**IEEE P802.15**

**Wireless Personal Area Networks**

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| Source | Billy Verso (DecaWave),  Michael McLaughlin (DecaWave)  Igor Dotlić (NICT)  Huan-Bang Li (NICT)  Marco Hernandez (NICT)  Ryu Miura (NICT) | billy.verso @ decawave.com  michael.mclaughlin @ decawave.com  dotlic @ nict.go.jp  lee @ nict.go.jp  marco @ nict.go.jp  ryu @ nict.go.jp |
| Re: | draft text of UWB PHY for 802.15.8 | |
| Abstract | This is the work in progress text of the Impulse Radio Ultra-Wideband PHY for IEEE 802.15.8 group for PAC, this is a merged text with . | |
| Purpose | This document provides the details of the PHY proposal to IEEE 802.15.8 | |
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# [This is draft text for the merged (BPM-BPSK & OOK) UWB PHY for TG8]

# Overview

# Definitions

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

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

***frame:*** format of aggregated bits that are transmitted together in time

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

***payload data:*** contents of a data message that is being transmitted

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

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

***ranging marker (RMARKER):*** the start of the first symbol of the physical layer (PHY) header (PHR) of a ranging frame (RFRAME)

***symbol:*** a 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.

# Acronyms and abbreviations

BPM burst position modulation

BPSK binary phase-shift keying

CRC cyclic redundancy check

DPS dynamic preamble selection

FCS frame check sequence

FEC forward error correction

LFSR linear feedback shift register

LSB least significant bit

MAC medium access control

MSB most significant bit

OOK on off keying

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

RFRAME ranging frame

RMARKER ranging marker

SFD start-of-frame delimiter

SHR synchronization header

SYNC synchronization

UWB ultra wide band

# General descriptions

## Concepts and architecture

## Topology

## Reference model

# MAC Layer

## Synchronization

UWB PHY PLACEHOLDER: In general MAC layer procedures should be applicable on top of the UWB PHY, however this place holder is to note that there may be some PHY specific elements to the synchronization procedures that need to be considered and noted here – e.g. MAC provisions for ranging and localization.

## Discovery

UWB PHY PLACEHOLDER: In general MAC layer procedures should be applicable on top of the UWB PHY, however this place holder is to note that there may be some PHY specific elements to the discovery procedures that need to be considered and noted here – e.g. MAC provisions for ranging and localization.

## Peering

UWB PHY PLACEHOLDER: In general MAC layer procedures should be applicable on top of the UWB PHY, however this place holder is to note that there may be some PHY specific elements to the peering procedures that need to be considered and noted here – e.g. MAC provisions for ranging and localization.

## Communications

UWB PHY PLACEHOLDER: In general MAC layer procedures should be applicable on top of the UWB PHY, however this place holder is to note that there may be some PHY specific elements to the communications procedures that need to be considered and noted here – e.g. MAC provisions for ranging and localization.

## Frame Check Sequence (FCS)

*<Note to editor: the text below is the standard text for FCS; this should be placed as a sub-clause within the clauses that deal with the general MAC frame format>*

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:

*G16(x) = x16+x12+x5+1*

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

* Let *M(x) = b0xk–1 + b1xk – 2 +…+ bk–2x + bk – 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 x16 × *M(x).*
* Divide x16 × *M(x)* modulo 2 by the generator polynomial, *G*16(*x*)*,* to obtain the remainder polynomial, *R(x) = r0x15 + r1x14 +…+ r14x + r15*.
* 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 (b0) transmitted first in time]

b0................................................................b23

The FCS for this case would be the following:

0010 0111 1001 1110 [leftmost bit (r0) transmitted first in time]

r0.......................................r15

A typical implementation is depicted in Figure 1.



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 1 – typical FCS implementation

# UWB Physical (PHY) layer specification

## General

The UWB PHY employs an impulse radio signaling scheme using band-limited pulses. The UWB PHY supports two alternative primary modulation modes of operation, a BPM-BPSK modulation mode and an OOK modulation mode, operating in channels between 3.1 GHz and 10.6 GHz.

The common elements of the UWB PHY are captured in this sub-clause, while the specifics of the BPM-BPSK and OOK modulation modes are in 6.2 and 6.3 respectively.

There are many parameter options within the UWB PHY, which for successful communications have to be the same at both ends of a link. The mechanisms for ensuring that are not defined within this PHY layer specification. These choices are typically preconfigured or mutually agreed.

Figure 2 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 2 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 2 – UWB PHY signal flow

### PPDU format

Figure 3 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. Unless otherwise stated, 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 PSDU contains MAC sub-layer messages.

### PPDU encoding process

The encoding process is composed of many steps as illustrated in Figure 3. 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:

1. Perform Reed-Solomon encoding on PSDU as described in 6.1.5.1.
2. Produce the PHR with SECDED check bits as described in 6.1.3 and prepend to the PSDU.
3. Perform convolutional coding as described in 6.1.5.2. Note that for the BPM-BPSK modulation mode 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.
4. Modulate and spread the PHR and PSDU according to the methods described for the BPM-BPSK modulation mode in 6.2.3.3 and 6.2.3.4, and for the OOK modulation mode in 6.3.3 and 6.3.4. Note that the PHR modulation rate may differ from that of the data field. The data field modulation rate is specified in the PHR. The PHR modulation rate options are defined in 6.1.3.
5. Produce the SHR preamble field consisting of the SYNC field and the SFD field (marking the end of the SHR and the start of the packet data). The SYNC and SFD fields are described for the BPM-BPSK modulation mode in 6.2.2.1 and 6.2.2.2, respectively, and for the OOK modulation mode in 6.3.2.



Figure 3 – UWB PHY PPDU encoding process

Table 1 and Table 2 show how the 19 header bits (H0‑H18), N data bits (D0‑DN-1), and two tail bits (T0‑T1) are mapped onto the symbols. In these tables, the operation in the g1column is an XOR. The tables also show when the transition from the header to the data takes place. Note that the delay line of the convolutional code is initialized to zero. For this reason, the g1bit (position bit for BPM-BPSK modulation mode) within Symbol 0 shall always be zero.

Table 1 – mapping of header bits, data bits and tail bits onto symbols with Viterbi rate 0.5

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Symbol #** | **Input data** | **g0** | **g1** |  |
| 0 | H0 | 0 | H0 | 21 symbols  of PHR at the appropriate  PHR modulation rate  for BPM-BPSK modulation mode  42 symbols of PHR at the appropriate PHR modulation rate for OOK modulation mode |
| 1 | H1 | H0 | H1 |
| 2 | H2 | H1 | H0  H2 |
| 3 | H3 | H2 | H0  H3 |
| … | … | … | … |
| 16 | H16 | H15 | H14  H16 |
| 17 | H17 | H16 | H15  H17 |
| 18 | H18 | H17 | H16  H18 |
| 19 | D0 | H18 | H17  D0 |
| 20 | D1 | D0 | H18  D1 |
| 21 | D2 | D1 | D0  D2 | N symbols  of data  at the data rate for BPM‑BPSK modulation mode  2 × N symbols of data at the data rate  for OOK modulation mode |
| … | … | … | … |
| N + 17 | DN-2 | DN-3 | DN-4  DN-2 |
| N + 18 | DN-1 | DN-2 | DN-3  DN-1 |
| N + 19 | T0 | DN-1 | DN-2  T0 |
| N + 20 | T1 | T0 | DN-1  T1 |

Note for the BPM-BPSK modulation mode g0 is the position bit and, g1 is the polarity bit.

Table 2 –mapping of header bits, data bits and tail bits onto symbols with Viterbi rate 1

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Symbol #** | **Input data** | **g0** | **g1** |  |
| 0 | H0 | 0 | H0 | 21 symbols  of PHR at the appropriate  PHR modulation rate  for the BPM-BPSK modulation mode |
| 1 | H1 | H0 | H1 |
| 2 | H2 | H1 | H0  H2 |
| 3 | H3 | H2 | H0  H3 |
| … | … | … | … |
| 16 | H16 | H15 | H14  H16 |
| 17 | H17 | H16 | H15  H17 |
| 18 | H18 | H17 | H16  H18 |
| 19 | T0 | H18 | H17  T0 |
| 20 | T1 | D0 | H18  T1 |
| 21 | D0, D1 | D0 | D1 | N/2 symbols  of data  at the data rate  for the BPM-BPSK modulation mode |
| 22 | D2, D3 | D2 | D3 |
| … | … | … | … |
| N/2 + 19 | DN-6, DN-5 | DN-6 | DN-5 |
| N/2 + 20 | DN-4, DN-3 | DN-4 | DN-3 |
| N/2 + 21 | DN-2, DN-1 | DN-2 | DN-1 |

Note for the BPM-BPSK modulation mode g0 is the position bit and, g1 is the polarity bit.

### PHY header (PHR)

The PHR shall be transmitted 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 frame’s preamble, and the length of the frame payload. Additionally, six parity check bits are used to protect the PHR against channel errors.

The UWB PHY has two options for PHR, both 19 bits long, the one defined in 6.1.3.1 allows for PSDU of up to 127 octets (and supports reuse of the existing [HRP] UWB PHY standard defined in 802.15.4), while the PHR defined in 6.1.3.2 supports PSDU up to 1023 octets long.

For successful communications both ends of a link must use the same PHR options and modulation rate.

For the BPM-BPSK modulation mode the PHR shall be transmitted at the nominal rate of 110 kb/s (for the 110 kb/s data rate) and 850 kb/s for the higher data rates, and optionally at the data rate for 6.81 Mb/s and 27.24 Mb/s data rates. Table 3 gives the actual modulation rates of the PHR for the BPM-BPSK modulation, which are 15 % higher than the nominal rate because the PHR is not Reed-Solomon encoded

.

Table 3 – BPM-BPSK modulation mode PHR modulation rates

|  |  |
| --- | --- |
| Nominal PHR modulation rate | True PHR modulation rate |
| 110 kb/s | 121.87 kb/s |
| 850 kb/s | 975.00 kb/s |
| 6.81 Mb/s | 7.80 Mb/s |
| 27.24 Mb/s | 31.20 Mb/s |

For the OOK modulation mode PHR shall be transmitted at the nominal rate of 55 kb/s, which is equivalent to the true modulation rate of 62.5 kb/s.

#### PHR for frames up to 127 octets

This PHR is shown in Figure 4.



Figure 4 – UWB PHY bit assignment in PHR for frames up to 127 octets

The Data Rate field shall consist of two bits (R1, R0) that indicate the data rate of the PSDU, as per Table 4.

Table 4 – nominal data rates meaning

|  |  |  |
| --- | --- | --- |
| R1, R0 | Data rate for BPM‑BPSK modulation mode | Data rate for OOK modulation mode |
| 0, 0 | 110 kb/s (O) | 55 kb/s |
| 0, 1 | 850 kb/s (M) | 109 kb/s |
| 1, 0 | 6.81 Mb/s (O) | 218 kb/s |
| 1, 1 | 27.24 Mb/s (O) | 437 kb/s |

For the BPM-BPSK modulation mode the mandatory data rate shall be 850 kb/s, support for the other data rates listed in Table 4 is optional. For the OOK modulation mode the mandatory data rate shall be 55 kb/s, support for the other data rates listed in Table 4 is optional. Note: the nominal modulation mode data rates are calculated by multiplying the base modulation rate by 0.87 to allow for the overhead of the Reed-Solomon encoding.

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 sub-layer has request the PHY to transmit. Note that the high order bit of the length, L6, is transmitted first in time.

The Ranging bit, RNG, when set to 1 indicates that the frame is an RFRAME; otherwise RNG is set to 0.

The Preamble Duration field, P1–P0, represents the length of the SYNC portion of the SHR, as per Table 5.

Table 5 – Preamble Duration field values in PHR for frames up to 127 octets

|  |  |  |
| --- | --- | --- |
| P1, P0 | SYNC length (Nsync) for BPM‑BPSK modulation mode | SYNC length (Nsync) for OOK modulation mode |
| 0, 0 | Reserved | 8 symbols |
| 0, 1 | 64 to 512 symbols | 32 to 64 symbols |
| 1, 0 | 1024 to 2048 symbols | 128 to 256 symbols |
| 1, 1 | 4096 symbols | 512 symbols |

The Preamble Duration field may be used by a receiver set the value of the preamble duration for the ACK frame.

Valid preamble lengths for the BPM-BPSK modulation mode are 64, 128, 256, 512, 1024, 1536, 2048 and 4096 symbols. Valid preamble lengths for the OOK modulation mode are 8, 32, 64, 128, 256 and 512 symbols. Where the Preamble Duration field in the transmitted frame covers a range of preamble lengths, a receiver may count the number of preamble symbols received to additionally inform the choice of preamble length for any response frames.

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 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)

#### PHR for frames up to 1023 octets

This PHR is shown in Figure 4.



Figure 5 – UWB PHY bit assignment in PHR for frames up to 1023 octets

The Data Rate field shall have the same function and encoding as the PHR defined in 6.1.3.1 and Table 4.

The Frame Length field, L9–L0, shall be an unsigned 10-bit integer number that indicates the number of octets in the PSDU from the MAC sub-layer. Note that the high order bit of the length, L9, is transmitted first in time.

A single bit, P0, provides the Preamble Duration field, indicates the length of the SYNC portion of the SHR, as per Table 6.

Table 6 – Preamble Duration field values in PHR for frames up to 1023 octets

|  |  |  |
| --- | --- | --- |
| P0 | SYNC length (Nsync) for BPM‑BPSK modulation mode | SYNC length (Nsync) for OOK modulation mode |
| 0 | 64 to 1024 symbols | 8 to 64 symbols |
| 1 | 1536 to 4096 symbols | 128 to 512 symbols |

The Preamble Duration field may be used by a receiver set the value of the preamble duration for the ACK frame.

Valid preamble lengths for the BPM-BPSK modulation mode are 64, 128, 256, 512, 1024, 1536, 2048 and 4096 symbols. Valid preamble lengths for the OOK modulation mode are 8, 32, 64, 128, 256 and 512 symbols. Since the Preamble Duration field in the transmitted frame covers a range of preamble lengths, a receiver may count the number of preamble symbols received to additionally inform the choice of preamble length for any response frames.

The SECDED (single error correct, double error detect) field, S5–S0, 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 calculation is the same as that defined in 6.1.3.1 except the resultant buts C5–C0 are inverted to get S5–S0 as follows:

S0= *NOT* (C0)

S1 = *NOT* (C1)

S2 = *NOT (*C2)

S3 = *NOT* (C3)

S4 = *NOT* (C4)

S5 = *NOT* (C5)

In the receiver the same checker and corrector block can be used for both PHR encodings, once the received SECDED bits S5–S0 are inverted.

### Data field

The Data field is the last component of the PPDU and is encoded as shown in Figure 6.



Figure 6 – 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 6.1.5.1.
* Encode the output of the Reed-Solomon block code using a systematic convolutional encoder as described in 6.1.5.2, except in the cases where the Viterbi rate is 1.0 in which case the convolutional encoder is bypassed. For the BPM-BPSK modulation mode the Viterbi rates are given in Table 11.
* Spread and modulate the encoded block. For the BPM-BPSK modulation this is described in 6.2.3.3 and 6.2.3.4, and for the OOK modulation mode in 6.3.3.

### 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.

For all modes of OOK modulation the coding is always concatenation of outer Reed-Solomon and inner Viterbi code, however for the BPM-BPSK modulation mode the inner convolutional code is not necessarily enabled at all data rates, i.e. the rows of Table 11 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, *b0, b1, …, bM-1*, is shown in Figure 7. The Reed-Solomon encoder shall append 48 parity bits, *p0, p1, …, p47*, 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 2*M* + 96 bits.

For BPM-BPSK modulation mode: 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, except where the Viterbi rate is 1.0 where even outputs of the Reed-Solomon encoder *(b0, b2,..., bM–2, p0, p2,…, p46)* shall be used to encode the position of the burst, and odd outputs *(b1, b3,..., bM–1, p1, p3,…, p47)* 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.

For OOK modulation mode the output modulation bits always represent concatenation of bits and as described in detail in 6.3.3.



Figure 7 – FEC encoding process

#### Reed-Solomon encoding

The systematic Reed-Solomon code is over Galois field, GF(26), which is built as an extension of GF(2). The systematic Reed-Solomon code shall use the generator polynomial



where α = 010000 is a root of the binary primitive polynomial  in GF(26).

In Reed-Solomon encoding RS6(*K* + 8, *K*), a block of *I* bits (with ) is encoded into a codeword of *I* + 48 bits. The Reed-Solomon encoding procedure is performed in the following five steps:

1. *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*, ..., d*329} where *d*0 is the first in time.

* *Bit-to-symbol conversion*. The 330 bits {*d*0*, d*1*, ..., d*329} are converted into 55 Reed-Solomon symbols {*D*0*, D*1*, ..., D*54} having the following polynomial representation:



Resulting 6-bit symbols are presented as , where *d*6k+5 is the MSB and *d*6k is the LSB.

* *Encoding*. The information symbols {*D*0*, D*1*, ..., D*54} are encoded by systematic RS6(63,55) code with output symbols {*U*0*, U*1*, ..., U*62} ordered as follows:



where *Pk* are parity check symbols added by RS6(63,55) encoder.

The information polynomial associated with the information symbols {*D*0*, D*1*, ..., D*54} is denoted as . The parity check polynomial associated with the parity check symbols is denoted as . The parity check symbols are calculated as:



* *Symbol-to-bit conversion*. The output symbols {*U*0*, U*1*, ..., U*62} are converted into binary form with LSB coming out first, resulting in a block of 378 bits {*u*0*, u*1*, ..., u*377}.
* *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, ..., u*377} with *u*330-*I* being first in time.

#### 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 8. 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 8 – systematic convolutional encoder

For BPM-BPSK modulation mode: The 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.

### UWB PHY band allocation

The set of operating frequency bands are as defined in Table 7. The operating channel band shall be chosen to suit the regulations of the deployment region. In each channel band one or more mandatory frequencies are available. At least one of the available mandatory frequencies shall be occupied. The minimum 10 dB bandwidth shall be 500 MHz.

For interworking between units that occupy less than the full band width available within a channel, the receiving device needs to know the mandatory frequencies occupied by the transmitting device.

Table 7 – UWB PHY band allocation

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Channel Index** | **Lower Band Edge (MHz)** | **Upper Band Edge (MHz)** | **Max Bandwidth (MHz)** | **Mandatory frequencies (MHz)** | | | | | | | |
| **3500** | **4000** | **4500** | **6500** | **7500** | **8000** | **8500** | **9000** |
| 1 | 4200 | 4800 | 600 | x |  |  |  |  |  |  |  |
| 2 | 3100 | 4800 | 1700 | x | x | x |  |  |  |  |  |
| 3 | 3400 | 4800 | 1400 | x | x | x |  |  |  |  |  |
| 4 | 3100 | 5700 | 2600 | x | x | x |  |  |  |  |  |
| 5 | 5925 | 7200 | 1275 |  |  |  | x |  |  |  |  |
| 6 | 6000 | 9000 | 3000 |  |  |  | x | x | x | x |  |
| 7 | 7250 | 10250 | 3000 |  |  |  |  | x | x | x | x |
| 8 | 7200 | 10200 | 3000 |  |  |  |  | x | x | x | x |
| 9 | 6000 | 10600 | 4600 |  |  |  | x | x | x | x | x |

## BPM-BPSK modulation mode

### General

The BPM-BPSK modulation mode employs 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 data 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, and the data modulation can be done at two mean PRF that are nominally 16 MHz or 64 MHz.

The SHR preamble for the BPM-BPSK modulation mode, employs a number of codes and spreading factors that result in various mean PRF between 3.85 MHz and 230.5 MHz which together give a total of 48 independent (non-interfering) communications channels that can be used in a single channel band or across the set of channel bands allowed in the deployed operating region.

### 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.

Figure 9 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 6.2.2.3, while 6.2.2.1 and 6.2.2.2 detail the different portions of the preamble.



Figure 9 – SHR preamble structure

The length of the SYNC field is determined by the number of preamble symbol repetitions used, which is decided by the application layer. Valid SYNC lengths for the BPM-BPSK modulation mode are 64, 128, 256, 512, 1024, 1536, 2048 and 4096 preamble symbols.

#### SHR SYNC field

The SYNC field is specified by a preamble code and a spreading factor. The BPM-BPSK modulation supports 11 preamble code sequences of different lengths, each consisting of a sequence of code symbols drawn from a ternary alphabet {-1,0,1} and selected for use in the PHY because of their perfect periodic autocorrelation properties. The code sequences are defined in Table 8. The preamble code sequences are spread by the mechanism described below, by 1 or more specified spreading factors, to yield the final preamble symbol. Table 9 lists the spreading factors supported by each code index and the resultant symbol length. The combination of code index and spreading factor results in a total of 48 preambles of unique symbol period, which essentially provide 48 independent communications channels or networks that can share a single RF channel band (or the set of channel bands available in the operational area) with an extremely low level of mutual interference.

Table 8 – BPM-BPSK modulation SYNC field ternary codes

| Code index | Code Length | Code sequence |
| --- | --- | --- |
| 1 | 7 | 00+0++- |
| 2 | 13 | +0+0++00--++- |
| 3 | 21 | --0-+00-++-0+0+-+++++ |
| 4 | 31 | ++00+00---+-0++-000+0+0-+0+0000  (This is the same as IEEE 802.15.4 HRP UWB PHY code #6) |
| 5 | 57 | +0+0++-++--+-0++++---+++++-+++-0-+0---+---+-+0++-+--+00-+ |
| 6 | 63 | 0000+00000000+0000-00000-0+0000+000000-00-+00000-0+00-+0+++0000 |
| 7 | 73 | 00+0+++0++-+-+-0++++--++---+---0++-+0++++---++-+----+-0++-+---+0++-++-++- |
| 8 | 91 | +0+0-+-+----0+-++-++------0+-+++-+++-+++++0+-+-+0-+-+++---+++++--+-++-++--00-++0--0++--+++- |
| 9 | 127 | +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--+  (This is the same as IEEE 802.15.4 HRP UWB PHY code #9) |
| 10 | 133 | +00+---++++++++-0++0+0+++0-+---+0---++-+++-++----+-+-0-+++-+-0+-+---+-+----+-++-+--+++0+---+++++0++--++--+--0++--+-+---++++-++-+--++- |
| 11 | 183 | -0--+++-+++--+-+--+-+++++0--++--++-+---0+0+++0+-0-----+-++--0++++-+----+++-+-+--++-++-+0-++++-+-++++-++-+++++++-+--++---+0+-----++--+++++++--++0+-+-+-+--00--+-+-++--++--+-0---++--0-++ |

Table 9 – BPM-BPSK modulation preamble sequences and symbol durations

| Code index (*i*) | *Ci* Code Length | Preamble Sequence ID | Spreading Factor (L), or Delta Length δL | # chips per preamble symbol | Preamble symbol  duration, *Tpsym* (ns) | Base Rate Msymbol/s | Mean PRF (MHz) |
| --- | --- | --- | --- | --- | --- | --- | --- |
| 1 | 7 | 1 | 57 | 399 | 799.3 | 1.25 | 5.00 |
| 2 | 58 | 406 | 813.3 | 1.23 | 4.92 |
| 3 | 59 | 413 | 827.3 | 1.21 | 4.83 |
| 4 | 61 | 427 | 855.4 | 1.17 | 4.68 |
| 5 | 64 | 448 | 897.4 | 1.11 | 4.46 |
| 6 | 67 | 469 | 939.5 | 1.06 | 4.26 |
| 7 | 68 | 476 | 953.5 | 1.05 | 4.19 |
| 8 | 70 | 490 | 981.6 | 1.02 | 4.08 |
| 9 | 71 | 497 | 995.6 | 1.00 | 4.02 |
| 10 | 74 | 518 | 1037.7 | 0.96 | 3.85 |
| 2 | 13 | 11 | 30 | 390 | 781.3 | 1.28 | 11.52 |
| 12 | 32 | 416 | 833.3 | 1.20 | 10.80 |
| 13 | 33 | 429 | 859.4 | 1.16 | 10.47 |
| 14 | 34 | 442 | 885.4 | 1.13 | 10.16 |
| 15 | 36 | 468 | 937.5 | 1.07 | 9.60 |
| 16 | 37 | 481 | 963.5 | 1.04 | 9.34 |
| 17 | 38 | 494 | 989.6 | 1.01 | 9.09 |
| 18 | 39 | 507 | 1015.6 | 0.98 | 8.86 |
| 19 | 40 | 520 | 1041.7 | 0.96 | 8.64 |
| 20 | 41 | 533 | 1067.7 | 0.94 | 8.43 |
| 3 | 21 | 21 | 20 | 420 | 841.3 | 1.19 | 19.02 |
| 22 | 22 | 462 | 925.5 | 1.08 | 17.29 |
| 23 | 23 | 483 | 967.5 | 1.03 | 16.54 |
| 24 | 25 | 525 | 1051.7 | 0.95 | 15.21 |
| 4 | 31 | 25 | 13 | 403 | 807.3 | 1.24 | 19.82 |
| 26 | 14 | 434 | 869.4 | 1.15 | 18.40 |
| 27 | 15 | 465 | 931.5 | 1.07 | 17.18 |
| 28 | 16 | 496 | 993.6s | 1.01 | 16.10 |
| 29 | 17 | 527 | 1055.7 | 0.95 | 15.16 |
| 30 | 18 | 558 | 1117.8 | 0.89 | 14.31 |
| 5 | 57 | 31 | 8 | 456 | 913.5 | 1.09 | 53.64 |
| 32 | 9 | 513 | 1027.6 | 0.97 | 47.68 |
| 33 | 10 | 570 | 1141.8 | 0.88 | 42.91 |
| 6 | 63 | 34 | 6 | 378 | 757.2 | 1.32 | 21.13 |
| 35 | 7 | 441 | 883.4 | 1.13 | 18.11 |
| 36 | 8 | 504 | 1009.6 | 0.99 | 15.85 |
| 37 | 9 | 567 | 1135.8 | 0.88 | 14.09 |
| 7 | 73 | 38 | 6 | 438 | 877.4 | 1.14 | 72.94 |
| 39 | 7 | 511 | 1023.6 | 0.98 | 62.52 |
| 40 | 8 | 584 | 1169.9 | 0.85 | 54.71 |
| 8 | 91 | 41 | 4 | 364 | 729.2 | 1.37 | 111.09 |
| 42 | 5 | 455 | 911.5 | 1.10 | 88.87 |
| 43 | 6 | 546 | 1093.8 | 0.91 | 74.06 |
| 9 | 127 | 44 | 3 | 381 | 763.2 | 1.31 | 83.86 |
| 45 | 4 | 508 | 1017.6 | 0.98 | 62.89 |
| 10 | 133 | 46 | 4 | 532 | 1065.7 | 0.94 | 113.54 |
| 11 | 183 | 47 | 2 | 366 | 733.2 | 1.36 | 230.50 |
| 47 | 3 | 549 | 1099.8 | 0.91 | 153.67 |

Note that to maintain the desired transmitter output power the pulse amplitude will need to be set depending on the average PRF resulting from the combination of the preamble code and the spreading factor being used.

When using the ternary code indexed by *i*, the SYNC field shall consist of *Nsync* repetitions of the symbol ***Si***,where ***Si*** is the code ***Ci***spread by the delta function δ*L* of length *L* as shown in Table 9. The spreading operation, where code ***Ci*** is extended to the preamble symbol duration indicated in Table 9, is described mathematically by



where the operator  indicates a Kronecker product. After the Kronecker operation, a preamble symbol is formed as depicted in Figure 10, where *L* – 1 zeros have been inserted between each ternary element of ***Ci****.*

The spreading factor *L*, number of chips per symbol, preamble symbol duration *Tpsym*, and base symbol rate for different channels are given in Table 9.



Figure 10 – BPM-BPSK construction of symbol *Si* from code *Ci*

Note that in Table 9, preamble code ID 28 which has length 31 code and spreading factor L=16 is identical to the 16 MHz PRF preamble sequence code 6 of the IEEE 802.15.4 HRP UWB PHY, and, preamble code ID 45 which has length 127 code and spreading factor L=4 is identical to the 64 MHz PRF preamble sequence code 9 of the IEEE 802.15.4 HRP UWB PHY.

Support for the preamble code ID 28 shall be mandatory in the BPM-BPSK modulation mode, while support for the others is optional.

#### SHR SFD

The SFD marks the end of the SHR and the start of the PHR, which identifies the RMARKER for time-stamping, and the switch from the SHR modulation to the data modulation. The BPM-BPSK modulation mode shall support the SFD sequences identified in Table 10. In use the selected SFD shall be spread by the preamble symbol *Si*, where the leftmost bit shall be transmitted first in time. The SFD then essentially consists of a sequence of SYNC symbols sent as normal where a +1 appears in the defined sequence, or inverted where a ‑1 appears in the sequence, or a symbol time of no energy where a zero (0) appears in the defined sequence. The structure of the SHR preamble SYNC and SFD are shown in Figure 9.

Table 10 – BPM-BPSK modulation SFD sequences

| Sequence  ID | SFD Sequence | SFD Length (symbols) | Usage |
| --- | --- | --- | --- |
| (a) | 0 +1 0 ‑1 +1 0 0 ‑1 | 8 | This is applicable to nominal data rates 850 kb/s, 6.81 Mb/s and 27 Mb/s, and is suitable for use in a network with non-coherent and/or coherent receivers. (This is the short SFD sequence defined in the IEEE 802.15.4 HRP UWB PHY) |
| (b) | -1 -1 -1 -1 +1 -1 0 0 | 8 | This is applicable to nominal data rates 850 kb/s, 6.81 Mb/s and 27 Mb/s, and is suitable for use in a network that consists only of coherent receivers. This is more robust than sequence (a). |
| (c) | ‑1 ‑1 ‑1 ‑1 +1 ‑1 +1 ‑1 ‑1 +1 +1 ‑1 ‑1 +1 0 0 | 16 | This is applicable to the 850 kb/s nominal data rate and a network that consists only of coherent receivers. This is more robust than sequence (b). |
| (d) | 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 | 64 | This is applicable to the 110 kb/s nominal data rate and is suitable for use in a network with non-coherent and/or coherent receivers. (This is the long SFD sequence defined in the IEEE 802.15.4 HRP UWB PHY) |
| (e) | -1 -1 -1 -1 -1 -1 -1 +1 -1 +1 -1 -1 -1 -1 ‑1 -1 +1 -1 -1 +1 -1 +1 -1 -1 +1 -1 -1 +1 ‑1 ‑1 +1 ‑1 -1 -1 +1 +1 -1 -1 -1 +1 +1 +1 -1 +1 -1 +1 -1 +1 -1 -1 -1 +1 -1 -1 +1 ‑1 -1 -1 -1 +1 +1 +1 0 0 | 64 | This is applicable to the 110 kb/s nominal data rate and is suitable for use in a network that consists only of coherent receivers. This is more robust than sequence (d). |

#### Preamble timing parameters

Due to the variability in the preamble code length and PRF, there are many admissible values for the timing parameters of a preamble symbol. These values are summarized in Table 9. A preamble symbol is defined as the waveform consisting of one whole repetition of the modulated preamble symbol (of length given in Table 9). Details of the construction of the preamble symbol for various code lengths and PRFs are given in 6.2.2. For each, the preamble is constructed from a preamble code, *Ci*, by inserting a number of chip durations between code symbols. The number of chip durations to insert is denoted by *δL*, values for each code length and PRF are given in Table 9, and the chip insertion is detailed in 6.2.2.1.

The base symbol rate is defined as the rate at which the preamble symbols are sent. The base rates for each preamble option are given in Table 9.

The duration of the SYNC portion of the SHR, *TSYNC*, is given by *Tpsym* × PSR, where *Tpsym* is the appropriate preamble symbol length from in Table 9 and PSR is one of the valid choices of preamble symbol repetitions: 64, 128, 256, 512, 1024, 1536, 2048 and 4096 preamble symbols.

The duration of the SFD portion of the SHR, *TSFD*, is given by *Tpsym* × SL, where *Tpsym* is the appropriate preamble symbol length from in Table 9 and SL is the SFD sequence length from Table 10.

The total duration of the SHR preamble *Tpre* as shown in Figure 9, is the sum of *TSYNC* and *TSFD*.

### PHR and PSDU - Symbol structure and modulation

With reference to the general UWB frame format of Figure 3, for the BPM-BPSK modulation mode, the modulation rate options for the PHR are defined in 6.1.3 and Table 3, while the modulation rate for the PSDU is defined by the data rate field within the PHR as listed in Table 4.

There are two choices for mean PRF for modulation of PHR and PSDU. These are nominally termed 16 MHz and 64 MHz PRF modes (but are actually more precisely 15.60 and 62.40 MHz). The data rate dependent timing parameters for these two PRF options are defined in Table 11.

#### Symbol structure for PHR and PSDU

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 11. Each symbol shall consist of an integer number of possible chip positions, *Nc*, each with duration *Tc*. The overall symbol duration denoted by *Tdsym* is given by *Tdsym*= *Nc* *×* *Tc*. Furthermore, each symbol is divided into two BPM intervals each with duration *TBPM* =*Tdsym* /2, which enables binary position modulation.

A burst is formed by grouping *Ncpb* consecutive chips and has duration *Tburst* = *Ncpb×Tc*. 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., *Tburst* << *TBPM*, provides for some multi-user access interference rejection in the form of time hopping. The total number of burst durations per symbol, *Nburst*, is given by *Nburst* = *Tdsym* /*Tburst*. In order to limit the amount of inter-symbol interference caused by multipath, only the first half of each *TBPM* period shall contain a burst. Therefore, only the first *Nhop*= *Nburst*/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 6.2.3.3 and 6.2.3.4.

#### PSDU timing parameters

The PSDU rate-dependent parameters and timing-related parameters are summarized in Table 11. The peak PRF shall be 499.2 MHz. This rate corresponds to the highest frequency at which a compliant transmitter shall emit pulses. The mean PRF is defined as the total number of pulses emitted during a symbol period divided by the length of the symbol duration.

The admissible data rates, data PRFs, and modulation timing parameters are listed in Table 11. Several data rates are supported. These 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, *Tdsym*, changes to obtain the stated symbol rate and bit rates.



Figure 11 – BPM-BPSK symbol structure

Table 11 – rate-dependent and timing dependent parameters

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **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)** |
| 0.5  0.5  0.5  1.0 | 0.87  0.87  0.87  0.87 | 0.44  0.44  0.44  0.87 | 32  32  32  32 | 8  8  8  8 | 128  16  2  1 | 4096  512  64  32 | 256.41  32.05  4.01  2.00 | 8205.13  1025.64  128.21  64.10 | 0.12  0.98  7.80  15.60 | 0.11  0.85  6.81  27.24 | 15.60  15.60  15.60  15.60 |
| 0.5  0.5  0.5  0.5 | 0.87  0.87  0.87  0.87 | 0.44  0.44  0.44  0.44 | 8  8  8  8 | 2  2  2  2 | 512  64  8  2 | 4096  512  64  16 | 1025.64  128.21  16.03  4.01 | 8205.13  1025.64  128.21  32.05 | 0.12  0.98  7.80  31.20 | 0.11  0.85  6.81  27.24 | 62.40  62.40  62.40  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 *Tc* by the formula Tc = 1/peakPRF. The value of *Tc* is approximately 2 ns. The channel bands are defined in Table 7. Note that the bandwidth is not necessarily the inverse of the chip duration *Tc*. Pulse shape and bandwidth are further defined in 6.2.4.1.

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 6.1.5.2 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 in the BPM-BPSK modulation mode. Reed-Solomon encoding is further described in 6.1.5.1.

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. *Nburst* 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 BPM-BPSK modulation mode pulses. The value is computed as *Nhop = Nburst*/4.

The chips per burst parameter is the number of chip *Tc* durations within each burst period *Tburst*. Each burst consists of a multiple number of consecutive chips, as illustrated in Figure 11. 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 *Ncpb* have been selected so that the following is a valid data rate: (2 × Overall FEC rate)/(*Ncpb × Nburst × Tc*).

The burst duration is computed as *Tburst = Ncpb × Tc*.

The symbol duration is the duration of a modulated and coded PSDU symbol on the air and is computed as follows: *Tdsym = Nburst × Tburst*.

The symbol rate is the inverse of the PSDU symbol duration 1/*Tdsym*.

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

*Bit Rate* = 2 × (*Overall FEC Rate*)/*Tdsym*

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

*Mean PRF = Ncpb/Tdsym*

#### Mathematical framework for BPM-BPSK modulation

The transmit waveform during the *kth* symbol interval may be expressed as



This equation describes the time hopping with polarity scrambling, which improves interference rejection capabilities of the BPM-BPSK modulation mode. The *kth* symbol interval carries two information bits  and . Bit  is encoded into the burst position whereas bit  is encoded into the burst polarity. The sequence  is the scrambling code used during the *kth* symbol interval,  is the *kth* burst hopping position, and *p*(*t*) is the transmitted pulse shape at the antenna input. The burst hopping sequence  provides for multiuser interference rejection. The chip scrambling sequence  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 12.



Figure 12 – BPM-BPSK reference symbol modulator

Note here that the FEC Encoder is not included if the modulation Viterbi rate is 1.0, as described in 6.1.4. 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.

#### Spreading

The time-varying spreader sequence  and the time-varying burst hopping sequence  shall be generated from a common PRBS scrambler.

The polynomial for the scrambler generator shall be 

where *D* is a single chip delay, *Tc*, 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

 where  denotes modulo-2 addition.

A linear feedback shift register (LFSR) realization of the scrambler is shown in Figure 13. The LFSR shall be initialized upon the transmission of bit 0 of the PHR. Note that *Ncpb* 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 13 – BPM-BPSK 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. If the resulting binary state is less than 15 bits long then it shall be extended by concatenating it with itself until the requisite 15 bits are available. Table 12 shows an example of this procedure for the Table 8preamble code index 4. Table 12 shows the initial state as well as the first 16 output bits from the scrambler.

Table 12 – Example LFSR initial state for preamble code index 4

|  |  |
| --- | --- |
| Initial state  (*s-15, s-14, …, s-1*) | LFSR output: First 16 bits  *s0, s1, …, s15* (*s0* 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 11. During the *kth* symbol interval, the LFSR shall be clocked *Ncpb* times, and the scrambler output shall be the *kth* scrambling code . Furthermore, the *kth* burst hopping position, shall be computed as follows:



where



As shown in Table 11, the number of hopping burst *Nhop* is always a power of two, and consequently *m* is always an integer. Note that for *Ncpb < m*,the LFSR is clocked *Ncpb* 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 11, and consequently *m* takes on the values 3 and the corresponding hopping sequence is as follows:

*h*

*k*





*s*

*k*

*N*

*c*

*p*

*b*

2

*s*

1

*k*

*N*

*c*

*p*

*b*

+

4

*s*

2

*k*

*N*

*c*

*p*

*b*

+

+

+

=

### BPM-BPSK modulation mode RF requirements

#### Transmitter baseband impulse response

The transmitted pulse shape *p*(*t*) of the BPM-BPSK modulation mode shall be constrained by the time domain mask defined in Figure 14. Note that this mask is for a pulse that has 500MHz 3dB bandwidth. For all other bandwidths, the pulse the times specified here should be divided by the ratio of the bandwidths.

-6

-4

-2

0

2

4

6

x 10 s

-9

0

0.2

0.4

0.6

0.8

1

-0.4

-0.2

(-2 ns, 0.1)

(-2 ns, 1.0)

(0 ns, -0.03)

(0 ns, -0.45)

Example Pulse (500MHz BW)

(-1.75 ns, 0.0)

(+1.75 ns, 0.0)

(+2.365 ns, -0.35)

(+2.98ns, 0.0)

Figure 14 – BPM-BPSK time domain mask for compliant pulse

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.

#### Transmit PSD mask

The transmitted spectrum shall be less than –10 dBr (dB relative to the maximum spectral density of the signal) for  and –18 dBr for . An example transmit spectrum mask is shown in Figure 15. The measurements shall be made using 1 MHz resolution bandwidth and a 1 kHz video bandwidth.



Figure 15 – BPM-BPSK example transmit spectrum mask for a band centered on 4 GHz

#### Chip rate clock and chip carrier alignment

A BPM-BPSK modulation mode transmitter shall be capable of chipping at the peak PRF given in Table 11 with an accuracy of ± 20 parts per million.

## OOK modulation mode

### General description

The OOK modulation mode is based on On-Off keying impulse radio signalling with a constant PRF of 1 MHz without hopping for all parts of PSDU. In contrast with the BPM-BPSK modulation mode described in 6.2, the transmitted UWB pulses are not constrained by a minimum cross-correlation with a specific pulse template and by a given spectral mask. Instead, these pulses are constrained in spectrum by the band plan specified in 6.1.6, which practically limits the transmitted signal spectrum by local regulations and neighboring ISM bands. These very wide channels allow transmission of UWB pulses with high energy. Furthermore, lack of the template pulse promotes usage of low-complexity impulse generators. High energy pulses along with relatively low data rates specified allow high communication range of this modulation mode.

### Format of SHR

PHR bits P1-P0 determine SYNC length () as specified in Table 5 and Table 6. Preamble shall consist of repetitions of the symbol - sequence *Vi* which -th sequence in the set of Gold sequences of length given in Table 13 with elements where . Since set of Gold sequences of length has 33 sequences, there are 33 virtual channels available per physical channel. Gold sequences of length 31 have relatively short length with good circular autocorrelation properties. SFD shall represent logical inversion of sequence *Vi* used in the preamble.

Table 13: Employed set of Gold sequences of length 31.

|  |  |
| --- | --- |
|  |  |
| 0 | 1111100110100100001010111011000 |
| 1 | 1111100100110000101101010001110 |
| 2 | 0000000010010100100111101010110 |
| 3 | 0000101111000101010000011000101 |
| 4 | 0001110101100110111111111100011 |
| 5 | 0011000000100001100000110101111 |
| 6 | 0110101010101111011110100110111 |
| 7 | 1101111110110010100010000000111 |
| 8 | 1011010110001001011011001100110 |
| 9 | 0110000111111110101001010100100 |
| 10 | 1100100100010001001101100100001 |
| 11 | 1001100011001110000100000101010 |
| 12 | 0011101101110000010111000111100 |
| 13 | 0111110000001100110001000010001 |
| 14 | 1111001011110101111101001001011 |
| 15 | 1110111100000111100101011111110 |
| 16 | 1101010011100011010101110010100 |
| 17 | 1010001100101010110100101000000 |
| 18 | 0100110010111001110110011101000 |
| 19 | 1001001110011111110011110111001 |
| 20 | 0010110111010011111000100011010 |
| 21 | 0101000101001011101110001011101 |
| 22 | 1010100001111011000011011010011 |
| 23 | 0101101000011010011001111001110 |
| 24 | 1011111011011000101100111110101 |
| 25 | 0111011101011101000110110000010 |
| 26 | 1110010001010110010010101101101 |
| 27 | 1100001001000000111010010110010 |
| 28 | 1000111001101101101011100001100 |
| 29 | 0001011000110111001000001110000 |
| 30 | 0010011010000010001111010001001 |
| 31 | 0100011111101000000001101111011 |
| 32 | 1000010100111100011100010011111 |

Hence, the vector of SHR chips shall be calculated as

.

### Spreading and data rates

Bits R1-R0 shall decide data rate and number of chips per symbol in PSDU as specified in Table 4 and Table 14 respectively. PHR shall always be transmitted at the lowest data rate specified of 54.56 Kbps and with 8 chips per symbols. The vector of coded PHR bits is denoted, while the vector of coded PSDU bits is denoted . shall be calculated as , where and are defined in Table 1 and with superscript denoting Symbol **#**. Similarly, shall be calculated as , again where and are defined in Table 1 and with superscript denoting Symbol #. Spreading of to the vector of PHR chips denoted shall be done as

,

for , where function returns vector length. Similarly, spreading of to the vector of PSDU chips shall be done as

,

for . The vector of all PPDU chips ( shall be calculated as concatenation of , and :

.

Intervals of indexes of elements of vector are denoted as follows. ,  
,  
].

Table 14: Number of chips per symbol with regard to bits R1-R0

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **R1-R0** | 00 | 01 | 10 | 11 |
| **Number of chips per symbol** ( | 8 | 4 | 2 | 1 |

### Symbol structure

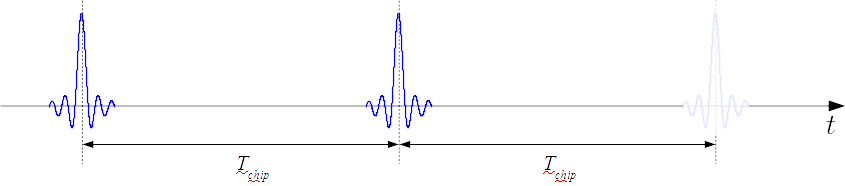


Figure 16: Symbol structure for OOK modulation mode

Symbol structure is illustrated in Figure 16. Note that in Figure 16 a constant chip duration of is used, zero chip which produces no emission is depicted as a dimmed pulse. The whole PPDU shall be transmitted using the constant chip interval of regardless of the data rate used. On-Off Keying (OOK) modulation shall be used for the whole PPDU. Transmitted signal for the -th transmitted chip shall be expressed as

,

for Here, transmitted pulse waveform is denoted is used for flattening the spectrum of the transmitted signal and shall be calculated as follows:

Here, shall be arbitrary pseudo-random or random sequence chosen by the implementer. Purpose of is to flatten the spectrum of the transmitted signal and totally avoid or at least reduce discrete frequency components.

### Compliant pulses

The transmitted pulse shall be considered compliant with the OOK modulation mode if it satisfies the band allocation specified in 6.1.6 and has duration not greater than.

## Timestamps and time units

The UWB PHY supports precision ranging and localization through the capability of time stamping, using a *ranging counter,* the precise instant that the RMARKER is received (or transmitted) at the device antenna.

#### Time units

For the BPM-BPSK modulation mode, the time units used for ranging 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.

For the OOK modulation mode, the time units used for ranging timestamps is defined by the least significant bit (LSB) of the time values which represents 1/64 of *Tchip* /1000 = 1 ns.

#### 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 period of 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.