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Wireless Personal Area Networks

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Source	Marco Hernandez, Huan-Bang Li, Igor Dotlić, Ryu Miura (NICT)
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Abstract	
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1. Symbols and Abbreviations

1.1 Symbols

1.2 Abbreviations

2. PHY specification

The proposed PHY specification is designed to offer robust performance for PAC systems and to provide a large scope for implementation opportunities for high performance, robustness, low complexity, and low power operation.

The proposed PHY provides a data interface to the MAC layer under the control of the physical layer convergence protocol (PLCP).

The proposed PHY provides four levels of functionality, as follows:

- Activation and deactivation of the radio transceiver.
- The transmission and reception of synchronization preambles to mantain network synchronization.
- An interface to the MAC for trasnmission and reception of discovery, peering, scheduling and data information.
- It may provide clear channel assessment (CCA) indication to the MAC in order to verify activity in the wireless medium.

3. PHY frame structure

The PHY frame format or physical layer protocol data unit (PPDU) can be formed for 2 types of PPDU. The PPDU ultra frame type 1 is formed by concatenating the synchronization preamble, the physical layer header (PHR), the discovery interval, peering interval, and the physical layer service data unit type 1 (PSDU$_1$), respectively, as illustrated in Figure 1. The PPDU ultra frame type 2 is formed by concatenating the synchronization preamble, the PHR, and PSDU$_2$, as illustrated in Figure 1 as well.

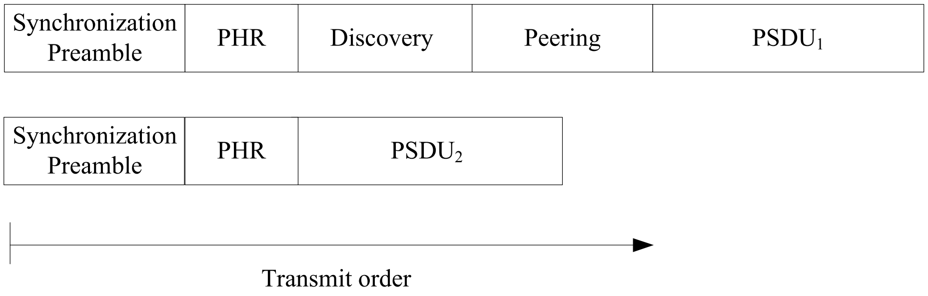


Figure 1—PPDU ultra frame structures type 1 and 2.

The PPDU ultra frame type 1 conveys discovery, peering and data information. The PPDU ultra frame type 2 can conveyed discovery or peering or data information in PSDU$_2$.

The PSDU, or super frame, is formed by *N* data-channels. Each data channel is sub-divided into scheduling and data frame. Each data frame consists of 10 TDD slots: two switching slots (denoted as

S) and eight data slots. Each data slot consists of seven OFDM or DFT-Spread OFDM symbols and last 0.5 msec, as illustrated in Figure 2.

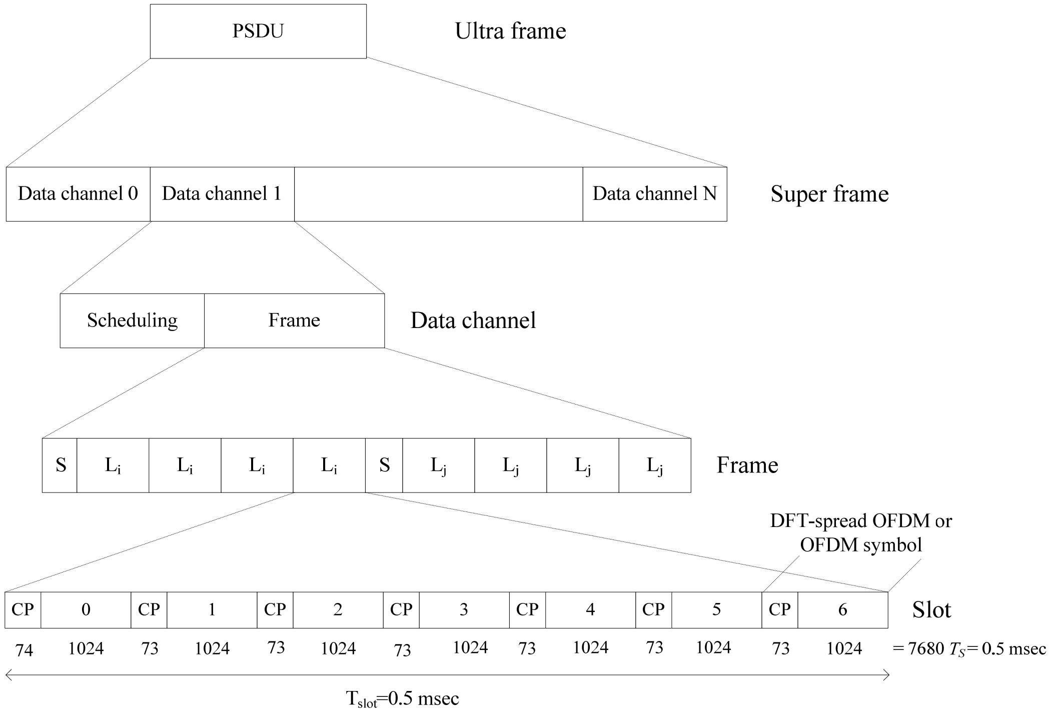


Figure 2—Generic PSDU structure

3.1 TDD frame

The TDD frame consists of two switching slots and eight data slots. For asymmetric traffic, three types of TDD frames are defined in Table 1.

Table 1—TDD asymmetric frame types

Type	Frame structure									
0	S	L_t	L_t	L_t	L_t	S	L_r	L_r	L_r	L_r
1	S	L_t	L_t	S	L_r	L_r	L_r	L_r	L_r	L_r
2	S	L_t	L_t	L_t	L_t	L_t	L_t	S	L_r	L_r

In frame type 1, the first four data slots, denoted as L_t, the PAC device (PD) transmits. After switching, in the remaining four data slots, the PD receives, L_r.

The TDD switching slot (denoted as S) consists of a guard interval, preamble for fine synchronization and channel sounding and control channel as illustrated in Figure 3. Note that the preamble and control channel are transmitted by the PD that was in receiving mode before the switching. The duration of S is 0.5 msec as well.

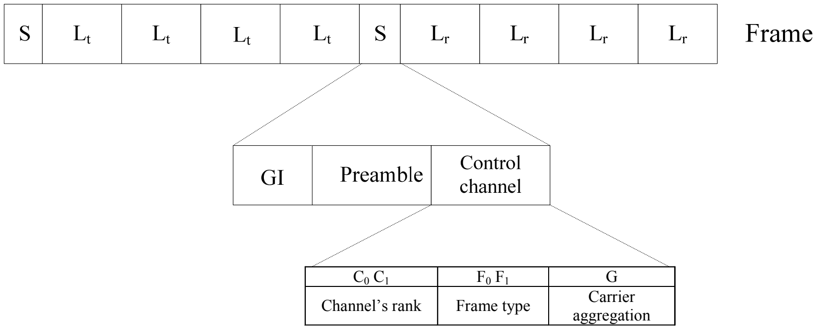


Figure 3—TDD switching slot

3.2 Guard interval

The last transmitted symbol of PD1 arrives to PD2 after a propagation time, T_p. Such symbol is detected over T_{dec}. PD2 switches from receiver to transmitter in T_{sw}. Then, the first transmitted symbol of PD2 arrives to PD1 after Tp. Consequently, the guard interval is given by

$$GI = T_p + T_{dec} + T_{sw} + T_p + T_{com} \qquad (1)$$

where T_{com} is compensation time to align to FFT sampling.

Considering T_p=1 Km/3x108 m/s = 3.3 μsec (worst case), or T_p=10 m/3x108 m/s = 0.033 μsec (typical case), T_{sw}=500 nsec, T_{dec}=0.9 μsec, then GI=10 μsec.

3.3 Preamble

The preamble is formed of a ZC sequence.

3.4 Control channel

Control channels passes information for the PD in receiving mode about previous channel's rank and TDD frame type.

Table 2—Channel's rank

C_0 C_1	Channel's rank
00	1
01	2
10	3
11	4

Table 3—TDD frame type

F_0 F_1	Frame type
00	0
01	1
10	2
11	r

4. Synchronization preamble

The synchronization preamble is repetitions of Zadoff-Chu (ZC) sequences. Those belong to family of Constant-amplitude zero-correlation (CAZAC) sequences. ZC sequences have good correlation properties and easy implementation for devices with multicarrier modulation. As ZC sequences have constant amplitude and so its N-point DFT, this limits the PAPR and simplifies implementation as only phases have to be generated and stored.

ZC sequences are well documented in the literature and it is possible to test and design a large set of orthogonal preambles or reference signals.

ZC sequences of length N is given by

$$a_k = \begin{cases} W_N^{\frac{k^2}{2}+qk} & N \text{ even} \\ W_N^{\frac{k(k+1)}{2}+qk} & N \text{ odd} \end{cases} \tag{2}$$

where $W_N = e^{-j\frac{2\pi r}{N}}$ is a primitive *n*th root of unity, *r* is a relative prime to *N*, *q* is any integer and sequence index $k = 1, 0, \ldots, N-1$.

The synchronization preamble is formed by repetitions of the ZC sequence with length $N = 63$, relative prime $r = 62$ and q = 0. The autocorrelation properties is illustrated in Figure 4.

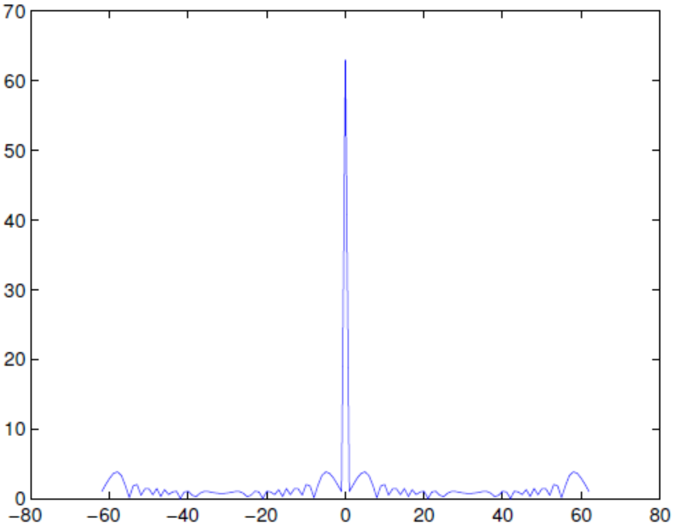


Figure 4—Autocorrelation of synchronization preamble.

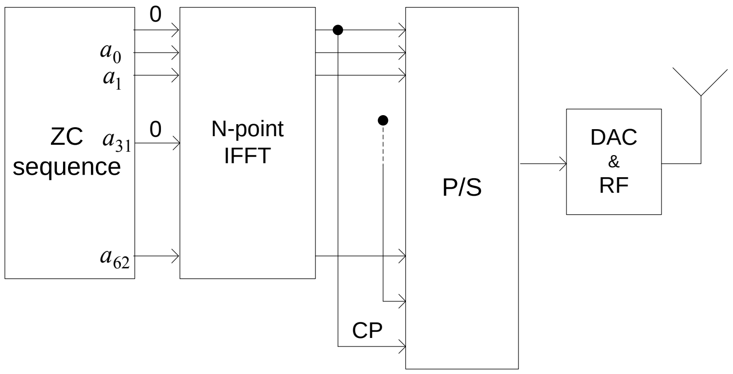


Figure 5—Implementation of synchronization preamble.

5. PHY header

The PHY header structure is illustrated in Figure 6, where the transmit order is from bit 0 to bit 26.

Bit 0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
R_0	R_1	R_2	r	L_0	L_1	L_2	L_3	L_4	L_5	L_6	L_7	r	r
Data rate				PSDU length									

Transmit order

14	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
B	$S1_0$	$S1_1$	$S1_2$	$S1_3$	$S1_4$	$S1_5$	$S2_0$	$S2_1$	$S2_2$	$S2_3$	$S2_4$	$S2_5$
Burst	1st seed						2nd seed					

Transmit order

27	**28**	**29**	**30**	**31**
F	P_1	P_2	r	r
Frame type	PSDU type		Reserved	

Transmit order

Figure 6—PHY header structure

5.1 Data rate

Data rates are indicated by (R_0, R_1, R_2), where R_2 is the most significant bit (MSB) and R_0 is the least significant bit (LSB).

5.2 PSDU length

A variable frame length is indicated by (L_0, L_1, L_2, L_3, L_4, L_5, L_6, L_7), where L_7 is the MSB and L_0 is the LSB.

5.3 Burst mode

The burst mode is indicated by (B) and defined in Table 56. The burst mode supports higher throughput by allowing the transmission of consecutive frames without ACK.

Table 4—Burst mode

B	Status
0	Next package is not part of burst
1	Next package is part of burst

5.4 Scrambler seeds

The two scrambler seeds (initial conditions) for the Gold code generator are indicated by ($S1_0$ $S1_1S1_2$ $S1_3$ $S1_4$ $S1_5$) for user ID and ($S2_0$ $S2_1$ $S2_2$ $S2_3$ $S2_4$ $S2_5$) for group ID.

5.5 Frame type

The frame type is indicated by (F) and defined in Table 5.

Table 5—Frame type

F	Status
0	Next package is type 1
1	Next package is type 2

5.6 PSDU type

For frame type 2, the PSDU may convey the discovery or peering or data information. This is indicated by (P1, P2) and defined in Table 6.

Table 6—PSDU type

P_1 P_2	PSDU status
00	Discovery
01	Peering
10	Data
11	Reserved

5.7 Header check sequence

The PLCP shall append 4-bits from CRC-4 ITU error detection coding to the PHR information. The CRC-4-ITU shall be the one’s complement of the remainder generated by the modulo-2 division of the PHR information by the polynomial:

$$1 + x + x^4 \tag{3}$$

The HCS bits shall be obtained in the transmit order as shown in Figure 7 after the PHR bits are processed in the shift register. The shift register stages shall be initialized to all ones.

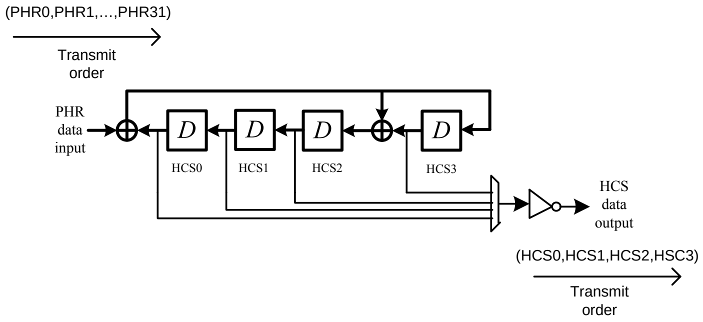


Figure 7—CRC-4 ITU data processing.

6. Discovery

For ultra-frame type 1, the discovery information is conveyed in a modified DFT-spread OFDM or OFDM signal denoted as discovery signal (DS).

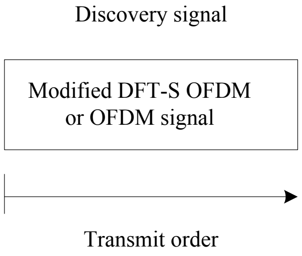


Figure 8—Discovery signal

6.1 Discovery signal

The discovery signal contains the discovery information of PDs in the neighborhood. It consists of a [discovery] resource block (DRB) formed by N_{fs} frequency slots and N_{ts} time slots. Once synchronized, a receiver PD knows the location of the discovery resource block (DRS) to scan for possible peers or for a transmitter PD to pick time-frequency slots to transmit its discovery signal. Moreover, across the frequency domain, users are orthogonal similar to OFDMA.

As all PDs are scanning the discovery resource block for either detection or transmission of the discovery signal, the process is energy intensive and prone to interference. Therefore, we propose to modify an OFDM or DFT-S OFDM signal by transmitting only one subcarrier over the OFDM symbol duration per user.

Consequently, the peak to average power ratio (PAPR) is set to the minimum, 0 dB, while having least interference to signals outside the one transmitting subcarrier. Moreover, power consumption is minimized.

Hence, the baseband discovery signal or the *n*th OFDM symbol transmitted over a *k*th subcarrier with a QPSK symbol (other $N-1$ subcarriers are set to zero) per user is given by

$$x_n[l,k] = \frac{1}{N} X_n[k] \exp\left(j \frac{2\pi\, l\, k}{N} \right) \tag{4}$$

where $l = -L+1, \ldots, 0, 1, \ldots, N-1$. The cyclic prefix's length is L.

The corresponding passband signal, without CP, over the central carrier $w_c = 2\pi f_c$ is given by

$$w(t) = \left| X_n[k] \right| \cos(w_c t - w_k t - \varphi_k) \qquad 0 \le t < T \tag{5}$$

where the QPSK symbol over the *k*th subcarrier of the *n*th OFDM symbol is denoted as $X_n[k]$, with magnitude $| X_n[k] |$ and phase φ_k. Figure 9 illustrates the signal discovery generation.

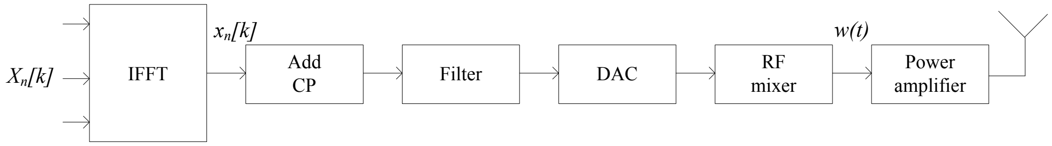


Figure 9—Discovery signal generation

The single tone OFDM signal is constructed with the parameters shown in Table 7.

Table 7—FFT parameters for discovery signal

Parameter	Value
No of subcarriers	M=128
Subcarrier spacing	Δf=15 kHz
Sampling time	$T_s = 1/(\Delta f\, M)$=520.83 nsec
Clock rate	R_c=1.92 MHz

The discovery signal contains N_{ts}xN_{fs} discovery resource blocks (DRBs) as illustrated in Figure 10.

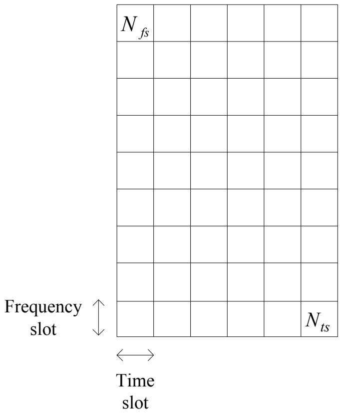


Figure 10—Discovery resource block.

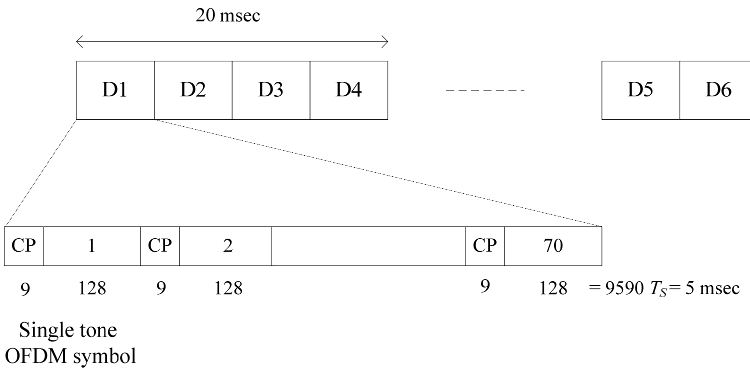


Figure 11—Discovery signal duty cycle

The discovery signal consist of N_{ts}=4 consecutive blocks of 20 msec containing 280 single tone OFDM symbols over 1.92 MHz split in N_{fs}= 128 single tone parallel channels, as illustrated in Figure 10 and Figure 11. The number of DRBs or users per PD is 512.

Depending on the configuration of the PHY and duty cycling of the PHY frame, the number of timing slots, N_{ts}, can be either 4 or 8 (the next block of 20 msec for discovery signal can be used as an extension of the discovery information).

In other words, the 512 DRBs can contain either 280 or 560 single tone OFDM symbols. Every single tone OFDM symbol conveys 2 bits of information via QPSK modulation. Considering half rate FEC to protect the discovery information, every DRB contains either 280 bits (35 bytes) or 560 bits (70 bytes).

Considering 280 bits means $1.9426689\text{x}10^{84}$ different combinations and 560 bits means $3.773962\text{x}10^{168}$ different combinations, this is more than enough for PD ID, user ID, group ID, application ID, etc.

7. Peering

After the discovery phase, PDs that intend to establish a communication link with a discovered PD request that with a random access preamble. According to the frame structure in clause 3, after discovery, PDs can transmit in the peering frame period for association with another PD. As such PDs can transmit at any moment; a set of orthogonal preambles is required in order to reduce interference from competing terminals.

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 A unique RAP is assigned to every device in a Group. Such unique RAP is used for fine synchronization and control messages (how a communication link is granted or how resources are assigned to PDs).

7.1 Random access preamble

The RAP signal structure is illustrated in Figure 12. There is a CP for and guard interval at the beginning and end, respectively.

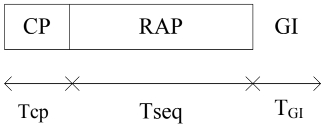


Figure 12—Random access preamble structure

The design of the RAP takes into account:

a) The RAP length must fit a slot time of 0.5 msec.
b) Maximum round-trip delay.
c) Granularity of subcarriers spacing.

T_{seq}, must allow round-trip estimation at the largest expected distance of d=500 m (1 km round-trip).

the maximum round-trip time and coverage performance for a maximum distance of 500m as follows:

The RAP duration,

$$T_{seq} \geq \frac{1000\,\text{m}}{3\text{x}10^8\ \text{m/s}} + \sigma_\tau \tag{6}$$

According to the Channel Model Document, the RMS delay spread is computed as $\sigma_\tau = C_a d^{\gamma_a}$ and values for a distance of 500 m are given in Table 8.

Consequently $T_{seq} \geq 5.33\,\mu\text{sec}$ (7)

Table 8—RMS delay spread for 500m

Frequency band	σ_τ
5.7 GHz	339 nsec
2.4 GHz	355 nsec
920 MHz	2 µsec

The coverage performance can be estimated from the link budget. It is possible to show that

$$T_{cp} = \frac{NF\ kT_0}{L(d)} \frac{E_P}{N_0} \tag{8}$$

where NF is the noise figure, kT_0 is the noise temperature, $L(d)$ is the path loss at distance d and E_p is the required preamble energy to meet a PFA of 10^{-3}.

According to the parameters d=500m, f_c=2.4 GHz, P_t=1 W, G_t=G_r=5 dBi, NF=5 dB, kT_0=−204 dB, the path loss model in clause 2.2.6 of the Channel Model Document, and through simulations the value E_p/N_0=18 dB. Consequently, T_{seq}=0.433 msec.

The CP and GI lengths at 500m are approximately 2(500 m)/3x10^8 m/s = 3.33µsec. Then, T_{seq} is upper bounded by

$$T_{seq} \leq 0.433\,\text{msec} - 2(3.33\,\mu\text{sec}) = 0.4263\,\text{msec} \tag{9}$$

The FFT size to implement the RAP must be a natural number multiple of a power of 2:

$$N_{FFT} = f_s T_{seq} = k \tag{10}$$

In order to minimize the subcarriers orthogonality loss between the RAP and subcarriers use to data, the subcarrier spacing, Δf, is a integer multiple of the RAP subcarrier spacing Δf_{RAP} computed as

$$\Delta f_{RAP} = \frac{\Delta f}{k} \tag{11}$$

where k is a natural number.

The sequence length that satisfies Equation (7), Equation (8) and Equation (11) simultaneously is T_{seq}=0.4 msec. Consequently, $\Delta f_{RAP}=1/T_{seq}$=2.5 KHz and from Equation (11), k=6 or granularity increment. The sampling time is given by $t_s=1/(1024\ \Delta f_{RAP})$. Finally, the RAP preamble length is computed as 0.4 msec/t_s=1024.

The CP duration is given by

$$T_{CP} = 0.5(T_{slot} - T_{seq}) + 0.5\sigma_{\tau} \tag{12}$$

The maximum RMS delay spread of 2 µsec is considered for maximum coverage and so protection against multipath interference. Hence, T_{CP}=51µsec and in terms of number of sampling points: $\lfloor T_{CP} / t_s \rfloor = 131$.

The maximum round trip delay (RTD) is the value for the GI:

$$T_{GI} = 0.5(T_{slot} - T_{seq}) \tag{13}$$

Hence, T_{GI}=50 µsec and shown in Figure 13.

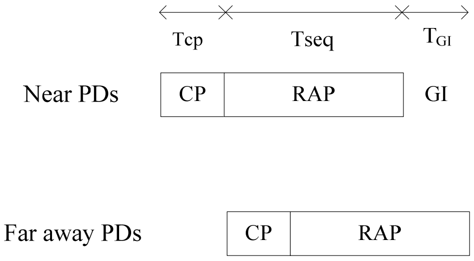


Figure 13—RAP dimensioning

Conclusion: a set of orthogonal preamble sequences of length 1024 can be generated from ZC sequences for random access, which satisfy maximum round-trip time and coverage performance for a maximum distance of 500m. Moreover, such set of orthogonal preambles is divided into Groups. Tentatively, 100 Groups with 64 RAPs each. Every PD identifies the supported RAP Group ID in the discovery signal.

7.2 Random access procedure

Once network synchronization and decoding of discovery RB information are achieved by PDs, such PDs may request association (peering) to a target PD at any time. Consequently, the random access can be requested during the peering period, in which control signals are interchanged in order to schedule the intended PDs for transmission (channel band, modulation, slot time, etc.).

As a general case, we assume the decoding of discovery RB are achieved by PD_2 over PD_1, PD_2 requests association (peering) to PD_1 by a random access procedure based on an orthogonal RAP.

Moreover, after the discovery phase, PD_2 can estimate the transmission power of PD_1, channel band used for association and RAP-ID Group handled by PD_1.

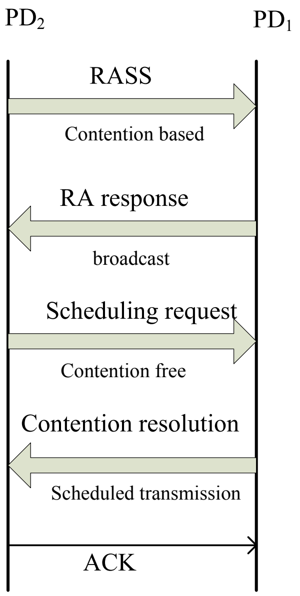


Figure 14—Random access procedure

The peering process is initiated and control by upper layers.

1) PD_2 sends a RAP to PD_1 requesting association, which is contention based. It is randomly selected from a pool of orthogonal ZC sequences that belong to the RAP Group supported by PD_1. Moreover, such RAP contains finer frequency granularity for PD_1 to acquire fine time and frequency synchronization of PD_2, plus information about the resources needed to transmit in 3).
2) PD_1 replies with a RA response message. It is broadcast and contains timing information (round-trip delay), RAP-ID of PD_2, plus resources, like time slot or time-frequency slot, to transmit in 3), etc.
3) PD_2 sends a scheduling request (note that it is contention free). It contains scheduling request information for transmission. If this message is successfully detected in PD_1, still contention remains unsolved for other terminals.
4) Contention resolution. PD_1 echoes PD_2 ID contained in 3) PD_2 detects its ID and sends ACK (RA terminated) a communication link is scheduled and established. PD_2 detects another ID (RA terminated, starts a new one) PD_2 fails to detect ID (RA terminated, starts a new one)

8. PSDU construction

The PSDU contains the MAC protocol data unit (MPDU) and forward error correction (FEC) bits. The PSDU construction process is illustrated in Figure 15.

The MPDU is passed to the PHY from the MAC. Such data is encoded by quasi-cyclic low density parity check codes (QC-LDPC). Such QC-LDPC FEC codes allow performance close to turbo codes, besides that encoder/decoder enable high throughput and low implementation complexity (efficient implementation in parallel architectures). That is, it is a better option than convolutional codes.

Quasi-cyclic LDPC codes are systematic, linear codes satisfying

$$\boldsymbol{H}c^{T} = \boldsymbol{0} \tag{14}$$

where $\boldsymbol{H}_{n-k \times k}$ is the parity check matrix. The codeword, $\boldsymbol{c} = (i_0, i_1, ..., i_{k-1}, p_0, p_1, ..., p_{n-k-1})$ of length n, consists of k data bits and n-k parity bits.

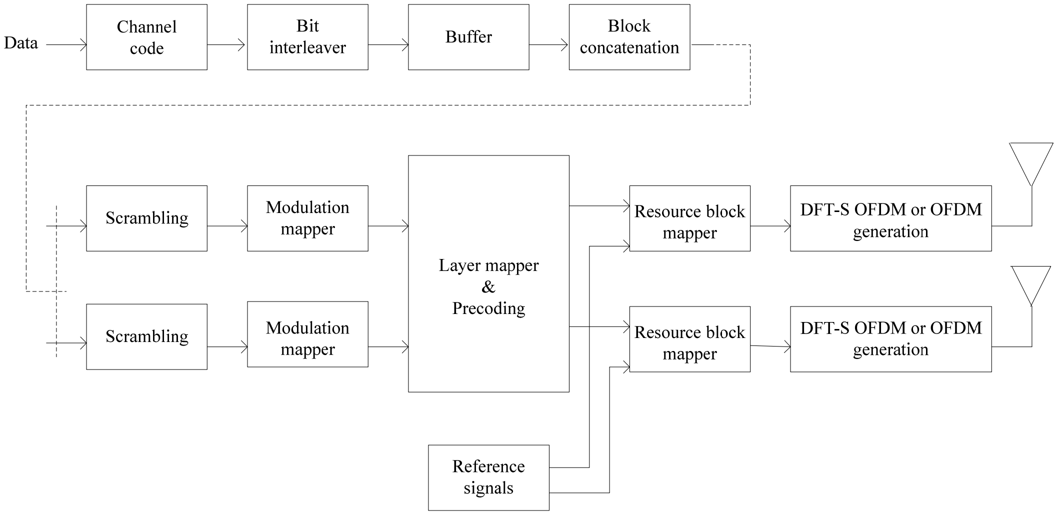


Figure 15—PSDU construction schematic diagram

The number of codewords in the PSDU is given by

$$N_{CW} = \left\lceil \frac{N_{MPDU}}{k} \right\rceil \tag{15}$$

where N_{MPDU} is the number of information bits in the MPDU. If the rem(N_{MPDU} ,k)≠0 , the last codeword in the PSDU requires $N_{bs}=N_{CW}k-N_{MPDU}$ bits stuffing. Otherwise, $N_{bs}=0$. The total number of uncoded bits is $N_{PSDU}=N_{MPDU}+N_{bs}$.

Total number of coded bits in a packet is $N_{Tcw}=N_{CW}\,n$ and such coded bits are indexed as:

$$c_{nq+i} \quad \text{for } i=0,1,\ldots,n-1 \text{ and } q=0,1,\ldots,N_{CW}-1. \tag{16}$$

H is constructed from a prototype matrix $\boldsymbol{H}_{\mathrm{p}}|_{Mp \times Np}$ by replacing each entry of the prototype matrix, denoted as $[H_p]_{\mathrm{i,j}}$, with either a cyclic shift matrix, $\boldsymbol{P}_c$, or identity matrix or null matrix of size ZxZ. The final size of ***H*** is M_pZ x N_pZ.

$$[\boldsymbol{H}_p]_{ij} = \begin{cases} \boldsymbol{I}_{ZxZ} & \text{If } [\boldsymbol{H}_p]_{ij} = 0 \\ \boldsymbol{0}_{\mathrm{ZxZ}} & \text{If } [\boldsymbol{H}_p]_{ij} = \text{'–'} \\ \boldsymbol{P}_c & \text{If } [\boldsymbol{H}_p]_{ij} = p \end{cases} \tag{17}$$

where p is integer number larger or equal to zero, and '-' denotes a character.

The cyclic-permutation matrix $\boldsymbol{P}_c$ is obtained by cyclically shifting the columns of $\boldsymbol{P}_0 = \boldsymbol{I}_{\mathrm{ZxZ}}$ to the right c times, for instance:

$$\boldsymbol{P}_0 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \boldsymbol{P}_1 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix} \quad \boldsymbol{P}_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

8.1 QC-LDPC encoder parameters

The QC-LDPC coding rates are indicated in Table 9, where k is the number of information bits, n is the number of coded bits and $n-k$ is the number of parity bits.

Table 9—Coding rates

Coding rate (C_R)	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 for the different data rates are in Annex A.

8.2 Interleaver

The interleaver is based on a maximum contention-free quadratic permutation interleaver. The objective is to minimize latency and the interleaver's integration on parallel architectures within the encoder/decoder chip implementation.

A maximum contention-free quadratic permutation interleaver is defined as:

$$\prod(i) = f_1 i + f_2 i^2 \text{ Mod } N_I \tag{18}$$

where N_I is the interleaver's length, and the interleaver's index i=0,1,…,N_I-1.

If N_I is even, f_1 is odd and relative prime to N_I and all prime factors of N_I are also factors of f_2.

The short length interleaver is given by

$$\prod(i) = 31\,i + 64\,i^2 \;\mathrm{Mod}\,1024 \tag{19}$$

The long length interleaver is given by

$$\prod(i) = 11\,i + 21\,i^2 \;\mathrm{Mod}\,15120 \tag{20}$$

The N_{Tcw} coded bits are interleaved in blocks of N_I bits as:

$$c_{\prod(i \,\mathrm{Mod}\, N_I)} \quad \text{for } i=0,1,\ldots,N_{Tcw}-1 \tag{21}$$

8.3 Scrambler

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

As the Gold code generator is formed by two PN sequences with period $L=2^{63}$, its output remains random for long packet sizes. Moreover, different initialization seeds, enables a different Gold code sequence per user and consequently low correlation respect to other user using a different seed.

The Gold code generator shall be constructed by two PN sequence generators with polynomials x^6+x+1 and $x^6+x^5+x^2+x+1$. The Gold code generator output is indicated by s_i, which is used to scramble the interleaved-coded bits as:

$$b_i = \left(c_{\prod(i \,\mathrm{Mod}\, N_I)} + s_{i \,\mathrm{Mod}\, L}\right)\mathrm{Mod}\;2 \qquad \text{for } i=0,1\ldots,N_{Tcw}-1 \tag{22}$$

The 63 shift register initialization shall be done by user ID for the first PN generator and group ID for the second PN generator. Fast forward both PN generators 100 times to reduce PAPR.

8.4 Modulation mapper

The scrambled-interleaved-coded-bits, b_i, shall be modulated with BPSK, QPSK, 16QAM or 64QAM.

8.4.1 Pad bits

Pad bits shall be appended at the end of the input bit stream to align on a symbol boundary. The number of pad bits is given by

$$N_{pad} = \log_2(M)\left\lceil \frac{N_{PSDU} + (n-k)N_{CW}}{\log_2(M)} \right\rceil - [N_{PSDU} + (n-k)N_{CW}] \tag{23}$$

where M is the cardinality of the modulation. In case of uncoded transmission $N_{CW}=0$.

The total number of bits on the air per PHY frame is given by

$$N_T = N_{PSDU} + (n-k)N_{CW} + N_{pad} \tag{24}$$

8.4.2 Modulations

The complex modulation symbols, denoted as d_l, as function of the input bits, are given in Table 10 and the modulation mappings are in Annex B, for bit index $i=0,\ldots,N_T-1$ and symbol index $l=0,\ldots,N_{sym}-1$ where $N_{sym}=N_T\,/\mathrm{Log}_2(M)$ is an integer.

The modulations symbols per codeword may be expressed as

$$d_{l+qN_{CW}} = d_l^q \quad \text{for } l=0,1,\ldots,N_{sym}^q-1 \text{ and } q=0,1,\ldots,N_{CW}-1. \tag{25}$$

where $N_{sym}^q = N_{sym}/N_{CW}$ is the number of symbols for the qth codeword.

Table 10 —Modulations

Modulation	Complex symbol	Log$_2$(*M*)
BPSK	$d_l(b_i)=I+jQ$	1
QPSK	$d_l(b_i, b_{i+1})=I+jQ$	2
16QAM	$d_l(b_i, b_{i+1}, b_{i+2}, b_{i+3})=I+jQ$	4
64QAM	$d_l(b_i, b_{i+1}, b_{i+2}, b_{i+3}, b_{i+4}, b_{i+5})=I+jQ$	6

9. Layer mapping

Two MIMO technologies are supported: open loop spatial multiplexing and transmit diversity for 2 and 4 antennas. The mandatory transmission in MIMO mode depends on the number of antennas that can be implemented in a PD.

The complex modulation symbols for the qth codeword, d_l^q for $l=0,1,\ldots,N_{sym}^q-1$ are mapped into several layers as

$$[d_0^q,\ldots,d_{N_{sym}^q-1}^q] \rightarrow [x_0(i),\ldots,x_{\nu-1}(i)]^T \quad \text{for } i=0,1,\ldots,N_{sym}^L-1. \tag{26}$$

where ν is the number of layers and N_{sym}^L is the number of symbols per layer. Layer stands for an independent stream of symbols in a MIMO configuration. Rank is defined as the number of layers transmitted.

9.1 Layer mapping for one antenna

In case of one antenna in a PD, only one layer is used, ν=1, and the mapping is given by the first row of Table 11.

9.2 Open loop spatial multiplexing

Spatial multiplexing represents the transmission of multiple parallel streams. The mapping of modulation symbols to layers is shown in Table 11. The number of layers is less or equal to the number of antennas, ν ≤ P.

Table 11—Mapping for spatial multiplexing

No of layers	No of codewords	Mapping	Parameter
1	1	$x_0(i) = d_i^0$	$N_{sym}^L = N_{sym}^0$
2	1	$x_0(i) = d_{2i}^0$ $x_1(i) = d_{2i+1}^0$	$N_{sym}^L = N_{sym}^0 / 2$
2	2	$x_0(i) = d_i^0$ $x_1(i) = d_i^1$	$N_{sym}^L = N_{sym}^0 = N_{sym}^1$
4	1	$x_0(i) = d_{4i}^0$ $x_1(i) = d_{4i+1}^0$ $x_2(i) = d_{4i+2}^0$ $x_3(i) = d_{4i+3}^0$	$N_{sym}^L = N_{sym}^0 / 4$
4	2	$x_0(i) = d_{2i}^0$ $x_1(i) = d_{2i+1}^1$ $x_2(i) = d_{2i}^0$ $x_3(i) = d_{2i+1}^1$	$N_{sym}^L = N_{sym}^0 / 2 = N_{sym}^1 / 2$

9.3 Transmit diversity

Transmit diversity is created by transmitting the same information from multiple antennas. The mapping of modulation symbols to layers is shown in Table 12.

Table 12—Mapping for transmit diversity

No of layers	No of codewords	Mapping	Parameter
2	1	$x_0(i) = d_{2i}^0$ $x_1(i) = d_{2i+1}^1$	$N_{sym}^L = N_{sym}^0 / 2$
4	1	$x_0(i) = d_{4i}^0$ $x_1(i) = d_{4i+1}^0$ $x_2(i) = d_{4i+2}^0$ $x_0(i) = d_{4i+3}^0$	$N_{sym}^L = \begin{cases} N_{sym}^0 / 4 & \text{If } N_{sym}\text{Mod}4 = 0 \\ \dfrac{N_{sym}^0 + m}{4} & \text{If } N_{sym}\text{Mod}4 \neq 0 \end{cases}$

If N_{sym}^q Mod4≠0 add *m* null symbols at the end such that N_{sym}^q +*m* Mod4=0.

10. Precoding

The block of symbols obtained from the layer mapping, $\boldsymbol{x}$, are mapped onto the block of symbols, $\boldsymbol{y}$, to be transmitted by *P* antennas as illustrated in Figure 16.

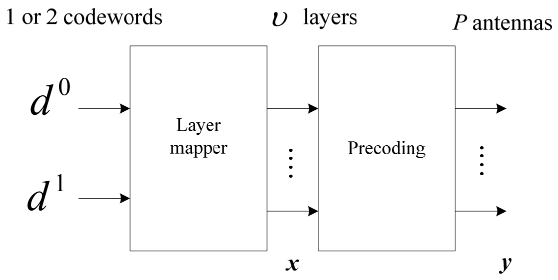


Figure 16—Precoding mapping

10.1 Single antenna mapping

Transmission with a single antenna, precoding is defined by

$$y_0(i) = x_0(i) \tag{27}$$

where i=0,1,…, $N_{sym}^{P} - 1$ and $N_{sym}^{P} = N_{sym}^{L}$ is the number of symbols transmitted per antenna.

10.2 Open loop spatial multiplexing

Precoding for open loop spatial multiplexing delivers performance robustness by feeding back the channel's rank. Such channel's rank is indicated by 2 bits in the control channel of the TDD frame. Consequently, transmitter can choose a pre-fixed codeword according to the channel's rank.

Precoding for multiple antennas is defined by

$$\begin{bmatrix} y_0(i) \\ \vdots \\ y_{P-1}(i) \end{bmatrix} = \boldsymbol{W}(i) \begin{bmatrix} x_0(i) \\ \vdots \\ x_{\nu-1}(i) \end{bmatrix} \tag{28}$$

where i=0,1,…, $N_{sym}^{P} - 1$ and $N_{sym}^{P} = N_{sym}^{L}$. The precoding codeword matrix $\boldsymbol{W}$ is chosen by the transmitter according to the reported channel's rank.

The codebook for P=2 antennas is given in Table 13 and P=4 antennas is given in Table 14.

Table 13—Codebook for transmission on 2 antennas

Index	ν=1	ν=2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -1 \end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ j \end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -j \end{bmatrix}$	

$j = e^{\pi/2}$

The codebook for 4 antennas is based on the Householder theorem: If $\boldsymbol{x}$ and $\boldsymbol{y}$ are vectors with the same norm, then exists an orthogonal symmetric matrix $\boldsymbol{W}$ such that $\boldsymbol{y}=\boldsymbol{W}\boldsymbol{x}$, where $\boldsymbol{W}=\boldsymbol{I}-2\boldsymbol{u}\boldsymbol{u}^{T}$ and $\|\boldsymbol{u}\|=1$.

Since $\boldsymbol{W}$ is orthogonal and symmetric, then $\boldsymbol{W}=\boldsymbol{W}^{-1}$, simplifying the implementation complexity considerably.

Table 14—Codebook for transmission on 4 antennas

n	$\boldsymbol{u}_n$	v=1	v=2	v=3	v=4
0	$[1\ \ -1\ \ -1\ \ -1]^T$	$W_0^{\{1\}}$	$W_0^{\{14\}}/\sqrt{2}$	$W_0^{\{124\}}/\sqrt{3}$	$W_0^{\{1234\}}/2$
1	$[1\ \ -j\ \ -1\ \ j]^T$	$W_1^{\{1\}}$	$W_1^{\{12\}}/\sqrt{2}$	$W_1^{\{123\}}/\sqrt{3}$	$W_1^{\{1234\}}/2$
2	$[1\ \ 1\ \ -1\ \ 1]^T$	$W_2^{\{1\}}$	$W_2^{\{12\}}/\sqrt{2}$	$W_2^{\{123\}}/\sqrt{3}$	$W_2^{\{3214\}}/2$
3	$[1\ \ j\ \ 1\ \ -j]^T$	$W_3^{\{1\}}$	$W_3^{\{12\}}/\sqrt{2}$	$W_3^{\{123\}}/\sqrt{3}$	$W_3^{\{3214\}}/2$
4	$\left[1\ \ (-1-j)/\sqrt{2}\ \ -j\ \ 1\right]^T$	$W_4^{\{1\}}$	$W_4^{\{14\}}/\sqrt{2}$	$W_4^{\{124\}}/\sqrt{3}$	$W_4^{\{1234\}}/2$
5	$\left[1\ \ (-1+j)/\sqrt{2}\ \ -j\ \ (-1-j)/\sqrt{2}\right]^T$	$W_5^{\{1\}}$	$W_5^{\{14\}}/\sqrt{2}$	$W_5^{\{124\}}/\sqrt{3}$	$W_5^{\{1234\}}/2$
6	$\left[1\ \ (1+j)/\sqrt{2}\ \ -j\ \ (-1+j)/\sqrt{2}\right]^T$	$W_6^{\{1\}}$	$W_6^{\{13\}}/\sqrt{2}$	$W_6^{\{134\}}/\sqrt{3}$	$W_6^{\{1324\}}/2$
7	$\left[1\ \ (-1+j)/\sqrt{2}\ \ j\ \ (1+j)/\sqrt{2}\right]^T$	$W_7^{\{1\}}$	$W_7^{\{13\}}/\sqrt{2}$	$W_7^{\{134\}}/\sqrt{3}$	$W_7^{\{1324\}}/2$
8	$[1\ \ -1\ \ 1\ \ 1]^T$	$W_8^{\{1\}}$	$W_8^{\{12\}}/\sqrt{2}$	$W_8^{\{124\}}/\sqrt{3}$	$W_8^{\{1234\}}/2$
9	$[1\ \ -j\ \ -1\ \ -j]^T$	$W_9^{\{1\}}$	$W_9^{\{14\}}/\sqrt{2}$	$W_9^{\{134\}}/\sqrt{3}$	$W_9^{\{1234\}}/2$
10	$[1\ \ 1\ \ 1\ \ -1]^T$	$W_{10}^{\{1\}}$	$W_{10}^{\{13\}}/\sqrt{2}$	$W_{10}^{\{123\}}/\sqrt{3}$	$W_{10}^{\{1324\}}/2$
11	$[1\ \ j\ \ -1\ \ j]^T$	$W_{11}^{\{1\}}$	$W_{11}^{\{13\}}/\sqrt{2}$	$W_{11}^{\{134\}}/\sqrt{3}$	$W_{11}^{\{1324\}}/2$
12	$[1\ \ -1\ \ -1\ \ 1]^T$	$W_{12}^{\{1\}}$	$W_{12}^{\{12\}}/\sqrt{2}$	$W_{12}^{\{123\}}/\sqrt{3}$	$W_{12}^{\{1234\}}/2$
13	$[1\ \ -1\ \ 1\ \ -1]^T$	$W_{13}^{\{1\}}$	$W_{13}^{\{13\}}/\sqrt{2}$	$W_{13}^{\{123\}}/\sqrt{3}$	$W_{13}^{\{1324\}}/2$
14	$[1\ \ 1\ \ -1\ \ -1]^T$	$W_{14}^{\{1\}}$	$W_{14}^{\{13\}}/\sqrt{2}$	$W_{14}^{\{123\}}/\sqrt{3}$	$W_{14}^{\{3214\}}/2$
15	$[1\ \ 1\ \ 1\ \ 1]^T$	$W_{15}^{\{1\}}$	$W_{15}^{\{12\}}/\sqrt{2}$	$W_{15}^{\{123\}}/\sqrt{3}$	$W_{15}^{\{1234\}}/2$

$\boldsymbol{W}$ is conformed for the codebook for 4 antennas as follows: $\boldsymbol{W}_i^{\{c_1,\ldots,c_m\}}$ denotes the matrix formed by the columns $\{c_1,\ldots,c_m\}$ of the matrix $\boldsymbol{W}_i = \boldsymbol{I}_{4\text{x}4} - 2\boldsymbol{u}_i\boldsymbol{u}_i^H / \|\boldsymbol{u}_i\|$.

10.3 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, the space-frequency block codes (SFBC) are defined by

$$\begin{bmatrix} y_0(2i) & y_0(2i+1) \\ y_1(2i) & y_1(2i+1) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} x_0(i) & x_1(i) \\ -x_1^*(i) & x_0^*(i) \end{bmatrix} \tag{29}$$

for i=0, 1,…, $N_{sym}^{L}-1$ and $N_{sym}^{P}=2N_{sym}^{L}$.

In case of 4 antennas a combination of SFBC for 2 antennas with frequency switch transmission diversity is employed and defined as

$$\begin{bmatrix} y_0(4i) & y_0(4i+1) & y_0(4i+2) & y_0(4i+3) \\ y_1(4i) & y_1(4i+1) & y_1(4i+2) & y_1(4i+3) \\ y_2(4i) & y_2(4i+1) & y_2(4i+2) & y_2(4i+3) \\ y_3(4i) & y_3(4i+1) & y_3(4i+2) & y_3(4i+3) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} x_0(i) & x_1(i) & 0 & 0 \\ 0 & 0 & x_2(i) & x_3(i) \\ -x_1^*(i) & x_0^*(i) & 0 & 0 \\ 0 & 0 & -x_3^*(i) & x_2^*(i) \end{bmatrix} \quad (30)$$

for i=0, 1,…, $N_{sym}^{L}-1$ and $N_{sym}^{P}=4N_{sym}^{L}$.

11. Multicarrier modulation

The multicarrier modulation parameters for either DFT-spread OFDM or OFDM are given in Table 15. The subcarrier spacing of 15 KHz ensures a good compromise for handling delay spread in radio channels and implementation availability.

Table 15—Multicarrier parameters

Description	Notation
Total No of subcarriers	MFFT=1024
Subcarrier spacing	Δf=15 KHz
Sampling time	T_s=1/(Δf MFFT)=65.1 nsec
Clock rate	R_c=1/T_s=15.36 MHz

11.1 Cyclic prefix

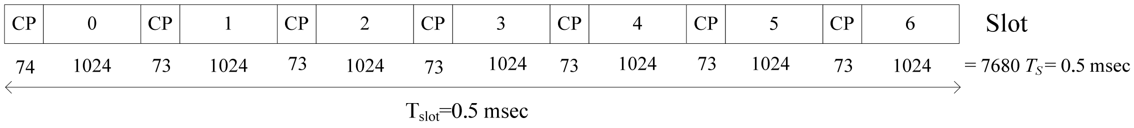
The cyclic prefix is chosen according to the typical RMS delay spread of the ISM and sub-GHz bands computed according to the Channel Model Document and shown in Table 16.

Table 16—Typical RMS delay spread

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 cyclic prefix length covers 73 sampling points with duration $73T_s$=4.75 µsec. this enables to design a slot time of 0.5 msec consisting of 7 DTF-Spread OFDM or OFDM symbols as shown in Figure 17.

Figure 17—Slot structure



11.2 Resource block

Resource block (RB) is a set of time-frequency slots for data communication and enabling multiple access. A RB is formed by a slot time of 0.5 msec (N_{symb}=7 OFDM symbols as in Figure 17 and Figure 18) and N_{sc}^{RB}=6 subcarriers or 90 KHz spectrum as show in Figure 18. The total number of RBs is N_{RB}=170 (the 2 upper and lower subcarriers are empty).

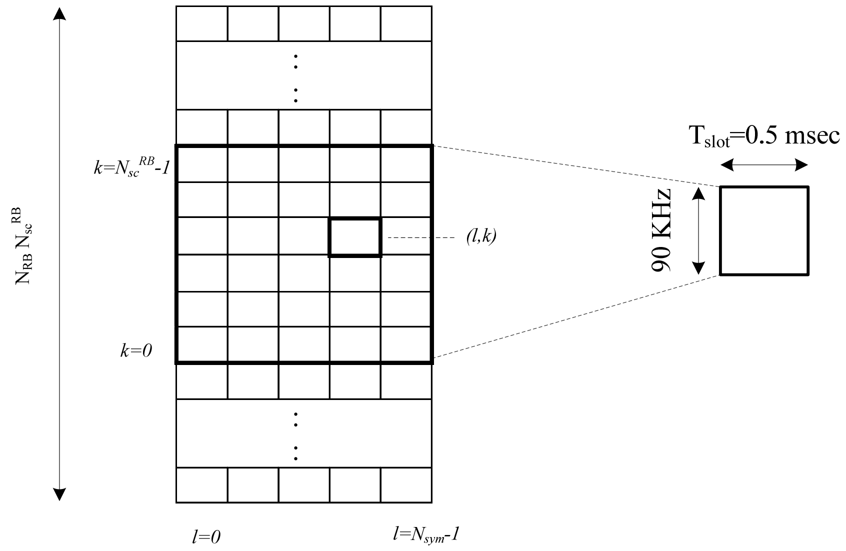


Figure 18—Resource block parameters

Transmission bandwidth (BW) is obtained by concatenating RBs as

$$BW = n\,N_{sc}^{RB}\Delta f \tag{31}$$

where $12 \le n \le 111$.

Several transmission bandwidths are available as shown in Table 17. These cover sub-GHz band as well as 2.4 and 5.7 GHz bands.

Table 17—Transmission bandwidths

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

For the sub-GHz band, the transmission bandwidth is 1 MHz, while for the 2.4 and 5.7 GHz bands, the maximum transmission considered is 10 MHz. the main reason is that PAC applications require as many channel resources for multiplexing (and consequently multiple access) as possible. For instance, it is preferable to have 15 channels of 10 MHz rather than 7 channels of 20 MHz to accommodate more users.

11.3 Carrier aggregation

However, we propose to use carrier aggregation, where one more channel of 10 MHz can be added together to increase the transmission bandwidth to 20 MHz as shown in Figure 19, if the scenario allows it. Such carrier aggregation is granted by the MAC and signaled to the PHY by one bit, G, in the control channel of the TDD frame (see sub-clause 3.1).

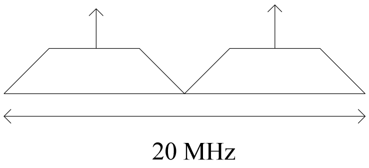


Figure 19—Carrier aggregation

The aggregated channel can be considered by the PD as a single enlarged channel of 20 MHz from the RF viewpoint. Hence, the same RF front end can be used without modifications.

11.4 Data rates

Data rates depend on the employed spectrum (number of subcarriers and carrier aggregation), modulation, coding rate, MIMO technology and overhead (pilots, control information, etc.).

The number of subcarriers is given by $nN_{sc}^{RB}N_{sym}$, where $N_{sc}^{RB}=6$ subcarriers per RB, $N_{sym}=7$ OFDM symbols and $12 \le n \le 111$. Every subcarrier conveys a modulation symbol. The number of bits per symbol is $\mathrm{Log}_2(M)$ where M is the cardinality of modulation. The coding rate C_R values are shown in Table 18. The carrier aggregation C_A may double the number of employed subcarriers. Open loop spatial multiplexing MIMO, C_M, may double or quadruple the capacity.

The different combinations are shown in Table 18 without overhead.

Table 18—Data rate parameters

n	$\mathrm{Log}_2(M)$	**Modulation**	C_A	**C_A mode**	C_R	C_M	**C_M mode**
12	1	BPSK	1	disable	1/2	1	disable
⋮	2	QPSK	2	enable	2/3	2	2x2
	4	16QAM			3/4	4	4x4
111	6	64QAM			5/6		

The different data rates are given by

$$R_b = \frac{nN_{sc}^{RB}N_{sym}\ \mathrm{Log}_2(M)}{0.5\ \mathrm{msec}}C_R C_A C_M \tag{32}$$

Example: the peak data rate is given by using all RBs, n=111, carrier aggregation, 64QAM, coding rate of 5/6 and 4x4 MIMO is R_b=372.96 Mbps.

12. Reference signals

Reference signals for channel estimation and equalization are based on ZC sequences. Such reference signals must be considered in the time and frequency domain.

12.1 Time domain

Considering a maximum speed of v=100 Km/h (27.78 m/s), the Doppler spread, $f_d=f_c\ v/c$ is given in Table 19.

Table 19—Doppler spread

f_c	f_d (Hz)	T_c (msec)
5.7 GHz	527.82	0.947
2.4 GHz	222.24	2.2
920 MHz	85.2	6

The minimum sampling time to reconstruct the channel is computed as $T_c=1/2f_d$, which is also given in Table 19. The slot time is 0.5 msec. Then, one reference symbol per slot is needed in the time domain to estimate the channel correctly.

12.2 Frequency domain

Considering the Channel Model Document, the 90% and 50% coherence bandwidth as $B_{c,90}=1/50\sigma_\tau$ and $B_{C,50}=1/5\sigma_\tau$, where σ_τ is the RMS delay spread, such coherence bandwidths can be computed as

$$\sigma_\tau = C_a d^{\gamma_a} \tag{33}$$

Such coherence bandwidths are shown in Table 20. If $B_{C,50} < BW$ then the radio channel contains frequency selective fading and equalization is needed.

We propose that the spacing between 2 reference symbols in the frequency domain is 30 KHz to resolve frequency variations.

Table 20—RMS delay spread

Frequency band	C_a	γ_a	σ_τ	$B_{c,90}$ (KHz)	$B_{C,50}$ (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

13. 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

$$s(t) = V\, s\left(2\pi f_c t + 2\pi\Delta f' \int_{-\infty}^{t} b(t')\, dt' + \varphi_0 \right) \tag{34}$$

where V is amplitude, $S(t)=\sin(2\pi f_c t)$ is the modulating-carrier signal, f_c is the central carrier frequency, $\Delta f=\beta/2T_{sym}$ is the peak frequency deviation, T_{sym} is the symbol time, $\beta=1$ is the modulation index, and φ_0 is the initial phase of the modulating-carrier signal.

The information bearing signal is given by

$$b(t) = \sum_m (1-2g_m)\, p(t - mT_{sym}) \tag{35}$$

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

14. Operating frequency bands

The frequency bands of operation are Sub-GHz, 2.4 GHz and 5.7 GHz.

Those are selected because they do not require operation license. Hence, implementers need only to comply with local regulations. Moreover, those bands cover all PAC applications in terms of capacity, mobility and operational distance.

PAC applications require discovery and data communication links for many PAC users as possible at moderate data rate. That is, sacrifice bandwidth against number of users. This is a different requirement as compared to other standards like WiFi, which requires sacrificing number of users against bandwidth, as it is well documented in the CSMA performance literature.

Hence, PAC applications require as many channel resources for multiplexing (and consequently multiple access) as possible. That is, it is preferable to have 15 channels of 10 MHz rather than 7 channels of 20 MHz to accommodate more users.

Multiplexing is how multiple users communicate simultaneously sharing a common wireless medium without interfering each other. Example: frequency division multiplexing (FDM), time division multiplexing (TDM), space division multiplexing (SDM), etc., or combinations like time-frequency division multiplexing, etc. Multiplexing is provided by the PHY.

Multiple access or channel access is how to allocate such resources in time, frequency or both, to users, even if there are more users than available resources. Example: time division multiplexing (TDMA), frequency division multiplexing (FDMA), OFDMA, SC-FDMA, CDMA, etc. Multiple access is based on a multiplexing method and control by the MAC.

Using 10 MHz channels with high order modulations and possibly MIMO technologies, PAC applications can have high throughput. We consider that support for high number of user rather than high data rate is a distinct requirement for PAC as compared to other standards, especially Wi-Fi. Coexistence with Wi-Fi and other systems can be achieved with power control, low duty cycle, etc., rather than using the same bandwidth.

However, as stated in clause 11.3, one carrier aggregation can be used to increase the bandwidth to 20 MHz.

14.1 Channelization of 920 MHz band

The channelization of 920 MHz band by regulations in Japan is shown in Table 21.

Table 21—Sub-GHz channelization by regulations in Japan

Band	Max Tx power (mW)	Frequency band (MHz)	Basic channelization
A[1]	1	915.9 – 928.1	61 channels of 200 KHz
B[1]	20	920.5 – 928.1	38 channels of 200 KHz
C[1]	250	920.5 – 923.5	15 channels of 200 KHz
D[2]	1	928.1 – 929.7	16 channels of 100 KHz

[1] bandwidth rule tolerance: (200 *n*) KHz, where n=1,2,3,4,5.

[2] bandwidth rule tolerance: (100 *n*) KHz, where n=1,2,3,4,5.

The proposed channelization for sub-GHz band in Japan is shown in Table 22.

Table 22—Proposed Sub-GHz channelization (Japan)

Band	Central frequency (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

14.2 Channelization of 2.4 GHz band

The 2.4 GHz band ranges from 2.4 GHz to 2.4835 GHz and it is divided into 8 channels of 10 MHz. The central frequencies are given by

$$f_c = 2405\,\text{MHz} + 10n \qquad \text{for } n=0,1,\ldots,7 \tag{36}$$

14.3 Channelization of 5.7 GHz band

The 5.7 GHz band ranges from 5.725 GHz to 5.875 GHz and it is divided into 15 channels of 10 MHz. The central frequencies are given by

$$f_c = 5730\,\text{MHz} + 10n \qquad \text{for } n=0,1,\ldots,14 \tag{37}$$

Annex A

(Normative)

QC-LDPC prototype matrices

Table A.1— H_p for n=648, Z=27 and R=1/2.

0	-	-	-	0	0	-	-	0	-	-	0	1	0	-	-	-	-	-	-	-	-	-	-
22	0	-	-	17	-	0	0	12	-	-	-	-	0	0	-	-	-	-	-	-	-	-	-
6	-	0	-	10	-	-	-	24	-	0	-	-	-	0	0	-	-	-	-	-	-	-	-
2	-	-	0	20	-	-	-	25	0	-	-	-	-	-	0	0	-	-	-	-	-	-	-
23	-	-	-	3	-	-	-	0	-	9	11	-	-	-	-	0	0	-	-	-	-	-	-
24	-	23	1	17	-	3	-	10	-	-	-	-	-	-	-	-	0	0	-	-	-	-	-
25	-	-	-	8	-	-	-	7	18	-	-	0	-	-	-	-	-	0	0	-	-	-	-
13	24	-	-	0	-	8	-	6	-	-	-	-	-	-	-	-	-	-	0	0	-	-	-
7	20	-	16	22	10	-	-	23	-	-	-	-	-	-	-	-	-	-	-	0	0	-	-
11	-	-	-	19	-	-	-	13	-	3	17	-	-	-	-	-	-	-	-	-	0	0	-
25	-	8	-	23	18	-	14	9	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
3	-	-	-	16	-	-	2	25	5	-	-	1	-	-	-	-	-	-	-	-	-	-	0

Table A.2— H_p for n=648, Z=27, R=2/3.

25	26	14	-	20	-	2	-	4	-	-	8	-	16	-	18	1	0	-	-	-	-	-	-
10	9	15	11	-	0	-	1	-	-	18	-	8	-	10	-	-	0	0	-	-	-	-	-
16	2	20	26	21	-	6	-	1	26	-	7	-	-	-	-	-	-	0	0	-	-	-	-
10	13	5	0	-	3	-	7	-	-	26	-	-	13	-	16	-	-	-	0	0	-	-	-
23	14	24	-	12	-	19	-	17	-	-	-	20	-	21	-	0	-	-	-	0	0	-	-
6	22	9	20	-	25	-	17	-	8	-	14	-	18	-	-	-	-	-	-	-	0	0	-
14	23	21	11	20	-	24	-	18	-	19	-	-	-	-	22	-	-	-	-	-	-	0	0
17	11	11	20	-	21	-	26	-	3	-	-	18	-	26	-	1	-	-	-	-	-	-	0

Table A.3— H_p for n=648, Z=27, R=3/4.

16	17	22	24	9	3	14	-	4	2	7	-	26	-	2	-	21	-	1	0	-	-	-	-
25	12	12	3	3	26	6	21	-	15	22	-	15	-	4	-	-	16	-	0	0	-	-	-
25	18	26	16	22	23	9	-	0	-	4	-	4	-	8	23	11	-	-	-	0	0	-	-
9	7	0	1	17	-	-	7	3	-	3	23	-	16	-	-	21	-	0	-	-	0	0	-
24	5	26	7	1	-	-	15	24	15	-	8	-	13	-	13	-	11	-	-	-	-	0	0
2	2	19	14	24	1	15	19	-	21	-	2	-	24	-	3	-	2	1	-	-	-	-	0

Table A.4—H_p for n=648, Z=27, R=5/6.

17	13	8	21	9	3	18	12	10	0	4	15	19	2	5	10	26	19	13	13	1	0	-	-
3	12	11	14	11	25	5	18	0	9	2	26	26	10	24	7	14	20	4	2	-	0	0	-
22	16	4	3	10	21	12	5	21	14	19	5	-	8	5	18	11	5	5	15	0	-	0	0
7	7	14	14	4	16	16	24	24	10	1	7	15	6	10	26	8	18	21	14	1	-	-	0

Table A.5—H_p for *n*=1944, *Z*=81, *R*=1/2.

57	-	-	-	50	-	11	-	50	-	79	-	1	0	-	-	-	-	-	-	-	-	-	-
3	-	28	-	0	-	-	-	55	7	-	-	-	0	0	-	-	-	-	-	-	-	-	-
30	-	-	-	24	37	-	-	56	14	-	-	-	-	0	0	-	-	-	-	-	-	-	-
62	53	-	-	53	-	-	3	35	-	-	-	-	-	-	0	0	-	-	-	-	-	-	-
40	-	-	20	66	-	-	22	28	-	-	-	-	-	-	-	0	0	-	-	-	-	-	-
0	-	-	-	8	-	42	-	50	-	-	8	-	-	-	-	-	0	0	-	-	-	-	-
69	79	79	-	-	-	56	-	52	-	-	-	0	-	-	-	-	-	0	0	-	-	-	-
65	-	-	-	38	57	-	-	72	-	27	-	-	-	-	-	-	-	-	0	0	-	-	-
64	-	-	-	14	52	-	-	30	-	-	32	-	-	-	-	-	-	-	-	0	0	-	-
-	45	-	70	0	-	-	-	77	9	-	-	-	-	-	-	-	-	-	-	-	0	0	-
2	56	-	57	35	-	-	-	-	-	12	-	-	-	-	-	-	-	-	-	-	-	0	0
24	-	61	-	60	-	-	27	51	-	-	16	1	-	-	-	-	-	-	-	-	-	-	0

Table A.6—H_p for *n*=1944, *Z*=81, *R*=2/3.

61	75	4	63	56	-	-	-	-	-	-	8	-	2	17	25	1	0	-	-	-	-	-	-
56	74	77	20	-	-	-	64	24	4	67	-	7	-	-	-	-	0	0	-	-	-	-	-
28	21	68	10	7	14	65	-	-	-	23	-	-	-	75	-	-	-	0	0	-	-	-	-
48	38	43	78	76	-	-	-	-	5	36	-	15	72	-	-	-	-	-	0	0	-	-	-
40	2	53	25	-	52	62	-	20	-	-	44	-	-	-	-	0	-	-	-	0	0	-	-
69	23	64	10	22	-	21	-	-	-	-	-	68	23	29	-	-	-	-	-	-	0	0	-
12	0	68	20	55	61	-	40	-	-	-	52	-	-	-	44	-	-	-	-	-	-	0	0
58	8	34	64	78	-	-	11	78	24	-	-	-	-	-	58	1	-	-	-	-	-	-	0

Table A.7—H_p for *n*=1944, *Z*=81, *R*=3/4.

48	29	28	39	9	61	-	-	-	63	45	80	-	-	-	37	32	22	1	0	-	-	-	-
4	49	42	48	11	30	-	-	-	49	17	41	37	15	-	54	-	-	-	0	0	-	-	-
35	76	78	51	37	35	21	-	17	64	-	-	-	59	7	-	-	32	-	-	0	0	-	-
9	65	44	9	54	56	73	34	42	-	-	-	35	-	-	-	46	39	0	-	-	0	0	-
3	62	7	80	68	26	-	80	55	-	36	-	26	-	9	-	72	-	-	-	-	-	0	0
26	75	33	21	69	59	3	38	-	-	-	35	-	62	36	26	-	-	1	-	-	-	-	0

Table A.8—H_p for for *n*=1944, *Z*=81, *R*=5/6.

13	48	80	66	4	74	7	30	76	52	37	60	-	49	73	31	74	73	23	-	1	0	-	-
69	63	74	56	64	77	57	65	6	16	51	-	64	-	68	9	48	62	54	27	-	0	0	-
51	15	0	80	24	25	42	54	44	71	71	9	67	35	-	58	-	29	-	53	0	-	0	0
16	29	36	41	44	56	59	37	50	24	-	65	4	65	52	-	4	-	73	52	1	-	-	0

Annex B

(Normative)

Modulation mapping

Table B.1—BPSK mapping

b_i	I	Q
0	1/√2	1/√2
1	−1/√2	−1/√2

Table B.2—QPSK mapping

b_i,b_{i+1}	I	Q
0 0	1/√2	1/√2
0 1	1/√2	−1/√2
1 0	−1/√2	1/√2
1 1	−1/√2	−1/√2

Table B.3—16QAM mapping

$b_i,b_{i+1},b_{i+2},b_{i+3}$	I	Q
0 0 0 0	1/√10	1/√10
0 0 0 1	1/√10	3/√10
0 0 1 0	3/√10	1/√10
0 0 1 1	3/√10	3/√10
0 1 0 0	1/√10	−1/√10
0 1 0 1	1/√10	−3/√10
0 1 1 0	3/√10	−1/√10
0 1 1 1	3/√10	−3/√10
1 0 0 0	−1/√10	1/√10
1 0 0 1	−1/√10	3/√10
1 0 1 0	−3/√10	1/√10
1 0 1 1	−3/√10	3/√10
1 1 0 0	−1/√10	−1/√10
1 1 0 1	−1/√10	−3/√10
1 1 1 0	−3/√10	−1/√10
1 1 1 1	−3/√10	−3/√10

Table B.4—64QAM mapping

$b_i\ b_{i+1}\ b_{i+2}\ b_{i+3}\ b_{i+4}\ b_{i+5}$	I	Q	$b_i\ b_{i+1}\ b_{i+2}\ b_{i+3}\ b_{i+4}\ b_{i+5}$	I	Q
0 0 0 0 0 0	$3/\sqrt{42}$	$3/\sqrt{42}$	1 0 0 0 0 0	$-3/\sqrt{42}$	$3/\sqrt{42}$
0 0 0 0 0 1	$3/\sqrt{42}$	$1/\sqrt{42}$	1 0 0 0 0 1	$-3/\sqrt{42}$	$1/\sqrt{42}$
0 0 0 0 1 0	$1/\sqrt{42}$	$3/\sqrt{42}$	1 0 0 0 1 0	$-1/\sqrt{42}$	$3/\sqrt{42}$
0 0 0 0 1 1	$1/\sqrt{42}$	$1/\sqrt{42}$	1 0 0 0 1 1	$-1/\sqrt{42}$	$1/\sqrt{42}$
0 0 0 1 0 0	$3/\sqrt{42}$	$5/\sqrt{42}$	1 0 0 1 0 0	$-3/\sqrt{42}$	$5/\sqrt{42}$
0 0 0 1 0 1	$3/\sqrt{42}$	$7/\sqrt{42}$	1 0 0 1 0 1	$-3/\sqrt{42}$	$7/\sqrt{42}$
0 0 0 1 1 0	$1/\sqrt{42}$	$5/\sqrt{42}$	1 0 0 1 1 0	$-1/\sqrt{42}$	$5/\sqrt{42}$
0 0 0 1 1 1	$1/\sqrt{42}$	$7/\sqrt{42}$	1 0 0 1 1 1	$-1/\sqrt{42}$	$7/\sqrt{42}$
0 0 1 0 0 0	$5/\sqrt{42}$	$3/\sqrt{42}$	1 0 1 0 0 0	$-5/\sqrt{42}$	$3/\sqrt{42}$
0 0 1 0 0 1	$5/\sqrt{42}$	$1/\sqrt{42}$	1 0 1 0 0 1	$-5/\sqrt{42}$	$1/\sqrt{42}$
0 0 1 0 1 0	$7/\sqrt{42}$	$3/\sqrt{42}$	1 0 1 0 1 0	$-7/\sqrt{42}$	$3/\sqrt{42}$
0 0 1 0 1 1	$7/\sqrt{42}$	$1/\sqrt{42}$	1 0 1 0 1 1	$-7/\sqrt{42}$	$1/\sqrt{42}$
0 0 1 1 0 0	$5/\sqrt{42}$	$5/\sqrt{42}$	1 0 1 1 0 0	$-5/\sqrt{42}$	$5/\sqrt{42}$
0 0 1 1 0 1	$5/\sqrt{42}$	$7/\sqrt{42}$	1 0 1 1 0 1	$-5/\sqrt{42}$	$7/\sqrt{42}$
0 0 1 1 1 0	$7/\sqrt{42}$	$5/\sqrt{42}$	1 0 1 1 1 0	$-7/\sqrt{42}$	$5/\sqrt{42}$
0 0 1 1 1 1	$7/\sqrt{42}$	$7/\sqrt{42}$	1 0 1 1 1 1	$-7/\sqrt{42}$	$7/\sqrt{42}$
0 1 0 0 0 0	$3/\sqrt{42}$	$-3/\sqrt{42}$	1 1 0 0 0 0	$-3/\sqrt{42}$	$-3/\sqrt{42}$
0 1 0 0 0 1	$3/\sqrt{42}$	$-1/\sqrt{42}$	1 1 0 0 0 1	$-3/\sqrt{42}$	$-1/\sqrt{42}$
0 1 0 0 1 0	$1/\sqrt{42}$	$-3/\sqrt{42}$	1 1 0 0 1 0	$-1/\sqrt{42}$	$-3/\sqrt{42}$
0 1 0 0 1 1	$1/\sqrt{42}$	$-1/\sqrt{42}$	1 1 0 0 1 1	$-1/\sqrt{42}$	$-1/\sqrt{42}$
0 1 0 1 0 0	$3/\sqrt{42}$	$-5/\sqrt{42}$	1 1 0 1 0 0	$-3/\sqrt{42}$	$-5/\sqrt{42}$
0 1 0 1 0 1	$3/\sqrt{42}$	$-7/\sqrt{42}$	1 1 0 1 0 1	$-3/\sqrt{42}$	$-7/\sqrt{42}$
0 1 0 1 1 0	$1/\sqrt{42}$	$-5/\sqrt{42}$	1 1 0 1 1 0	$-1/\sqrt{42}$	$-5/\sqrt{42}$
0 1 0 1 1 1	$1/\sqrt{42}$	$-7/\sqrt{42}$	1 1 0 1 1 1	$-1/\sqrt{42}$	$-7/\sqrt{42}$
0 1 1 0 0 0	$5/\sqrt{42}$	$-3/\sqrt{42}$	1 1 1 0 0 0	$-5/\sqrt{42}$	$-3/\sqrt{42}$
0 1 1 0 0 1	$5/\sqrt{42}$	$-1/\sqrt{42}$	1 1 1 0 0 1	$-5/\sqrt{42}$	$-1/\sqrt{42}$
0 1 1 0 1 0	$7/\sqrt{42}$	$-3/\sqrt{42}$	1 1 1 0 1 0	$-7/\sqrt{42}$	$-3/\sqrt{42}$
0 1 1 0 1 1	$7/\sqrt{42}$	$-1/\sqrt{42}$	1 1 1 0 1 1	$-7/\sqrt{42}$	$-1/\sqrt{42}$
0 1 1 1 0 0	$5/\sqrt{42}$	$-5/\sqrt{42}$	1 1 1 1 0 0	$-5/\sqrt{42}$	$-5/\sqrt{42}$
0 1 1 1 0 1	$5/\sqrt{42}$	$-7/\sqrt{42}$	1 1 1 1 0 1	$-5/\sqrt{42}$	$-7/\sqrt{42}$
0 1 1 1 1 0	$7/\sqrt{42}$	$-5/\sqrt{42}$	1 1 1 1 1 0	$-7/\sqrt{42}$	$-5/\sqrt{42}$
0 1 1 1 1 1	$7/\sqrt{42}$	$-7/\sqrt{42}$	1 1 1 1 1 1	$-7/\sqrt{42}$	$-7/\sqrt{42}$

b_i b_{i+1} b_{i+2} b_{i+3} b_{i+4} b_{i+5}	I	Q	b_i b_{i+1} b_{i+2} b_{i+3} b_{i+4} b_{i+5}	I	Q
0 0 0 0 0 0	$3/\sqrt{42}$	$3/\sqrt{42}$	1 0 0 0 0 0	$-3/\sqrt{42}$	$3/\sqrt{42}$
0 0 0 0 0 1	$3/\sqrt{42}$	$1/\sqrt{42}$	1 0 0 0 0 1	$-3/\sqrt{42}$	$1/\sqrt{42}$
0 0 0 0 1 0	$1/\sqrt{42}$	$3/\sqrt{42}$	1 0 0 0 1 0	$-1/\sqrt{42}$	$3/\sqrt{42}$
0 0 0 0 1 1	$1/\sqrt{42}$	$1/\sqrt{42}$	1 0 0 0 1 1	$-1/\sqrt{42}$	$1/\sqrt{42}$
0 0 0 1 0 0	$3/\sqrt{42}$	$5/\sqrt{42}$	1 0 0 1 0 0	$-3/\sqrt{42}$	$5/\sqrt{42}$
0 0 0 1 0 1	$3/\sqrt{42}$	$7/\sqrt{42}$	1 0 0 1 0 1	$-3/\sqrt{42}$	$7/\sqrt{42}$
0 0 0 1 1 0	$1/\sqrt{42}$	$5/\sqrt{42}$	1 0 0 1 1 0	$-1/\sqrt{42}$	$5/\sqrt{42}$
0 0 0 1 1 1	$1/\sqrt{42}$	$7/\sqrt{42}$	1 0 0 1 1 1	$-1/\sqrt{42}$	$7/\sqrt{42}$
0 0 1 0 0 0	$5/\sqrt{42}$	$3/\sqrt{42}$	1 0 1 0 0 0	$-5/\sqrt{42}$	$3/\sqrt{42}$
0 0 1 0 0 1	$5/\sqrt{42}$	$1/\sqrt{42}$	1 0 1 0 0 1	$-5/\sqrt{42}$	$1/\sqrt{42}$
0 0 1 0 1 0	$7/\sqrt{42}$	$3/\sqrt{42}$	1 0 1 0 1 0	$-7/\sqrt{42}$	$3/\sqrt{42}$
0 0 1 0 1 1	$7/\sqrt{42}$	$1/\sqrt{42}$	1 0 1 0 1 1	$-7/\sqrt{42}$	$1/\sqrt{42}$
0 0 1 1 0 0	$5/\sqrt{42}$	$5/\sqrt{42}$	1 0 1 1 0 0	$-5/\sqrt{42}$	$5/\sqrt{42}$
0 0 1 1 0 1	$5/\sqrt{42}$	$7/\sqrt{42}$	1 0 1 1 0 1	$-5/\sqrt{42}$	$7/\sqrt{42}$
0 0 1 1 1 0	$7/\sqrt{42}$	$5/\sqrt{42}$	1 0 1 1 1 0	$-7/\sqrt{42}$	$5/\sqrt{42}$
0 0 1 1 1 1	$7/\sqrt{42}$	$7/\sqrt{42}$	1 0 1 1 1 1	$-7/\sqrt{42}$	$7/\sqrt{42}$
0 1 0 0 0 0	$3/\sqrt{42}$	$-3/\sqrt{42}$	1 1 0 0 0 0	$-3/\sqrt{42}$	$-3/\sqrt{42}$
0 1 0 0 0 1	$3/\sqrt{42}$	$-1/\sqrt{42}$	1 1 0 0 0 1	$-3/\sqrt{42}$	$-1/\sqrt{42}$
0 1 0 0 1 0	$1/\sqrt{42}$	$-3/\sqrt{42}$	1 1 0 0 1 0	$-1/\sqrt{42}$	$-3/\sqrt{42}$
0 1 0 0 1 1	$1/\sqrt{42}$	$-1/\sqrt{42}$	1 1 0 0 1 1	$-1/\sqrt{42}$	$-1/\sqrt{42}$
0 1 0 1 0 0	$3/\sqrt{42}$	$-5/\sqrt{42}$	1 1 0 1 0 0	$-3/\sqrt{42}$	$-5/\sqrt{42}$
0 1 0 1 0 1	$3/\sqrt{42}$	$-7/\sqrt{42}$	1 1 0 1 0 1	$-3/\sqrt{42}$	$-7/\sqrt{42}$
0 1 0 1 1 0	$1/\sqrt{42}$	$-5/\sqrt{42}$	1 1 0 1 1 0	$-1/\sqrt{42}$	$-5/\sqrt{42}$
0 1 0 1 1 1	$1/\sqrt{42}$	$-7/\sqrt{42}$	1 1 0 1 1 1	$-1/\sqrt{42}$	$-7/\sqrt{42}$
0 1 1 0 0 0	$5/\sqrt{42}$	$-3/\sqrt{42}$	1 1 1 0 0 0	$-5/\sqrt{42}$	$-3/\sqrt{42}$
0 1 1 0 0 1	$5/\sqrt{42}$	$-1/\sqrt{42}$	1 1 1 0 0 1	$-5/\sqrt{42}$	$-1/\sqrt{42}$
0 1 1 0 1 0	$7/\sqrt{42}$	$-3/\sqrt{42}$	1 1 1 0 1 0	$-7/\sqrt{42}$	$-3/\sqrt{42}$
0 1 1 0 1 1	$7/\sqrt{42}$	$-1/\sqrt{42}$	1 1 1 0 1 1	$-7/\sqrt{42}$	$-1/\sqrt{42}$
0 1 1 1 0 0	$5/\sqrt{42}$	$-5/\sqrt{42}$	1 1 1 1 0 0	$-5/\sqrt{42}$	$-5/\sqrt{42}$
0 1 1 1 0 1	$5/\sqrt{42}$	$-7/\sqrt{42}$	1 1 1 1 0 1	$-5/\sqrt{42}$	$-7/\sqrt{42}$
0 1 1 1 1 0	$7/\sqrt{42}$	$-5/\sqrt{42}$	1 1 1 1 1 0	$-7/\sqrt{42}$	$-5/\sqrt{42}$
0 1 1 1 1 1	$7/\sqrt{42}$	$-7/\sqrt{42}$	1 1 1 1 1 1	$-7/\sqrt{42}$	$-7/\sqrt{42}$

Bibliography

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