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**IEEE P802.15
Wireless Personal Area Networks**

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Abstract	
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1 **Contents**

2 1. Symbols and Abbreviations 3

3 1.1 Symbols 3

4 1.2 Abbreviations 3

5 2. PHY specification 3

6 3. PHY frame structure 3

7 3.1 TDD frame 4

8 3.2 Guard interval 5

9 3.3 Preamble 5

10 3.4 Control channel 5

11 4. Synchronization preamble 6

12 5. PHY header 7

13 5.1 Data rate 7

14 5.2 PSDU length 7

15 5.3 Burst mode 8

16 5.4 Scrambler seeds 8

17 5.5 Frame type 8

18 5.6 PSDU type 8

19 5.7 Header check sequence 8

20 6. Discovery 9

21 6.1 Discovery signal 9

22 7. Peering 11

23 7.1 Random access preamble 11

24 7.2 Random access procedure 13

25 8. PSDU construction 14

26 8.1 QC-LDPC encoder parameters 16

27 8.2 Interleaver 16

28 8.3 Scrambler 17

29 8.4 Modulation mapper 17

30 9. Layer mapping 18

31 9.1 Layer mapping for one antenna 18

32 9.2 Open loop spatial multiplexing 18

33 9.3 Transmit diversity 19

34 10. Precoding 19

35 10.1 Single antenna mapping 20

36 10.2 Open loop spatial multiplexing 20

37 10.3 Transmit diversity 21

38 11. Multicarrier modulation 22

39 11.1 Cyclic prefix 22

40 11.2 Resource block 23

41 11.3 Filtered OFDM symbols for sub-1 GHz band 24

42 11.4 Carrier aggregation 24

43 11.5 Data rates 24

1 12. Reference signals..... 25
2 12.1 Time domain..... 25
3 12.2 Frequency domain 26
4 13. Optional GFSK modulation..... 26
5 14. Operating frequency bands..... 26
6 14.1 Channelization of 920 MHz band 27
7 14.2 Channelization of 2.4 GHz band..... 28
8 14.3 Channelization of 5.7 GHz band..... 28
9 Annex A (Normative) QC-LDPC prototype matrices 29
10 Annex B (Normative) Modulation mapping..... 31
11 Bibliography..... 34
12

1 **1. Symbols and Abbreviations**

2 **1.1 Symbols**

3 **1.2 Abbreviations**

4 **2. PHY specification**

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

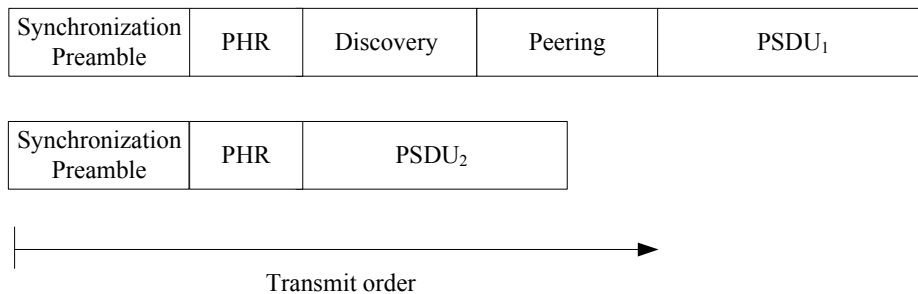
8
 9 The proposed PHY provides a data interface to the MAC layer under the control of the physical layer
 10 convergence protocol (PLCP).

11
 12 The proposed PHY provides four levels of functionality, as follows:

- 13 — Activation and deactivation of the radio transceiver.
- 14 — The transmission and reception of synchronization preambles to maintain network
 15 synchronization.
- 16 — An interface to the MAC for transmission and reception of discovery, peering, scheduling and
 17 data information.
- 18 — It may provide clear channel assessment (CCA) indication to the MAC in order to verify
 19 activity in the wireless medium.

20 **3. PHY frame structure**

21 The PHY frame format or physical layer protocol data unit (PPDU) can be formed for 2 types of
 22 PPDU. The PPDU ultra frame type 1 is formed by concatenating the synchronization preamble, the
 23 physical layer header (PHR), the discovery interval, peering interval, and the physical layer service
 24 data unit type 1 (PSDU₁), respectively, as illustrated in Figure 1. The PPDU ultra frame type 2 is
 25 formed by concatenating the synchronization preamble, the PHR, and PSDU₂, as illustrated in Figure 1
 26 as well.

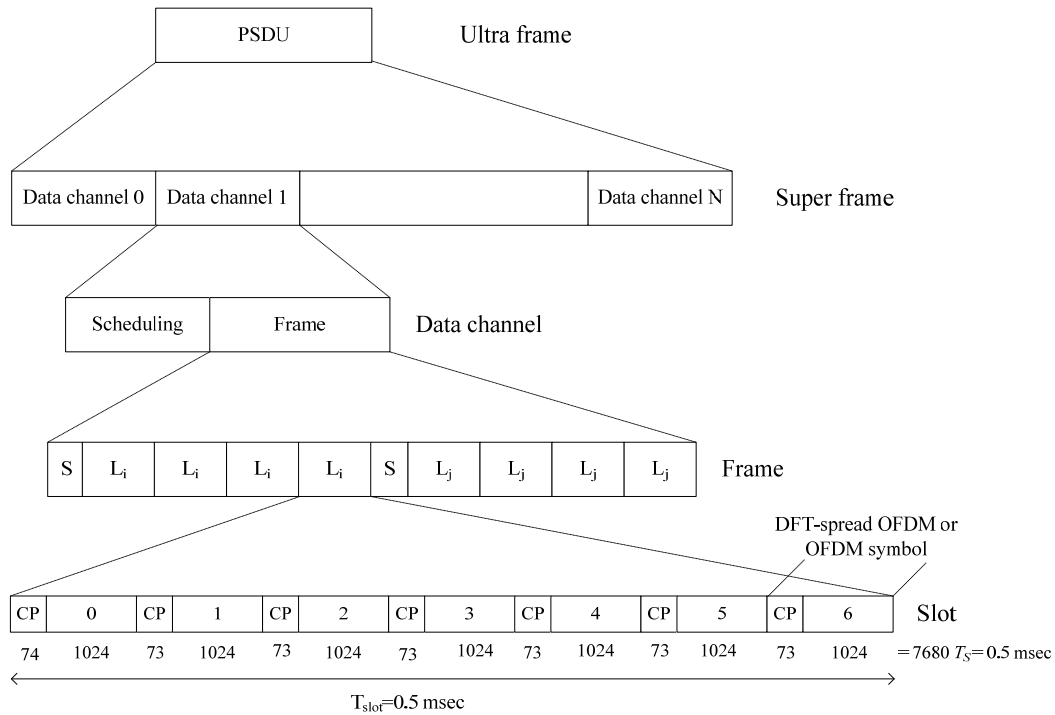


30 **Figure 1—PPDU ultra frame structures type 1 and 2.**

31
 32 The PPDU ultra frame type 1 conveys discovery, peering and data information. The PPDU ultra frame
 33 type 2 can conveyed discovery or peering or data information in PSDU₂.

34
 35 The PSDU, or super frame, is formed by *N* data-channels. Each data channel is sub-divided into
 36 scheduling and data frame. Each data frame consists of 10 TDD slots: two switching slots (denoted as
 37 S) and eight data slots. Each data slot consists of seven OFDM or DFT-Spread OFDM symbols and
 38 last 0.5 msec, as illustrated in Figure 2.

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Figure 2—Generic PSDU structure

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6 **3.1 TDD frame**

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

9

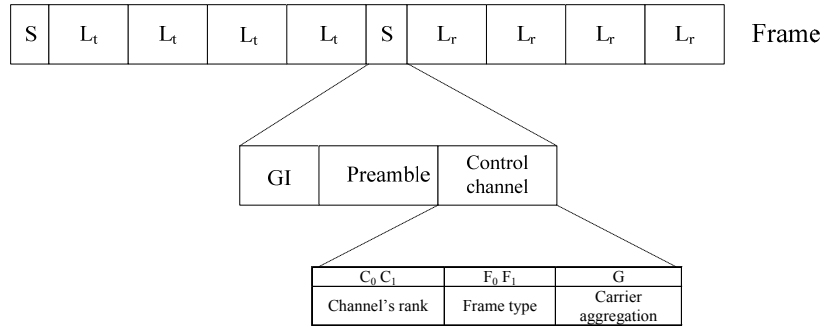
Table 1—TDD asymmetric frame types

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

10

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

13 The TDD switching slot (denoted as S) consists of a guard interval, preamble for fine synchronization
14 and channel sounding and control channel as illustrated in Figure 3. Note that the preamble and control
15 channel are transmitted by the PD that was in receiving mode before the switching. The duration of S is
16 0.5 msec as well.



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Figure 3—TDD switching slot

3 **3.2 Guard interval**

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

7
$$GI = T_p + T_{dec} + T_{sw} + T_p + T_{com} \tag{1}$$

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

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

11 **3.3 Preamble**

12 The preamble is formed of a ZC sequence.

13 **3.4 Control channel**

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

16

Table 2—Channel's rank

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

17

18

Table 3—TDD frame type

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

19

1 4. Synchronization preamble

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

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

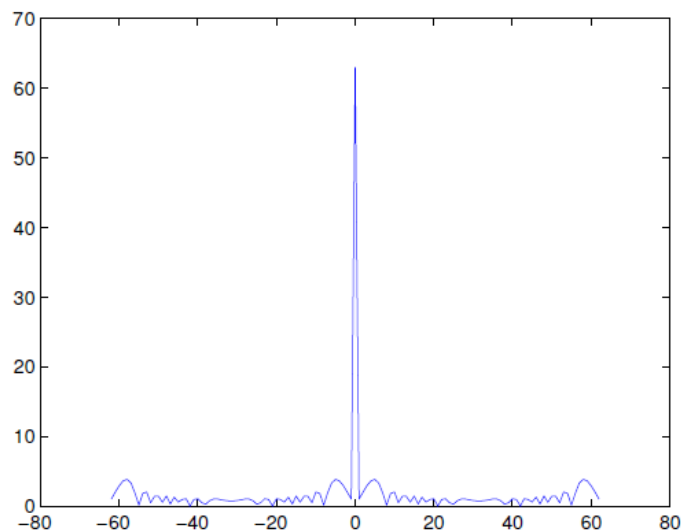
9 ZC sequences of length N is given by

$$10 \quad a_k = \begin{cases} W_N^{\frac{k^2}{2} + qk} & N \text{ even} \\ W_N^{\frac{k(k+1)}{2} + qk} & N \text{ odd} \end{cases} \quad (2)$$

11 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
 12 sequence index $k = 1, 0, \dots, N-1$.

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

15

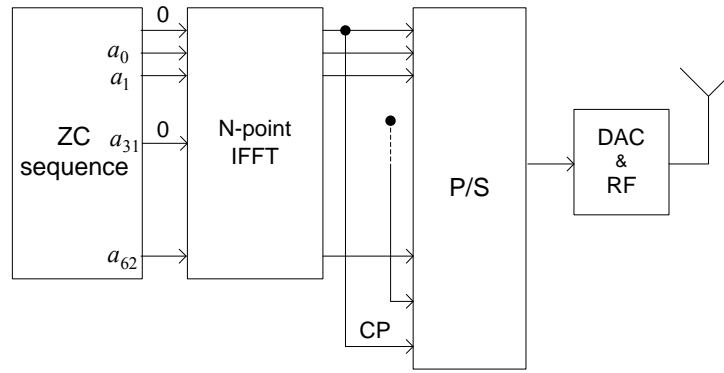


16

17 **Figure 4—Autocorrelation of synchronization preamble.**

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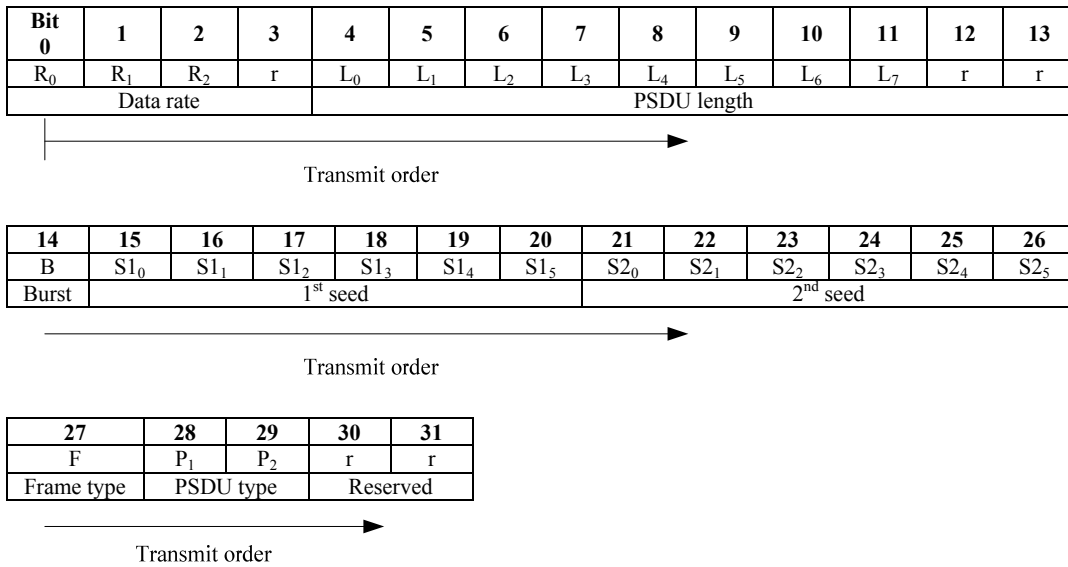
2 **Figure 5—Implementation of synchronization preamble.**

3

4 **5. PHY header**

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

6



7

8

9

10 **Figure 6—PHY header structure**

11 **5.1 Data rate**

12 Data rates are indicated by (R₀, R₁, R₂), where R₂ is the most significant bit (MSB) and R₀ is the least
 13 significant bit (LSB).

14 **5.2 PSDU length**

15 A variable frame length is indicated by (L₀, L₁, L₂, L₃, L₄, L₅, L₆, L₇), where L₇ is the MSB and L₀ is
 16 the LSB.

1 5.3 Burst mode

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

4

5

Table 4—Burst mode

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

6

7 5.4 Scrambler seeds

8 The two scrambler seeds (initial conditions) for the Gold code generator are indicated by (S₁₀ S₁₁S₁₂
9 S₁₃ S₁₄S₁₅) for user ID and (S₂₀ S₂₁ S₂₂ S₂₃ S₂₄ S₂₅) for group ID.

10 5.5 Frame type

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

12

13

Table 5—Frame type

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

14

15 5.6 PSDU type

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

18

19

Table 6—PSDU type

P ₁ P ₂	PSDU status
00	Discovery
01	Peering
10	Data
11	Reserved

20

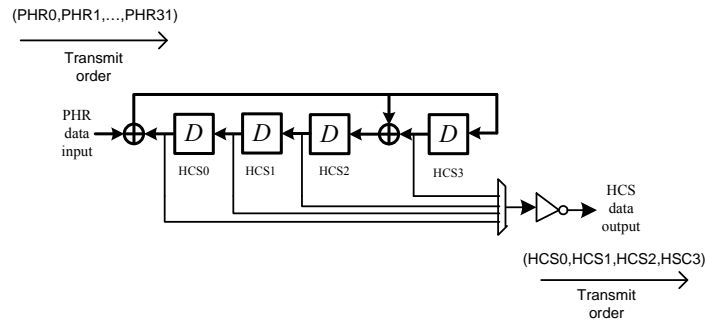
21 5.7 Header check sequence

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

$$25 \quad 1 + x + x^4 \quad (3)$$

26

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

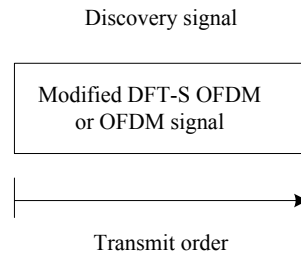


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Figure 7—CRC-4 ITU data processing.

6 **6. Discovery**

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



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 10
 11

Figure 8—Discovery signal

12 **6.1 Discovery signal**

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

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

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

25 Hence, the baseband discovery signal or the n th OFDM symbol transmitted over a k th subcarrier with a
 26 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 $l = -L+1, \dots, 0, 1, \dots, N-1$. 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

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

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.

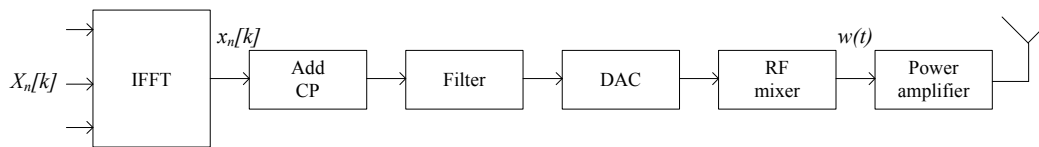


Figure 9—Discovery signal generation

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	$\Delta f=15$ kHz
Sampling time	$T_s=1/(\Delta f M)=520.83$ nsec
Clock rate	$R_c=1.92$ MHz

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

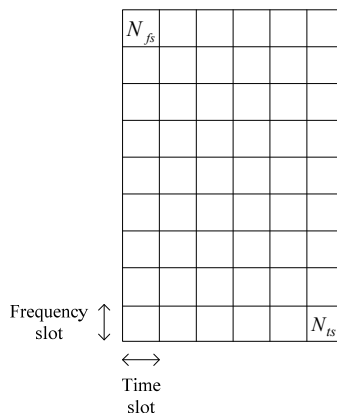


Figure 10—Discovery resource block.

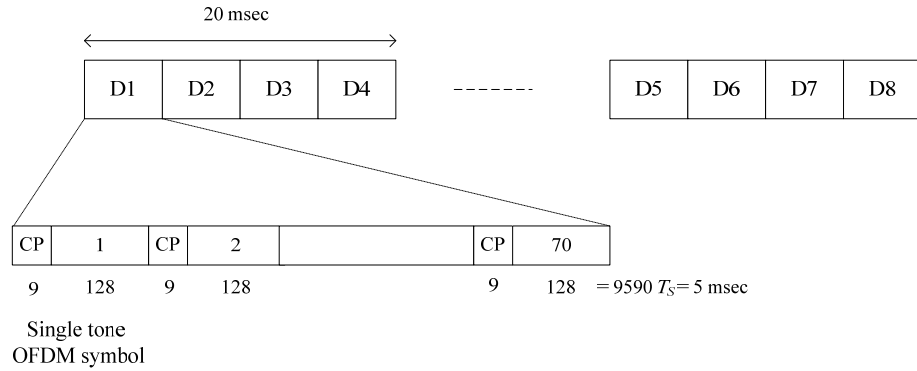


Figure 11—Discovery signal duty cycle

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

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

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

13 Considering 280 bits means 1.9426689×10^{84} different combinations and 560 bits means
 14 3.773962×10^{168} different combinations, this is more than enough for PD ID, user ID, group ID,
 15 application ID, etc.

16 **7. Peering**

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

22 The random access association preambles are named Random Access Preambles (RAPs). Such RAPs
 23 are formed with ZC sequences as well. Hence, a pool of orthogonal RAPs is formed A unique RAP is
 24 assigned to every device in a Group. Such unique RAP is used for fine synchronization and control
 25 messages (how a communication link is granted or how resources are assigned to PDs).

26 **7.1 Random access preamble**

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

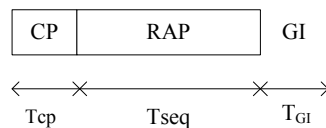


Figure 12—Random access preamble structure

29

30

1 The design of the RAP takes into account:

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

5

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

7

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

9 The RAP duration,

$$10 \quad T_{seq} \geq \frac{1000 \text{ m}}{3 \times 10^8 \text{ m/s}} + \sigma_\tau \quad (6)$$

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

$$13 \quad \text{Consequently } T_{seq} \geq 5.33 \mu\text{sec} \quad (7)$$

14

Table 8—RMS delay spread for 500m

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

15

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

$$17 \quad T_{cp} = \frac{NF kT_0 E_p}{L(d) N_0} \quad (8)$$

18 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
 19 the required preamble energy to meet a PFA of 10^{-3} .

20 According to the parameters $d=500$ m, $f_c=2.4$ GHz, $P_t=1$ W, $G_t=G_r=5$ dBi, $NF=5$ dB, $kT_0=-204$ dB, the
 21 path loss model in clause 2.2.6 of the Channel Model Document, and through simulations the value
 22 $E_p/N_0=18$ dB. Consequently, $T_{seq}=0.433$ msec.

23 The CP and GI lengths at 500m are approximately $2(500 \text{ m})/3 \times 10^8 \text{ m/s} = 3.33 \mu\text{sec}$. Then, T_{seq} is upper
 24 bounded by

$$25 \quad T_{seq} \leq 0.433 \text{ msec} - 2(3.33 \mu\text{sec}) = 0.4263 \text{ msec} \quad (9)$$

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

$$27 \quad N_{FFT} = f_s T_{seq} = k \quad (10)$$

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

1
$$\Delta f_{RAP} = \frac{\Delta f}{k} \tag{11}$$

2 where k is a natural number.

3 The sequence length that satisfies Equation (7), Equation (8) and Equation (11) simultaneously is
 4 $T_{seq}=0.4$ msec. Consequently, $\Delta f_{RAP}=1/T_{seq}=2.5$ KHz and from Equation (11), $k=6$ or granularity
 5 increment. The sampling time is given by $t_s=1/(1024 \Delta f_{RAP})$. Finally, the RAP preamble length is
 6 computed as $0.4 \text{ msec}/t_s=1024$.

7 The CP duration is given by

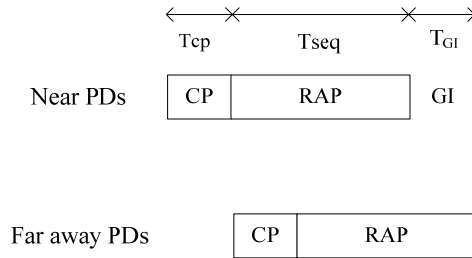
8
$$T_{CP} = 0.5(T_{slot} - T_{seq}) + 0.5\sigma_\tau \tag{12}$$

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

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

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

14 Hence, $T_{GI}=50 \mu\text{sec}$ and shown in Figure 13.



15

16 **Figure 13—RAP dimensioning**

17

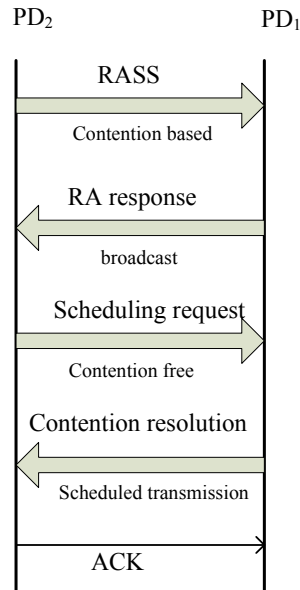
18 Conclusion: a set of orthogonal preamble sequences of length 1024 can be generated from ZC
 19 sequences for random access, which satisfy maximum round-trip time and coverage performance for a
 20 maximum distance of 500m. Moreover, such set of orthogonal preambles is divided into Groups.
 21 Tentatively,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

23 **7.2 Random access procedure**

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

28 As a general case, we assume the decoding of discovery RB are achieved by PD₂ over PD₁, PD₂
 29 requests association (peering) to PD₁ by a random access procedure based on an orthogonal RAP.
 30 Moreover, after the discovery phase, PD₂ can estimate the transmission power of PD₁, channel band
 31 used for association and RAP-ID Group handled by PD₁.

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Figure 14—Random access procedure

The peering process is initiated and control by upper layers.

- 1) PD₂ sends a RAP to PD₁ 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 PD₁. Moreover, such RAP contains finer frequency granularity for PD₁ to acquire fine time and frequency synchronization of PD₂, plus information about the resources needed to transmit in 3).
- 2) PD₁ replies with a RA response message. It is broadcast and contains timing information (round-trip delay), RAP-ID of PD₂, plus resources, like time slot or time-frequency slot, to transmit in 3), etc.
- 3) PD₂ sends a scheduling request (note that it is contention free). It contains scheduling request information for transmission. If this message is successfully detected in PD₁, still contention remains unsolved for other terminals.
- 4) Contention resolution. PD₁ echoes PD₂ ID contained in 3) PD₂ detects its ID and sends ACK (RA terminated) a communication link is scheduled and established. PD₂ detects another ID (RA terminated, starts a new one) PD₂ 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.

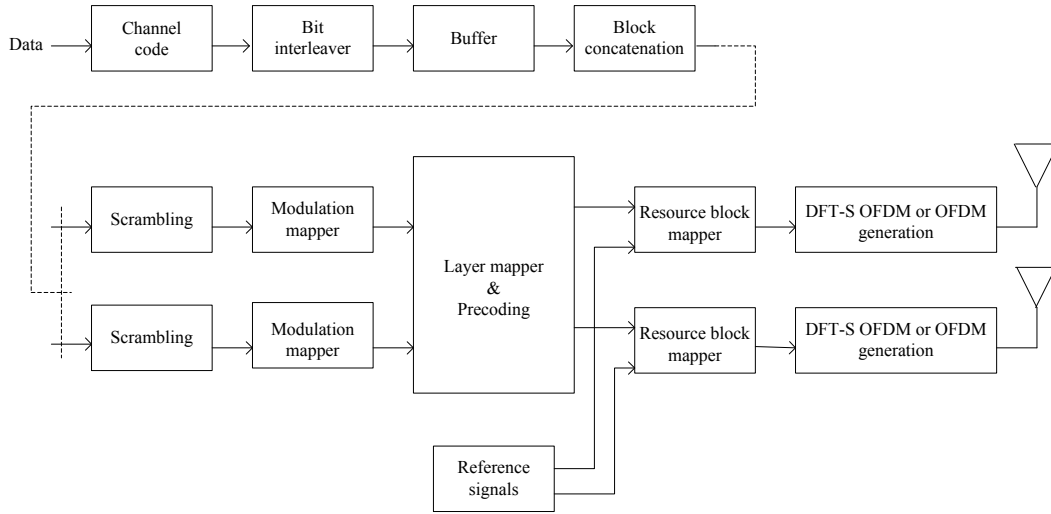
1 The MPDU is passed to the PHY from the MAC. Such data is encoded by quasi-cyclic low density
 2 parity check codes (QC-LDPC). Such QC-LDPC FEC codes allow performance close to turbo codes,
 3 besides that encoder/decoder enable high throughput and low implementation complexity (efficient
 4 implementation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

5 Quasi-cyclic LDPC codes are systematic, linear codes satisfying

$$6 \quad \mathbf{H}\mathbf{c}^T = \mathbf{0} \quad (14)$$

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

9



10
11

12 **Figure 15—PSDU construction schematic diagram**

13

14 The number of codewords in the PSDU is given by

$$15 \quad N_{CW} = \left\lceil \frac{N_{MPDU}}{k} \right\rceil \quad (15)$$

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

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

$$20 \quad c_{nq+i} \quad \text{for } i=0,1,\dots,n-1 \text{ and } q=0,1,\dots,N_{CW}-1. \quad (16)$$

21 \mathbf{H} is constructed from a prototype matrix $\mathbf{H}_{p|M_p \times N_p}$ by replacing each entry of the prototype matrix,
 22 denoted as $[H_p]_{i,j}$, with either a cyclic shift matrix, \mathbf{P}_c , or identity matrix or null matrix of size $Z \times Z$. The
 23 final size of \mathbf{H} is $M_p Z \times N_p Z$.

$$1 \quad [H_p]_{ij} = \begin{cases} I_{ZxZ} & \text{If } [H_p]_{ij} = 0 \\ \mathbf{0}_{ZxZ} & \text{If } [H_p]_{ij} = \text{'-'} \\ P_c & \text{If } [H_p]_{ij} = p \end{cases} \quad (17)$$

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

3 The cyclic-permutation matrix P_c is obtained by cyclically shifting the columns of $P_0=I_{ZxZ}$ to the right c
 4 times, for instance:

$$5 \quad P_0 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad P_1 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix} \quad P_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

6

7 8.1 QC-LDPC encoder parameters

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

10

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

11

12 The prototype matrices for the different data rates are in Annex A.

13 8.2 Interleaver

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

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

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

19 where N_I is the interleaver’s length, and the interleaver’s index $i=0,1,\dots,N_I-1$.

20 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 .

21 The short length interleaver is given by

$$22 \quad \Pi(i) = 31 i + 64 i^2 \text{ Mod } 1024 \quad (19)$$

1 The long length interleaver is given by

$$2 \quad \Pi(i) = 11i + 21i^2 \text{ Mod } 15120 \quad (20)$$

3 The $N_{T_{cw}}$ coded bits are interleaved in blocks of N_I bits as:

$$4 \quad c_{\Pi(i \text{ Mod } N_I)} \quad \text{for } i=0,1,\dots,N_{T_{cw}}-1 \quad (21)$$

5 **8.3 Scrambler**

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

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

11 The Gold code generator shall be constructed by two PN sequence generators with polynomials x^6+x+1
12 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
13 interleaved-coded bits as:

$$14 \quad b_i = \left(c_{\Pi(i \text{ Mod } N_I)} + s_{i \text{ Mod } L} \right) \text{ Mod } 2 \quad \text{for } i=0,1,\dots,N_{T_{cw}}-1 \quad (22)$$

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

17

18 **8.4 Modulation mapper**

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

20 **8.4.1 Pad bits**

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

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

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

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

$$26 \quad N_T = N_{PSDU} + (n-k)N_{CW} + N_{pad} \quad (24)$$

27 **8.4.2 Modulations**

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

31 The modulations symbols per codeword may be expressed as

1 $d_{l+qN_{CW}} = d_l^q$ for $l=0,1,\dots,N_{sym}^q - 1$ and $q=0, 1,\dots, N_{CW} - 1$. (25)

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

3 **Table 10—Modulations**

Modulation	Complex symbol	$\text{Log}_2(M)$
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

4

5 **9. Layer mapping**

6 Two MIMO technologies are supported: open loop spatial multiplexing and transmit diversity for 2 and
 7 4 antennas. The mandatory transmission in MIMO mode depends on the number of antennas that can
 8 be implemented in a PD.

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

11 $[d_0^q, \dots, d_{N_{sym}^q-1}^q] \rightarrow [x_0(i), \dots, x_{v-1}(i)]^T$ for $i=0,1,\dots, N_{sym}^L - 1$. (26)

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

15

16 **9.1 Layer mapping for one antenna**

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

19

20 **9.2 Open loop spatial multiplexing**

21 Spatial multiplexing represents the transmission of multiple parallel streams. The mapping of
 22 modulation symbols to layers is shown in Table 11. The number of layers is less or equal to the number
 23 of antennas, $v \leq P$.

24

1

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	$x_0(i) = d_{2i}^0$ $x_1(i) = d_{2i+1}^1$ $x_2(i) = d_{2i}^0$ $x_3(i) = d_{2i+1}^1$	$N_{sym}^L = N_{sym}^0 / 2 = N_{sym}^1 / 2$

2

3

4 **9.3 Transmit diversity**

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

7

8

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	$x_0(i) = d_{4i}^0$ $x_1(i) = d_{4i+1}^0$ $x_2(i) = d_{4i+2}^0$ $x_3(i) = d_{4i+3}^0$	$N_{sym}^L = \begin{cases} N_{sym}^0 / 4 & \text{If } N_{sym}^0 \text{ Mod } 4 = 0 \\ \frac{N_{sym}^0 + m}{4} & \text{If } N_{sym}^0 \text{ Mod } 4 \neq 0 \end{cases}$

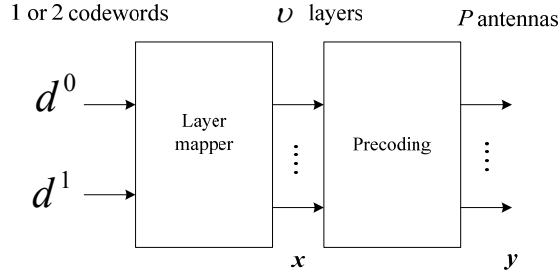
9 If $N_{sym}^q \text{ Mod } 4 \neq 0$ add m null symbols at the end such that $N_{sym}^q + m \text{ Mod } 4 = 0$.

10

11 **10. Precoding**

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

14



1
2

Figure 16—Precoding mapping

3 **10.1 Single antenna mapping**

4 Transmission with a single antenna, precoding is defined by

5
$$y_0(i) = x_0(i) \tag{27}$$

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

7 **10.2 Open loop spatial multiplexing**

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

11 Precoding for multiple antennas is defined by

12
$$\begin{bmatrix} y_0(i) \\ \vdots \\ y_{P-1}(i) \end{bmatrix} = \mathbf{W}(i) \begin{bmatrix} x_0(i) \\ \vdots \\ x_{v-1}(i) \end{bmatrix} \tag{28}$$

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

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

16 **Table 13—Codebook for transmission on 2 antennas**

Index	v=1	v=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	$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -j \end{bmatrix}$	

17

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

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

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

5

6 **Table 14—Codebook for transmission on 4 antennas**

n	\mathbf{u}_n	$\mathbf{v}=1$	$\mathbf{v}=2$	$\mathbf{v}=3$	$\mathbf{v}=4$
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	$[1 \ (-1-j)/\sqrt{2} \ -j \ 1]^T$	$W_4^{\{1\}}$	$W_4^{\{14\}}/\sqrt{2}$	$W_4^{\{124\}}/\sqrt{3}$	$W_4^{\{1234\}}/2$
5	$[1 \ (-1+j)/\sqrt{2} \ -j \ (-1-j)/\sqrt{2}]^T$	$W_5^{\{1\}}$	$W_5^{\{14\}}/\sqrt{2}$	$W_5^{\{124\}}/\sqrt{3}$	$W_5^{\{1234\}}/2$
6	$[1 \ (1+j)/\sqrt{2} \ -j \ (-1+j)/\sqrt{2}]^T$	$W_6^{\{1\}}$	$W_6^{\{13\}}/\sqrt{2}$	$W_6^{\{134\}}/\sqrt{3}$	$W_6^{\{1324\}}/2$
7	$[1 \ (-1+j)/\sqrt{2} \ j \ (1+j)/\sqrt{2}]^T$	$W_7^{\{1\}}$	$W_7^{\{13\}}/\sqrt{2}$	$W_7^{\{134\}}/\sqrt{3}$	$W_7^{\{1324\}}/2$
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	$[1 \ 1 \ 1 \ 1]^T$	$W_{15}^{\{1\}}$	$W_{15}^{\{12\}}/\sqrt{2}$	$W_{15}^{\{123\}}/\sqrt{3}$	$W_{15}^{\{1234\}}/2$

7

8 \mathbf{W} is conformed for the codebook for 4 antennas as follows: $W_i^{\{c_1, \dots, c_m\}}$ denotes the matrix formed by
 9 the columns $\{c_1, \dots, c_m\}$ of the matrix $W_i = \mathbf{I}_{4 \times 4} - 2\mathbf{u}_i\mathbf{u}_i^H / \|\mathbf{u}_i\|$.

10

11 10.3 Transmit diversity

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

14 In case of 2 antennas, the space-frequency block codes (SFBC) are defined by

$$15 \begin{bmatrix} y_0(2i) & y_0(2i+1) \\ y_1(2i) & y_1(2i+1) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} x_0(i) & x_1(i) \\ -x_1^*(i) & x_0^*(i) \end{bmatrix} \quad (29)$$

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

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

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

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

5

6 11. Multicarrier modulation

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

10

Table 15—Multicarrier parameters

Description	Notation
Total No of subcarriers	MFFT=1024
Subcarrier spacing	$\Delta f=15$ KHz
Sampling time	$T_s=1/(\Delta f \text{ MFFT})=65.1$ nsec
Clock rate	$R_c=1/T_s=15.36$ MHz

11

12 11.1 Cyclic prefix

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

15

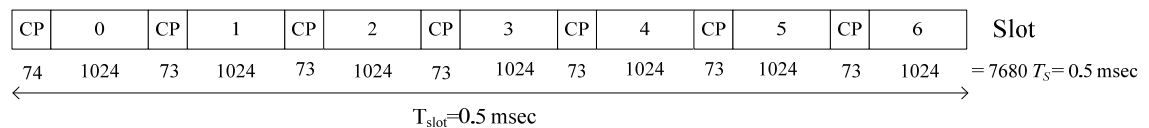
Table 16—Typical RMS delay spread

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

16

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

19



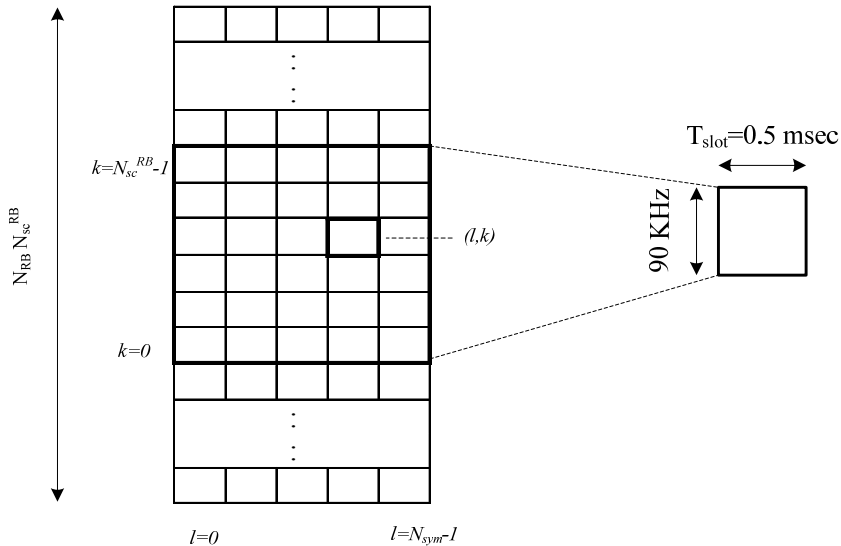
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22 **Figure 17—Slot structure**

23

1 **11.2 Resource block**

2 Resource block (RB) is a set of time-frequency slots for data communication and enabling multiple
 3 access. A RB is formed by a slot time of 0.5 msec ($N_{syms}=7$ OFDM symbols as in Figure 17 and Figure
 4 18) and $N_{sc}^{RB}=6$ subcarriers or 90 KHz spectrum as show in Figure 18. The total number of RBs is
 5 $N_{RB}=170$ (the 2 upper and lower subcarriers are empty).



6
 7 **Figure 18—Resource block parameters**

8
 9 Transmission bandwidth (BW) is obtained by concatenating RBs as

10
$$BW = n N_{sc}^{RB} \Delta f \tag{31}$$

11 where $12 \leq n \leq 111$.

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

14
 15 **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

16
 17 For the sub-GHz band, the transmission bandwidth is 1 MHz, while for the 2.4 and 5.7 GHz bands, the
 18 maximum transmission considered is 10 MHz. the main reason is that PAC applications require as
 19 many channel resources for multiplexing (and consequently multiple access) as possible. For instance,
 20 it is preferable to have 15 channels of 10 MHz rather than 7 channels of 20 MHz to accommodate more
 21 users.

1 **11.3 Filtered OFDM symbols for sub-1 GHz band**

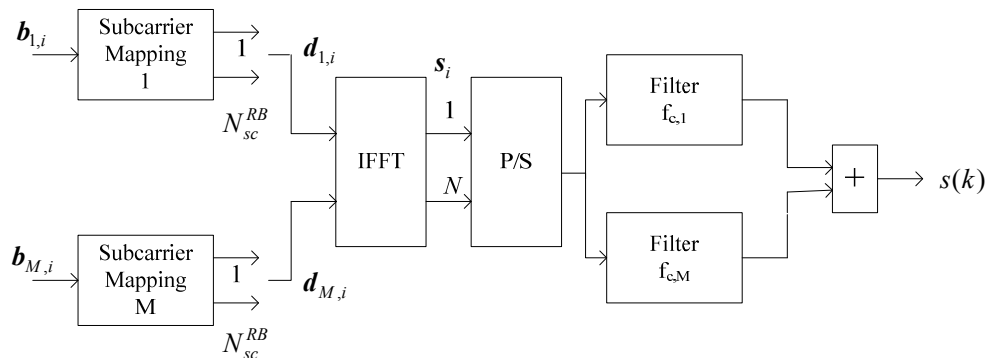
2 In order to improve performance, the cyclic prefix is replaced by the coefficients of symmetric
 3 Blackman-Harris filter given by

4
$$w(n) = a_0 - a_1 \cos\left(\frac{2\pi n}{N-1}\right) + a_2 \cos\left(\frac{4\pi n}{N-1}\right) + a_3 \cos\left(\frac{6\pi n}{N-1}\right); \quad 0 \leq n \leq N-1 \quad (32)$$

$$a_0 = 0.35875; a_1 = 0.48829; a_2 = 0.14128; a_3 = 0.01168$$

5 where $N=73/74$. The window is applied around a resource block as illustrated in Figure 19.

6



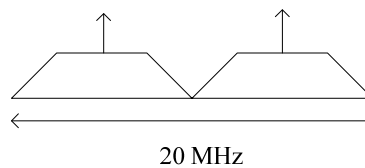
7

8 **Figure 19—Multicarrier modulation for sub-1 GHz band**

9

10 **11.4 Carrier aggregation**

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



15

16 **Figure 20—Carrier aggregation**

17

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

20 **11.5 Data rates**

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

1 The number of subcarriers is given by $nN_{sc}^{RB}N_{sym}$, where $N_{sc}^{RB} = 6$ subcarriers per RB,
 2 $N_{sym} = 7$ OFDM symbols and $12 \leq n \leq 111$. Every subcarrier conveys a modulation symbol. The
 3 number of bits per symbol is $\text{Log}_2(M)$ where M is the cardinality of modulation. The coding rate C_R
 4 values are shown in Table 18. The carrier aggregation C_A may double the number of employed
 5 subcarriers. Open loop spatial multiplexing MIMO, C_M , may double or quadruple the capacity.
 6 The different combinations are shown in Table 18 without overhead.

7
 8

Table 18—Data rate parameters

n	$\text{Log}_2(M)$	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		

9

10 The different data rates are given by

$$11 \quad R_b = \frac{nN_{sc}^{RB}N_{sym} \text{Log}_2(M)}{0.5 \text{ msec}} C_R C_A C_M \quad (33)$$

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

14 **12. Reference signals**

15 Reference signals for channel estimation and equalization are based on ZC sequences. Such reference
 16 signals must be considered in the time and frequency domain.
 17

18 **12.1 Time domain**

19 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
 20 Table 19.
 21

22

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

23
 24
 25
 26
 27
 28

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.

1 12.2 Frequency domain

2 Considering the Channel Model Document, the 90% and 50% coherence bandwidth as
 3 $B_{c,90} = 1/50\sigma_\tau$ and $B_{c,50} = 1/5\sigma_\tau$, where σ_τ is the RMS delay spread, such coherence bandwidths
 4 can be computed as

$$5 \quad \sigma_\tau = C_a d^{\gamma_a} \quad (34)$$

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

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

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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

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13 13. Optional GFSK modulation

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

$$18 \quad s(t) = V s \left(2\pi f_c t + 2\pi \Delta f \int_{-\infty}^t b(t') dt' + \varphi_0 \right) \quad (35)$$

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

22 The information bearing signal is given by

$$23 \quad b(t) = \sum_m (1 - 2g_m) p(t - mT_{sym}) \quad (36)$$

24 where g_m is information bits, $p(t)$ is a Gaussian pulse shape of bandwidth-symbol duration product of
 25 0.8.

26 14. Operating frequency bands

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

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

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

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

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

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

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

21 However, as stated in clause 11.4, one carrier aggregation can be used to increase the bandwidth to 20
 22 MHz.

23 **14.1 Channelization of 920 MHz band**

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

25
 26 **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

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

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

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

30 **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

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1 14.2 Channelization of 2.4 GHz band

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

$$4 \quad f_c = 2405 \text{ MHz} + 10n \quad \text{for } n=0,1,\dots,7 \quad (37)$$

5 14.3 Channelization of 5.7 GHz band

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

$$8 \quad f_c = 5730 \text{ MHz} + 10n \quad \text{for } n=0,1,\dots,14 \quad (38)$$

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1 **Annex B**

2 (Normative)

3 **Modulation mapping**

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Table B.1—BPSK mapping

b_i	I	Q
0	$1/\sqrt{2}$	$1/\sqrt{2}$
1	$-1/\sqrt{2}$	$-1/\sqrt{2}$

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Table B.2—QPSK mapping

$b_i b_{i+1}$	I	Q
00	$1/\sqrt{2}$	$1/\sqrt{2}$
01	$1/\sqrt{2}$	$-1/\sqrt{2}$
10	$-1/\sqrt{2}$	$1/\sqrt{2}$
11	$-1/\sqrt{2}$	$-1/\sqrt{2}$

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Table B.3—16QAM mapping

$b_i b_{i+1} b_{i+2} b_{i+3}$	I	Q
0000	$1/\sqrt{10}$	$1/\sqrt{10}$
0001	$1/\sqrt{10}$	$3/\sqrt{10}$
0010	$3/\sqrt{10}$	$1/\sqrt{10}$
0011	$3/\sqrt{10}$	$3/\sqrt{10}$
0100	$1/\sqrt{10}$	$-1/\sqrt{10}$
0101	$1/\sqrt{10}$	$-3/\sqrt{10}$
0110	$3/\sqrt{10}$	$-1/\sqrt{10}$
0111	$3/\sqrt{10}$	$-3/\sqrt{10}$
1000	$-1/\sqrt{10}$	$1/\sqrt{10}$
1001	$-1/\sqrt{10}$	$3/\sqrt{10}$
1010	$-3/\sqrt{10}$	$1/\sqrt{10}$
1011	$-3/\sqrt{10}$	$3/\sqrt{10}$
1100	$-1/\sqrt{10}$	$-1/\sqrt{10}$
1101	$-1/\sqrt{10}$	$-3/\sqrt{10}$
1110	$-3/\sqrt{10}$	$-1/\sqrt{10}$
1111	$-3/\sqrt{10}$	$-3/\sqrt{10}$

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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
000000	$3/\sqrt{42}$	$3/\sqrt{42}$	100000	$-3/\sqrt{42}$	$3/\sqrt{42}$
000001	$3/\sqrt{42}$	$1/\sqrt{42}$	100001	$-3/\sqrt{42}$	$1/\sqrt{42}$
000010	$1/\sqrt{42}$	$3/\sqrt{42}$	100010	$-1/\sqrt{42}$	$3/\sqrt{42}$
000011	$1/\sqrt{42}$	$1/\sqrt{42}$	100011	$-1/\sqrt{42}$	$1/\sqrt{42}$
000100	$3/\sqrt{42}$	$5/\sqrt{42}$	100100	$-3/\sqrt{42}$	$5/\sqrt{42}$
000101	$3/\sqrt{42}$	$7/\sqrt{42}$	100101	$-3/\sqrt{42}$	$7/\sqrt{42}$
000110	$1/\sqrt{42}$	$5/\sqrt{42}$	100110	$-1/\sqrt{42}$	$5/\sqrt{42}$
000111	$1/\sqrt{42}$	$7/\sqrt{42}$	100111	$-1/\sqrt{42}$	$7/\sqrt{42}$
001000	$5/\sqrt{42}$	$3/\sqrt{42}$	101000	$-5/\sqrt{42}$	$3/\sqrt{42}$
001001	$5/\sqrt{42}$	$1/\sqrt{42}$	101001	$-5/\sqrt{42}$	$1/\sqrt{42}$
001010	$7/\sqrt{42}$	$3/\sqrt{42}$	101010	$-7/\sqrt{42}$	$3/\sqrt{42}$
001011	$7/\sqrt{42}$	$1/\sqrt{42}$	101011	$-7/\sqrt{42}$	$1/\sqrt{42}$
001100	$5/\sqrt{42}$	$5/\sqrt{42}$	101100	$-5/\sqrt{42}$	$5/\sqrt{42}$
001101	$5/\sqrt{42}$	$7/\sqrt{42}$	101101	$-5/\sqrt{42}$	$7/\sqrt{42}$
001110	$7/\sqrt{42}$	$5/\sqrt{42}$	101110	$-7/\sqrt{42}$	$5/\sqrt{42}$
001111	$7/\sqrt{42}$	$7/\sqrt{42}$	101111	$-7/\sqrt{42}$	$7/\sqrt{42}$
010000	$3/\sqrt{42}$	$-3/\sqrt{42}$	110000	$-3/\sqrt{42}$	$-3/\sqrt{42}$
010001	$3/\sqrt{42}$	$-1/\sqrt{42}$	110001	$-3/\sqrt{42}$	$-1/\sqrt{42}$
010010	$1/\sqrt{42}$	$-3/\sqrt{42}$	110010	$-1/\sqrt{42}$	$-3/\sqrt{42}$
010011	$1/\sqrt{42}$	$-1/\sqrt{42}$	110011	$-1/\sqrt{42}$	$-1/\sqrt{42}$
010100	$3/\sqrt{42}$	$-5/\sqrt{42}$	110100	$-3/\sqrt{42}$	$-5/\sqrt{42}$
010101	$3/\sqrt{42}$	$-7/\sqrt{42}$	110101	$-3/\sqrt{42}$	$-7/\sqrt{42}$
010110	$1/\sqrt{42}$	$-5/\sqrt{42}$	110110	$-1/\sqrt{42}$	$-5/\sqrt{42}$
010111	$1/\sqrt{42}$	$-7/\sqrt{42}$	110111	$-1/\sqrt{42}$	$-7/\sqrt{42}$
011000	$5/\sqrt{42}$	$-3/\sqrt{42}$	111000	$-5/\sqrt{42}$	$-3/\sqrt{42}$
011001	$5/\sqrt{42}$	$-1/\sqrt{42}$	111001	$-5/\sqrt{42}$	$-1/\sqrt{42}$
011010	$7/\sqrt{42}$	$-3/\sqrt{42}$	111010	$-7/\sqrt{42}$	$-3/\sqrt{42}$
011011	$7/\sqrt{42}$	$-1/\sqrt{42}$	111011	$-7/\sqrt{42}$	$-1/\sqrt{42}$
011100	$5/\sqrt{42}$	$-5/\sqrt{42}$	111100	$-5/\sqrt{42}$	$-5/\sqrt{42}$
011101	$5/\sqrt{42}$	$-7/\sqrt{42}$	111101	$-5/\sqrt{42}$	$-7/\sqrt{42}$
011110	$7/\sqrt{42}$	$-5/\sqrt{42}$	111110	$-7/\sqrt{42}$	$-5/\sqrt{42}$
011111	$7/\sqrt{42}$	$-7/\sqrt{42}$	111111	$-7/\sqrt{42}$	$-7/\sqrt{42}$

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$b_i b_{i+1} b_{i+2} b_{i+3}$ $b_{i+4} b_{i+5}$	I	Q	$b_i b_{i+1} b_{i+2} b_{i+3}$ $b_{i+4} b_{i+5}$	I	Q
000000	$3/\sqrt{42}$	$3/\sqrt{42}$	100000	$-3/\sqrt{42}$	$3/\sqrt{42}$
000001	$3/\sqrt{42}$	$1/\sqrt{42}$	100001	$-3/\sqrt{42}$	$1/\sqrt{42}$
000010	$1/\sqrt{42}$	$3/\sqrt{42}$	100010	$-1/\sqrt{42}$	$3/\sqrt{42}$
000011	$1/\sqrt{42}$	$1/\sqrt{42}$	100011	$-1/\sqrt{42}$	$1/\sqrt{42}$
000100	$3/\sqrt{42}$	$5/\sqrt{42}$	100100	$-3/\sqrt{42}$	$5/\sqrt{42}$
000101	$3/\sqrt{42}$	$7/\sqrt{42}$	100101	$-3/\sqrt{42}$	$7/\sqrt{42}$
000110	$1/\sqrt{42}$	$5/\sqrt{42}$	100110	$-1/\sqrt{42}$	$5/\sqrt{42}$
000111	$1/\sqrt{42}$	$7/\sqrt{42}$	100111	$-1/\sqrt{42}$	$7/\sqrt{42}$
001000	$5/\sqrt{42}$	$3/\sqrt{42}$	101000	$-5/\sqrt{42}$	$3/\sqrt{42}$
001001	$5/\sqrt{42}$	$1/\sqrt{42}$	101001	$-5/\sqrt{42}$	$1/\sqrt{42}$
001010	$7/\sqrt{42}$	$3/\sqrt{42}$	101010	$-7/\sqrt{42}$	$3/\sqrt{42}$
001011	$7/\sqrt{42}$	$1/\sqrt{42}$	101011	$-7/\sqrt{42}$	$1/\sqrt{42}$
001100	$5/\sqrt{42}$	$5/\sqrt{42}$	101100	$-5/\sqrt{42}$	$5/\sqrt{42}$
001101	$5/\sqrt{42}$	$7/\sqrt{42}$	101101	$-5/\sqrt{42}$	$7/\sqrt{42}$
001110	$7/\sqrt{42}$	$5/\sqrt{42}$	101110	$-7/\sqrt{42}$	$5/\sqrt{42}$
001111	$7/\sqrt{42}$	$7/\sqrt{42}$	101111	$-7/\sqrt{42}$	$7/\sqrt{42}$
010000	$3/\sqrt{42}$	$-3/\sqrt{42}$	110000	$-3/\sqrt{42}$	$-3/\sqrt{42}$
010001	$3/\sqrt{42}$	$-1/\sqrt{42}$	110001	$-3/\sqrt{42}$	$-1/\sqrt{42}$
010010	$1/\sqrt{42}$	$-3/\sqrt{42}$	110010	$-1/\sqrt{42}$	$-3/\sqrt{42}$
010011	$1/\sqrt{42}$	$-1/\sqrt{42}$	110011	$-1/\sqrt{42}$	$-1/\sqrt{42}$
010100	$3/\sqrt{42}$	$-5/\sqrt{42}$	110100	$-3/\sqrt{42}$	$-5/\sqrt{42}$
010101	$3/\sqrt{42}$	$-7/\sqrt{42}$	110101	$-3/\sqrt{42}$	$-7/\sqrt{42}$
010110	$1/\sqrt{42}$	$-5/\sqrt{42}$	110110	$-1/\sqrt{42}$	$-5/\sqrt{42}$
010111	$1/\sqrt{42}$	$-7/\sqrt{42}$	110111	$-1/\sqrt{42}$	$-7/\sqrt{42}$
011000	$5/\sqrt{42}$	$-3/\sqrt{42}$	111000	$-5/\sqrt{42}$	$-3/\sqrt{42}$
011001	$5/\sqrt{42}$	$-1/\sqrt{42}$	111001	$-5/\sqrt{42}$	$-1/\sqrt{42}$
011010	$7/\sqrt{42}$	$-3/\sqrt{42}$	111010	$-7/\sqrt{42}$	$-3/\sqrt{42}$
011011	$7/\sqrt{42}$	$-1/\sqrt{42}$	111011	$-7/\sqrt{42}$	$-1/\sqrt{42}$
011100	$5/\sqrt{42}$	$-5/\sqrt{42}$	111100	$-5/\sqrt{42}$	$-5/\sqrt{42}$
011101	$5/\sqrt{42}$	$-7/\sqrt{42}$	111101	$-5/\sqrt{42}$	$-7/\sqrt{42}$
011110	$7/\sqrt{42}$	$-5/\sqrt{42}$	111110	$-7/\sqrt{42}$	$-5/\sqrt{42}$
011111	$7/\sqrt{42}$	$-7/\sqrt{42}$	111111	$-7/\sqrt{42}$	$-7/\sqrt{42}$

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1 **Bibliography**

2 Bibliographical references are resources that provide additional or helpful material but do not need to
3 be understood or used to implement this standard. Reference to these resources is made for
4 informational use only.

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