blink frame carries an additional optional extended ID 1, 1 – Reserved.
TSD	5	This bit defines whether the frame contains Temperature Sensor Data, with the following meanings: 0 – means no Temperature Sensor data 1 – means Temperature Sensor data is present in the frame
Bi-Level telemetry	4, 3, 2	These bits are available for signaling the value of three separate bits of bi-level sensor telemetry data. The meaning and use is tag manufacturer ID dependant. Example uses are for conveying button state, motion sensor trigger, or anti-tamper alarms.
Battery Level	1,0	These bits are used to signal the battery health, with the following meanings: 0, 0 – Battery Good 1, 0 – Battery 10% to 30% 0, 1 – Battery 0% to 10% 1, 1 – Tag does not provide battery status

Note: This encoding header may be elided to send the minimal length blink shown in Figure 18. If the encoding header is omitted, it may be assumed that the bi-level telemetry values and the battery level are either unknown or unchanged from any previous report, and there shall not be any additional data present in the frame. A tag may send a mixture of minimal blinks and longer blinks.

		ISO/IEC 15963 ID, 6 octets				
1 octet	1 octet	1 octet	1 octet	4 octets	2 octets	
Frame Control (FC)	Sequence Number	Allocation Class	Mfg ID	Tag ID	FCS	10 octets for Minimum ISO ID blink
0x05						

Figure 18 — Minimal blink frame encoding with an ISO ID

The minimal blink may be used when there is no additional information to convey other than the tag's ID. The longer forms of blink encoding may be used when the tag has additional information to convey.

7.1.1.4 ISO/IEC 15963 ID

The ISO/IEC 15963 ID is a 6-octet field, consisting of an Allocation Class octet, a Manufacturer ID octet, and a four octet Tag ID defined as follows:

Allocation Class: The current class is 0, so this is eight bits of "0".

Manufacturer ID: This is a Unique Identification of the manufacturer of the tag. A single manufacturer may have multiple IDs assigned to them. The manufacture ID defines the interpretation of the EXT Data.

Tag ID: Unique Identification of the Tag (4-Bytes).

7.1.1.5 Temperature Sensor Data

This is an optional octet present if the TSD bit of the Encoding Header is set to 1.

This octet gives the temperature as a signed 8-bit integer with the range -128 °C to +127 °C.

7.1.1.6 Optional extended ID

This is an optional field present if the encoding mode bits (7, 6) of the Encoding Header are set to 1, 0. When the extended ID is present it consists of an *Ex-ID Source* octet, an *Ex-ID Length* octet, and a variable length *ExID* field, which are defined as follows:

Ex-ID Source: This octet defines the source of the ID (originating organization and/or ID encoding type). Values 0-255, allocated according to Table 15.

Ex-ID Length: This octet defines the length of the ExID in octets as shown in Table 14. Bits 0-4 represent the number of octets and bits 5-7 are reserved and shall be set to zero upon transmission and may be ignored upon receipt.

Table 14 — Ex-ID length

Ex-ID length		Reserved
b0 (LSbit) – b4 (MSbit)		b5 – b7
00000 10000 --- 01111 11111	1 octet 2 octets --- 31 octets 32 octets	000

ExID: The Identification Number. The *ExID* occupies the next n bytes of the extended ID field, where n is *Ex-ID Length* divided by 8, or the next highest integer if the result is fractional. An *Ex-ID Length* value of 0 means 256 bits or 32 octets. The least significant bits of the *ExID* are sent first, and the final bits of the *ExID* in any partially filled final octet are justified into the least significant bits of this octet with the unused bits set to zero.

Table 15 — Ex-ID Source codes and their meaning

Ex-ID Source	Description
0x00 to 0xBF	Reserved. ISO/IEC may define these Ex-ID Source codes in future versions of this standard.
0xC0 to 0xFF	Manufacturer Specific. Manufacturers may define their own meaning for these Ex-ID Source codes. Interpretation of these codes then is dependent on the manufacturer ID that is defined in clause 7.1.1.4 or within IEEE ID defined in clause 7.2.1.3.

7.1.1.7 EXT Data

This field is an extension to allow the blink message to carry manufacturer specific information. The interpretation of data within this field depends on the Manufacturer ID, see 7.1.1.4.

7.2 Encoding of blink frames with IEEE EUI-64 tag ID

This encoding carries an IEEE EUI-64 ID giving IEEE addressing compliance. Figure 19 shows the fields within the frame.

					Optional Extended ID, 0/3-34 octets			Optional EXT Variable # octets		
1 octet	1 octet	8 octets	1 octet	0/1 octet	1 octet	1 octet	1-32 octets	1 octet	Variable # octets	2 octets
Frame Control (FC)	Sequence Number	Tag ID – EUI-64 (Source Address)	Encoding Header	Temp Sensor	Ex-ID Source	Ex-ID Length	ExID	EXT Header	EXT Data	FCS
0xC5										

Frame Control (FC)							
Bit 0	Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit7
1	0	1	0	0	0	1	1
Multipurpose			SFC	No DST addr		64-bit SRC	

Figure 19 — Blink frame encoding with an IEEE EUI-64 ID

7.2.1 Sub-fields of the blink frame with IEEE ID

The individual sub-fields, shown in Figure 19, are described in the sub-clauses below.

7.2.1.1 Frame control (FC)

The FC (octet) of the blink frame that carries an IEEE ID has fixed value of 0xC5, indicating the multipurpose data frame with: a short 1-octet frame control, no destination address and a 64-bit source address (the Tag ID). A destination address is unnecessary as the blink message is a broadcast frame.

7.2.1.2 Sequence Number

The sequence number octet contains the current value of the Data Sequence Number (DSN). The DSN is inserted into the outgoing blink frame, after which the DSN is incremented by 1 (modulo 256).

7.2.1.3 TAG ID (EUI-64)

The TAG ID within this blink frame is the 64-bit source address (EUI-64). Every tag employing this blink format shall have a unique EUI-64 identifier. Typically this is assigned and permanently stored in the device during its manufacture.

7.2.1.4 Encoding Header

The encoding header octet has a number of sub-fields defining the remaining contents of the frame. These are defined in Table 16.

Table 16 — Encoding header sub-fields in the blink frame that carries an IEEE ID

Field	Bit number(s)	Meaning
Encoding Mode	7, 6	This two-bit field defines the encoding mode of the frame with the following meanings: 0, 0 – Reserved. 0, 1 – The blink frame has no optional extended ID 1, 0 – The blink frame carries an additional optional extended ID 1, 1 – Reserved.
TSD	5	This bit defines whether the frame contains Temperature Sensor Data, with the following meanings: 0 – means no Temperature Sensor Data is provided 1 – means Temperature Sensor data is present in the frame
Bi-Level telemetry	4, 3, 2	These bits are available for signaling the value of three separate bits of bi-level sensor telemetry data. The meaning and use is tag manufacturer ID dependant. Example uses are for conveying button state, motion sensor trigger, or anti-tamper alarms.
Battery Level	1,0	These bits are used to signal the battery health, with the following meanings: 0, 0 – Battery Good 1, 0 – Battery 10% to 30% 0, 1 – Battery 0% to 10% 1, 1 – Tag does not provide battery status

Note it is allowed to omit this Encoding Header in order to send the minimal length blink shown in Figure 20. In this case it may be assumed that the bi-level telemetry values and the battery level are either unknown (or unchanged from any previous report). In this case there can be no additional data present in the frame.

1 octet FC	1 octet	8 octets	2 octets
0xC5	Seq. Num	64-bit Tag ID	FCS

12 octets for Minimum IEEE ID blink

Figure 20 — Minimal blink frame encoding with an IEEE ID

The minimal blink may be used when there is no additional information to convey other than the tag's ID. The longer forms of blink encoding may be used when the tag has additional information to convey. A tag may send a mixture of minimal blinks and longer blinks.

7.2.1.5 Temperature Sensor Data

This is an optional octet present if the TSD bit of the Encoding Header is set to 1.

This octet gives the temperature as a signed 8-bit integer with the range -128 °C to +127 °C.

7.2.1.6 Optional extended ID

This is an optional field present if the encoding mode bits (7, 6) of the Encoding Header are set to 1, 0.

The encoding of this optional extended ID field is the same as that defined in clause 7.1.1.6.

7.2.1.7 EXT Header

The EXT Header is a single octet bitmap which defines and indicates additional standard elements of the EXT Data field. The meaning of the bits within the EXT Header bitmap is given in Table 17. Each of the bits indicates the inclusion of an optional element. The optional elements are individually described in succeeding clauses.

Table 17 — Definition of EXT Header bits

Bit #	Designation	Description
0	BRL	Blink Rate and Listening. This allows for the inclusion of fields indicating how often the tag is blinking and if it is capable of receiving commands when it will next be listening for them. When the BRL bit is 1 the blink rate and listening fields defined in 7.2.1.8.1 are included in the blink frame. When the BRL is 0 these fields are not included in the blink frame.
1	TLN	Tag Listening Now. TLN = 1 indicates that the tag will listen directly after this blink. Where the blink rate and listening fields are included (i.e. when BRL = 1), the TLN bit shall agree with the blinks to next listen sub-field, so that TLN shall be 1 when the number of blinks to next listen is zero, and TLN shall be 0 for non-zero number of blinks to next listen. Where TLN = 1 and BRL = 0 the preamble code used for listening shall be the same as that used for sending the blink.
2 to 7	R	Reserved. Sent as zero. These bits are reserved to allow for future definitions extending the use of the blink message.

Note Where there is no EXT Data it is allowed to omit the EXT Header. In this case it can be assumed that the Tag will not be listening for a response to the Blink.

7.2.1.8 EXT Data

This field is an extension to allow the blink message to extra information. Some of the EXT Data content is defined by the EXT Header, see 7.2.1.7, any remaining octets included in the EXT Data are manufacturer specific, and should only be interpreted if the manufacturer can be identified from the EUI-64 ID.

One standard element is defined in 7.2.1.8.1, which can be interpreted irrespective of the EUI-64 ID value.

7.2.1.8.1 Blink Rate and Listening Indication

The Blink Rate and Listening field is 4 octets in length and includes three separate sub-fields, described below, which indicate how often the tag is blinking and whether it is capable of receiving a response and if so when it will next be listening for a response. The order of transmission of these sub-fields is “Blink Rate" followed by "Number of blinks to next listen" followed by "Listen mode". The 2-octet "Blink Rate" sub-field is sent least significant octet first. If the tag cannot listen and/or the application does not need to know the blink rate information then these four Blink Rate and Listening Indication octets may be omitted and the BRL bit in the EXT Header should be set to 0.

7.2.1.8.1.1 Blink Rate

The blink rate sub-field is 2 octets in length and encodes the blink rate as defined by Table 18.

Table 18 – blink rate encoding

Bit 15	Bit 14	Bits 13 to 0	Blink Rate range defined by bits 13 to 0
0	0	1 to 16383	Blink rate value is in milliseconds. Range = 1 ms to 16.38 s.
0	1	1 to 16383	Blink rate value is in units of 25ms. Range = 25 ms to 6.8 minutes.
1	0	1 to 16383	Blink rate value is in seconds. Range = 1 second to 4.5 hours.
1	1	-	reserved

Note: This encoding is also used for configuring a blink rate, a value of 0x0000 is used for the whole 16-bit field where this field is present in a configuration message but no change in blink rate is being made.

7.2.1.8.1.2 Number of blinks to next listen

The number of blinks to next listen sub-field is 1 octet encodes a countdown in blinks to the next listening time. The meaning of this is defined in Table 19.

7.2.1.8.1.3 Listen mode

The listen mode sub-field is 1-octet field encoding the mode of listening as defined in Table 20. The five low-order bits of the listen mode indicate the code which the tag will use to listen. The individual codes allowed to be used on each channel are given in Table 6 and Table 7. The three high-order bits of the listen mode are reserved for future use.

Table 19 — Number of blinks to next listen

blinks to next listen value	Meaning
255	Tag will not be listening
254	Tag will listen but will not be listening until another 254 or more blinks have been sent.
253	Tag will listen after 253 more blinks.
...	...
2	Tag will listen after the two more blinks.
1	Tag will listen after the next blink.
0	Tag will listen directly after this blink.

Table 20 — Listen mode encoding

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
R	R	R	Value range = 1 to 24				
Reserved (TX as zero)			This defines the preamble code the tag will use to listen for a response.				

8 Two-way communication – data messages

This is an optional mode of operation allows bidirectional data communication between infrastructure and tags. Two-way communication is initiated by the infrastructure responding to a blink that includes an indication that the tag will be listening for a response, see 7.2.1.8.1.

The two-way communication employs the data message encoding format defined in clause 8.1. The operational details of the two-way communicatrions mode are defined in clause 8.2.

8.1 Data Messages

The data frame encoding is used for the two-way communication that is an optional part of this standard. The one-way transmission of a blink from tag to infrastructure is sufficient to implement a Real Time Location System (RTLS) using the Time Difference of Arrival (TDOA) algorithm. Two-way communications allows for additional features such as control of the tag, and, Time of Flight (TOF) range measurements, giving the possibility of locating a tag from a hand-held device or implementing the RTLS based on TOF measurements.

The encoding defined here supports the transmission of various application level data frames in both directions between tags and the infrastructure. For this communication both source and destination addresses (IDs) need to be included. The encoding used here is aligned with IEEE 802.15.4 data frame encoding.

2 octet	1 octet	2 octets	2 or 8 octets	2 or 8 octets	Variable # octets	2 octets
Frame Control (FC)	Sequence Number	Application ID	Destination Address	Source Address	Application data	FCS

Frame Control (FC)																
Bit 0	Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit7	Bit 8	Bit 9	10	11	12	13	14	15	
1	0	0	0	0	0	1	0	0	0	DestAddrMode		0	0	SrcAddrMode		
Data			SEC	PEND	ACK					0	1	16-bit		0	1	16-bit
										1	1	64-bit		1	1	64-bit

Figure 21 — Data frame encoding

8.1.1 Data frame sub-fields

The data frame has six sub-fields, (not including the terminating FCS), which are: the FC (2-octets), the sequence number octet, the application ID, source and destination addresses, and, the application level data. These sub-fields are described below:

8.1.1.1 Frame Control (FC)

The FC octets in a data frame have different values depending on the settings of the various sub-field bits within the FC. These are discussed below in separate sub-clauses. The SEC, PEND and ACK bits are not used in this standard but they might be employed by co-operating applications following IEEE 802.15.4 rules as part of implementing additional functionality.

8.1.1.1.1 Destination Addressing Mode

The DestAddrMode selects whether a 16-bit or a 64-bit address is used for the destination address. Typically a tag will have a 64-bit address while the infrastructure devices may have 16-bit addresses. A 16-bit address may be temporarily assigned to a tag by the infrastructure.

8.1.1.1.2 Source Addressing Mode

The SrcAddrMode selects whether a 16-bit or 64-bit address is used for the source address.

8.1.1.2 Sequence Number

The sequence number octet contains the current value of the Data Sequence Number (DSN). The current value of DSN is inserted into the outgoing data frame, after which the DSN is incremented by 1 (modulo 256).

8.1.1.3 Application ID

This is a 16-bit value. Its frame location corresponds to the network ID within the IEEE 802.15.4 frame format. A value of 0x609A is used in all data frames defined in this standard. The low order byte is sent first. Tags and infrastructure devices complying with this standard may ignore received frames with other Application ID values.

8.1.1.4 Destination Address

This may be 16 or 64 bits long depending on the Destination Addressing Mode indicated in the Frame Control field. The sending tag or infrastructure node will insert the appropriate destination address when it is sending a data frame. Tags and infrastructure devices complying with this standard shall ignore received data frames with a destination address that does not match their own assigned address.

8.1.1.5 Source Address

This may be 16 or 64 bits long depending on the Source Addressing Mode indicated in the Frame Control field. When sending a frame the source address should be set to be the sending node's assigned address.

8.1.1.6 Application Data

This field carries data defined in clause 8.2.

8.2 Operation of two-way communication

Two way communications is an optional part of this standard allowing for a richer set of functionality.

The main (and default) message sent by the RTLS tag is the blink message. Where a tag is able to listen and engage in two-way exchanges with the infrastructure, these data message exchanges may be used to carry out additional control of the tag, and, optionally to do two-way ranging, where the tag is sufficiently capable.

It is expected that TDOA RTLS based on the reception of one-way blink messages will be the predominant activity of the infrastructure. For this only one-way communication is necessary, therefore a tag that listens (after blinking) should not expect a response every time it is listening, and to save power its receiver should remain on only for sufficient time to receive the longest expected response.

While two-way communications allows general configuration and control of the tag by the infrastructure, another usage is for two-way ranging which may be useful for finding a tagged item using a hand-held reader.

8.2.1 The mechanics of two-way Communication

If a blink message indicates that the sending tag will be listening directly after the blink, the infrastructure may choose to respond, (usually from the nearest infrastructure node capable of two-way communications). The infrastructure's response and any subsequent resulting interactions shall employ the two-way messages defined here. These two-way messages use the data frame encoding defined in clause 8.1.

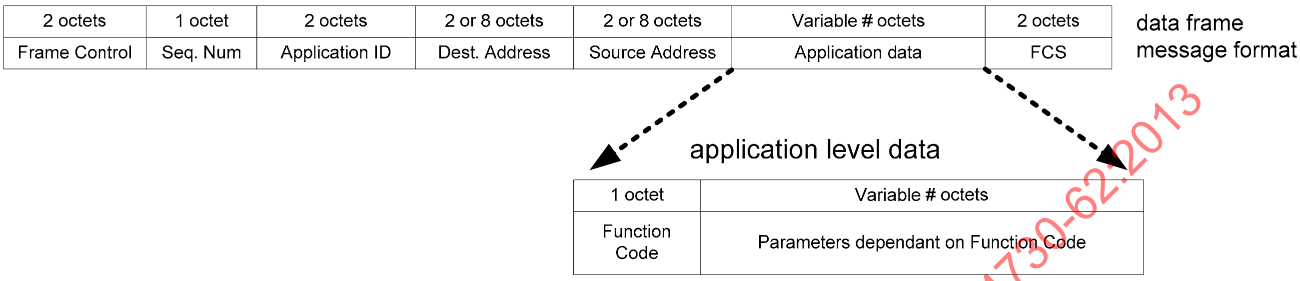


Figure 22 — Application data frame

Figure 22 shows the application level data within the data frame message. For the remainder of this clause the application payload messages are shown without the data frame formatting that wraps around it.

The destination addresses for any communication to the tag (and the source address for any communication from the tag) will be the tag's unique 64-bit address as used in the blink, unless a 16-bit address is temporarily assigned to that tag by the infrastructure.

For communication to a tag, the infrastructure messages may use 16-bit or 64-bit. Where a message from the infrastructure elicits a response from a tag, the source address from the infrastructure message shall be used as the destination address in the tag's response.

The meaning of the application data messages and the functionality deriving from them depends on the function code octet that is the first octet of every application data message. Table 21 lists the application function codes and their function. Succeeding clauses cover the various supported functions.

Each function code selects a particular function and defines the length of the parameter data that follows it. Manufacturer specific data may follow these standard defined parameters. Any such data should only be interpreted if the manufacturer has been identified, e.g. via the EUI-64 ID in the blink message.

Table 21 — Application function codes

Function Code	Selected Meaning/Function
0x10	Activity control from infrastructure
0x12	Read tag capabilities – infrastructure command
0x13	Response to read tag capabilities
0x14	Read tag configuration – infrastructure command
0x15	Response to read tag configuration
0x16	Set tag configuration – infrastructure command
0x17	Response to set tag configuration
0x19	Error Response to set tag configuration
0x20	Ranging initiation – infrastructure command
0x21	Ranging Tag initial Poll response
0x23	Ranging Tag final response message with embedded TX time
0x25	Ranging Tag final response message with no embedded TX time

Function Code	Selected Meaning/Function
0x27	Ranging Tag TX time report of final response message (0x25)
0x60..0x77 and 0xE0..0xF7	User Codes - Specific applications may add functionality controlled and commanded by these codes. The manufacturer unique component of the ID should be used to check for compatibility before issuing any Manufacturer Application specific user commands.
All other Function Codes	Reserved

8.2.1.1 Expected responses to a blink (and other messages)

Upon transmission of a blink message which indicates that the tag is subsequently listening, the tag should expect any of the following responses:

- No response
- Activity control, see 8.2.2
- Read tag capabilities command, see 8.2.3
- Read tag configuration command, see 8.2.4
- Set tag configuration command, see 8.2.5
- Perform two-way ranging command, see 8.2.6

In the case of no response, the tag should continue its periodic blinking, as per Clause 7. For each of the other responses listed above, the indicated clause describes the interaction and subsequent activity.

After any of the interactions described below, where the tag completes an interaction by sending a message to the infrastructure, the tag should listen (as it does after a blink) for additional commands from the infrastructure, and should resume its periodic blinking, as per Clause 7, if no additional commands are received.

8.2.2 Activity Control

The *activity control* message is used to command continued activity during the various message interactions described in succeeding clauses, and it is also used to signal the end of these activities.

The format of the 4-octet activity control message is shown in Figure 23. The activity message contains a one-octet activity code parameter and a related 2-octet activity parameter P. The meaning of the activity code is defined in Table 22.

Table 22 — Activity control codes and their meaning

Activity Code	Description
0x00	Activity Finished – Tag should return to blinking. The 2-octer parameter ‘P' specifies a new blink rate as defined in Table 18. This is used at the end of a ranging exchange, see 8.2.6, but may also be used in response to a blink.
0x01	Ranging Confirm – This is used during two-way ranging to confirm the success of a ranging exchange and to initiate a new ranging exchange to the infrastructure node using the 16-bit address given by P. See clause 8.2.6 for a description of the ranging exchange and the use of this activity control command
0x02	Ranging Continue – This is used during two-way ranging to confirm the receipt of the tag’s poll message and to solicit the final response message from the tag. P is ignored in this case. Clause 8.2.6 describes the ranging exchange where this message is used.

1 octet	Variable # octets		
Function Code	Parameters dependant on Function Code		application level data format
0x10	1 octet	2 octets	activity control message
	Activity code	Parameter (P)	

Figure 23 — Activity control message format

8.2.3 Read Tag Capabilities

The *read tag capabilities* command from the infrastructure to the tag has no additional parameters.

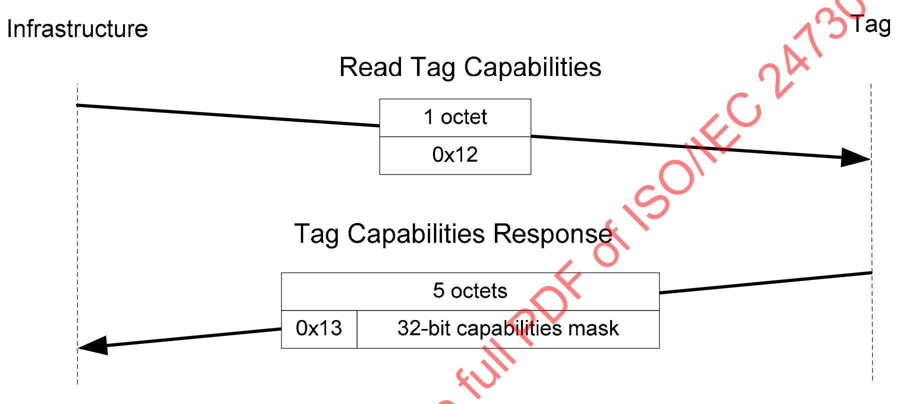


Figure 24 — Reading tag capabilities

The interaction is shown in Figure 24. The response to the read tag capabilities command is a tag capabilities response which contains the capabilities bitmap. Table 23 defines the fields within the capabilities bitmap. This bitmap is transmitted in the order laid down in the table and for each field the least significant bit is transmitted first.

After sending the capabilities response the tag should listen for additional commands, which may be any of those, listed in 8.2.1.1, normally expected after a blink. In the case of no additional commands, the tag should resume its periodic blinking, as per Clause 7.

Table 23 — Tag capabilities bitmap

Parameter	Bit width	Description
Supported channels	15	This is a bitmask, with one bit for each supported channel. The low order bit being for channel 1 and the high order bit being for channel 15, and the intervening bits being for channels 2 to 14 in order. When a bit is set it means that communication on that channel is supported, and also implies support for all the preamble codes that are specified for that channel by Table 6 and Table 7.
Supports PRF 64	1	This bit when set indicates that the tag can optionally send and receive using the nominal 64 MHz PRF. Support for the default nominal 16 MHz PRF is assumed.

Parameter	Bit width	Description
Supported data rates	3	This is a bitmask, with one bit for each data rate supported, with the bits from low-order to high-order meaning 110 kb/s, 6.8 Mb/s and 27 Mb/s. It is assumed that the device is capable of the mandatory default 850 kb/s data rate.
Supported preamble lengths	8	This is a bitmask, with one bit for each preamble length supported, running from the low-order bit to the high-order bit the bits of this bitmap indicate support for the following preamble lengths: 64, 128, 256, 512, 1024, 1536, 2048 and 4096 symbols.
Supports two-way ranging	1	This bit when set indicates that the tag can do two-way ranging.
Padding	4	Unused bits, which should always be zero, used to pad out the tag capabilities bitmap to full octets.
Total	32	Total size of the tag capabilities bitmap, in bits.

8.2.4 Read Tag Configuration

The *read tag configuration* command from the infrastructure to the tag has no additional parameters.

The *read tag configuration* interaction is shown in Figure 25. The response to the read tag configuration command is a tag configuration response which gives the current tag configuration. Table 24 defines the fields within this configuration structure. This structure is transmitted in the order laid down in the table and for each field the least significant bit is transmitted first. This structure is also employed by the set tag configuration command (see 8.2.5).

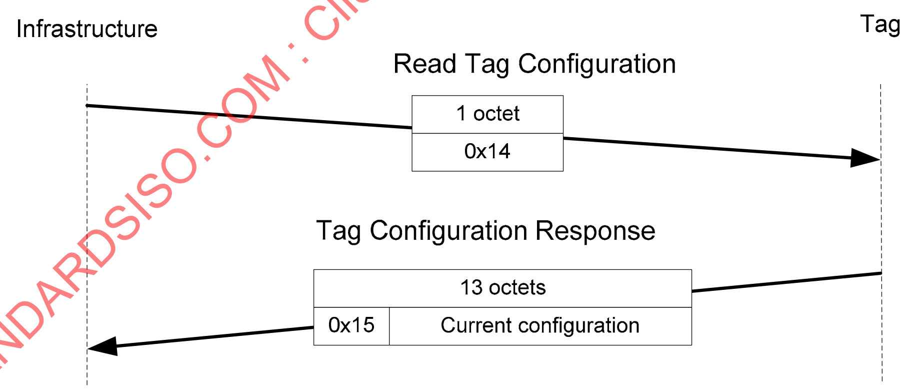


Figure 25 — Reading tag configuration

After transmitting the tag configuration response, the tag should listen for additional commands, which may be any of those listed in 8.2.1.1. Where no additional commands are received the tag should resume its periodic blinking, as per Clause 7.

Table 24 — Tag configuration structure

Parameter	Bit width	Description
Configuration ID (PHY) & Length	8	Value = 0x03. The high order 3 bits of this field give a code (000) which indicates this is configuration block 0 (for the PHY). The low order 5 bits of this field give the length of the block (3 octets in this case for block 0 – PHY configuration).
PHY Channel Number	4	(Octet 1): current channel number 1 to 15
PHY Preamble length	3	(Octet 1): current preamble length: 0 means 64 symbols, 1 means 128 symbols, and so on up to 7 meaning 4096 symbols.
PHY nominal PRF	1	(Octet 1): 0 means 16 MHz and 1 means 64 MHz
PHY Blink TX Code	5	(Octet 2): The preamble codes being used for blink transmission. Note the code used should be one of those specified for that channel according to Table 6 or Table 7 depending on the PRF.
Padding1	3	(Octet 2): unused 3 bits of padding set to zero
PHY 2W Code	5	(Octet 3): The preamble codes being used for reception of blink response and 2-way message interactions. This should be one of the codes specified for the selected channel according to Table 6 or Table 7 depending on the PHY nominal PRF setting.
Padding2	3	(Octet 3): unused 3 bits of padding set to zero
Configuration ID (APP) & Length	8	Value = 0x27. The high order 3 bits of this field give a code (001) which indicates this is configuration block 1 (for the application). The low order 5 bits of this field give the length of the block (7 octets in this case for block 1 – application configuration).
APP – Blink Rate	16	(Octets 1&2): Application blink rate as defined in Table 18
APP – RX On Time	16	(Octets 3&4): This is the *RxOnTime* in microseconds for which the receiver stays on awaiting a response after a blink, (or a follow on command after any interaction). When this time expires (i.e. with no message received) then the receiver is turned off and the tag resumes (or continues) its periodic blink.
APP – Response Time	16	(Octets 5&6): Time in microseconds that the tag uses in two-way ranging between receiving a ranging message and generating a response message
APP – Max Poll Retries	8	(Octet 7): Defines the number of times the tag will attempt to initiate a two-way ranging exchange, by sending its poll message, if it does not receive a response from the infrastructure to its poll. The default value of this parameter is 3 retries.
Total number of octets	12	Total size of the tag configuration structure in octets.

Notes: The structure defined by Table 24 allows for extension. Only two of the eight possible ID values of the "Configuration ID & Length" octets have been used and the 5-bit length parameter allows extension of current configurations. An implementation then, might extend the length of PHY or application configurations, or add additional Configuration IDs. The infrastructure should only change such values when it recognizes the tag via its ID as a known type with known extensions. In all other cases the infrastructure should first get the configuration and any values beyond those defined here should be left unchanged when setting the tag configuration.

8.2.5 Set Tag Configuration

The *set tag configuration* command from the infrastructure to the tag allows for the setting of the configurable items within the tag.

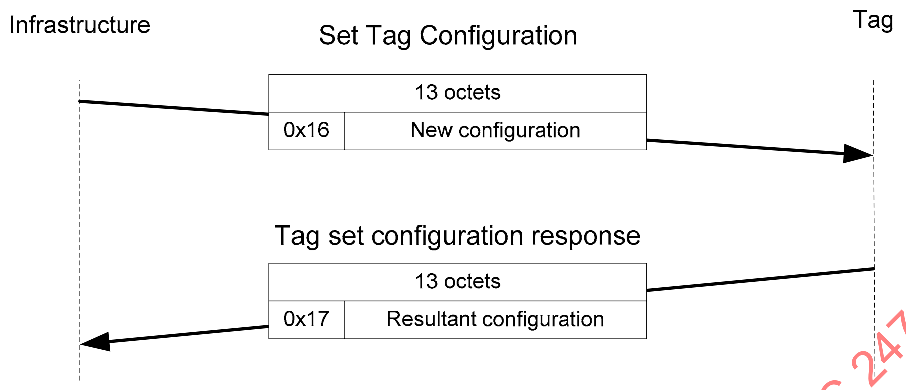


Figure 26 — Setting tag configuration

The *set tag configuration* interaction is shown in Figure 26. The both the new configuration, in the set tag configuration command, and the resultant configuration, in the tag set configuration response message are formatted configuration structures as defined by Table 24. These structures are transmitted in the order laid down in the table and each field is transmitted least significant bit is first.

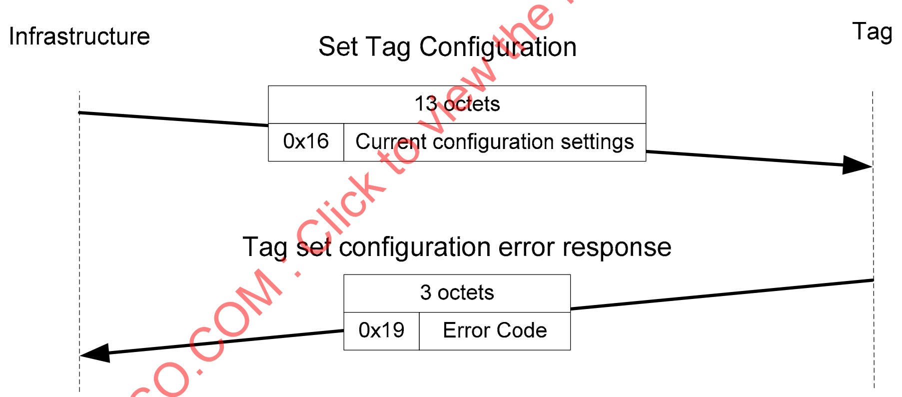


Figure 27 — Error setting tag configuration

In the case of an error where the tag detects an attempt to configure some item to an unsupported value the tag shall ignore the whole re-configuration attempt and respond with a tag set configuration error response as shown in Figure 27. This includes a 16-bit error code which may be used as an aid to determining the source of the error. The meaning of this error code is tag implementation dependant.

Assuming there is no error, the configuration change shall take effect immediately after the tag sends its tag set configuration response. After sending the response to the set configuration command, the tag should listen for additional commands, which may be any of those listed in 8.2.1.1. Where no additional commands are received the tag should resume its periodic blinking, as per Clause 7.

8.2.6 Perform two-way ranging

The *perform two-way ranging* command initiates a series of message exchanges to perform two-way ranging. Figure 28 shows the typical ranging interactions. The ranging initiation command assigns a temporary short address to the tag. This is used for subsequent interactions until the tag is told, in an activity control ranging confirm message that the interaction period is over (or the tag otherwise times out after not receiving any infrastructure messages) and the tag returns to its periodic blinking activity.

The tag begins the two-way ranging exchange with a poll message.

The addressed infrastructure node that received the poll (at T_{PR}), responds with an *activity control response (to poll)* message (at T_{RT}). This includes an option octet, allowing control of the next activity of the tag, and a further 2-octet parameter whose utility depends on the option octet. For the ranging exchange to continue at this point this option octet shall indicate Ranging Continue as per Table 22.

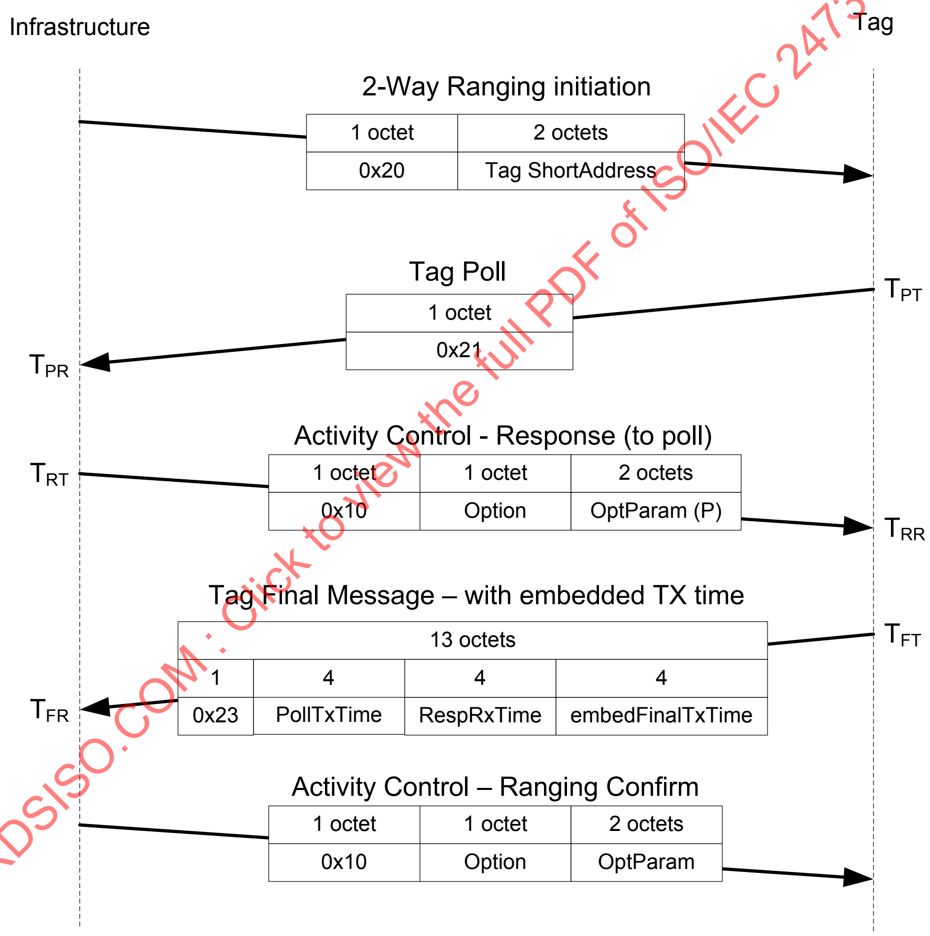


Figure 28 — Two-way ranging

Continuing with the ranging exchange the tag then sends the *tag final* message, reporting the 32-bit time of transmission of the poll message (T_{PT}), followed by the 32-bit time of reception of the *activity control response (to poll)* message (T_{RR}), followed by the accurately predicted transmit time of this final message (T_{FT}), also 32 bits. Clause 5.6 describes the timestamps and their units. The infrastructure notes the arrival time of the final message (T_{FR}).

Note: The embedded transmit time needs to include the transmit antenna delay and all system effects to accurately predict the transmit timestamp to be identical to what it would have been if it had been was determined after transmission normally.

Where the tag is not capable of embedding the transmit time of the final message in the final message, a two-step final message exchange is used as shown in Figure 29, here the final message with no embedding just includes the 32-bit time of transmission of the poll message (T_{PT}), followed by the 32-bit time of reception of the activity control response (to poll) message (T_{RR}). This tag final response message with no embedded TX time message is immediately followed by a tag transmit time report message which reports the omitted send time (T_{FT}) of the preceding final message.

The poll, response and final messages comprise a complete two way ranging exchange. The success of this is confirmed by the activity control ranging confirm message, indicating in its option octet that the ranging was a success, and stipulating whether the tag should perform ranging to another node or that the period of two-way ranging is over and the tag should return to its idle blink state.

If the tag does not receive the activity control ranging confirm message it shall re-initiate a two-way ranging exchange by sending the poll again. The infrastructure's activity control response may act to redo the ranging exchange or may confirm the previous exchange telling the tag to move on to perform ranging to another node or may tell the tag to return to its idle blink state.

If the tag does not receive a response to the initial poll it shall retry by transmitting it again, up to *MaxNumberOfPollRetries* after which the Tag should revert to blinking at its configured blink period.

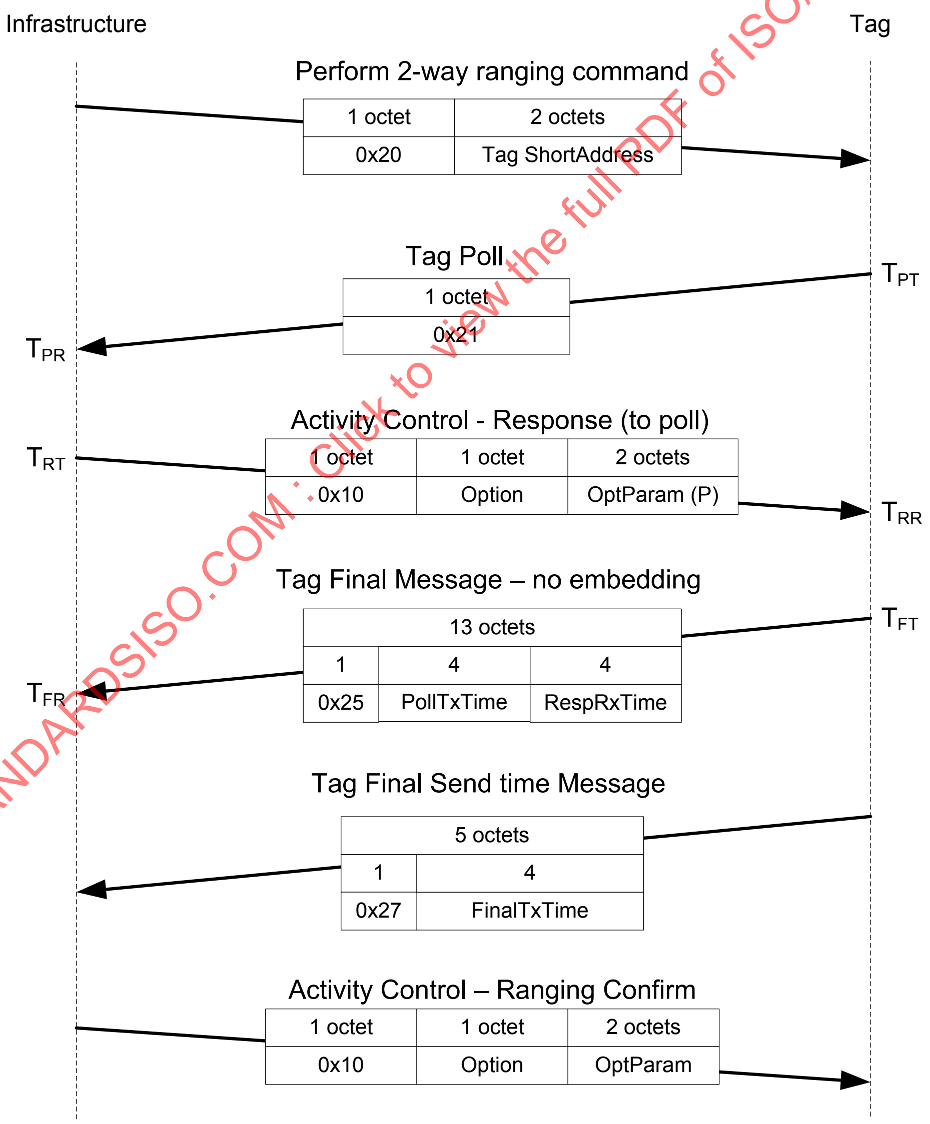


Figure 29 — Two-way ranging no embedding

The meaning of option octet in the activity control messages and the usage of the associated two-octet parameter is defined in clause 8.2.2.

If *c* is the speed of light in air then the range is given by the expression:

$$\tfrac{1}{4} \cdot c \cdot (((T_{RR} - T_{PT}) - (T_{RT} - T_{PR})) + ((T_{FR} - T_{RT}) - (T_{FT} - T_{RRT})))$$

Which may be simplified to: $\tfrac{1}{4} \cdot c \cdot (2 \cdot T_{RR} - 2 \cdot T_{RT} - T_{PT} + T_{PR} + T_{FR} - T_{FT})$.