**IEEE P802.15**

**Wireless Personal Area Networks**

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The enumeration is based on the PAC framework document DCN 328.

**6.1 NICT PHY architecture diagram**



**6.2 Channelization**

Frequency bands of operation are: Sub-GHz, 2.4 GHz and 5.7 GHz bands.

**6.2.1 Channelization of 5.7 GHz band**

Such frequency band ranges from 5.725 GHz to 5.875 GHz, which is divided into 14 channels of 10 MHz. By regulation, the maximum transmit power at the input antenna is 1 W. The central frequencies are given by

*fc = 5735* MHz *+ 10n for n = 0, 1, ..., 13*

**6.2.2 Channelization of 2.4 GHz band**

Such frequency band ranges from 2.4 GHz to 2.5 GHz, which is divided into 9 channels of 10 MHz. By regulation, the maximum transmit power at the input antenna is 1 W. The central frequencies are given by

*fc = 2410* MHz *+ 10n for n = 0, 1, ..., 8*

**6.2.3 Channelization of sub-GHz band**

The basic channelization by regulations in Japan is summarized in the following table:

|  |  |  |  |
| --- | --- | --- | --- |
| Band | Max Tx power (mW) | Frequency band (MHz) | Basic channelization |
| A1 | 1 | 915.9 – 928.1 | 61 channels of 200 KHz |
| B1 | 20 | 920.5 – 928.1 | 38 channels of 200 KHz |
| C1 | 250 | 920.5 – 923.5 | 15 channels of 200 KHz |
| D2 | 1 | 928.1 – 929.7 | 16 channels of 100 KHz |

1bandwidth rule tolerance: *200* *n* kHz, where *n*=*1,2,3,4,5.*

2bandwidth rule tolerance: *100* *n* kHz, where *n*=*1,2,3,4,5.*

Proposed channelization:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Band | Central freq (MHz) | n | No of channels | Max Tx power (mW) |
| A | fc=917+n | 0,1,…,10 | 11 channels of 1 MHz | 1 |
| B | fc=922+n | 0,1,…,5 | 6 channels of 1 MHz | 20 |
| C | fc=921.5+n | 0,1 | 2 channels of 1 MHz | 250 |
| D | fc=928.7+n | 0,1 | 2 channels of 500 KHz | 1 |

**6.3 Duplex**

Support for TDD and FDD frames.

**6.4 Multiplex scheme**

Support for time-frequency multiplexing.

**6.5 Frame structure**

**6.5.1 Frame structure in FDD mode**

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One slot contains 7 DTF-S OFDM or OFDM symbols.

**6.5.2 Frame structure in TDD mode**



where L1=PD1 transmits and PD2 receives, L2=PD2 transmits and PD1 receives, S-L1=synchronization for L1, RS-L1=reference signals for L1, RA=random access or channel sounding for MIMO or beamforming, GP=guard period.

The GP is computed as GP=(73+1024)Ts=71.42 µsec and satisfies Tp+Tdec+Tsw+Tcomp+Tp=GP

where Tdec=time to detect the last symbol, Tsw=time to switch from Rx to Tx or vice-versa,

Tcomp=compensation time to align to GP, and Tp=1 Km/3x108m/s=3.3 µsec (worst case).

The TDD frame configuration is given in the following table:

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| TDD  configuration | Slot number | | | | | | | | | | | | | | | | | | | |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 0 | L1 | S | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | S | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 |
| 1 | L1 | S | L2 | L2 | L2 | L2 | S | L1 | L1 | L1 | L1 | S | L2 | L2 | L2 | L2 | S | L1 | L1 | L1 |
| 2 | L1 | S | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | S | L1 | L1 | L1 | L1 | L1 |
| 3 | L1 | S | L2 | L2 | L2 | L2 | L2 | L2 | S | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 |
| 4 | L1 | S | L2 | L2 | L2 | L2 | S | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 | L1 |
| 5 | L1 | S | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | L2 | S | L1 | L1 | L1 |

**6.5.3 Cyclic prefix**

The cyclic prefix is based on the typical RMS delay spread of the considered unlicensed bands:

|  |  |  |
| --- | --- | --- |
| Frequency | Scenario | RMS delay spread |
| 5.2 GHz | Indoor commercial | 190 nsec |
| 5.2 GHz | Indoor office | 60 nsec |
| 5.2 GHz | Indoor residential | 23 nsec |
| 2.4 GHz | Outdoor | 295 nsec |
| 900 MHz | Indoor | 30.55 nsec |
| 900 MHz | Urban | 1.82 usec |

The CP length is 73*Ts*=4.75 µsec. For sampling time *Ts* see clause **6.6.2.1**.

**6.5.4 Resource block**

A resource block (RB) is a set of time-frequency slots that enables multiplexing in the time and frequency domains.



where **7 DFT-spread OFDM or OFDM symbols (see clause **6.5.2.1**),  6 subcarriers, and  170 (2 upper and lower subcarriers are empty).

Transmission bandwidth (BW) is obtained by concatenating RBs as



The proposed bandwidths for a maximum FFT size of *M*=1024 are given in the table

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| BW (MHz) | No of RBs | No subcarriers | FFT size | Sampling rate |
| 1 | 12 | 72 | 128 | 1.92 MHz |
| 3 | 33 | 198 | 256 | 3.84 MHz |
| 5 | 56 | 336 | 512 | 7.68 MHz |
| 10 | 111 | 666 | 1024 | 15.36 MHz |
| 15 | 166 | 996 | 1024 | 15.36 MHz |

**6.5.5 Data frame structure**

The physical layer protocol data unit (PPDU) is formed by concatenating synchronization header (SHR), Discovery header (DIS), physical layer header (PHR) and physical layer service data unit (PSDU) as illustrated:



Reference signals for demodulation/equalization are embedded in the PSDU.

The MAC protocol data unit (MPDU) is passed to the PHY. Such data is encoded by QC-LDPC codes.

**6.6 Modulation and coding scheme**

**6.6.1 Channel coding**

Channel coding is based on quasi-cyclic low density parity check codes (QC-LDPC).

Quasi-cyclic LDPC codes are systematic, linear codes satisfying **Hc**T=**0,** where **c** is the codeword and **H** is the parity check matrix.

**H** is constructed from the prototype matrix **H**p of size MpxNp by replacing each entry of such matrix [**H**p]i,j with either a cyclic shift matrix **P**c, or identity matrix or null matrices of size ZxZ. The final size of **H** is MpZxNpZ.

Details of the encoding process can be found in document with DCN 369r1.

QC-LDPC parameters for different coding rates to enable link adaptation are given by

|  |  |  |
| --- | --- | --- |
| Coding rate | *k* | *n* |
| 1/2 | 972 | 1944 |
| 1/2 | 324 | 648 |
| 2/3 | 1296 | 1944 |
| 2/3 | 432 | 648 |
| 3/4 | 1458 | 1944 |
| 3/4 | 486 | 648 |
| 5/6 | 1620 | 1944 |
| 5/6 | 540 | 648 |

The prototype matrices **H**p for different coding rates can be found in document with DCN 369r1.

**6.6.2 Modulation**

In the modulation mapper, the scrambled coded bits *bi* for *i=0,1,…,n-1* are modulated with either BSPK, QPSK or 16QAM modulations, resulting in the a block of complex modulation symbols *di* for *i=0,1,…,Nsym-1,* where *di=I+jQ.*

The mapping between bits onto symbols are given by

BPSK mapping:

|  |  |  |
| --- | --- | --- |
| *bi* | *I* | *Q* |
| 0 |  |  |
| 1 |  |  |

QPSK mapping:

|  |  |  |
| --- | --- | --- |
| *bi  bi+1* | *I* | *Q* |
| 00 |  |  |
| 01 |  |  |
| 10 |  |  |
| 11 |  |  |

16QAM mapping:

|  |  |  |
| --- | --- | --- |
| *bi  bi+1 bi+2 bi+3* | *I* | *Q* |
| 0000 |  |  |
| 0001 |  |  |
| 0010 |  |  |
| 0011 |  |  |
| 0100 |  |  |
| 0101 |  |  |
| 0110 |  |  |
| 0111 |  |  |
| 1000 |  |  |
| 1001 |  |  |
| 1010 |  |  |
| 1011 |  |  |
| 1100 |  |  |
| 1101 |  |  |
| 1110 |  |  |
| 1111 |  |  |

**6.6.2.1 DFT-S OFDM or OFDM**

The Parameters are given by

|  |  |
| --- | --- |
| Description | Notation |
| Total No. of subcarriers | *M* |
| Transmission bandwidth | *BW* |
| No. of used subcarriers | *N* |
| Subcarrier spacing | *∆f=BW/N* |
| Sampling time | *Ts* |
| Clock rate | *Rc* |
| Frame time | *Tframe* |
| Slot time | *Tslot* |

*∆f* is constant and equal to 15 KHz.

Maximum FFT size *M*=1024.



Sampling time

Timing based on a common clock at rate



**6.6.2.2 Optional GFSK modulation**

An *optional* and *very low power* PHY based on CP-2FSK modulation is contemplated for the sub-GHz band with no support for MIMO technologies, i.e., layer mapper and precoding are not necessary. The proposed channel encoder, bit interleaver and scrambler are used as well. The modulation mapper is CP-2FSK that is given by



where *V* is amplitude, *S(t)*=sin*(*2*πfc t)* is the modulating-carrier signal, *fc*is the central carrier frequency, *Tsym* is the symbol time, *β=*1 is the modulation index, *∆f=β/*2*Tsym* is the peak frequency deviation, and *φ0* is the initial phase of the modulating-carrier signal.

The information bearing signal is given by



where *gm* is information bits, *p(t)* is a Gaussian pulse shape of bandwidth-symbol duration product of 0.8.

**6.7 Multiple antennas**

**6.7.1 Layer mapping**

Two MIMO technologies are supported: open loop spatial multiplexing and transmit diversity space- frequency block codes (SFBC) for 2 and 4 antennas.

The [complex] modulation symbols per codeword *di* for *i=*0*,*1*,…,Nsym-*1are mapped onto several layers as (a layer represents an independent stream of symbols in a MIMO configuration, and rank is the number of layers transmitted):



where ν is the number of layers and *NLsym*is the number of symbols per layer for the *q*th codeword.

**6.7.1.1 Open loop spatial multiplexing**

Open loop spatial multiplexing enables the transmission of parallel data streams. The mapping of codeword symbols onto layer streams can be found in document with DCN 369r1.

#### 6.7.1.2 Transmit diversity

Transmit diversity enables to transmit the same information from multiple antennas. The mapping of codeword symbols onto layer streams can be found in document with DCN 369r1.

**6.7.2 Precoding**

Precoding allows increasing system performance and robustness by feeding back to the transmitter channel state information (CSI). The schematic diagram of MIMO support with precoding is illustrated as



**6.7.2.1 Open loop spatial multiplexing**

Precoding for open loop spatial multiplexing increases robustness by feeding back the rank of the wireless channel (RI=rank indicator). The transmitter chooses a pre-fixed codeword according to the RI.

Single antenna mapping is trivial and given by



where *pɛ*{0,1,2,3}, *i*=0,1,…,*NPsym*-1, and *NPsym=NLsym*.

Multiple antennas mapping is given by



The transmitter chooses a codeword according to reported RI=*ν*. The codebook for 2 and 4 antennas can be found in document with DCN 369r1.

**6.7.2.2 Transmit diversity**

Transmit diversity is aimed to increase robustness in scenarios with low SNR, low delay tolerance or no feedback to the transmitter is available or reliable.

In case of 2 antennas:

* + STBC (space-time block code) for DTF-Spread OFDM.
  + SFBC (space-frequency block code) for OFDM.

SFBC for 2 antennas is given by



In case of 4 antennas there is a combination of SFBC (2 antennas) with frequency switch transmission diversity and given by



**6.8 Bit interleaver**

In order to minimize latency and integration on parallel architectures within the encoder/decoder implementation in a chip, an algebraic interleaver is proposed.

A maximum contention-free quadratic permutation interleaver is defined as

Short length interleaver: 

Long length interleaver: 

where *i=*0,1,…,*NI*-1. *NI* is the length of interleaver. Elements of codewords (*ci* for *i=*0,1,…,*n*-1*)* are interleaved in blocks of *NI* bits as *c*∏(*j*) for *j=*0,1,…,*NI*-1.

**6.9 Scrambling**

A scrambler is used to shape the data spectrum and to randomize data across users in order to reduce interference. A Gold code generator of length 63 is proposed as scrambler.

Such PN sequence with period 263 appears truly random even for long packets. Moreover, different initialization seeds enable a different Gold code per user with low correlation respect to other user using a different seed.

The Gold code generator outputs *si* for *i=*0,1,…,263-1, which is used to scramble the interleaved codeword bits *ci* for *i=*0,1,…,*n*-1 prior to the modulation mapper as



The shift registers initialization at the start of a packet is given by

* + User ID (1st register) and group ID (2nd register).
  + Fast forward both shift registers 100 times to reduce PAPR.

**6.10 Discovery**

The *discovery preamble (*DP) is based on a ZC sequence and a *discovery* *resource block* (DRB) from a modified DTF-S OFDM or OFDM signal. The DP and DRB formed the Discovery Signal (DS).

Moreover, we propose to use one channel (from the proposed channelization for sub-GHz, 2.4 GHz and 5.7 GHz bands) for only discovery of devices.

PAC devices can either transmit or receive the DS in this unique channel asynchronously. Such unique channel for discovery is named Shared Discovery Channel (SDCH). The discovery signal (DS) sent over a discovery shared channel (DSCH) is illustrated as



The DS consists of a preamble sequence plus a DRB formed by *Nfs* frequency slots and *Nts* time slots. Once synchronized, a receiver knows the location of the discovery resource block (DRS) to scan for possible peers or to pick time-frequency slots to transmit its DS.

The proposed ZC sequence for initial synchronization during discovery (or communication mode) is a ZC sequence with the following parameters: Sequence length *N = 63*, relative prime *r = 62* and *q = 0*.

Such ZC sequence is mapped onto 62 sub-carriers. The first subcarrier and the DC subcarrier are empty. Of course, several repetitions of the DP may be transmitted to improve reliability.



The discovery process is energy intensive. In order to minimize power consumption only one subcarrier of the N-point IFFT is used per user. Consequently, the PAPR is set to the minimum value. Furthermore, across the frequency domain, users are orthogonal (OFDM).

For discovery, the *n*th symbol transmitted over the *k*th subcarrier is given by



where *l=L*+1,…,0,1,…,*N*-1 and *L* is the cyclic prefix length.

Contiguous subcarriers are orthogonal as illustrated in the figure:



The DS is transmitted with a predefined duty-cycle (see NICT MAC proposal). From upper layers, terminals pick time-frequency slots in the DRB to transmit the DS.

A set of 126 symbols are transmitted per time slot. Such frame contains information about a given peer (peer ID, group ID, service ID, application ID, etc.) and which channel is used for association or peering (different from the SDCH).

The number of frequency slots *Nfs =*1024 (IFFT size) and the number of time slots *Nts* is chosen as 20. Consequently, the DRB can support up to *Nfs*x*Nts*=20,480 users for discovery per group.

The discovery data is formatted as illustrated in the figure:



Append 57 bits for user ID, device ID, Group ID, etc.

Append 6 bits from CRC-6-ITU error detection code.

Append 63 bits from shorten BCH(126,63) code.

**6.10.1 Discovery procedure**

Devices are in three possible states:

* + **RDM** – receiving discovery mode,
  + **TDM** – transmitting discovery mode,
  + **Sleep** – idle.

Also, devices are equipped with clear channel assessment (CCA).

**1)** At start up or after idle or after command, a device enters into receiving discovery mode (**RDM**) and listens for a DS.

The synchronization subsystem detects the preamble (and hence the position of the DRB) and the detection subsystem scans the DRB for DRB usage and detection of peer ID, service ID, etc. Go to **Sleep** mode.

**2)** After command, a device enters into transmitting discovery mode (**TDM)**.

Device chooses a free time-frequency slot to transmit its DS over the next DRB transmission. Go to **Sleep** mode.

Of course, there are intermediate steps like time-out for DRB scanning, miss detection, etc. Here, we present the core algorithm idea only.

**6.11 Peering**

For association or peering, intended devices that want to establish a communication link, request peering through a random access preamble transmitted in the ACH.

The random access association preambles are named Random Access Preambles (RAPs).

Such RAPs are formed with ZC sequences as well. Hence, a pool of orthogonal RAPs is formed in order to reduce interference from competing terminals for random access.

A unique RAP is assigned to every device in a Group. Such unique RAP is used for fine synchronization and control messages that control how a communication link is granted.

The RAP signal is illustrated as



where GI is guard interval.

Thus, a set of orthogonal preamble sequences of length 1024 can be generated from ZC sequences for random access, which satisfy the maximum round-trip time and coverage performance for a maximum distance of 500m. Details of preamble design can be found in document with DCN 369r1.

The CP and GI lengths are given by



**6.11.1 Peering procedure**

Once initial synchronization and detection of discovery RB are achieved by Terminal 2 over Terminal 1, for instance, the peering procedure flow is as follows:

Terminal 2 requests association by a random access procedure based on an orthogonal RAP (the process is initiated and control by the MAC and possibly upper layers):



**1)** Terminal 2 sends a **RAP** over the ACH.

The RAP is randomly selected from a pool of orthogonal ZC sequences. It contains finer frequency granularity for Terminal 1 to acquire fine time and frequency synchronization of Terminal 2, plus information about the resources needed to transmit in step **3)**.

**2)** Terminal 1 replies with a **RA response** message.

It contains timing information (round-trip delay), RAP-ID, RB element grant to transmit in step **3)**, plus Group identifier, etc.

**3)** Scheduling request

It contains scheduling request information for transmission. If this message is successfully detected in Terminal 1, still contention remains unsolved for other terminals. A quick resolution is needed.

**4)** Contention resolution

Terminal 1 echoes Terminal 2 ID contained in **3)**, so that one of the following statements is true:

Terminal 2 detects its ID and sends ACK (RA terminated) a communication link is scheduled and established.

Terminal 2 detects another ID (RA terminated and restarts a new one).

Terminal 2 fails to detect ID (RA terminated and starts a new one).

**6.12 Reference signals**

Reference signals are required to perform channel estimation for doubly dispersive wireless channels (time and frequency) for reliable detection, equalization and synchronization.

**6.12.1 Channel’s time dispersion**

Considering a maximum speed of *v*=100 Km/h (27.78 m/s).

The Doppler spread is given by *fd=fc v/c*, where *fc* is the carrier’s central frequency.

The minimum sampling time to reconstruct the channel is *Tc=1/2fd*.

|  |  |  |
| --- | --- | --- |
| Freq. band | fd (Hz) | Tc (msec) |
| 5.7 GHz | 527.82 | 0.947 |
| 2.4 GHz | 222.24 | 2.2 |
| 920 MHz | 85.2 | 6 |

The DFT-spread OFDM or OFDM frame structure has a slot time of *Tslot*=0.5 msec. Then, *one* reference symbol per slot is needed in the time domain to estimate the channel correctly.

**6.12.2 Channel’s frequency dispersion**

Considering 90% and 50% coherence bandwidth as *BC*,90=1/50 *στ* and *BC*,50=1/5 *στ* ,

where *στ* is the channel’s RMS delay spread.

Such RMS delay spread is estimated as . For a distance *d=*500m, the 90% and 50% coherence bandwidth are given in the table:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Freq. band | Ca | γa | στ | Bc,90 (KHz) | BC,50 (KHz) |
| 5.7 GHz | 10 | 0.51 | 238 nsec | 84 | 840 |
| 2.4 GHz | 55 | 0.27 | 295 nsec | 67 | 678 |
| 920 MHz | 1254.3 | 0.06 | 1.82 usec | 11 | 110 |

If *BC*,50*<BW*, then the wireless channel is frequency selective fading and frequency domain equalization is required. We propose that the spacing between 2 reference symbols in the frequency domain in a RB is 30 KHz to resolve the channel’s frequency dispersion.

**6.12.3 Zadoff-Chu sequences**

Preambles or beacons for synchronization and random access are formed with Zadoff-Chu (ZC) sequences of length *N.*

ZC sequences are constant-amplitude zero-correlation (CAZAC) sequences given by



where  is a primitive *n*th root of unity, *r* is a relative prime to *N*, k is the sequence index such that *k =* 0, 1*,* ...,*N*-1and *q* is any integer.

ZC sequences have constant amplitude and so its *N*-point DFT. Hence, this limits the PAPR and simplifies implementation as only phases have to be generated and stored. Furthermore, ZC sequences have ideal cyclic autocorrelation, i.e., the correlation with its shifted version is a delta function. Consequently, a [large] set of orthogonal preambles are possible to generate.