**Project: IEEE P802.15 Working Group for WPANs**

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| Title | NBA-UWB Technical Framework |
| Date Submitted | February 2023 |
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| Re: | Contribution to IEEE 802.15.4ab |
| Abstract |  |
| Purpose | This submission proposes text to for the IEEE Std 802.15.4ab specification framework document. |
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1. Acronyms and Abbreviations

NBA narrow-band assistance

MMS multi-millisecond

NBA-UWB narrow-band assisted ultra-wideband

RSF ranging sequence fragment

RIF ranging integrity fragment

MMRS multi-millisecond ranging sequence

N\_MSR number of MMRS symbol repetitions within one RSF

RSF-RMARKER ranging marker in ranging sequence fragment

RIF-RMARKER ranging marker in ranging integrity fragment

1. Narrow-Band Assisted Ultra-Wideband (NBA-UWB)
   1. Introduction

In this document, we provide the texts for narrow-band assisted UWB (NBA-UWB) that will be incorporated into the draft-0 specification of IEEE 802.15.4ab.

In NBA-UWB, a tight clock synchronization is assumed between NB and UWB. It is recommended that both PHYs are driven by the same clock so that there is no extra work need to determine relative accuracy.

There are two main sections: One focuses on MAC aspects of NBA-UWB, and the other one details the PHY aspects.

* 1. MAC

NBA-UWB can be viewed as an umbrella feature that comprises several semi-independent features, such as:

* 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.

Text proposal for NBA-UWB MAC can be found in [1].

* 1. 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.

* + 1. 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 is the minimum common mode. 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
  + Availability of 5 and 6 GHz bands and related regulations vary by region.
* 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.

The US UNII-3 band is at 5725-5850 MHz. In UNII-3 band, there are 50 NB channels defined for NBA-UWB. The US UNII-5 band is at 5925-6425 MHz. In UNII-5 band, there are 200 NB channels defined for NBA-UWB. The arrangement of the defined NB channels is shown in the figure below where the center frequencies *fn* for the NB channels 0 <= n <= 249 are defined as

, in the UNII-3 band, and

, in the UNII-5 band.



NB channels in UNII-3 and UNII-5

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 is mandatory. One optional mapping table is specified in next subsection  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 is mandatory. One optional mapping table is specified in next subsection  Note-5: Symbol/Bit-to-chip mapping as: (c0, c1, c2, c3) = (b0, b1, b2, b3)  Note-6: FEC is applied to either PHR or Payload or both as specified in 21.3.6 of IEEE 802.15.4-2020. In particular, FEC shall employ rate-1/2 convolutional code with generator polynomials (133, 171) as specified in Clause 21.3.6 of IEEE 802.15.4-2020 | | | | | | |

Out-of-band signalling is the baseline scheme to signal the NB configuration. Accordingly, the SFD shall be formatted as in Figure 12-3 in IEEE 802.15.4-2020.

* + - 1. Optional Symbol-to-Chip Mapping and In-Band Signalling

The following symbol-to-chip mapping table could be optionally used for Config #1 250 kbps without channel coding.

|  |  |
| --- | --- |
| 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 following symbol-to-chip mapping table could be optionally used for Config #4 250 kbps with channel coding. Note the chip sequences specified in the following table should be time reversed before mapping as illustrated in the figure below for even-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 |

Table

Description automatically generated

Mapping of Chip Sequences for Even-Indexed Symbols

In-band NB configuration signalling is optional where the NB packet signals the NB configuration by using different SFDs. The SFDs shall be formatted as in the following table in the case of in-band NB configuration signalling.

SFDs for In-Band NB Configuration signaling

|  |  |
| --- | --- |
| 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 |

* + 1. 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 as defined in the table below are the baseline to suppress the co-channel interference. 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 as defined in Table 15-7a of IEEE 802.15.4z-2020 and Table 15-7 of IEEE 802.15.4-2020 can 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 STS waveform of pseudo-randomly modulated pulses for ranging integrity based on 4z designs. STS is as specified in 15.2.9 of 802.15.4z-2020
  + Each RIF contains one STS segment with a spreading factor L=4. Each STS segment is of the same length. The length of the STS segment is allowed from the set {32, 64, 128, 256} in the unit of 512 chips.
  + 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

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 symbol repetitions: N\_MSR within each RSF can be configured as follows.

* Set of values: N\_MSR {32, 40, 48, 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.

Length-128 MMRS Sequences

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

One MMS UWB packet could be either an RSF-only MMS, RIF-only MMS, or a mixed MMS. An 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. An RIF-only MMS packet only contains RIFs. The following figure provides an illustration of a generic MMS packet with/without NB assistance. The same pulse shape shall be used for the entire MMS packet and all the pulses within one MMS packet shall be modulated with a constant amplitude. The pulse shape used in MMS packet shall follow the time domain mask as specified in Figure 15-13a in IEEE 802.15.4z-2020. The details about the allowed configurations of X, Y, Z are detailed further in the following paragraphs for different types of MMS packets.



Generic MMS Packet with/without NBA

Let denote the start timing of the first UWB MMS fragment (either RSF or RIF), the start timing of the x-th RSF and the y-th RIF can be determined as follows.

* When X>0, there exists at least 1 RSF
  + Start timing of RSF-x in unit of ms:
  + Start timing of RIF-y in unit of ms:
* When X=0, there are no RSFs
  + Start timing of RIF-y in unit of ms:

For RSF-only MMS packets with NB assistance, 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.



NBA-UWB RSF-Only MMS Packet

In the case of mixed MMS packets for ranging integrity with NB assistance, 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.



NBA-UWB Mixed MMS Packet

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 according to the HPRF mode in IEEE 802.15.4z-2020

SYNC is with length 91 ternary codes in Table 15-7a of IEEE 802.15.4z-2020

SFD is as defined in 15.2.6.3 of IEEE 802.15.4z-2020

* 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



UWB-Only RIF-Only MMS Packet

* + 1. Recommended NBA-UWB MMS Operating Parameter Sets

In this section, we recommend a list of operating parameter sets as a subset of the full set of all allowed 4ab configurations. This brings down the testing cost and facilitates inter-operation.

The list of recommended parameter sets can be found in [2]. Note that [2] is a live document and evolves over time reflecting consensus among the group.

* 1. References

[1] DCN: 15-22-0381-0x-04ab, NBA-MMS-UWB ranging text proposal for 15.4ab TFD

[2] DCN: 15-23-0097-0x-04ab, NBA-UWB MMS Operating Parameter Sets