IEEE P802.15.4a
Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	**TG4a drafting**
Date Submitted	November 27, 2005
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Re:	Draft specification for 802.15.4a
Abstract	UWB and CSS PHYs are combined with ranging and MAC content to provide the main structure of the TG4a draft.
Purpose	To provide a working document for the TG4a draft.
Notice	
Release	

This document combines the work of the contributors and editors of TG4a

r0 combines 05/680r5, 5/706r1, and 410r4 (with editing) into a single document.

{ When we are ready for it the correct title for this standard as taken from the PAR is: Amendment to Standard for Telecommunications and Information Exchange Between Systems – LAN/MAN Specific Requirements – Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Alternate Physical Layer Extension for Low Rate Wireless Personal Area Networks (WPAN)}

{To Do: Most of the font sizes need to be cleaned up for consistency}

We need a list of the editors and major contributors to this standard

Table of Contents

{Pat Kinney will provide outline for this sub clause}

6. PHY Specification

Insert at end of bulleted list

-- Precision ranging

Insert after last paragraph

Further additions to the rates supported in IEEE Std 802.15.4:2003, two high data rate PHYs have been added. They are Chirp Spread Spectrum (CSS) in the 2.4GHz band UltraWideband (UWB) operating in the 3GHz to 10GHz band.

6.1.1 Operating frequency range

Change the 2450 row in table 1

2450 in column one becomes 2450 DS

Insert rows at the end of table 1

Table 1 – Frequency bands and data rates

PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchips/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbols/s)	Symbols
2450 CSS	2400-2483.5			250		
				1000		
3000 UWB	3200-4693	See table 1{?}				
6000	5931.9-	See table 1{?}				

UWB	10304.25	

6.1.2 Channel Assignments

Replace in the first paragraph
From “868/9215 …. O-QPSK PHY” to “several PHY types operating in several frequency bands”

Insert the following after 6.1.2

6.1.2.1a Channel numbering for CSS PHY

A total of 14 frequency channels, numbered 1 to 14, are available across the 2.4 GHz band. Different subsets of these frequency channels are available in different regions of the world. In North America and Europe 3 frequency channels can be selected such that the non-overlapping frequency bands are used.

Table 1 Center Frequencies of CSS

Frequency channel number	Frequency [MHz]
1	2412
2	2417
3	2422
4	2427
5	2432
6	2437
7	2442
8	2447
9	2452
10	2457
11	2462
12	2467
13	2472
14	2484

Channel assignments

A channel frequency defines the center frequency of each band for CSS.

Fc = 2412 + 5 x (k-1) in megahertz, for k = 1, 2, **...,** 13

Fc = 2484 in megahertz, for k = 14

where k is the band number.

14 different frequency bands in combination with 4 different sub-chirp sequences form a set of 14 x 4 = 56 channels.

6.1.2.1b Channel numbering for UWB PHY

In the frequency range 3211 – 4693 MHz the channel numbering is as follows

$$f_c = 3458 + (k-1) * 494$$

The UWB PHY admits 15 frequency bands as listed in {?}. A compliant device shall be capable of transmitting in channel 2 with a signal whose 3dB bandwidth is 494MHz. Transmission in all other frequency band is optional. However, if transmission in the frequency range 5931.9-10304.25 MHz is desired then a transmitter shall be capable of transmitting in channel 8.

Table {?} UWB PHY Channel Frequencies

Channel Number	Center frequency (MHz)	Band Width (3dB)	Mandatory/Optional
1	3458	494	Optional
2	3952	494	Mandatory
3	4446	494	Optional
4	3952	1482	Optional
5	6337.5	507	Optional
6	7098	507	Optional
7	7605	507	Optional
8	8112	507	Optional (Mandatory in High Band)
9	8619	507	Optional
10	9126	507	Optional
11	9633	507	Optional
12	10140	507	Optional
13	6591	1318.2	Optional
14	8112	1352	Optional
15	8961.75	1342.5	Optional

6.1.2.2 Channel pages

Insert rows before the last row (3-31) and change last row to 5-31 (binary to 00101) of Table 2.

{It is not likely that one channel page is sufficient for UWB so channel page 4 is a placeholder only}

{ It may be necessary to change the structure of Table 2 to provide for the CSS field definitions. CSS calls for bits 0 – 13 be band, 14—17 sub-chirp sequence, 18—data rate. A similar scheme may be good for UWB as well.}

Table 2 – Channel page and channel number

Channel page (decimal)	Channel page (binary) (*b31*,*b30*,*b29*,*b28*,*b27*)	Channel number(s) (decimal)	Channel number description
3	00011		Channels for CSS PHY
4	00100		Channels for UWB PHY

6.1.3 Minimum LIFS and SIFS periods

Insert rows in Table 3

{Add the UWB values}

Table 3 – Minimum LIFS and SIFS period

PHY	***aMinSIFSPeriod***	***aMinLIFSPeriod***	**Units**
2400-2483.5 MHz CSS	12	40	symbols
3100 – 10000 MHz	?	?	symbols

6.2 PHY Service Specifications

6.2.1. PHY Data Service

{The ranging and UWB PHY options (some of them) require per-packet primitive parameters to be added. What is follows will be updated when the options are stable.}

6.2.1.1. PD-Data.request

6.2.1.1.1 Semantics of the Service Primitive

Insert additional parameters into the PD-DATA.request

The semantics of the PD-DATA.request primitive is as follows:

```
PD-DATA.request (
            psduLength,
            psdu,
            UWBPreambleType,
)           UWBDataRate
```

Table 6 specifies the parameters for the PD-DATA.request primitive.

Insert additional rows into table 6

Table 6—PD-DATA.request parameters

Name	Type	Valid range	Description
UWBPreambleType	Enumeration	TYPE_1, TYPE_2, TYPE_3, ..	Optional. The preamble type of the PHY frame to be transmitted by the PHY entity. {update with new preamble types}
UWBDataRate	Enumeration	{list rates}	The data rate of the PHY frame to be transmitted by the PHY entity.

6.2.1.2 PD-Data.confirm

{more parameters to add for UWB and ranging}

6.2.1.2.1 Semantics of the Service Primitive

The semantics of the PD-DATA.confirm primitive is as follows:

```
PD-DATA.confirm (
            status,
            Timestamp
            )
```

Table 7 specifies the parameters for the PD-DATA.confirm primitive.

Table 7—PD-DATA.confirm parameters

Name	Type	Valid range	Description
...	...	...	...
Timestamp	Integer	0x000000-0xFFFFFF	Optional. The timestamp with high resolution (see 6.8.3.3) of the PHY frame transmitted by the PHY entity. Implementation specific.

6.2.1.3 PD-Data.indication

6.2.1.3.1 Semantics of the Service Primitive

The semantics of the PD-DATA.indication primitive is as follows:

```
PD-DATA.indication (
        psduLength,
        psdu,
        ppduLinkQuality,
        PreambleType,
        Timestamp
)
```

Table 8 specifies the parameters for the PD-DATA.indication primitive.

Name	Type	Valid range	Description
...	...	...	...
ppduLinkQuality	Bitmap	0x0000000-0xFFFFFFFF	The 8 LSBs represent the link quality (LQI) value measured during reception of the PPDU (see 6.9.8). Optional. The 24 MSBs represent the figure of merit information of a ranging operation (see 6.8.3.4).
PreambleType	Enumeration	TYPE_1, TYPE_2, TYPE_3, ..	Optional. The preamble type of the PHY frame received by the PHY entity.
Timestamp	Integer	0x000000-0xFFFFFF	Optional. The timestamp with high resolution (see 6.8.3.3) of the PHY frame received by the PHY entity. Implementation specific.

6.3 PPDU Format

Change second bullet to

-- A PHY header (PHR), which contains frame length information and rate and preamble information for UWB PHYs.

6.3.1 General packet format

Change the sentence to

The PPDU packet structure shall be formatted as illustrated in figures 16, 16a, 16b, and table 18a. {add additional figures and tables so we have distinct parts for 15.4/b, CSS, and UWB.}

Insert following figure 16.

		Octets		
		2		variable
Preamble	SFD	Rate (see figure 16b)	Length	PSDU
SHR		PHR		PHY payload

Figure 16a – Format of the UWB PDU

The rate octet shall be format as shown in figure 16b. The enumeration of the data rate encoding field is shown in table 18a. All values

Bit 7	6	5	4	3	2	1	0
Reserved bits					Data rate encoding field (see figure 16b)		

Figure 16b –Data rate PHY header octet

The data rate field shall be encoded as shown in figure 16b. All values not defined in figure 16b are reserved for use by future versions of the standard. All unused bits in figure 16b and enumerations not in table 18a are reserved for future standards use.

Table 18a – Data rate field

PHY rate	Bit 2	Bit 1	Bit 0
0.101 Mb/s	0	0	0
0.811 Mb/s	0	0	1
3.24 Mb/s	0	1	0
12.97 Mb/s	0	1	1
26.03 Mb/s	1	0	0

{The PTI field gets moved into the data rate octet for UWB PHY header}

6.3.1.5 PTI Field

The PTI field is xx bits in length and specifies the preamble length. For improved robustness the field contains redundant information to tolerate bit errors. Table 21a summarizes the PTI field value versus the preamble length.

{These Preamble values require updating to the new UWB values}

Table 21—PTI values

PTI field	Preamble length
0x?	50 µs
0x?	500 µs
0x?	4000 µs

Table 4.1 CSS PPDU format

Data-rate	SHR		PHR	PSDU
	Preamble	SFD		
1 Mb/s	8 chirps	4 chirps	2 chirps	variable
250 kb/s (optional)	20 chirps	4 chirps	8 chirps	variable

Note: The preamble sequence includes the starting reference symbol which is required for differential transmission

Table 4.2 PHR

PHR	
Frame length (8 bits)	Reserved (4 bits)
bit 0, bit1,…, bit7	bit 8, bit 9. bit 10, bit 11

Note: At 1 Mbit/s 1 chirp will carry 6 bits while at 250 kb/s 1 chirp will carry 1.5 bits.
Note: Transmission will start with bit 0.

6.3.1.1 Preamble field

6.3.1.2 SFD field

The SFD should be a sequence which is reliably detectable (high detection probability, low false alarm probability, low miss probability) after the preamble sequence. The bit sequence**s** defined **in table 5 are** such sequence**s**. Different SFD sequences are defined for the two different data rates. A SFD sequence from table 5 shall be applied directly to both inputs (I and Q) of the QPSK Mapper as shown in Figure 1. A SFD sequence starts with bit 0.

Table 5 SFD Sequence

Data-rate	bit (0:15)
1 Mb/s	-1 1 1 1 -1 1 -1 -1 1 -1 -1 1 1 1 -1 -1
250 kb/s (optional)	-1 1 1 1 1 -1 1 -1 -1 -1 1 -1 -1 -1 1 1

6.4 PHY Constants and PIB attributes

6.4.1 PHY constants

Table 6 PHY constants

Constant	Description	Value
aMaxPHYPacketSize	The maximum PSDU size (in octets) the PHY shall be able to receive.	255
aTurnaroundTime	TX-to-RX maximum turnaround time	12 chirp symbol periods

6.4.2 PIB Attributes

Add the following row to clause 6.4.2 table 23
{ the default column is not part of the existing 4b draft – do we need it?}

Table 23—PHY PIB attributes

Attribute	Identifier	Type	Range	Description	Default
...	...	...	...	...	
phyRangingSupported†	0x05	Boolean	TRUE or FALSE	This indicates whether the PHY sublayer supports the optional ranging features*.	FALSE
phyTxSyncSymbolOffset†	0x06	Integer	0x000000 - 0xFFFFFF	Optional. The offset, measured in high resolution, between the symbol boundary at which the PLME captures the timestamp of each transmitted frame, and the onset of the first symbol past the SFD leaving the antenna.	Implementation specific
phyRxSyncSymbolOffset†	0x07	Integer	0x000000 - 0xFFFFFF	Optional. The offset, measured in high resolution, between the symbol boundary at which the PLME captures the timestamp of each received frame, and the onset of the first symbol past the SFD arriving on the antenna.	Implementation specific

Attribute	**Identifier**	**Type**	**Range**	**Description**	**Default**
phyPreambleSymbLength	0x08	Boolean	1 or 0	0 indicates preamble symbol length is 31, 1 indicates that length127 symbol is used	TBD
phyUWBDataRatesSupported (read only)	{Next available value}	Bitmap	0x00-0x1f	A bit string that indicates the status (1= available, 0= unavailable) for each of the 5 valid data rates.	

*optional PHY ranging features: to be listed

...

Insert the following after 6.5

6.5a 2450 MHz PHY Chirp Spread Spectrum (CSS) PHY

The requirements for the 2450 MHz CSS PHY are specified in 6.5a.1 through 6.5a.5.

6.5a.1 Data rates

The data rate of the Chirp Spread Spectrum (2450MHz) PHY shall be 1 Mb/s. An additional data rate 250 kb/s shall be optional.

6.5a.2 Modulation and spreading

This PHY uses Chirp Spread Spectrum (CSS) techniques in combination with Differential Quadrature Phase Shift Keying and 8-ary or 64-ary Bi-Orthogonal Coding for 1 Mb/s data-rate or 250 kb/s data-rate, respectively. By using time alternating time-gaps in conjunction with sequences of chirp signals (sub-chirps) in different frequency sub-bands with different chirp directions, this CSS PHY provides sub-chirp sequence division as well as frequency division.

6.5a.2.1 Reference Modulator Diagram

The functional block diagram in Figure 1 is provided as a reference for specifying the 2450 MHz CSS PHY modulation for both 1 Mb/s and optional 250 kb/s. The number in each block refers to the sub-clause that describes that function. All binary data contained in the PHR and PSDU shall be encoded using the modulation shown in Fig**ure 1.**

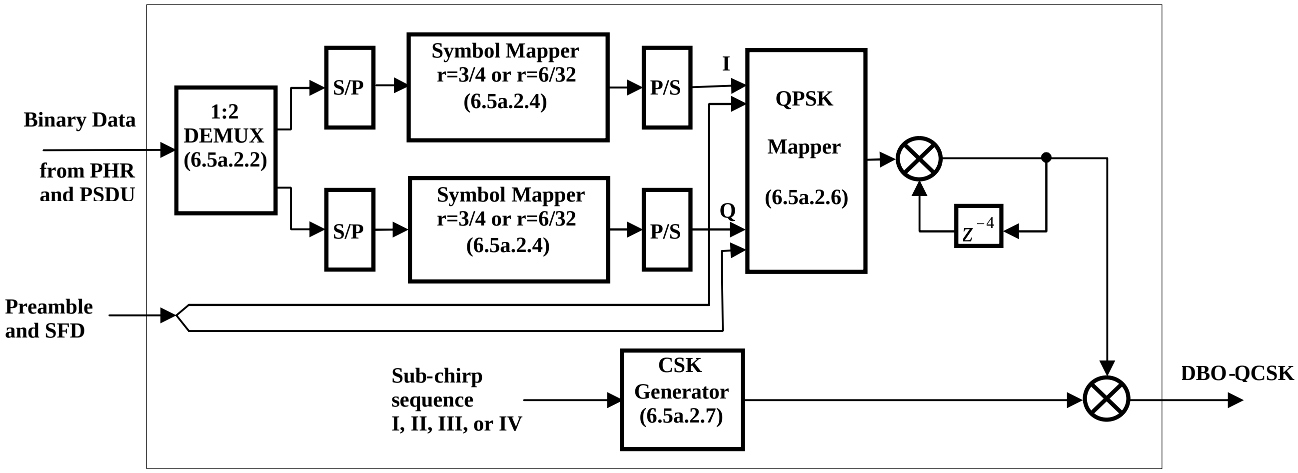


Figure 1 Differential Bi-Orthogonal Quaternary-Chirp-Shift-Keying Modulator and Spreading (r=3/4 for 8-ary 1Mb/s, r=6/32 for 64-ary 250kb/s)

6.5a.2.2 De-Multiplexer (DEMUX)

The incoming stream of information bits shall be divided into two sub streams by alternatively assigning information bits to either one sub stream.

6.5a.2.3 Serial to Parallel Mapping (S/P)

By using two serial to parallel converters the sub streams are independently partitioned into sets of bits to form data symbol**s**. For the mandatory data rate of 1 Mb/s a data symbol shall consist of three bits while for the optional data rate of 250 kb/s a data symbol shall consist of 6 bits.

6.5a.2.4 Data Symbol - to - Bi-Orthogonal Code Word mapping

Each 3bit **data** symbol shall be mapped onto a 4-chip Bi-Orthogonal code word *(co, c1, c2, c3)* for 1 Mb/s data-rate as specified in Table 7-1. Each 6bit data symbol shall be mapped onto a 32-chip Bi-Orthogonal code word *(co, c1, c2, ... , c31)* for the optional 250 kb/s data-rate as specified in Table 7-2.

Table 7-1 the 8-ary Bi-Orthogonal Mapping Table (r = 3/4)

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

7	111	-1 1 1 -1

Table 7-2 the optional 64-ary Bi-Orthogonal Mapping Table (r = 6/32).

64-ary Bi-Orthogonal r = 6/32 Code		
Data Symbol (Decimal)	Data Symbol (Binary) ($b_0 b_1 b_2 b_3 b_4 b_5$)	Code Word ($c_o c_1 c_2$ ... c_{31})
0	000000	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1	000001	1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
2	000010	1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1
3	000011	1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1
4	000100	1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1
5	000101	1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1
6	000110	1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1
7	000111	1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1
8	001000	1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1
9	001001	1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1
10	001010	1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1
11	001011	1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1
12	001100	1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1
13	001101	1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1
14	001110	1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1
15	001111	1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1
16	010000	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1
17	010001	1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1
18	010010	1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1
19	010011	1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1
20	010100	1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1
21	010101	1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1
22	010110	1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1
23	010111	1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1
24	011000	1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1
25	011001	1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1
26	011010	1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1
27	011011	1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1
28	011100	1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1
29	011101	1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1
30	011110	1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1
31	011111	1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1
32	100000	-1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1
33	100001	-1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1
34	100010	-1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1
35	100011	-1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1
36	100100	-1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1
37	100101	-1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1
38	100110	-1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1
39	100111	-1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1
40	101000	-1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1
41	101001	-1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1
42	101010	-1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1
43	101011	-1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1
44	101100	-1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1

45	101101	-1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1
46	101110	-1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1
47	101111	-1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1
48	110000	-1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
49	110001	-1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
50	110010	-1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1
51	110011	-1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1
52	110100	-1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1
53	110101	-1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1
54	110110	-1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1
55	110111	-1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1
56	111000	-1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1
57	111001	-1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1
58	111010	-1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1
59	111011	-1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1
60	111100	-1 -1 -1 -1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1
61	111101	-1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1
62	111110	-1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1
63	111111	-1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1

6.5a.2.5 Parallel - to - Serial Converter (P/S) and QPSK Symbol Mapping

Each Bi-Orthogonal code **word** shall be converted to a serial chip sequence.
Each pair of I and Q chips shall be mapped onto a QPSK symbol as specified in Table 8.

Table 8 QPSK Mapping Table

QPSK Symbol Mapping

Input chips (I_k, Q_k)	Magnitude	Phase (degree)
1, 1	1	45
-1, 1	1	135
1, -1	1	-45
-1, -1	1	-135

6.5a.2.6 Differential-QPSK (DQPSK) Coding

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

6.5a.2.7 DQPSK - to - DQCSK modulation

The stream of DQPSK symbols shall be modulated onto the stream of sub-chirps which is generated by the CSK Generator.

6.5a.2.8 CSK Generator

The CSK Generator shall periodically generate one of the four defined sub-chirp sequences (chirp symbols) with the appropriate timing. Since each chirp symbol consists of four sub-chirps the sub-chirp rate is 4 times higher than the chirp symbol rate.

6.5a.3 Preamble

The preamble **for 1Mb/s** consists of 8 chirp symbols **and the preamble for optional 250kb/s consists of 20 chirp symbols** as specified in Table 9**. The preamble sequence on table 9 should be applied directly to both I input and the Q input of QPSK Mapper as shown in Figure 1.**

Table 9 Preamble Sequence

Data-rate	Preamble Sequence
1 Mb/s	ones(0:31)
250 kb/s	ones(0:79)

6.5a.4 Waveform and Sub-Chirp Sequences

Four individual chirp signals, here called *sub-chirps*, shall be concatenated to form a full chirp symbol (sub-chirp sequence) which occupies two adjacent frequency sub-bands. Four different sub-chirp sequences are defined. Each sub-chirp is weighted with a raised cosine window in the time domain

6.5a.4.1 Graphical presentation of chirp symbols (sub-chirp sequences)

Four different sequences of sub-chirp signals are available for use.
Figure 2 depicts the four different chirp symbols (sub-chirp sequences) as time frequency diagrams. It can be seen, that four sub-chirps which either have a linear down chirp characteristic or linear up chirp characteristic and a center frequency which has either a positive or a negative frequency offset are concatenated.

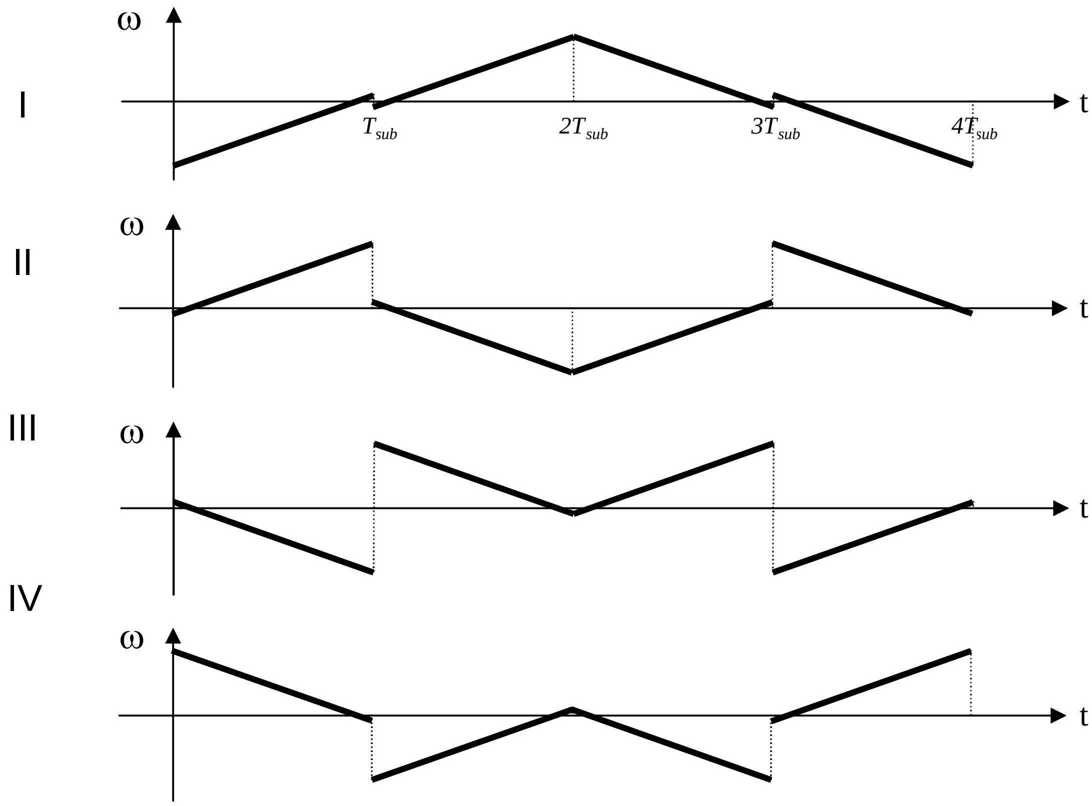


Figure 2 Four different combinations of sub-chirps

6.5a.4.2 Active usage of time gaps

In conjunction with the sub-chirp **sequence** different pairs of time-gaps are defined. These time gaps shall be applied alternatively between subsequent chirp **symbols** as shown in Figure 3. The values of the time gaps are calculated from the **timing parameters** specified in Table 2-(c).

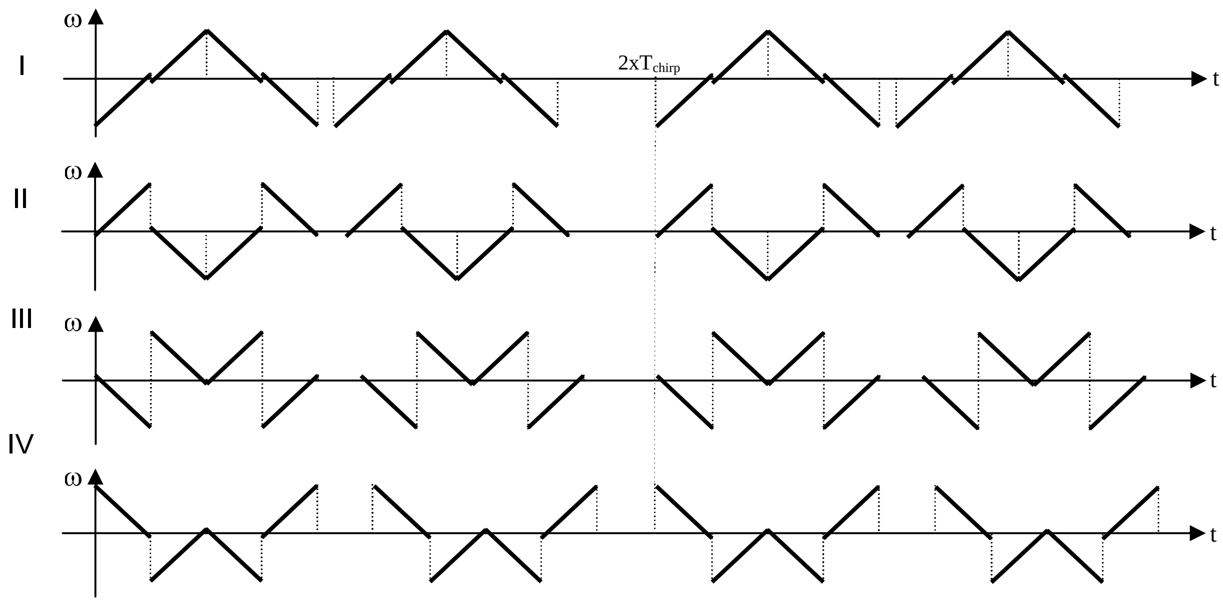


Figure 3 Four different time-gap pairs for four different sub chirp sequences

6.5a.4.3 Mathematical representation of the continuous time CSS Base-band signal

The mathematical representation of a continuous time-domain base-band signal $\tilde{s}^{m}(t)$ built of chirp symbols (sub-chirp sequences) as shown in Figure 2 with alternating time-gaps as shown in Figure 3 is given by equation (1).

$$\tilde{s}^{m}(t) = \sum_{n=0}^{\infty} \tilde{s}^{m}(t,n)$$

$$= \sum_{n=0}^{\infty}\sum_{k=1}^{4} \tilde{c}_{n,k} \exp\left[j\left(\hat{\omega}_{k,m} + \frac{\mu}{2}\xi_{k,m}\left(t - T_{n,k,m}\right)\right)\left(t - T_{n,k,m}\right)\right]\cdot P_{RC}\left(t - T_{n,k,m}\right) \qquad (1)$$

Where $m = 1, 2, 3, 4$ (I, II, III, and IV in Figure 2) defines which of the four different possible chirp symbols (sub-chirp sequences) is used. $n = \mathbf{0}, \mathbf{1}, \mathbf{2} \ldots$ is the sequence number of the chirp symbols. $\hat{\omega}_{k,m} = 2\pi \times f_{k,n}$ are the center frequencies of the sub-chirp signals. This value depends on m and $k=\mathbf{1}, 2, 3, 4$ which defines the sub-chirp number in the sub-chirp sequence.

$$T_{n,k,m} = \left(k + \frac{1}{2}\right) T_{sub} + nT_{chirp} - \left(1 - \left(-1\right)^{n}\right)\tau_{m} \qquad (2)$$

,

$T_{n,k,m}$ defines the starting time of the actual sub-chirp signal to be generated. It is determined by T_{chirp} which is the duration of a chirp symbol and by T_{sub} which is the duration of a sub chirp signal.
$T_{n,k,m}$ further depends on *n*, *k* and m.
The constant μ defines the characteristics of the sub chirp signal. A value of
$\mu = 2\pi \times 7.3158 \times 10^{12} [rad/\sec^2]$ shall be used·
The **constant** τ_m is either added or subtracted and thus determines the time-gap which was applied before the actual chirp symbol as shown in Figure 3. Since the choice of one of the four possible sub-chirp sequences also determines the pair of time-gaps to be applied alternatively, τ_m is dependent on *m*.
Table 10 shows th**e values for** the sub-band center frequencies, the sub-chirp directions, and the timing parameters in equation (1).

Table 10 Numerical Parameters in the Equation (1)

(a) Sub-band center frequencies, $f_{k,m}$ [MHz]

m\k	1	2	3	4
1	fc-3.15	fc+3.15	fc+3.15	fc-3.15
2	fc+3.15	fc-3.15	fc-3.15	fc+3.15
3	fc-3.15	fc+3.15	fc+3.15	fc-3.15
4	fc+3.15	fc-3.15	fc-3.15	fc+3.15

(b) Sub-chirp directions, $\xi_{k,m}$

m\k	1	2	3	4
1	+1	+1	-1	-1
2	+1	-1	+1	-1
3	-1	-1	+1	+1
4	-1	+1	-1	+1

(c) Timing parameters

T_{chirp}	*6 us*
T_{sub}	*1.1875 us*
τ_1	*468.75 ns*
τ_2	*312.5 ns*
τ_3	*156.25 ns*
τ_4	*0 ns*

6.5a.4.4 the Raised Cosine Window for Chirp Pulse Shaping

The Raised-cosine time-window described by equation (3) shall be used to shape the sub-chirp. The Raised Cosine Window $P_{RC}(t)$ is applied to every sub-chirp signal in the time domain.

$$p_{RC}(t)=\begin{cases} 1 & |t|\le\frac{(1-\alpha)}{(1+\alpha)}\frac{T_{sub}}{2} \\ \frac{1}{2}\left[1+\cos\left(\frac{(1+\alpha)\pi}{\alpha T_{sub}}\left(|t|-\frac{(1-\alpha)}{(1+\alpha)}\frac{T_{sub}}{2}\right)\right)\right] & \frac{(1-\alpha)}{(1+\alpha)}\frac{T_{sub}}{2}<|t|\le\frac{T_{sub}}{2} \\ 0 & |t|>\frac{T_{sub}}{2} \end{cases} \quad (3)$$

where $\alpha = 0.25$

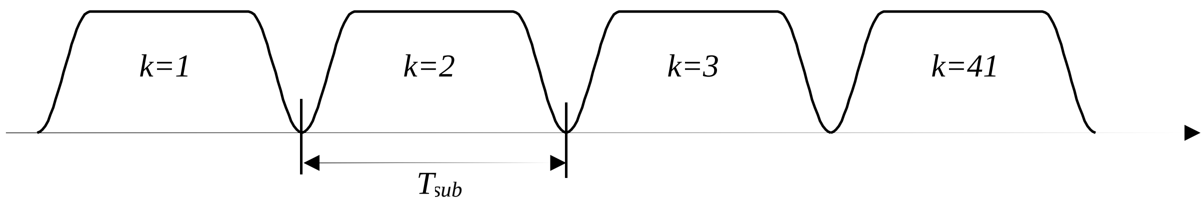


Figure 4 Sub-chirp Time-domain Pulse Shaping

6.5a.4.5 Sub-Chirp transmission order

During each chirp symbol period the sub-chirp 1 (k=1), is transmitted first and the most significant chirp, sub-chirp 4 (k=4) is transmitted last.

6.5a.5 2450 MHz band radio specification

In addition to meeting regional regulatory requirements, devices operating in the 2450 MHz band shall also meet the radio requirements in 6.5a.5.1 through 6.5a.5.4.

6.5a.5.1 Transmit power spectral density (PSD) mask

The transmitted spectral power density shall be within the relative limits specified in the template shown in Figure 5. The average spectral power shall be measured using a 100 kHz resolution bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ± 11 MHz of the carrier frequency.

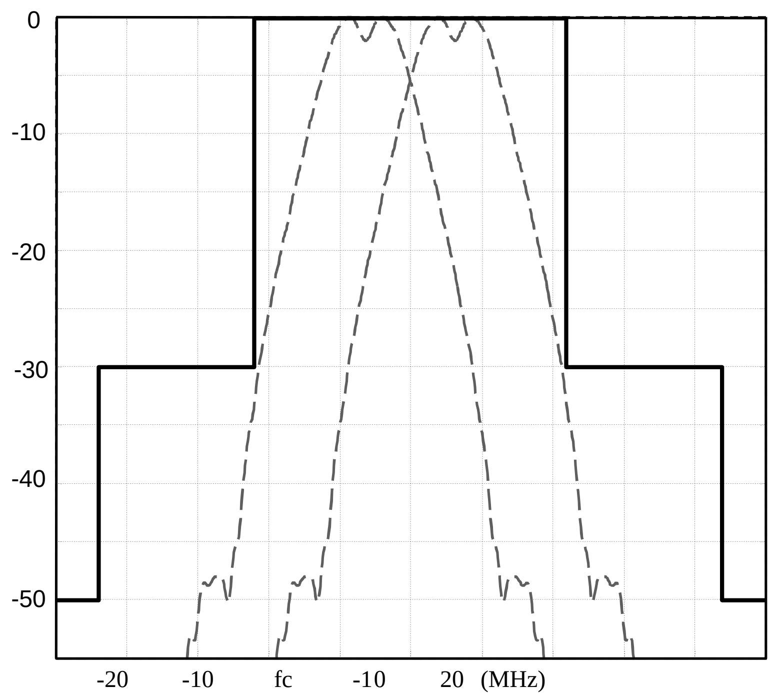


Figure 5 Transmit power spectral density mask

6.5a.5.2 Symbol rate

The 2450 MHz PHY DQCSK symbol rate shall be 166.667 ks/s (1/6 Ms/s) ± 40 ppm.

6.5a.5.3 Receiver sensitivity

Under the conditions specified in 6.1.6 **of 15.4.2003**, a compliant device shall be capable of achieving a sensitivity of -80 dBm or better.

6.5a.5.4 Receiver Jamming Resistance (Informative)

Table 11 gives jamming resistance levels **which can be realized with modest effort**. **An adjacent channel is defined to have a center frequency offset of 20 MHz. An alternate channel is defined to have a center frequency offset of 40 MHz**

The adjacent channel rejection shall be measured as follows. The desired signal shall be a compliant 2450 MHz IEEE 802.15.4a signal of pseudo-random data. The desired signal is input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity given in 6.5a.5.3.

In the adjacent or the alternate channel, an IEEE 802.15.4a signal of the same or **a** different **sub chirp sequence as** the victim device is input at the relative level specified in Table **11**. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 6.1.6 **of 15.4-2003** under these conditions.

Table 11 Minimum receiver jamming resistance levels for 2450 MHz CSS PHY

Data-rate	Adjacent Channel Rejection (20 MHz offset)	Alternate Channel Rejection (40 MHz offset)
1 Mb/s	26 dB	42 dB
250 kb/s (optional)	30 dB	46 dB

Insert the following after 6.8

6.8a. 3100 to 10000MHz PHY Ultra Wide Band (UWB)

{Add text giving general overview of UWB Phy Features}

6.8a.1 Data Rates

The data rate of the UWB PHY shall be 0.811 Mbps. {EDITOR'S NOTE: Do we need to define this to be the data rate at the PHY/MAC SAP??).}

Table 1 Mandatory and optional data rates

Data Rate (MHz)	Mandatory/Optional (M/O)
0.1	**O**
0.811	**M**
3.24	**O**
6.49	**O**
12.97	**O**
26.03	**O**

6.8a.2 Ranging/Acquisition Symbol (Preamble)

The preamble field is used by the transceiver to obtain chip and symbol synchronization with an incoming message and to track signal leading edge for ranging. The available options for the preamble length are shown in Table 1**.**

Table 1 Preamble field length

Code Length	Preamble Index	Mandatory /Optional	Mean PRF (MHz)	Preamble Length	Duration
31	**1**	**M**	**15.875**	**64 symbols**	**124.976 uS**
31	**2**	**M**	**15.875**	**256 symbols**	**500 uS**
31	**3**	**M**	**15.875**	**1024 symbols**	**2 mS**
31	**4**	**M**	**3.96875**	**64 symbols**	**500 uS**
31	**5**	**M**	**3.96875**	**256 symbols**	**2 mS**
31	**6**	**M**	**3.96875**	**1024 symbols**	**7.998 mS**
127	**7**	**O**	**127.48**	**64 symbols**	**32.907 uS**
127	**8**	**O**	**127.48**	**256 symbols**	**131.627 uS**
127	**9**	**O**	**127.48**	**1024 symbols**	**526.51 uS**

A code from Table 1 is used as a ranging/acquisition code Si. The code can be selected from length 31 or length 127 Ternary codes. Length 31 Ternary codes are given in Table Z1. These are the six codes with the best cross-correlation of the 12 possible codes with perfect periodic auto-correlation. Out of seventy two length-127-Ternary-codes, listed in Table Z2 are the 26 codes with perfect periodic autocorrelation and best cross-correlation properties.

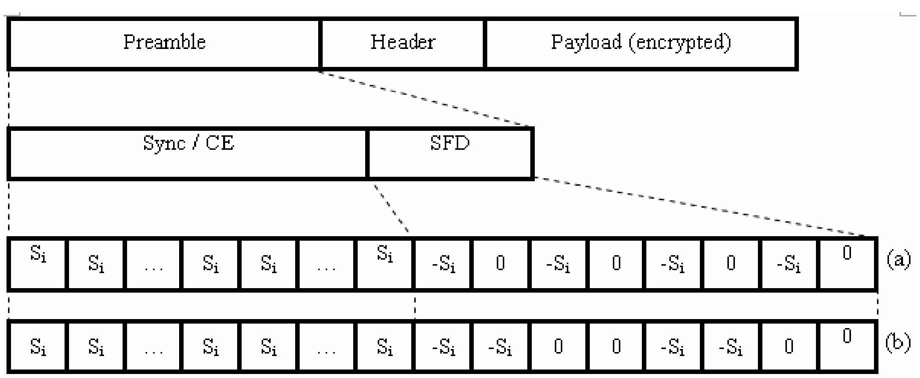
Table Z1 Length 31 Ternary codes

Index	ID	Sequence
1	S_1	**+0++000−+−++00++0+00−0000−0+0−−**
2	S_2	**+−0+0+00+000+0++−−−0−+00−++0000**
3	S_3	**000+−00−00−++++0+−+000+0−0++0−0**
4	S_4	**0+0000−00−0+−00+++−+000−+0+++0−**
5	S_5	**+0+−0+0+000−++0−+−−−00+00++0000**
6	S_6	**000+00−0−0++0000−−+00−+0++−++0+**

Table Z2 Length 127 Ternary codes

Index	ID	Sequence
1	S_7	**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+--0000-00++**
2	S_8	**-0++0-+00-00-000+-+0000-0++-++00+0+0+--00+-0-000-00-+-+000-0+0000--00000-000000+++-++-0+0+0-00-+00+++0--+0+00-0++000++0+++-0--0**
3	S_9	**+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+0+00--00-+++0+0**
4	S_{10}	**0+-0++0+000+--+-0000++-000+0+00++000000++0-0--+0-00+0-0+0++0+--00+0000+000+00-00+-++0-0+00000-0-+-+00---0----+++0+-00+0-+000-+0**
5	S_{11}	**0+--+000-+-0---0+0-+-+0+00+0+-00+0-00+++00-000++000+0+++0000-0000-+0+00000+--+-0++000000-0+0-+0----+--00++0+-0+0-0+000+00-00++0**
6	S_{12}	**-+000000++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**

The preamble consists of repetitions of the selected code Si. The ranging preamble should be transmitted in one of the forms given in Figure Z1.



The Si indicates the selected code with corresponding index i. Sync / CE is the combined synchronization frame and channel estimation sequence. SFD is the synchronization frame delimiter (a) Normal preamble (b) Preamble for 128kps.

Figure Z1 Illustration of synchronization part of ranging packet preamble.

6.8a.3 Waveform, Pulse Shape, and Chipping Rates

The UWB PHY uses an impulse radio based signaling scheme in which each information bearing symbol is represented by a sequence/burst of short time duration (hence large bandwidth) pluses. The duration of an individual pulse is nominally considered to be the length of a chip. A UWB PHY compliant device shall be capable of transmitting pulses at a rate of 494 MHz. This is equivalent to a chip duration of 2.02429 ns or a chipping rate of 494MHz.

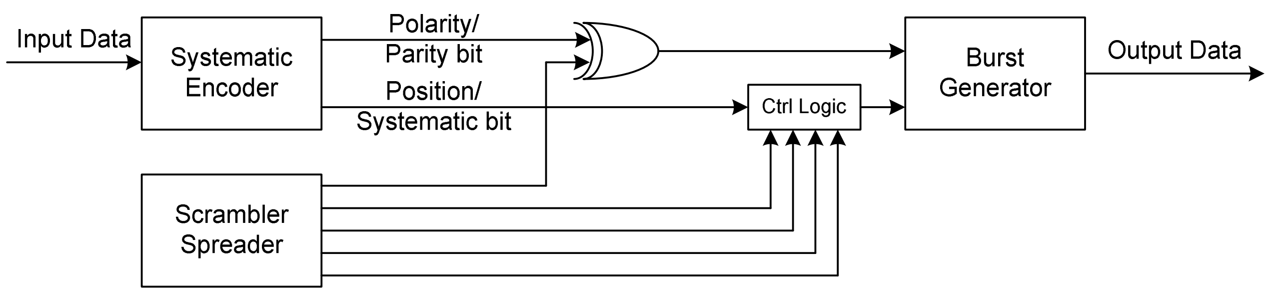


Figure 1 Reference Modulator (After FEC encoding)

As the UWB PHY is required to support both coherent and non coherent receivers the modulation format chosen is a combination of both Pulse Position Modulation (PPM) and Binary Phase Shift Keying (BPSK). Nominally, a UWB PHY 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. { Error! Reference source not found.**} is provided as a reference for specifying the processing of coded symbols and their subsequent conversion to an analog waveform. Each block is described in more detail in the following subsections of this clause.**

6.8a.3.1 Structure of a UWB PHY symbol

Figure 2 a depicts the structure and timing of a UWB PHY symbol assuming the mandatory data rate of 1 Mbps. Each symbol shall consist of an integer number of chips which have duration of 2.02429 ns. Several consecutive chips are grouped together to form a burst. And 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 is used to indicate a second bit of information. For a given symbol duration, T_{sym}, the number of chips each in each symbol is

$$N_c = \lfloor T_s / 2.0429 \rfloor \quad 1$$

Where $\lfloor \ \rfloor$ indicates a floor operation. A burst duration, $T_{burst,}$ is related to the chip duration, T_c, and N_c and by

$$T_{burst} = N_b * T_c \quad 2$$

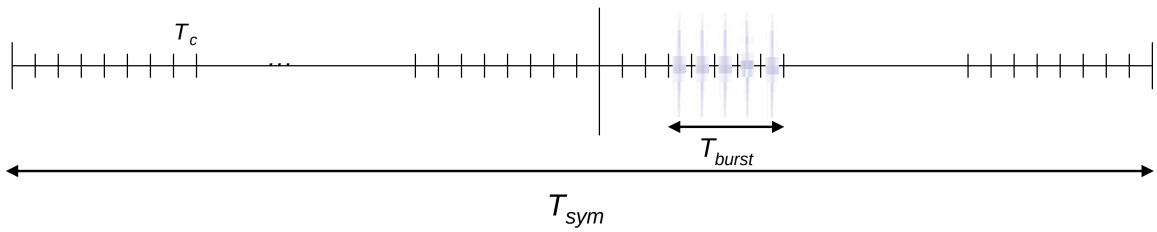


Figure 2 UWB PHY Symbol Timing

In addition to the modulation of data the UWB PHY symbol provides for some multi-user access interference rejection in the form of time hopping. Since each symbol contains a single burst of pulses and the burst length is typically much shorter than the duration of the symbol the location of the pulse within each burst can be varied from on a symbol to symbol basis according to a time hopping code. This is part of the functionality provided by the “Scrambler and Burst Positon Hopping” block as depicted in Error! Reference source not found..

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6.8a.3.2 UWB PHY Symbol Timing Details

The UWB PHY shall support two average Pulse Repitition Frequencies (PRF). Namely 15.4375MHz and 3.859375MHz. These PRFs in addition to the data rate, modulation and coding rate determines the overall timing of a UWB PHY symbol. Table 2 defines the parameters of the PHY UWB symbol.

Table 2 UWB PHY Symbol Timing Parameters (Mandatory Data Rate)

Avg. PRF (MHz)	**Chip Rate (MHz)**	**Modulation Order (bits/ Symbol)**	**Data Rate (Mbps)**	**FEC rate (outer code)**	**FEC rate (inner code)**	**Code rate**	**Symbol Rate (MHz)**	**Pulses per Burst (N_{burst})**	**Burst Duration (ns)**	**# of slots (N_s)**
15.4375	494	2	1	1/2	.88	.44	0.996	16	32.4	31
3.859375	494	2	1	1/2	.88	.44	0.996	4	8.1	124

The additional data rates shown in Table 1 require that the number of pulses per burst are modified this in turn alters the burst duration and other symbol timing parameters as specified in the following tables.

Table 3 UWB PHY Symbol Timing Parameters for Optional Data Rates and Average PRF of 15.94MHz

Data Rate (Mbps)	Symbol Duration (us)	Pulses per Burst (N_{burst})	Burst Duration (ns)	# of slots (Ns)
0.1	8.0324	128	259	31
3.24	0.251	4	8.1	31
12.97	0.0628	1	2.02	31
26.03				

Table 4 UWB PHY Symbol Timing Parameters for Optional Data Rates and Average PRF of 3.98MHz

Data Rate (Mbps)	Symbol Duration (us)	Pulses per Burst (N_{burst})	Burst Duration (ns)	# of slots (Ns)
0.1	8.0324	32	64.8	124
3.24	0.251	1	2.02	124
12.97	0.0628	1/4	0.51	124
26.03				

6.8a.3.3 UWB PHY Modulation Symbol Details

The UWB PHY symbol may be expressed using the following equation

$$x^{(k)}(t) = \sum_{j=1}^{N_{burst}} g_1^{(k)} s_j \, p\left(t - g_0^{(k)} T_{PPM} - jT_c - h^{(k)} T_{burst}\right) \qquad 3$$

In the above equation the $x^{(k)}(t)$ is the waveform of the k[th] information bearing symbol, g_0, and g_1 are the modulation symbols obtained from a mapping of the coded bits, s_j $\{j = 0,1,\ldots,N_{burst} -1\}$, is the scrambling sequence and takes the possible values {-1 or 1}, p(t) is the transmitted pulse shape at the input to the antenna, T_{PPM} is the duration of the binary pulse position modulation time slot. The hopping sequence $h^{(k)}$, provides suppression of multiuser interference and the scrambling sequence, s_j, provides additional interference supporesion among coherent receivers as well as spectral smoothing of the transmitted waveform. The tables below call out the numerical values for the various data rates and average pulse repetition frequencies.

Table 5 Numerical Parameters for Equation 3 (Mandatory data rate)

Average PRF (MHz)	Chip Duration (T_c) ns	Postion Duration (T_{PPM}) ns	Burst Length (T_{burst}) ns
15.4375	2.02429	502	32.4
3.859375	2.02429	502	8.1

Table 6 Numerical Parameters for Equation 3 (Optional data rates and Average PRF =15.94 MHz)

Data Rate (Mbps)	Chip Duration (T_c) ns	Postion Duration (T_{PPM}) ns	Burst Length (T_{burst}) ns
0.1	2.02429	4.016	259
3.24	2.02429	0.126	8.1
12.97	2.02429	0.031	2.02
26.03			

Table 7 Parameters for Equation 3 (Optional data rates and Average PRF =3.98 MHz)

Data Rate (Mbps)	Chip Duration (T_c) ns	Postion Duration (T_{PPM}) ns	Burst Length (T_{burst}) ns
0.1	2.02429	4.016	64.8
3.24	2.02429	0.126	2.02
6.49	2.02429	0.063	1.01
12.97	2.02429	0.031	0.51
26.03			

6.8a.3.3.1 UWB PHY Symbol Mapping

The UWB PHY shall map groups of two consecutive bits into modulation symbols according to Table 8

Table 8 UWB PHY Bit to Modulation Symbol Mapping

Information bits (b_1b_0)	Modulation Symbols (g_1g_0)
00	-10
01	-11
10	10
11	11

6.8a.3.3.2 UWB PHY Pulse Shape

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

$$\phi(\tau) = \frac{1}{\sqrt{E_r E_p}} \int_{-\infty}^{\infty} r(t) p^*(t+\tau) dt \qquad 4$$

The reference, $r(t)$, pulse used by the UWB PHY is a root raised cosine pulse with roll-off factor of $\beta = 0.6$. Mathematically this is

$$r(t) = \sin c\left(\frac{\pi t}{T_c}\right) \frac{\cos(\pi \beta t / T_c)}{1 - (2\beta t / T_c)^2}$$

5

In order for a UWB PHY transmitter to be compliant with the standard the transmitted pulse shall have a cross correlation coefficient that is greater or equal to 0.7, that is

$$\phi(0) = \frac{1}{\sqrt{E_r E_p}} \int_{-\infty}^{\infty} r(t) p^*(t) dt \geq 0.7 \qquad 6$$

6.8a.3.3.3 UWB PHY Optional Pulse Shapes

An optional pulse shape that consists of a weighted linear combination of the pulses. This new optional pulseshape is denoted *p'(t)* and is the sum of *N* weighted and delayed "fundamental" pulses *p(t)*

$$p'(t) = \sum_{i=1}^{N} a_i p(t - \tau_i) \qquad 7$$

where *p(t)* has to follow the specifications of fundamental pulses according to Sec. 6.8a.3.3.2. The number of pulses *N* is set to a fixed value of 4 (though smaller values can be realized by setting the amplitudes of some of the pulses to zero. The values of the pulse delays shall be limited to $0 \le \tau_i \le 4ns$. The numerical values of the delays and amplitudes of the pulses shall be transmitted following the general framework of optional pulseshapes, as defined in {Sec. ??? }

6.8a.3.3.4 UWB PHY Optional Chirp pulses

This clause specifies a scheme of Chirp on UWB (CoU) which is an optional mode in addition to the mandatory direct sequence (DS) mode of UWB PHY. The purpose of CoU is to provide an additional dimension to support SOP as well as to achieve better ranging accuracy.

Since CoU mode is an optional pulse shape in addition to the mandatory pulse shape, all modulation specifications will remain the same as they are in the mandatory DS mode except those defined description of the pulse shape when a device implements the CoU option..

A mathematical representation of chirped DS pulse of CoU at baseband is given by Equation (1) and a graphical example of chirped DS pulse is shown in Figure 3**.**

$$P_{CoU}(t) = \begin{cases} P(t)\exp j\left(-\dfrac{\pi\mu t^2}{2}\right) & ; \quad -\dfrac{T}{2} \le t \le \dfrac{T}{2} \\ 0 & ; \quad otherwise \end{cases} \qquad (1)$$

where P(t) denotes the mandatory pulse and $\mu = B/T$ the chirping rate (chirping slope). Moreover, B and T are the bandwidth and time duration of the chirped pulse respectively. When Raised cosine pulse is used as the mandatory pulse, we have

$$P(t) = \begin{cases} 1 & ; \quad |t| \le \dfrac{1-\alpha}{1+\alpha}\dfrac{T}{2} \\ \dfrac{1}{2}\left(1+\cos\left(\dfrac{(1+\alpha)\pi}{\alpha T}\left(|t| - \dfrac{(1-\alpha)}{(1+\alpha)}\dfrac{T}{2}\right)\right)\right) & ; \quad \dfrac{1-\alpha}{1+\alpha}\dfrac{T}{2} < |t| \le \dfrac{T}{2} \\ 1 & ; \quad |t| > \dfrac{T}{2} \end{cases} \qquad (2)$$

{(HUAN BANG please include a table that shows what the parameters of equation 1 need to be for each channel shown in table 1. From the motion passed in Vancouver we have 2 slopes in each of the 500MHz bands and 4 in each of the optional wider bandwidth channels)}

Channel Number	**μ (slopes)**
1	
2	

3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

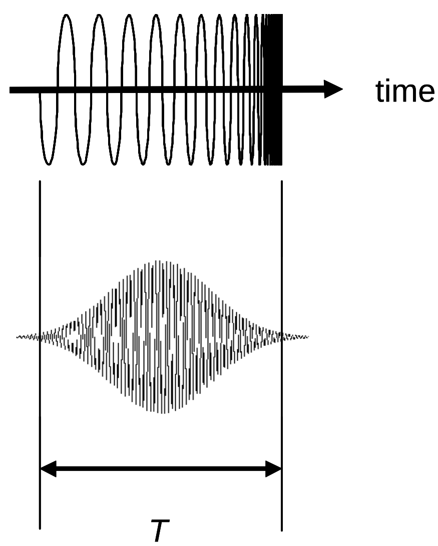


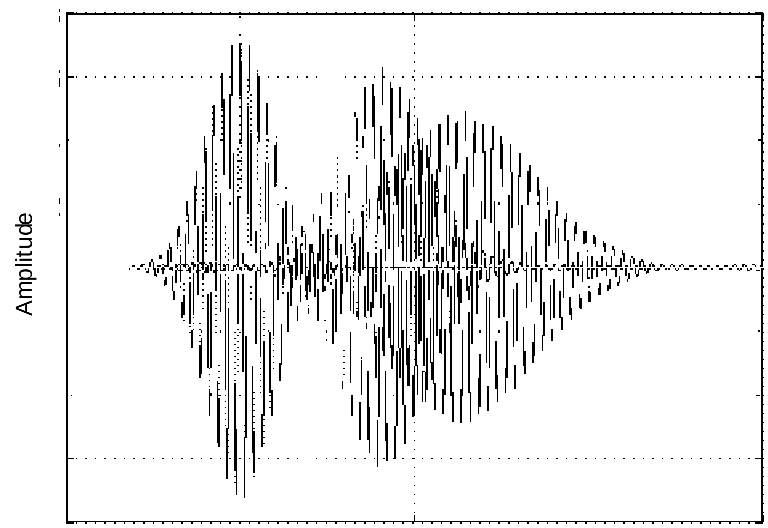
Figure 3 Graphical view of chirped pulse

6.8a.3.3.5 UWB PHY Optional Continious Spectrum (CS) pulses

This clause specifies a scheme of Continuous Spectrum (CS) pulse which is an optional mode in addition to the mandatory direct sequence (DS) mode of UWB PHY. The purpose of CS filtering is to reduce the interference level between different piconets and then enhance SOP performance

Since CS mode is an optional pulse shape in addition to the mandatory pulse shape, all modulation specifications will remain the same as they are in the mandatory DS mode except those defined description of the pulse shape when a device implements the CS option.

Figure 7 Examples of CS filtered pulses.



A mathematical representation of CS filtered pulse is given by Equation (3) and a graphical example of chirping operation is shown in Figure 6.

$$g_{cs}(t) = \int G(f)\exp\{-j2\pi f[t-\tau(f)]\}df \qquad (3)$$

where, $g(t)$ denotes the original mandatory pulse, $\tau(f)$ the group delay and

$$G(f) = \int g(t)\exp(-j2\pi ft)dt \qquad (4)$$

Some examples of the CS filtered pulses with different group delays are given in Figure 7.

{(HUAN BANG please include a table that shows what the parameters of equation 1 need to be for each channel shown in table 1. From the motion passed in Vancouver we have 2 CS waveforms in each of the 500MHz bands and 4 in each of the optional wider bandwidth channels)}

Channel Number	$\tau(f)$ **(group**

	delays)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

6.8a.3.3.5 UWB PHY Optional Chaotic pulses

{ need content for this sub-clause}

6.8a.5. UWB PHY Spreading and Hopping Sequences

The constituent pulses in each burst are scrambled by applying a time varying scrambling sequence {(s_j) in equation 3}. This scrambler is simply a the pseudo-random binary sequence (PRBS) defined by a polynomial generator. The polynomial generator, g(D), for the pseudo-random binary sequence (PRBS) generator shall be g(D) = $1 + D^{14} + D^{15}$, where D is a single bit delay element. The polynomial not only forms a maximal length sequence, but is also a primitive polynomial. Using this generator polynomial, the corresponding PRBS, s_j, is generated as

$$s_j = s_{j-14} \oplus s_{j-15}, \quad j = 0,1,2,...$$

where "$\oplus$" denotes modulo-2 addition**.**

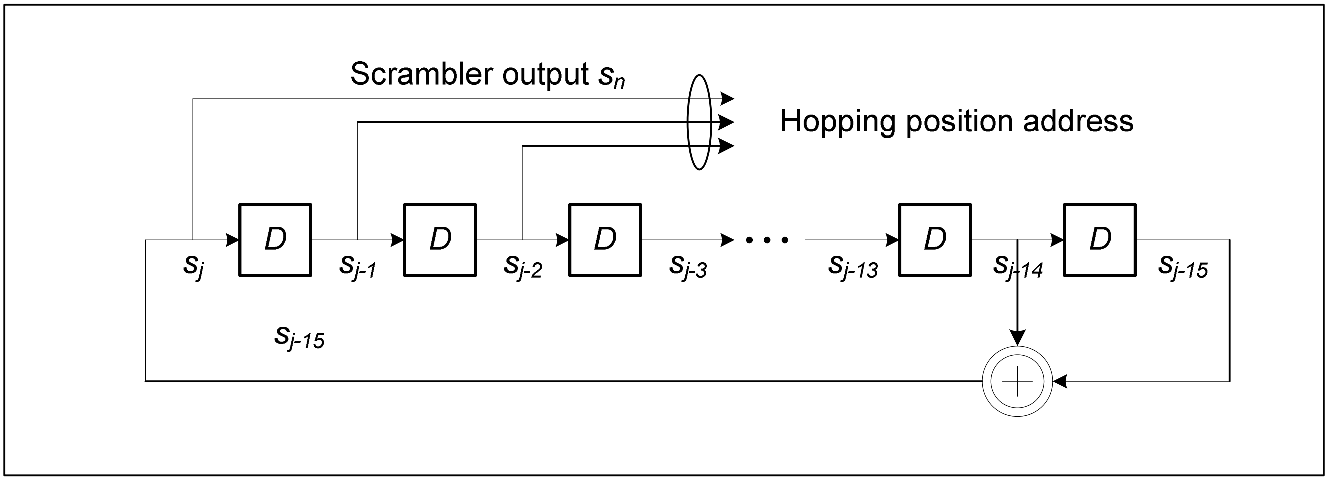


Figure 3 Realization of the scrambler linear feedback shift registers

Furthermore the hopping sequence is derived from the same linear feedback shift registers by using the output of the first three registers. Specifically, when each symbol, $x^{(k)}(t)$, is generated by the UWB PHY the spreader of **Error! Reference source not found.** is run at the chip rate for N_{burst} cycles the N_{burst} consecutive outputs of the spreader are the spreading sequence for the symbol (s_j, $j = 1,2, \ldots, N_{burst}$). Additionally, the current hopping position, $h^{(k)}$ is determined according to the following equation

$$h^{(k)} = s_j \times 2^0 + s_{j-1} \times 2^1 + s_{j-2} \times 2^2$$

Here the values of the state variables are sampled at the start of the transmission of the current modulation symbol.

6.8a.6. UWB PHY Channel coding within a band

{TBD (Phil and Ismail aren't sure what goes here is it description of when to start scrambling and FEC within a PHY PDU, e.g., after the PHY header?)}

6.8a.7. UWB PHY Forward Error Correction

The FEC used by the UWB PHY is a concatenated code consisting of an outer Reed-Solomon (RS) systematic block code and an inner systematic convolutional code. The outer RS code shall be a $RS_6(K+8,K)$ over Galois field $GF(2^6)$. The Galois field $GF(2^6)$ is built as an extension of GF(2). The systematic Reed Solomon code shall use the generator polynomial

$$g(x) = \prod_{k=0}^{7}\left(x + a^k\right)$$

where a= 010000 is a root of the binary primitive polynomial $1+x+x^6$ in $GF(2^6)$. Both RS encoding with default codeword operation (K = 55) and shortened codeword operation, as defined below, are shall be required.

6.8a.7.1 Default Codeword Operation

,

In default codeword operation, $RS_6(63,55)$, a block of 330 bits is encoded into a codeword of 378 bits. The RS encoding procedure is performed in the following 3 steps:

a. Bit to Symbol Conversion

The information bits $\{d(0), d(1), \ldots, d(329)\}$ are converted into 55 RS symbols $\{D(0), D(1), \ldots, D(54)\}$ as following:

$D(k) = 32d(6k+5) + 16d(6k+4) + 8d(6k+3) + 4d(6k+2) + 2d(6k+1) + d(6k)$ for $k = 0,1, \ldots,54$

Resulting 6-bit symbols are presented as:

$D(k) = \{d(6k+5), d(6k+5), d(6k+4), d(6k+3), d(6k+2), d(6k+1), d(6k)\}$ for $k = 0,1, \ldots,54$

where $d(6k+5), \ldots, d(6k)$ are ordered from the most significant bit (MSB) to the less significant bit (LSB). The polynomial representation of a single information symbol over $GF(2^6)$ in terms of a is given by:

$D_a(k) = a^5d(6k+5) + a^4d(6k+4) + a^3d(6k+3) + a^2d(6k+2) + a^1d(6k+1) + d(6k)$

b. Encoding

The information symbols $D(0), D(1), \ldots, D(54)$ are encoded by systematic $RS_6(63,55)$ code with output symbols $U(0), U(1), \ldots, U(54)$ ordered as:

$U(k) = D(k)$ for $k = 0,1, \ldots,54$;
$U(k) = P(k)$ for $k = 55, 56, \ldots,62$;

where $P(k)$ are parity check symbols added by $RS_6(63,55)$ encoder.
Information symbols are ordered in the descending polynomial order such that $D_a(54)$ corresponds to the lowest degree term of: $D(x) = D_a(54) + D_a(53)\, x + \ldots + D_a(0)\, x^{54}$, where D(x) is the polynomial representation of information symbols $\{D(0), D(1), \ldots, D(54)\}$ over Galois field.

Parity check symbols in polynomial representation over Galois field are ordered in the descending polynomial order such that $P_a(62)$ is the lowest degree of $P(x) = P_a(62) + P_a(61)\, x + \ldots + P_a(0)\, x^7$. The parity check symbols are calculated as:

$P(x) = \text{remainder}\, [x^8D(x)/g(x)]$, and $U(x) = D(x) + x^8P(x)$, i.e.

$U_a(k) = D_a(k)$ for $k = 0, 1, \ldots,54$;
$U_a(k) = P_a(k)$ for $k = 55,56, \ldots,62$.

c. Symbol to Bit Conversion

The output symbols $\{U_a(0), U_a(1), \ldots, U_a(62)\}$ are converted back into symbols $\{U(0), U(1), \ldots, U(62)\}$ and then into binary with LSB coming out first, resulting in a block of 378 bits $\{u(0), u(1), \ldots, u(377)\}$.

6.8a.7.2 Shortened Codeword Operation

Shortened codeword operation, $RS_6(K,K+8)$,of a block of N bits is described by the follwing steps:

a. Expand the block to 330 bits by adding 330-N dump (zero) bits
b. Encode the expanded block using default codeword operation
c. Remove the 330-N dump bits,

The outer encoding of the frame shall be peeformed in the following manner. The PLCP header (consisting of the PHY header, the MAC header and the HCS) shall be encoded using shortened codeword operation as an outer code. Next, the MPDU (MAC frame body followed by the FCS) shall be partitioned into blocks of 330 bits. Each block shall be encoded as $RS_6(63,55)$ using default codeword operation. The last block shall be shortened to the appropriate length using the shortened codeword operation.

The inner convolutional encoder shall use the rate R = 1/2 code with generator polynomials, $g_0 = [010]_2$ and $g_1 = [101]_2$, as shown in Figure 3. In order to return the encoder to the all zero state one ‘zero’ bit shall be appended to the PDPU by the UWB PHY.

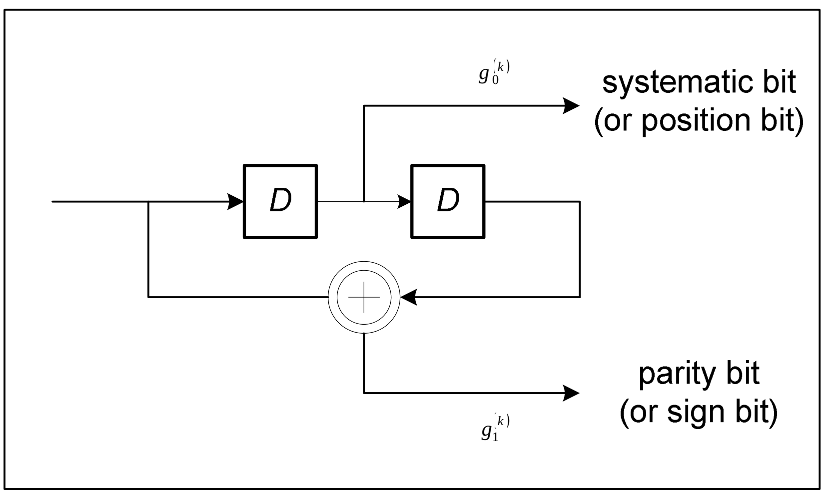


Figure 3 systematic convolutional encoder

6.9 General radio specifications

{ may have updates but uncertain at this time – Pat Kinney leading}

6.9.9a Frame structure which supports optional CCA modes

The optional CCA modes are used to support heavy loaded network which consists of large number of devices in a piconet.

Because of the low radiation power, carrier-less, sparse and transient nature of impulse UWB signal, CCA of impulse UWB signal is considered to be difficult. Distinguishing from the carrier sense in the narrow band systems where CCA is provided by detecting energy from carrier, the CCA of impulse UWB symbol is implemented by detecting presense of UWB traffic. There are regular structures in the preamble portion of a frame (7.5.7a.2.1). The periodicity of preamble remains ever after multipath channel propogation. This enables the time average processing without frame synchronization. Spreading gain of the preamble symble also benefits detection of preamble symbol. As a contrast, after scrambling by a long scrambler sequence, the data portion is random and lack of reliable structure. To enable CCA of impulse UWB signal at any time, we introduce redular structure into the data portion of frame by interleaving preamble segments in the PSDU segments in time domain. The insterted preamble segments server as regular CCA structure of the frame.

Figure CS-1 shows the frame structure which support optional CCA modes. The PSDU part of frame originates from the MAC sublayer (5.4.3). After adding SHR and PHR at the beginning of PSDU, the PHY layer of transmitter regularly inserts preamble segments into the PSDU. Therefore the PSDU segments are interleaved by preamble segments alternatively. Each preamble segment consists of *numPreSegSym* preamble symbols. Each PSDU segments consists of *numPSDUBit* PSDU bits. The PSDU shall be ended with a preamble segment.

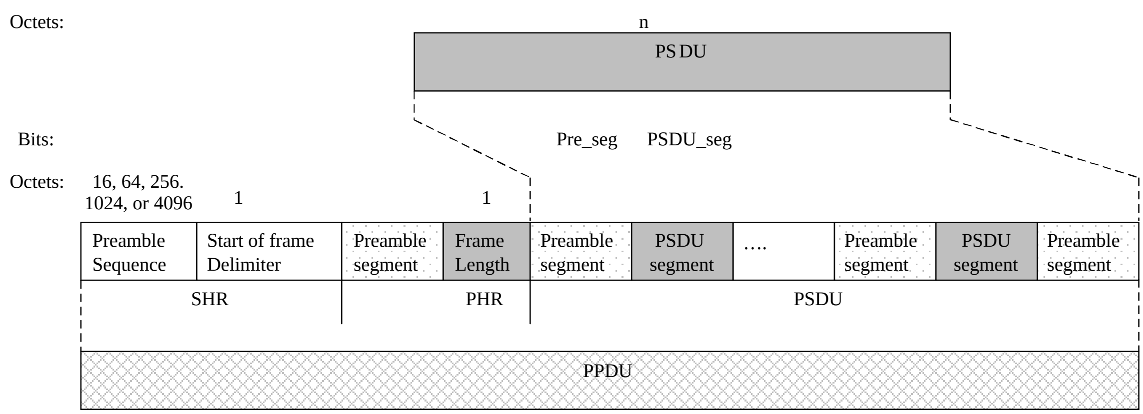


Fig.CS-1 Schematic view of frame structure which support optional CCA modes

The modulation of insterted preamble segements shall use mandatory data rate. The spread code of insterted preamble symbol shall be the same as that of the regular frame preamble. The time interval between neighbour insterted preamble segments is computed as per mandatory data rate (1Mbps). The PHY layers shall guarantee the constant time interval no matter which optional data rate is used.

The PHY PIB attribute *phyCCAMode* (see 6.4) shall indicate the appropriate optional CCA mode. Figure CS-2 shows the constant CCA detection window shall be equal to *numCCAWin*. Wherever the CCA detection window starts, either from the regular preamble or from the data portion in a frame, the CCA detectors shall find at least *numPreSeg*numPreSegSym* preamble symbols in the CCA detection window. [1]

[1] **We are waiting for input of typical preamble length and data portion to decide the optimal value of *numPreSeg*, *numPreSegSym*, and *numCCAWin*.**

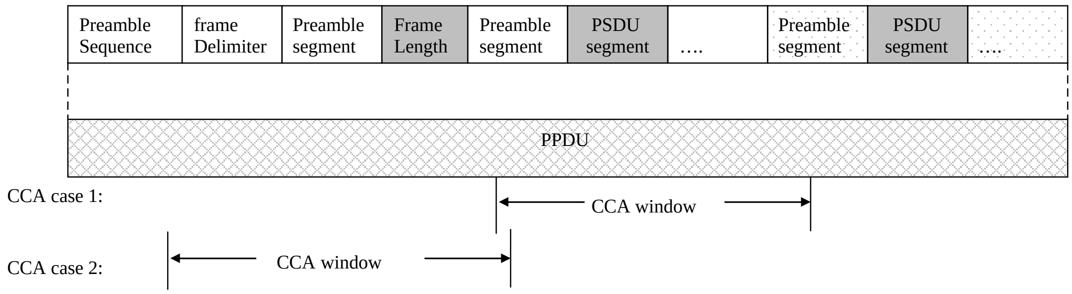


Fig.CS-2 CCA detection window

The frame structures shall only be applied to data frame and MAC frame in the CAP when the PHY PIB attribute *phyCCAMode* (see 6.4) is set to the optional CCA mode. The frame structures shall not applied to

- **all frames when PHY PIB attribute *phyCCAMode* (see 6.4) is set to mandatory ALOHA mode;**
- **data frame in the CFP;**
- **beacon frame and acknowledgement frame[2].**

If the PLME-CCA.request primitive is received by the PHY during reception of a PPDU, CCA shall report a busy medium. Otherwise, an idle medium shall be reported.

When receving the frame structure, the PHY layer of the destinated device simply skipps or discards the inserted preamble segements. Only the de-spread PSDU is passed to the MAC.

7. MAC Sub-Layer Specification

7.1 MAC Sub-Layer Service Specification

7.1.1 MAC Data Service

7.1.1.1 MCPS-DATA.request

7.1.1.1.1 Semantics of the Service Primitive

The semantics of the MCPS-DATA.request primitive is as follows:

MCPS-DATA.request (
SrcAddrMode,
SrcPANId,
SrcAddr,
DstAddrMode,
DstPANId,
DstAddr,
msduLength,

[2] In the beacon frame, only the mandotary features can be used. The ACK frame does not need to be CCA enabled because there are tow times of CCA in the CSMA-CA algorithm.

msdu,
msduHandle,
TxOptions,
SecurityLevel,
KeyIdMode,
KeyId,
ServiceType
)

Table 41 specifies the parameters for the MCPS-DATA.request primitive.

Table 41—MCPS-DATA.request parameters

Name	Type	Valid range	Description
...	...	...	...
ServiceType	Enumeration	SERVICE_DATA, SERVICE_RANGING	Optional. The service type of the MSDU to be transmitted by the MAC sublayer entity.

7.1.1.2 MCPS-DATA.confirm

7.1.1.2.1 Semantics of the Service Primitive

The semantics of the MCPS-DATA.confirm primitive is as follows:

MCPS-DATA.confirm (
msduHandle,
status,
Timestamp,
TimestampAck,
mpduLinkQualityAck
)

Table 42 specifies the parameters for the MCPS-DATA.confirm primitive.

Table 42—MCPS-DATA.confirm parameters

Name	Type	Valid range	Description
...	...	...	...

Name	Type	Valid range	Description
Timestamp	List of Integer	0x000000-0xFFFFFF	Optional. List of two values. The first value represents the time in symbols, at which the data were transmitted (see 7.5.4.1). The value(s) of this parameter will only be considered valid if the value of the status parameter is SUCCESS; if the status parameter is not equal to SUCCESS, the value of the Timestamp parameter shall not be used for any other purpose. The symbol boundary is determined by *macSyncSymbolOffset* (see Table 86). This is a 24-bit value, and the accuracy of this value shall be a minimum of 20 bits, with the lowest 4 bits being the least significant. The second value determines the symbol boundary with high resolution (see 6.2.1.1.4) instead of by the *macSyncSymbolOffset* attribute. Implementation specific.
TimestampAck	List of Integer	0x000000-0xFFFFFF	Optional. List of two values. The first value represents the time in symbols, at which the acknowledgment frame was received. The values of this parameter will only be considered valid if the value of the status parameter is SUCCESS; if the status parameter is not equal to SUCCESS, the value of the Timestamp parameter shall not be used for any other purpose. This is a 24-bit value, and the accuracy of this value shall be a minimum of 20 bits, with the lowest 4 bits being the least significant. The second value determines the symbol boundary with high resolution. Implementation specific. Parameter is only valid, when an acknowledged transmission was requested and the acknowledgment was received successfully.
mpduLinkQualityAck	Bitmap	0x00000000-0xFFFFFFFF	Optional. The 8 LSBs represent the link quality indication (LQI) value measured during reception of the acknowledgment frame. Lower values represent lower LQI (see 6.9.8). The 24 MSBs represent the figure of merit information of a ranging operation (see 6.8.3.4). Parameter is only valid, when an acknowledged transmission was requested.

7.1.1.3 MCPS-DATA.indication

7.1.1.3.1 Semantics of the Service Primitive

The semantics of the MCPS-DATA.indication primitive is as follows:

```
MCPS-DATA.indication (
          SrcAddrMode,
          SrcPANId,
          SrcAddr,
          DstAddrMode,
          DstPANId
          DstAddr,
          msduLength,
          msdu,
```

mpduLinkQuality,
SecurityLevel,
DSN,
Timestamp,
TimestampAck,
GrpAddress,
SrcAddrMatch,
status,
ServiceType
)

Table 43 specifies the parameters for the MCPS-DATA.indication primitive.

Table 43—MCPS-DATA.indication parameters

Name	Type	Valid range	Description
...	...	...	...
mpduLinkQuality	Bitmap	0x00000000-0xFFFFFFFF	The 8 LSBs represent the link quality indication (LQI) value measured during reception of the acknowledgment frame. Lower values represent lower LQI (see 6.9.8). Optional. The 24 MSBs represent the figure of merit information of a ranging operation (see 6.8.3.4).
...	...	...	...
Timestamp	List of Integer	0x000000-0xFFFFFF	Optional. List of two values. List of three values. The first value represents the time in symbols, at which the data were received (see 7.5.4.1). The symbol boundary is determined by *macSyncSymbolOffset* (see Table 86). This is a 24-bit value, and the accuracy of this value shall be a minimum of 20 bits, with the lowest 4 bits being the least significant. The second value determines the symbol boundary with high resolution (see 6.2.1.2.1) instead of by the *macSyncSymbolOffset* attribute. Implementation specific.
TimestampAck	List of Integer	0x000000-0xFFFFFF	Optional. List of two values. The first value represents the time in symbols, at which the acknowledgment frame was transmitted. The value of this parameter will only be considered valid if the value of the status parameter is ACK; if the status parameter is not equal to ACK, the value of the Timestamp parameter shall not be used for any other purpose. This is a 24-bit value, and the accuracy of this value shall be a minimum of 20 bits, with the lowest 4 bits being the least significant. The second value determines the symbol boundary with high resolution. Implementation specific.
status	Enumeration	ACK, NO_ACK	Optional. The status of the acknowledgment.
ServiceType	Enumeration	SERVICE_DATA, SERVICE_RANGING	Optional. The service type of the MSDU received is indicated to the higher layer.

7.1.1.3.2 When Generated

....

If the MPDU was received successfully, and an acknowledgment, if requested, was transmitted, the MAC sub-layer will issue the MCPS-DATA.indication primitive with a status of ACK, otherwise with a status of NO_ACK.

....

7.2 MAC Frame Formats

...

7.2.1 General MAC Frame Format

The MAC frame format is composed of a MHR, a MAC payload, and a MFR. The fields of the MHR appear in a fixed order; however, the addressing fields may not be included in all frames. The general MAC frame shall be formatted as illustrated in Figure X1.

Octets: 2	1	0/2	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2
Frame control	Sequence number	Destination PAN identifier	Destination address	Source PAN identifier	Source address	Auxiliary security header	Frame payload	FCS
		Addressing fields						
MHR							MAC payload	MFR

Figure X1 General MAC Frame Format

7.2.1.1 Frame Control Field

The frame control field is 16 bits in length and contains information defining the frame type, addressing fields, and other control flags. The frame control field shall be formatted as illustrated in Figure X2.

Bits: 0–2	3	4	5	6	7–9	10–11	12–13	14–15
Frame type	Security enabled	Frame pending	Ack. request	PAN ID compression	Reserved	Dest. addressing mode	Frame version	Source addressing mode

Figure X2 Format of the Frame Control Field

7.2.1.1.1 Frame Type Value

The frame type subfield is 3 bits in length and shall be set to one of the non-reserved values listed in Table X1.

Table X1 - Values of the frame type subfield

***b*2 *b*1 *b*0**	**Description**
000	Beacon
001	Data
010	Acknowledgment
011	MAC command
100-111	Reserved

7.2.2.4 MAC command frame format

The MAC command frame shall be formatted as illustrated in Figure X3.

Octets: 2	1	(see 7.2.2.4.1)	0/5/6/10/14	1	variable	2
Frame control	Sequence number	Addressing fields	Auxiliary security header	Command frame identifier	Command payload	FCS
MHR				MAC payload		MFR

Figure X3 MAC command frame format

The order of the fields of the MAC command frame shall conform to the order of the general MAC frame as illustrated in Figure X1.

7.2.2.4.1 MAC command frame MHR fields

...

7.2.2.4.2 Command frame identifier field

The command frame identifier field identifies the MAC command being used. This field shall be set to one of the non-reserved values listed in Table 82.

7.2.2.4.3 Command payload field

The command payload field contains the MAC command itself. If protection is required on an outgoing command frame, this frame shall be processed using information, such as the security level, contained in the auxiliary security header. The device shall process an incoming command frame using information, such as the security enabled subfield of the frame control field, and information, such as the security level, contained in the auxiliary security header (if present) of the incoming frame, in order to determine the intended MAC command. If the MAC command type indicates that it is a private ranging notification packet, the payload should contain a reference or index to Ternary sequences to be used in preambles of the data packets to be exchanged for ranging. It is recommended that preamble of forward data packet and backward data packet is formed from different Ternary sequences to increase privacy level. In this case, the payload should contain an identifier index for each sequence. The receiving device should also infer from the command frame identifier that if it is a command for range notification, which is used for private ranging, it shall dither its turn-around time. The formats of the individual commands are described in 7.3.

7.3 MAC Command Frames

The command frames defined by the MAC sub-layer are listed in Table 67. An FFD shall be capable of transmitting and receiving all command frame types, with the exception of the GTS request command, while the requirements for an RFD are indicated in the table. MAC commands shall only be transmitted in the CAP for beacon-enabled PANs or at any time for non-beacon-enabled PANs.

How the MLME shall construct the individual commands for transmission is detailed in 7.3.1 through 7.3.3. MAC command reception shall abide by the procedure described in 7.5.6.2.

Table 82 MAC command frames

Command frame identifier	Command frame	RFD		Sub-clause
		Tx	Rx	
0x01	Association request	X		7.3.1.1
0x02	Association response		X	7.3.1.2
0x03	Disassociation notification	X	X	7.3.1.3
0x04	Data request	X		7.3.2.1
0x05	PAN ID conflict notification	X		7.3.2.2
0x06	Orphan notification	X		7.3.2.3
0x07	Beacon request			7.3.2.4
0x08	Coordinator realignment		X	7.3.2.5
0x09	GTS request			7.3.3.1
0x0a	Range notification		X	7.3.4.1
0x0b-0xff	Reserved			-----

7.3.4 Private Ranging

These commands are used to allow devices to perform private ranging with their coordinators.

7.3.4.1 Range notification

Range notification command is sent by a ranging source (typically a coordinator) to one of its target associated devices. It is transmitted prior to ranging data packet exchanges and only if the ranging is desired to be performed in the private mode. Coordinators should be capable of sending this command, while coordinators and RFDs are required to be capable of receiving it.

Range notification command shall be formatted as illustrated in Figure YY.

octet: 17/23	1	1 bit	1	1
MHR Fields	Command frame identifier (see Table 67)	Ternary Sequence Length	Forward preamble Ternary sequence identifier index	Backward preamble Ternary sequence identifier index

Figure YY Range notification command format

7.3.4.1.1 MHR Fields

The fields of the MHR of the general MAC frame format (see Figure X1) shall be specified as indicated in this sub-clause.

The destination addressing mode subfield of the frame control field shall be set to 2 (i.e., 16 bit short addressing), and the source addressing mode subfield shall be set to 2 (i.e. 16 bit short addressing).

The destination PAN identifier field shall contain the broadcast PAN identifier (i.e., 0xffff). The destination address field shall contain the short address of the destination, which is the target node in ranging process.

7.3.4.1.2 Forward preamble Ternary sequence identifier

This field specifies the Ternary sequence by which the preamble of the ranging data packet to be transmitted by the source shall be formed. The four octet long field enables an explicit identification of a length-31 sequence. If a look-up table is used, full length sequence does not have to be specified, but just 1-octet pointer to the sequence. This is more efficient, if the Ternary sequences are selected from a set in which the length of each sequence is 127.

7.3.4.1.3 Backward preamble Ternary sequence identifier

This field specifies the Ternary sequence by which the preamble of the ranging data packet to be transmitted by the target (e.g. acknowledgment) shall be formed. The four octet long field enables an explicit identification of a length-31 sequence. If a look-up table is used, full length sequence does not have to be specified, but just 1-octet pointer to the sequence. This is more efficient, if the Ternary sequences are selected from a set in which the length of each sequence is 127.

7.3.4.1.4 Ternary Sequence Length

This 1-bit field is set to 0 if length-31 sequences are to be used for ranging preamble and set to 1 if length 127 sequences are to be used.

7.4 MAC Constants and PIB Attributes

Table 86—MAC PIB attributes

Attribute	Identifier	Type	Range	Description	Default
...	...	...	...	...	
macAckWaitDuration	0x40	List of Integer	38, 50, 54 or 120, ?	The maximum number of symbols to wait for an acknowledgment frame to arrive following a transmitted data frame. List of two values, second is optional. These values are dependent on the supported PHY, which determines both the selected logical channel and channel page and the used preamble length for ranging. The calculated values are time to commence transmitting the ACK plus the length of the ACK frame. The commencement time is described in 7.5.6.4.2. The first list value is used for the data service, the second for the ranging service.	Dependent on supported PHY and default ranging preamble length.
...	...	...	...	...	...
macRangingSupported†	0x60	Boolean	TRUE or FALSE	This indicates whether the MAC sublayer supports the optional ranging features*.	FALSE
macRangingPreambleType	0x61	Enumeration	TYPE_2, TYPE_3,...	Optional. The preamble type used for ranging.	TYPE_2
macRangingSynbolLength	0x62	Boolean	1 or 0	0 indicates the basis symbol for the preamble is length 31, otherwise length-127	TBD

*optional MAC ranging features: to be listed ...

....

Table 90— PIB security attributes

Attribute	Identifier	Type	Range	Description	Default
...	...	...	...	...	
macMPDUOffset	0x7c	Integer	0x00-0xFF	Optional. Added delay of the MPDU for privacy on ranging. Implementation specific, minimum range is 300? ns, maximum step size is 3? ns.	0x00

7.5 MAC Functional Description

Insert the following after 7.5.7

7.5.7a Ranging

For ranging a data-acknowledgment frame sequence is utilized. Data and acknowledgment frames deliver timestamps at reception and transmission with high precision to the next higher layer. A higher layer or the application layer can calculate the distance from the time stamps of a data-acknowledgment round trip measurement. The calculation of distance or location of a radio is out of the scope of this standard and in responsibility of a higher layer. A ranging sequence is initiated by the higher layer through the MCPS-DATA request service primitive. In addition an acknowledged transmission must be requested through the service request. Both, the data and the acknowledgment frame utilized for ranging are ordinary MAC frames as used in MAC data service. Since ranging requires certain signal structures, the PHY frames of ranging sequences use different preamble types than ordinary data, acknowledgment, MAC command or beacon frames. The ranging support of the PHY is requested by the next higher layer above the MAC through an additional service type parameter. The information in this parameter is forwarded to the PHY, which in turn generates the PHY frames with the corresponding preamble. The service type of incoming frames is detected in the PHY, information is forwarded to the MAC and indicated to the next higher layer through the service type parameter of the MCPS-DATA indication primitive. The ranging frame sequence is not dedicated to ranging only, it may be utilized for additional data service between higher layers concurrently.

How ranging frame sequences are initiated, how ranging information is exchanged between ranging endpoints and other ranging specific protocol issues are out of the scope of this standard and in responsibility of a higher layer. This applies as well to the complete security and privacy mechanisms on ranging. However, MAC security features like encryption, replay protection and the MPDU offset may be utilized the by a higher layer for security and privacy on ranging.

7.5.7a.1 Classes of Service

Three classes of ranging service are supported in IEEE 802.15.4a: high accuracy ranging, fast ranging and cost effective ranging. The first two services are supported by coherent receivers. Non-coherent receivers only support the cost effective ranging.

7.5.7a.1.1 High Accuracy Ranging

The high accuracy ranging is referred to as a ranging accuracy of 10 cm at 50 meters in 8 milliseconds roundtrip time.

7.5.7a.1.2 Fast Ranging

The fast ranging is referred to as 10 cm accuracy at 20 meters in 1 milliseconds roundtrip time.

7.5.7a.1.3 Ranging with Non-coherent receivers

Ranging accuracy with coherent receivers is greater than that of non-coherent receivers. Cost effective ranging accuracy offered by non-coherent receivers is determined to be sub-meter, and it is highly dependent on receiver-end signal processing techniques.

7.5.7a.2 General Ranging Constructions

7.5.7a.2.3 Message Timestamps

7.5.7a.2.3.5 Mitigation of relative crystal drift

The standard supports two ways to manage crystal drifts referred to as implicit and explicit approaches. In the explicit approach the receiving node determines the relative drift and reports it back to the original sender. The implicit approach is also known as the symmetric double sided two way ranging (SDS-TWR). In SDS-TWR, the two nodes take turn in initiating ranging with each other. The time stamps when subtracted in the proper order would eliminate relative crystal drift.

7.5.7a.2.4.1 Definition

The goal of ranging is to determine the distance between two nodes. The purpose of positioning is to determine the position of a node in a network of nodes. Positioning, in simple words, utilizes triangulation using a number of estimated distances obtained through ranging measurements. The computational core of positioning is what is referred to as solver. One can think of the solver as a set of algorithms that work together to determine location. The goodness of the triangulation performed by the solver is heavily influenced by the quality of individual range measurements. Typically the solver assigns more weights to a more trustworthy measurement. The figure of merit is a measure of how worthy each ranging estimate is. Implementation of the solver is outside the scope of this standard. However, the standard does provide the figure of the merit to be used by solvers in any desired manner.

7.5.7a.2.6 Message sequences for two-way ranging

7.5.7a.2.6.1 MAC command to initiate two way ranging

Range notification command is used to initiate two-way ranging.

7.5.7a.2.6.2 The two-way ranging initiate packet

The two-way ranging initiate packet is prepared by the ranging originator. If a range notification command is transmitted before this initiate packet; and the sequence identifier and its length given in the range notification packet are different from their default, those should be used to form a preamble of the ranging initiate packet.

7.5.7a.2.6.3 The two-way ranging response packet

The two-way ranging response packet is a conventional ACK packet specified in IEEE 802.15.4b specifications. However, its preamble length should be one of the specified in Table xxx. During private ranging, the preamble of the ACK is formed from the sequence corresponding to the one given in "**backward preamble Ternary sequence identifier"** field of the range notification packet. If not private ranging, the preamble is formed by using the default length-31 sequence.

7.5.7a.2.6.4 Timestamp report message

The time stamp report is sent by a ranging target to the ranging source following ranging transaction packet exchange. Both coordinators and RFDs should be capable of sending this command. The target device that transmits a two-way ranging response packet, after transmission of the response packet forms and transmits a timestamp report message to the originator. The structure of the timestamp report message is illustrated in Figure TS.

Octet 17/23	1	4	4	3	b1 b0
MHR Fields	Command frame identifier (see Table 82)	Time Stamp	Tracking length	FOM /Tracking offset	Ranging Grade and Confidentiality

Figure TS Time stamp report command format

7.5.7a.2.6.4.1 Time Stamp

The total reply time of the target node is reported to the source in this field. A 32 bit field is allocated to this quantity.

7.5.7a.2.6.4.2 Tracking Length

The total tracking delay of the target node is reported to the source in this field. A 32 bit field is allocated to this quantity.

7.5.7a.2.6.4.3 Tracking Offset and Figure of Merit (FOM)

Tracking offset communicates the crystal offset information. Figure of merit (FOM) reflects the confidence in the accuracy of the extracted leading edge. FOM and crystal tracking offset are 5 and 19 bits wide, respectively. Altogether they require 3 bytes of information.

7.5.7a.2.6.4.4 Ranging Grades and Confidentiality

The bit b0 dedicated to "Ranging Grade" and the bit b1 is dedicated to state "Confidentiality". Ranging target can selectively degrade the time stamp provided to the source. Standard supports two grades of ranging accuracy defined as accurate or partially accurate. As such only one bit is allocated for this field in the time stamp report. "Accurate" is the default mode and set to 0. In the "degraded" mode, the target sets b0 to 1. Ranging target can request the source to treat its ranging information confidential or non-confidential. As such this field requires just one bit. The default mode is non-confidential. Hence, in the default mode b1 shall be set to 0 and 1 otherwise.

7.5.7a.4 Private Ranging

Ranging operations are vulnerable to attack for the purpose of fraudulent use and transmission interception. Data services can be protected by dedicated mechanisms which take place at higher layers. For instance, in IEEE Standard 802.15.4-2003 the MAC sub-layer is responsible for providing security services such as data encryption and frame integrity. However, ranging requires a protection on the PHY waveform to avoid potential acquisition by an unauthorized device.

Private ranging is an optional set of mechanisms which provide users with privacy in ranging operation. It aims to keep the measurements confidential and to prevent the user from attacks by malicious devices.

There are typically two motivations behind location related attacks. First, an intruder intends to figure out the location of sensor devices in a protected area and tries to tamper and disable them. In the latter, the intention is invisibly to be detrimental to a network. Relative positioning information in a network can be used to optimize high layer network operations such as route discovery and maintenance, multi-casting and broadcasting. If falsified position information is passed within the network, optimality of such network operations can be damaged. Malicious devices can be classified as snoopers, impostors and jammer.

A snooper device within the ranging concept observes or listens to the signals in the air in secret to obtain information on whereabouts of other devices. By measuring signal strength of transmissions and the delay between a range request and a range response, a snooper can have a coarse knowledge of its range to other devices.

An impostor device engages in deception under an assumed name or identity. By simply replaying originator's ranging message it can trigger a response at the target node and hence track the relative distance between them. In unsecure fast ranging networks, an impostor can impersonate target devices by transmitting a ranging reply before the target and cause the originator device to misread its range to the target.

A jammer device simply injects interference into the network and prevents neighboring devices from performing message exchanges. The most effective way to deal with a jammer is to back-off until it stops. Also, advanced signal processing techniques at the receiver can be used to remove interference from the desired signal.

The IEEE 802.15.4a PHY provides hooks for implementing private-ranging mechanisms for variety of applications. Although this standard targets a diverse range of applications, a baseline implementation is required in the PHY to offer basic private-ranging services and interoperability among all devices.

The higher layer shall control the use of private ranging at the PHY layer and shall transfer the material required by the private-ranging services which have been specified.

7.5.7a.4.1 Private Ranging Services

The PHY layer is in charge of providing private-ranging services on specified ranging frames when requested by the higher layers. The IEEE Standard 802.15.4a supports the following private-ranging services: authentication, confidentiality and information hiding.

7.5.7a.4.2 Ranging Modes

Depending on the mode in which the device is operating and the selected private-ranging suite, the PHY may provide different private-ranging services as explained below.

7.5.7a.4.2.1 Non-Private Mode

This mode relies only on the existing MAC layer security mechanisms in IEEE 802.15.4a and does not require additional processing to enhance privacy of range measurements against malicious devices. Typically in TOA based ranging, the MAC layer of the originator (device A), generates a range-request primitive and passes it to the PHY layer. Then, the PHY transmits a ranging packet to a target node (device B). The range packet consists of a preamble, header and an encrypted payload; B performs acquisition and ranging on the ranging packet preamble. Then, the target MAC layer checks the authenticity of the source. If the ranging packet is identified to be from a legitimate source, a reply ranging packet is formed and transmitted and to the source.

Upon reception of the reply, the source A can track the round trip flight time and correspond it to a distance. Assume that the elapsed time between the departure time of A's signal and the arrival time of the reply from B at A is T_r . The time T_r can be approximated as $T_r = 2T_f + \tau_{ta}$, where T_f is the one-way time of flight of the signal and τ_{ta} is the turn-around time, i.e., the time between the reception timestamp of signal at B and the departure timestamp of reply from B. A key to ensure an accurate range estimate is to have a short τ_{ta} and to accurately measure it. Prolonging τ_{ta} would necessitate factoring in clock drifts into range estimates. Finally, the timestamp of the reception of the first ranging packet and the timestamp of the departure of the second reply from the target are reported to the source in a separate packet by the target.

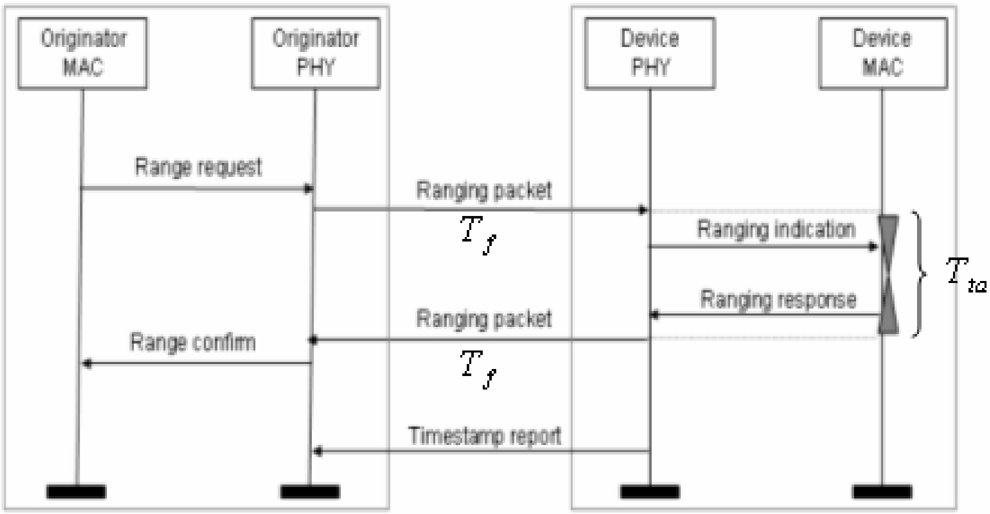


Figure 1 Illustration of typical ranging message exchanges between two ranging devices

7.5.7a.4.2.2 Private ranging mode

To deal with jamming and deceptive malicious devices, the Private ranging mode offers two defense mechanisms: dynamic selection of a ranging waveform for each ranging signaling and dithering of turn-around time.

7.5.7a.4.2.2.1 **Dynamic Preamble Selection (DPS)**

The set of ternary sequences to be used in ranging packet preambles is very small. For length 31 sequences, there exist only six codes with perfect periodic auto-correlation function, while there are only 92 of length 127 such Ternary sequences. If only one sequence from the set is dedicated to ranging, it becomes highly likely for a malicious device to track it. It can simply know what base sequence to track in the air. Furthermore, it can transmit the very same Ternary sequence into the air and those transmissions can be deceptive to legitimate ranging devices already expecting a ranging packet from their partners.

It is shown in simulations that if the Ternary sequences in the preamble of the ranging packets and the signal from a malicious device don't match each other, the detection of the leading edge and periodic auto-correlation peaks at legitimate receivers become easier. Otherwise, the signal from the malicious transmitter also causes the same perfect periodic auto-correlation peaks at legitimate receivers as the signals from desired ranging transmitters. Dynamic preamble selection for the preamble formation of the range packets lowers the likelihood that a malicious device will pick the same preamble sequence.

It is possible to improve the privacy level by selecting a different preamble base sequence for range packet to be transmitted from first device to the second and for that to be transmitted from the second to the first device as a reply.

7.5.7a.4.2.2.2 **Dithering turn-around time**

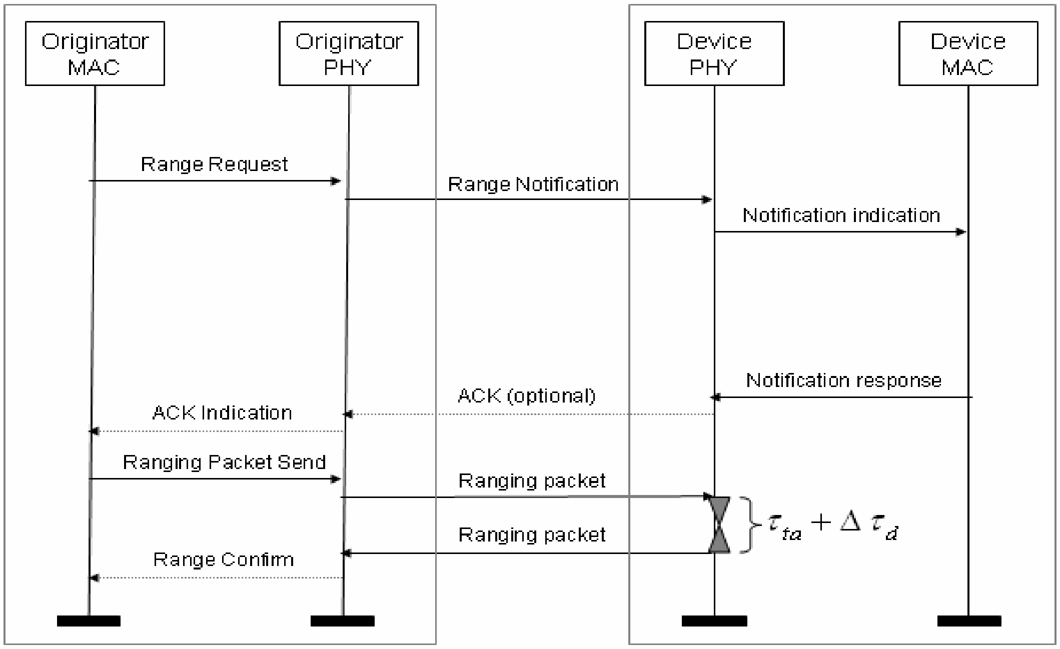
In two-way TOA, the second device receives a ranging packet from the first device; and then it returns a reply ranging packet. The time it elapses between the reception time of the range packet from the first device and transmission time of the reply range packet from the second device is referred to as "turn-around time".

As a privacy mechanism, if the second device simply dithers the turn-around time, any malicious device eavesdropping ranging packets in the air will be exposed to positive bias in its range estimates because of the dither amount unknown to the malicious device. How much to dither can be imposed on the second device by the first device, or simply the second device can delay the turn-around time itself and later on reports it to the first device. Note that it is harder for a device to track whether a predetermined turn-around time elapses. Therefore, the latter is preferred.

7.5.7a.4.2.2.3 **Functional description**

Assume that node A is to initiate a ranging process with node B. The DPS requires a range notification packet to be transmitted from the first device (A) to the second (B) prior to exchanging range packets. The range notification packet is used to inform the second device of what Ternary sequences to use for the ranging packet preambles. Therefore, it should include a sequence identifier. Following the notification packet, the first device forms a ranging packet with a preamble constructed from the selected sequence, and sends the ranging packet to the second device. This ensures that the range packet is manipulated randomly by using different base sequence for each ranging packet. The ranging packet consists of a preamble, header and a payload. The second device performs acquisition and leading edge detection on the preamble. It then, replies to the first device with a ranging packet with a preamble of the selected sequence after some delay time $\tau_{ta} + \Delta\tau_d$ that is known only to the first device and to the second device itself. The preamble sequence of the ranging packet by the first device may be different from that by the second device to increase privacy level.

The delay time can be either set by the first device and transmitted to the second device in an encrypted form in the range notification packet, or if the preference is for the second device to decide what the turn-around time dither $\Delta\tau_d$ would be, this information should be reported back to the first device after ranging packet exchanges are completed. The latter option is easier to implement and recommended over the first.



The timestamp of the reception of the first ranging packet at the second device and the timestamp of the departure of the second reply from the second device are reported to the first device in a separate packet by the target. Hence, the dither duration becomes factored into the time-stamps.

7.5.7b UWB option management

7.5.7b.1 Data rates

UWB PHYs optionally support multiple data rates as defined in {ref to 6.xxx}.A mandatory rate as defined in {reference 6.xxx} shall be present in all UWB PHYs. A PAN established at the mandatory rate may elect to operate with optional data rates. Table ccc defines this operation.

Table ccc – UWB data rate operation

		Mandatory operation		Optional low rate operation				
		PHR	PSDU	PHR	PSDU			
Coordinator traffic		base	base	Low base	Low base			
Initial		base	base	base	base			
App negotiated		base	All rates	Low base	Low base			

Methods for managing rates are left for higher layer protocols and are outside of the scope of this amendment.

Annex C
(normative)

Protocol implementation conformance statement (PICS) proforma

{Jay to collect inputs from editors}

{use the following as the template for new tables or row additions to existing tables in this annex

Item number	Item description	Reference	Status	Support N/A	Yes	No

}
C.7 PICS proforma tables

C.7.2.3 RF
Insert the following rows at the end of Table C.4—RF

Table C.4--RF

Item number	Item description	Reference	Status	Support N/A	Yes	No
RF3	2450 MHz CSS PHY	6.5a	O.3			
RF4	3100 to 10000 MHz UWB PHY	6.8a	O.3			
RF4.1	Low band 1		O			
RF4.2	Low band 2		M			
RF4.3	Low band 3		O			
RF4.4	Low band wide		O			
RF4.5	High band 1		O			
RF4.6	High band 2		O			
RF4.7	High band 3		O			

RF4.8	High band 4	O
RF4.9	High band 5	O

{add additional sub-clauses and tables for additional optional behaviors. Preambles, data rates, pulse shapes for radios and ranging for MAC/PHY}

Insert the following after Annex D

Annex D1 (informative) Ranging topics

{Will be developed as a distinct document and merged when available} {Camillo lead}

Annex E (informative) Coexistence with other IEEE standards and proposed standards

{Patricia lead}

Annex F (informative) Regulatory requirements

{Patricia lead}