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Contents

[1. Narrowband assisted Ultrawideband (NBA-UWB) 3](#_Toc118222647)

[1.1 Introduction 3](#_Toc118222648)

[1.2 MAC 3](#_Toc118222649)

[1.3 PHY 4](#_Toc118222650)

[1.3.1 O-QPSK 4](#_Toc118222651)

[1.3.2 UWB 7](#_Toc118222652)

1. Narrowband assisted Ultrawideband (NBA-UWB)

## Introduction

In this document, we would like to provide a skeleton for narrow-band assisted UWB (NBA-UWB) that will be developed into a draft. This is a **live** document that will evolve over time. All contributions and suggestions are welcome.

There are two main sections: One focuses on MAC aspects of various features that rely on NBA-UWB, and the other one develops the PHY level aspects required to support the features introduced in the MAC section.

## MAC

NBA-UWB can be viewed as an umbrella feature that comprises several semi-independent features. All these features share some common principles among which the most important one is that there is a tight clock synchronization between NB and UWB. It is desirable that both PHYs are driven by the same clock so that there is no extra work need to determine relative accuracy. Otherwise, there should be an explicit requirement on the relative clock drift/accuracy between different PHYs/radios. Such a tight coupling between NB and UWB opens a plethora of opportunities for UWB. So far, we have seen contributions for the following features:

* Mirroring channel: An NB channel can be used for discovery and control of a UWB channel. An NB radio can be used as pilot to provide an additional CCA mode for UWB to IEEE 802.15.4-2020.
* Multi-millisecond UWB (including secure MMS): In MMS-UWB, acquisition (CFO/SFO) as well as data-exchange are going to be offloaded to the NB PHY, which will enable link budget improvement as well as time-of-flight (ToF) accuracy improvement.
* NBA-TDOA: Link budget improvement and energy saving carry over to NBA-TDOA as well.
* NBA-Sensing: Multi-static sensing require data exchange for which NB could be useful.

There could be some common themes to be reused between these features as well as unique requirements of each one. Coexistence/interference aspects of both NB and UWB are important to address; considering that NBA-UWB systems will often operate in dense multi-user scenarios. Relevant topics for the NB radio include duty-cycle optimization, channelization, frequency hopping and blocked channel list agreement and Listen-Before-Talk (LBT) scheme. Ranging session definition and PHY level parameters must also be specified. MAC services provide for an open interface to pass the initial timing and frequency synchronization as well as schedule and configuration information obtained from the assisted NB to UWB operation. The goal in the MAC section is to provide a clean and generic baseline for as many use cases as possible. Each application could have slightly different requirements; therefore, instead of trying to find a one-fits-all solution, it is desirable to focus on the common denominator among applications of interest. This would also speed up the standardization efforts.

## PHY

The PHY section aims to add and/or improve the relevant IEEE 802.15.4 PHY sections to enable the NBA-UWB based features outlined in the MAC section. In particular, O-QPSK from Clause 12 of IEEE 802.15.4-2020, and UWB from Clause 15 of IEEE 802.15.4-2020 and the amendment 802.15.4z are going to cover the PHY aspects of NBA-UWB with some modifications and improvements. Alternatively, different PHYs other than O-QPSK can assist UWB as well by exploiting the open interfaces provided by MAC services.

### O-QPSK

O-QPSK from Clause 12 of IEEE 802.15.4-2020 provides a very good field-tested baseline for the NB aspects of UWB thanks to its good link budget and efficient implementation. The 250 kbps mode is the main workhorse given its relatively optimized air time. The improvements to this chapter are, but not limited to,

* addition of the new bands UNII-3 and UNII-5 in addition to the existing 802.15.4 2450 MHz band as in Clause 10.1.3.3 of IEEE 802.15.4-2020
  + Note UNII-3 band may not be available globally as well as UNII-5
* channelization of these bands to enable frequency-hopping and different services air-time reduction options (reduced preamble length and increased data rate)
* clock accuracy requirements.
* convolutional channel coding with generator polynomials (133, 171) as specified in Clause 21.3.6 of IEEE 802.15.4-2020, LDPC coding is optional

In terms of clock accuracy, the additional NB mode can align with the UWB. Per IEEE 802.15.4z, both the carrier frequency and the chip rate frequency of HRP UWB shall be derived from the same reference oscillator and shall have an accuracy of ± 20 ppm or better. There should be a similar optional mode for O-QPSK to better facilitate the NBA-UWB feature set.

The recommended PPDU formats based on O-QPSK in Clause 12 of IEEE 802.15.4-2020 are listed as follows. Note that PPDU Config-1 provides the baseline data rate of 250kbps to facilitate interop. Other PPDU configurations are defined as optional additions for optimized tradeoff between airtime and link budget. Also note that 1 chip is of duration 0.5us and 1 symbol carries 4 bits (note: these 4 bits are coded ones if FEC is applied). Meanwhile, the number of chips within 1 symbol is referred to as the Spreading Factor (SF).

|  |  |  |  |
| --- | --- | --- | --- |
| Preamble | SFD | PHR | Payloads |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Config # Data Rate | Preamble  Length (Symbols) | SFD Length (Symbols) | SF in Preamble & SFD | PHR Length (Symbols) | SF in PHR & Payload | FEC in  PHR & Payload |
| **#1**  250kbps | 8 | 2 | 32  Note-1 | 2 | 32  Note-1 | No |
| **#2**  500kbps | 4 | 2 | 32  Note-1 | 7  Note-2 | 8  Note-3 | CL7  Note-6 |
| **#3**  1000kbps | 4 | 2 | 32  Note-1 | 7  Note-2 | 8  Note-3 | CL7 for PHR  Note-6  No FEC on Payload |
| **#4**  250kbps | 8 | 2 | 32  Note-1 | 7  Note-2 | 16  Note-4 | CL7  Note-6 |
| **#5**  1000kbps | 4 | 2 | 32  Note-1 | 7  Note-2 | 4  Note-5 | CL7  Note-6 |
| Note-1: Symbol/bit-to-chip mapping according to Table 12-1 or Table 21-16 in IEEE 802.15.4-2020 as the default mode. The following symbol-to-chip mapping table could be used optionally:   |  |  | | --- | --- | | Data symbol | Chip values | | 0 | 1 1 0 0 1 0 1 0 1 0 0 1 0 0 0 0 1 1 0 0 1 0 1 0 0 1 1 0 1 1 1 1 | | 1 | 1 0 1 0 1 1 0 0 1 1 1 1 0 1 1 0 1 0 1 0 1 1 0 0 0 0 0 0 1 0 0 1 | | 2 | 1 0 0 1 0 0 0 0 1 1 0 0 1 0 1 0 1 0 0 1 0 0 0 0 0 0 1 1 0 1 0 1 | | 3 | 1 1 1 1 0 1 1 0 1 0 1 0 1 1 0 0 1 1 1 1 0 1 1 0 0 1 0 1 0 0 1 1 | | 4 | 1 0 0 1 1 1 1 1 0 0 1 1 1 0 1 0 1 0 0 1 1 1 1 1 1 1 0 0 0 1 0 1 | | 5 | 1 1 1 1 1 0 0 1 0 1 0 1 1 1 0 0 1 1 1 1 1 0 0 1 1 0 1 0 0 0 1 1 | | 6 | 1 1 0 0 0 1 0 1 0 1 1 0 0 0 0 0 1 1 0 0 0 1 0 1 1 0 0 1 1 1 1 1 | | 7 | 1 0 1 0 0 0 1 1 0 0 0 0 0 1 1 0 1 0 1 0 0 0 1 1 1 1 1 1 1 0 0 1 | | 8 | 1 0 0 1 1 1 1 1 1 1 0 0 0 1 0 1 0 1 1 0 0 0 0 0 1 1 0 0 0 1 0 1 | | 9 | 1 1 1 1 1 0 0 1 1 0 1 0 0 0 1 1 0 0 0 0 0 1 1 0 1 0 1 0 0 0 1 1 | | 10 | 1 1 0 0 0 1 0 1 1 0 0 1 1 1 1 1 0 0 1 1 1 0 1 0 1 0 0 1 1 1 1 1 | | 11 | 1 0 1 0 0 0 1 1 1 1 1 1 1 0 0 1 0 1 0 1 1 1 0 0 1 1 1 1 1 0 0 1 | | 12 | 1 1 0 0 1 0 1 0 0 1 1 0 1 1 1 1 0 0 1 1 0 1 0 1 0 1 1 0 1 1 1 1 | | 13 | 1 0 1 0 1 1 0 0 0 0 0 0 1 0 0 1 0 1 0 1 0 0 1 1 0 0 0 0 1 0 0 1 | | 14 | 1 0 0 1 0 0 0 0 0 0 1 1 0 1 0 1 0 1 1 0 1 1 1 1 0 0 1 1 0 1 0 1 | | 15 | 1 1 1 1 0 1 1 0 0 1 0 1 0 0 1 1 0 0 0 0 1 0 0 1 0 1 0 1 0 0 1 1 |   The method to signal the symbol/bit-to-chip mapping mode is TBD.  Note-2: 7 symbols convey (8 information bits + 6 padding bits) x 2 = 28 coded bits  Note-3: Symbol/Bit-to-chip mapping according to Table 21-14 in IEEE 802.15.4-2020  Note-4: Symbol/Bit-to-chip mapping according to Table 21-15 in IEEE 802.15.4-2020 as the default mode. The following symbol-to-chip mapping table could be used optionally for odd-indexed symbols:   |  |  | | --- | --- | | Data symbol | Chip values | | 0 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | | 1 | 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 | | 2 | 1 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 | | 3 | 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 | | 4 | 1 1 1 1 0 0 0 0 1 1 1 1 0 0 0 0 | | 5 | 1 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1 | | 6 | 1 1 0 0 0 0 1 1 1 1 0 0 0 0 1 1 | | 7 | 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1 0 | | 8 | 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 | | 9 | 1 0 1 0 1 0 1 0 0 1 0 1 0 1 0 1 | | 10 | 1 1 0 0 1 1 0 0 0 0 1 1 0 0 1 1 | | 11 | 1 0 0 1 1 0 0 1 0 1 1 0 0 1 1 0 | | 12 | 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1 1 | | 13 | 1 0 1 0 0 1 0 1 0 1 0 1 1 0 1 0 | | 14 | 1 1 0 0 0 0 1 1 0 0 1 1 1 1 0 0 | | 15 | 1 0 0 1 0 1 1 0 0 1 1 0 1 0 0 1 |   For even-indexed symbols, the chip sequence in the above table is time reversed before mapping as illustrated below.    The method to signal the symbol/bit-to-chip mapping mode is TBD.  Note-5: Symbol/Bit-to-chip mapping as: (c0, c1, c2, c3) = (b0, b1, b2, b3)  Note-6: Rate-1/2 convolutional code with generator polynomials (133, 171) as specified in Clause 21.3.6 of IEEE 802.15.4-2020 or in Clause 15.3.3 of IEEE 802.15.4z-2020 | | | | | | |

For example, with a PSDU payload of 10 bytes, the data rate and length of each PPDU configuration are given as follows.

* PPDU Config-1: Data Rate = 250kbps
  + Preamble length = 128us, SFD length = 32us, PHR length = 32us, Payload length = 320us
  + Total packet duration: 512us
* PPDU Config-2: Data Rate = 500kbps
  + Both PHR and the payload go through the rate-1/2 convolutional code
  + Preamble length = 64us, SFD length = 32us, PHR length = 28us, Payload length = 172us
    - PHR carries (8+6)x2 = 28 coded bits
    - Payload carrier (80+6)x2 = 172 coded bits
  + Total packet duration: 296us
* PPDU Config-3: Data Rate = 1000kbps
  + Preamble length = 64us, SFD length = 32us, PHR length = 28us, Payload length = 80us
  + Total packet duration: 204us

Both out-of-band signaling and in-band signaling could be used for NB configuration indication. In the case of out-of-band signaling, the SFD shall be formatted as in Figure 12-3 in IEEE 802.15.4-2020. In the case of in-band signaling, the following SFDs shall be used to indicate different NB configurations as follows.

|  |  |
| --- | --- |
| SFD | NB Config #  Data Rate |
| 1 1 1 0 0 1 0 1  (Figure 12-3 in IEEE 802.15.4-2020) | #1  250kbps |
| 1 0 0 0 1 0 1 0 | #2  500kbps |
| 0 1 0 0 1 0 0 1 | #3  1000kbps |
| 0 0 1 0 1 0 1 1 | #4  250kbps |
| 1 0 1 0 0 0 0 1 | #5  1000kbps |

### UWB

The UWB PHY from Clause 15 of IEEE 802.15.4-2020 will be the starting point. The 802.15.4z amendment already introduced a no-data packet format to improve link budget. The multi-millisecond (MMS) UWB can be seen as an extension of this packet format to improve the link budget and ToF accuracy further. In this packet format, there will be short fragments that have a start-to-start spacing of at least a millisecond and the overall packet will span over multiple fragments, hence the name multi-millisecond. Note that 1 millisecond corresponds to 499200 chips.

An MMS UWB packet consists of multiple fragments which can be classified into two types:

* Ranging sequence fragment (RSF)
  + Each RSF contains a repetition of a selected multi-millisecond ranging sequence (MMRS). One common MMRS is utilized in all RSFs
  + 16 length-128 complementary sets-based MMRS sequences are defined as in the table below. Each MMRS sequence from the table can be split into two parts: [A, B], where A and B are of length 64. One gap G consisting of 0~64 zeros could be added to form an MMRS with gaps as [A, G, B, G]
  + Length-91 and length-127 4z ternary codes could be optionally employed as MMRS. Note that the usage of those 4z ternary codes here could cause more interference to legacy 4z devices nearby than those MMRSs as defined in the following table.
  + A spreading factor L=4 is applied to the MMRS with/without gaps before repeating within one RSF
* Ranging integrity fragment (RIF)
  + Each RIF carries waveform of pseudo-randomly modulated pulses for ranging integrity based on 4z designs. STS as specified in 15.2.9 of 802.15.4z-2020 is the baseline waveform. [Optional RIF waveform is under discussion, e.g., doc: 15-22-0413-00-04ab. Will update accordingly when reaching convergence.]
  + Each RIF contains one STS segment with a spreading factor L=4. Each STS segment is of the same length
  + The polarities of all STS pulse in all RIFs within one MMS UWB packet are generated by using a DRBG based on AES-128 in counter mode as specified in 15.2.9 of IEEE 802.15.4z-2020

Length-128 MMRS Sequences

|  |  |
| --- | --- |
| Code Index | MMRS Sequence |
| 33 | **+-++-++++-+++---+-++-+++-+---++++-++-++++-+++----+--+---+-+++--- +-++-++++-+++---+-++-+++-+---+++-+--+----+---++++-++-+++-+---+++** |
| 34 | **+--++--+++----+++-+--+-++++++++++-+-+-+-++++----+--+-++-++--++-- +--++--+++----+++-+--+-+++++++++-+-+-+-+----++++-++-+--+--++--++** |
| 35 | **+--++--+-+-++-+-++++++++--++++--+--+-++--+-+-+-+++++------++--++ +--++--+-+-++-+-++++++++--++++---++-+--++-+-+-+-----++++++--++--** |
| 36 | **+---+----+---+--+----++++-++-+--+----+++-+--+-+++---+---+-+++-++ +---+----+---+--+----++++-++-+---++++---+-++-+---+++-+++-+---+--** |
| 37 | **+----++++-+++-+++---+---+-++-+--+----++++-+++-++-+++-+++-+--+-++ +----++++-+++-+++---+---+-++-+---++++----+---+--+---+---+-++-+--** |
| 38 | **++--+-+------++---++-+-+-----++---++-+-++++++--+--++-+-+-----++- ++--+-+------++---++-+-+-----++-++--+-+------++-++--+-+-+++++--+** |
| 39 | **------+++-+--++-++--++++-++-+-+-------+++-+--++---++----+--+-+-+ ++++++---+-++--+--++----+--+-+-+------+++-+--++---++----+--+-+-+** |
| 40 | **-----++------++---++-+-+++--+-+------++-+++++--+--++-+-+--++-+-+ +++++--++++++--+++--+-+---++-+-+-----++-+++++--+--++-+-+--++-+-+** |
| 41 | **--++-++------+-+++---++-----+-+------+-+--++-++-++++-+-+--+++--+ ++--+--++++++-+---+++--+++++-+-+-----+-+--++-++-++++-+-+--+++--+** |
| 42 | **-+---+---+++-++++-++-+---++++----+--+-++-++++---+-+++-++-+++-+++ +-+++-+++---+----+--+-+++----+++-+--+-++-++++---+-+++-++-+++-+++** |
| 43 | **-+---+--+-++-+---++++---+---+----+---+---+--+-++-++++----+++-+++ +-+++-++-+--+-+++----+++-+++-+++-+---+---+--+-++-++++----+++-+++** |
| 44 | **-+-++-+----------++--++---++++---++-+--+--++--++-+-+-+-+----++++ +-+--+-++++++++++--++--+++----++-++-+--+--++--++-+-+-+-+----++++** |
| 45 | **-++--++-++----++-+-++-+-+++++++++-+-+-+-----+++++--+-++---++--++ +--++--+--++++--+-+--+-+--------+-+-+-+-----+++++--+-++---++--++** |
| 46 | **+--++--+-+-++-+-++++++++--++++--+--+-++--+-+-+-+++++------++--++ -++--++-+-+--+-+--------++----+++--+-++--+-+-+-+++++------++--++** |
| 47 | **+--+----+--+-----+-+++--+-+---++-++-+++++--+----+-+---+++-+---++ -++-++++-++-+++++-+---++-+-+++---++-+++++--+----+-+---+++-+---++** |
| 48 | **++---+-+----+--+--+++-+-----+--+--+++-+-++++-++---+++-+-----+--+ --+++-+-++++-++-++---+-+++++-++---+++-+-++++-++---+++-+-----+--+** |

A RSF-only MMS packet format enables efficient and fast CIR generation with multi-millisecond coherent combining. In a mixed MMS packet format for ranging integrity, RIFs may follow RSFs. The following figure provides an illustration of a generic MMS packet with/without NB assistance. The details about the allowed configurations of X, Y, Z are as follows.

In each RSF, we first construct one MMRS symbol and then repeat the MMRS symbol for N\_MSR times. One MMRS symbol can be constructed as follows.

* When utilizing an MMRS based on complementary sets
  + Step-1: Determine MMRS without gap, i.e., [A, B], where A and B are sequences of length 64
  + Step-2: Determine the gap G and get MMRS with gap as S=[A, G, B, G]
  + Step-3: Spread S with L=4 and get an MMRS symbol S’=[A’, G’, B’, G’]
* When utilizing an Ipatov sequence for MMRS
  + Step-1: Determine the Ipatov sequence S
  + Step-2: Spread S with L=4 and get an MMRS symbol S’

The number of MMRS repetitions N\_MSR within each RSF can be configured as follows.

* Set of values: N\_MSR {32, 40, 64, 128, 256}
  + A small N\_MSR enables better co-existence due to the short active transmission
  + A large N\_MSR facilitates full energy usage without requiring powerful PA

The value of N\_MSR is the same in all RSFs within one MMS packet.



MMS Illustration

For RSF-only MMS packets, to facilitate incremental processing gain, the following numerology is recommended:

* + The number of preamble fragments X could take one value from the set {1, 2, 4, 8, 16}
  + RSF-RMARKER is defined as the peak of the 1st pulse in the 1st RSF.



RSF-Only MMS Packet

In the case of mixed MMS packets for ranging integrity, the following numerology is recommended when NB is utilized to assist timing/frequency synchronization:

* Additional RIF-RMARKERs are defined as the peak of the first pulse and the peak of the last pulse in each RIF
  + RIF-RMARKER y : peak of the first pulse in RIF-y
  + RIF-RMARKER y’: peak of the last pulse in RIF-y
* To enable incremental gains, the number of RSFs: X and the number of RIFs: Y are allowed to be configured as long as they are from the following sets:
  + X{0, 1, 2, 4, 8}, Y{1, 2, 4, 8}
  + Note that X=0 implies a RIF-only MMS packet
* The baseline modes are defined as the following combinations:
  + (X=Y=1,2,4,8)
  + (X=1, Y=2,4,8)
  + Other combinations are allowed as optional additions
* Additional 1ms gap between RSFs and RIFs when Z=2 in the following figure provides additional time budget to process all the RSFs before starting processing the fragments for integrity validation.



Mixed MMS Packet with NBA

When NB is not exploited to assist timing/frequency synchronization, the following numerology is recommended in the case of mixed MMS packets for ranging integrity:

* SYNC + SFD as shown in the following figure is formatted as in legacy 15.4z HRP;
* Additional RIF-RMARKERs are defined as the peaks of the first pulse and the peak of the last pulse in each RIF
* Configurations of X and Y are allowed if they are from the following sets:
  + - * + X{0, 1, 2, 4, 8}, Y{0, 1, 2, 4, 8}
        + Note: Y=0 is allowed without providing ranging integrity
* (X=0, Y=1) is the default baseline mode to facilitate interoperability
* When X>0, additional 1ms gap between RSFs and RIFs when Z=2 provides additional time budget to process all the RSFs before starting to process the fragments for integrity validation.



UWB-only Mixed MMS Packet with RSFs: X>0



UWB-only Mixed MMS Packet with only RIFs: X=0, Y>0

Further improvements include the following:

* Potential enhancements to IEEE 802.15.4z to facilitate better interference detection and ranging performance for NBA-UWB schemes.
* Schemes that only use UWB radio to achieve link budget improvement relative to 802.15.4z with multi-millisecond ranging.