Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [High-Rate Close-Proximity Sony Proposal (Preliminary)]
Date Submitted: [9 July, 2015]

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Re: [In response to TG3e High Rate Close Proximity Call for Proposals (0381/r2)]

Abstract: [Sony proposal for High-Rate Close Proximity]

Purpose: [To be considered in the IEEE802.15.3e standard]

Introduction

- ✓ **A full PHY/MAC proposal, as a preliminary version**
- ✓ **Extremely high PHY-SAP payload-bit rates outperforming those of 15.3c**
  - Min. 2 Gb/s and Max. 13 Gb/s, using a single channel with 2.16 GHz bandwidth
  - Max. 100 Gb/s, using MIMO and a channel aggregation
- ✓ **Reusing the best error-correction code respecting 15.3c**
  - Reusing the rate-14/15 low-density parity-check (LDPC) code
  - Introducing a new rate-11/15 LDPC code whose decoder compatible with that for the rate-14/15 LDPC code to obtain moderate bit rates
- ✓ **Simple PHY/MAC format enabling low-power system**
- ✓ **Fulfills TG3e's requirements in the technical guidance document (TGD)**

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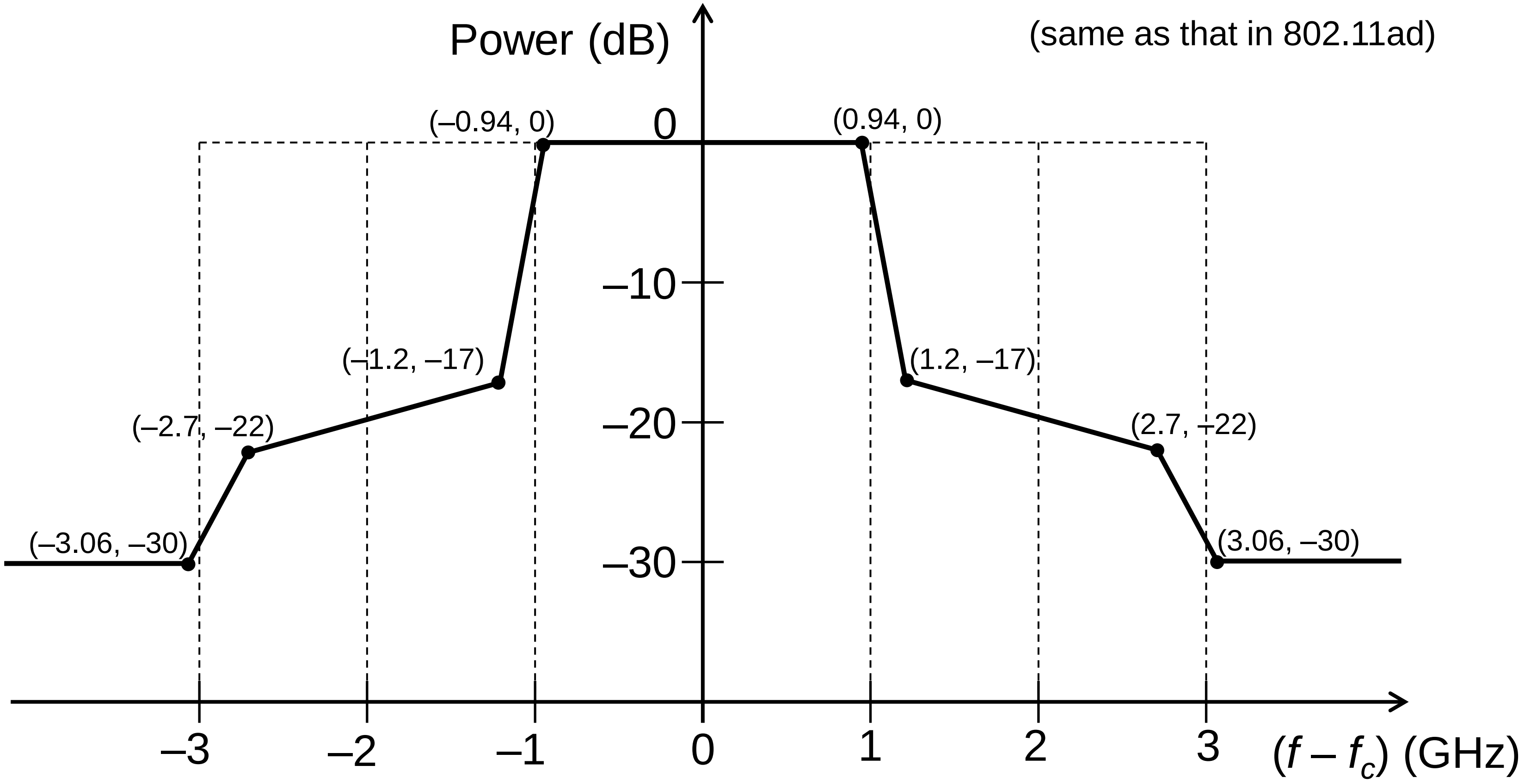
Channel assignments

MmWave-PHY channelization

CHNL_ID	Start frequency[a]	Center frequency	Stop frequency[a]
1	57.240	58.320	59.400
2	59.400	60.480	61.560
3	61.560	62.640	63.720
4	63.720	64.800	65.880

[a] The start and stop frequencies are nominal values. The frequency spectrum of the transmitted signal needs to conform to the transmit spectral mask as well as any regulatory requirement.

Transmit spectral mask



Modulation and coding scheme (MCS)

Minimum 2 Gb/s and Maximum 100 Gb/s MCSs using a simple FEC scheme

MCS identifier	single-carrier modulation	FEC Rate	PHY-SAP payload-bit rate (Gb/s)							
			x1 mode		x2 mode		x4 mode		x8 mode	
			w/o PW	w/ PW	w/o PW	w/ PW	w/o PW	w/ PW	w/o PW	w/ PW
0	π/2 QPSK	11/15	2.5813	2.2587	5.1627	4.5173	10.3253	9.0347	20.6507	18.0693
1	π/2 QPSK	14/15	3.2853	2.8747	6.5707	5.7493	13.1413	11.4987	26.2827	22.9973
2	16QAM	11/15	5.1627	4.5173	10.3253	9.0347	20.6507	18.0693	41.3013	36.1387
3	16QAM	14/15	6.5707	5.7493	13.1413	11.4987	26.2827	22.9973	52.5653	45.9947
4	64QAM	11/15	7.7440	6.7760	15.4880	13.5520	30.9760	27.1040	61.9520	54.2080
5	64QAM	14/15	9.8560	8.6240	19.7120	17.2480	39.4240	34.4960	78.8480	68.9920
6	256QAM	14/15	13.1413	11.4987	26.2827	22.9973	52.5653	45.9947	105.1367	91.9893

x1 mode: SISO x single channel
x2 mode: SISO x dual channels, or 2x2 MIMO x single channel
x4 mode: 2x2 MIMO x dual channels, or 4x4 MIMO x single channel
x8 mode: 4x4 MIMO x dual channels, or 8x8 MIMO x single channel

PW: pilot word
PW length/sub-block length = 0.125

Forward Error Correction

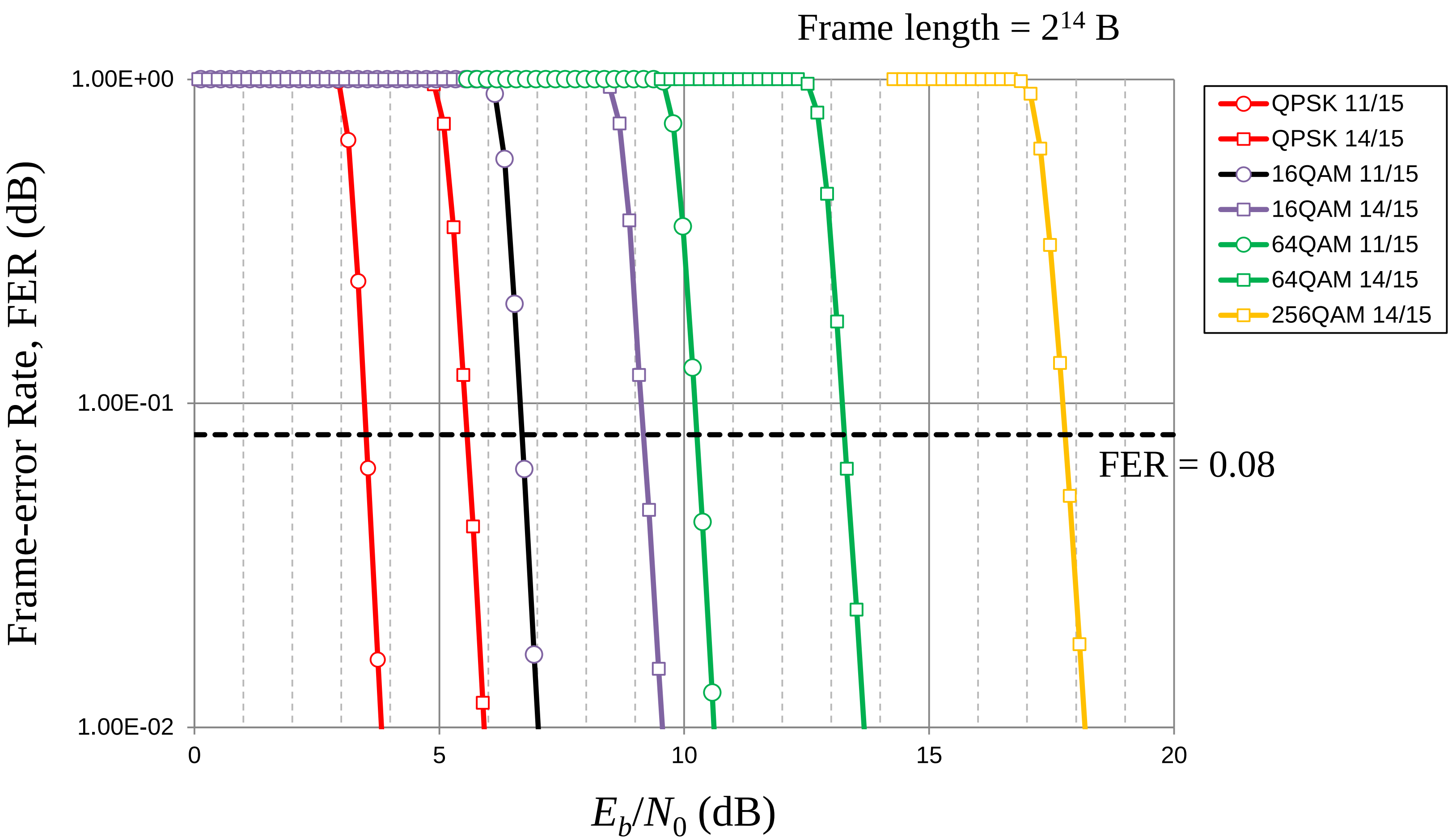
Reuse the 14/15 LDPC code and a new 11/15 LDPC code with the best code efficiencies.

Gap between SNR_r* obtained by floating point simulation and the Shannon limit in binary AWGN channel for codes employed in standards.

	code	standard	rate	SNR_r (dB)	Shannon limit (dB)	gap (dB)
	RS(240,224) on GF(2^8)	T J	0.933	9.77	6.51	–3.26
rate 14/15	LDPC(1440,1344)	15.3c	0.933	8.46	6.51	–1.96
	LDPC(672,588)	15.3c	0.875	7.55	5.27	–2.28
	LDPC(672,546)	11ad	0.813	6.96	4.26	–2.70
	LDPC(672,504)	11ad	0.750	5.91	3.39	–2.53
rate 11/15	LDPC(1440,1056)	New	0.733	5.36	3.17	–2.20

SNR_r*: signal-to-noise ratio required for a bit-error rate of 10^{-6}

MCS performance, FER v.s. E_b/N_0 in AWGN



Link budget for the x1 mode in AWGN

MCS		MCS0	MCS1	MCS2	MCS3	MCS4	MCS5	MCS6
Tx	frequency for CH4 (GHz)	64.8	64.8	64.8	64.8	64.8	64.8	64.8
	PHY-SAP bit rate (Gb/s)	2.5813	3.2853	5.1627	6.5707	7.7440	9.8560	13.1413
	Tx power (dBm)	1	1	1	1	1	1	1
	Tx antenna gain (dBi)	4	4	4	4	4	4	4
channel	distance(m)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	1m loss (dB)	68.67	68.67	68.67	68.67	68.67	68.67	68.67
	path Loss (dB)	-20.00	-20.00	-20.00	-20.00	-20.00	-20.00	-20.00
	propagation loss index	2	2	2	2	2	2	2
	Rx input level (dBm)	-43.67	-43.67	-43.67	-43.67	-43.67	-43.67	-43.67
	average noise power per bit (dBm)	-79.88	-78.83	-76.87	-75.82	-75.11	-74.06	-72.81
Rx	Rx antenna gain (dBi)	4	4	4	4	4	4	4
	noise figure (dB)	8	8	8	8	8	8	8
	implementation loss (dB)	6	6	6	6	6	6	6
	shadowing margin (dB)	1	1	1	1	1	1	1
	receiving Eb/N0 (dB)	25.21	24.16	22.20	21.15	20.44	19.39	18.14
required Eb/N0 for AWGN		**3.51**	**5.57**	**6.69**	**9.17**	**10.26**	**13.27**	**17.78**
margin		**21.70**	**18.59**	**15.51**	**11.98**	**10.18**	**6.12**	**0.36**

(This budget will be changed after simulations incorporating RF impairments and channel model)

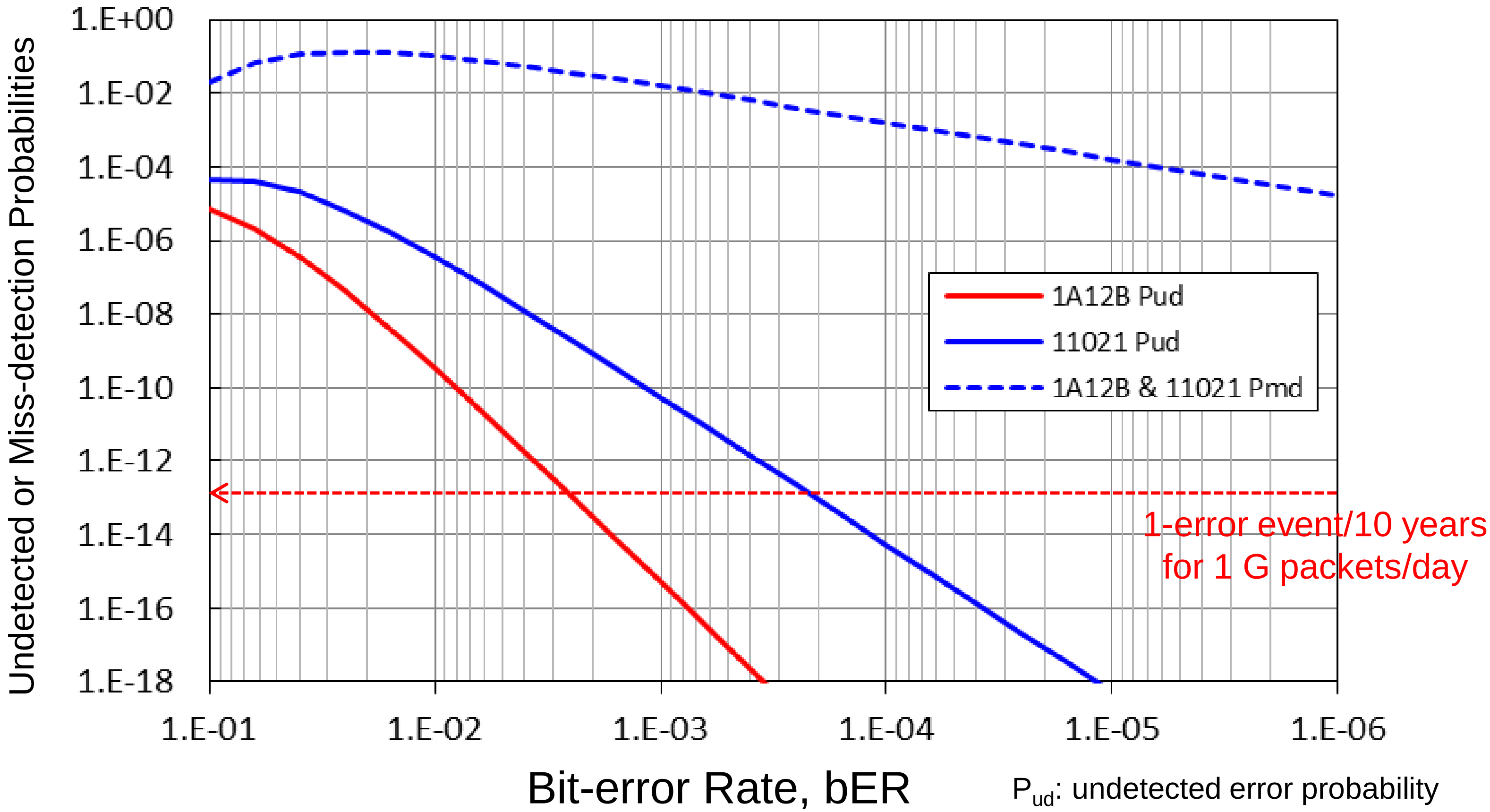
PHY header format

MCS field is assigned at the first-three digits and encoded separately.

Field Name	Number of bits	Start bit	Description
MCS	3	0	Index into the Modulation and Coding Scheme table
Scrambler seed ID	4	3	The initial state for payload scrambling
Pilot word	1	7	Shall be set to 1 if the pilot word is used
Reserved	8	8	Set to 0, ignored by the receiver
Frame length	19	16	Number of data octets in the PSDU
HCS	16	35	Header check sequence

16-bit Header CRC* for HCS

generator polynomial: 1A12B (new, d_{min} = 6), 11021 (ITU-T, d_{min} = 4)

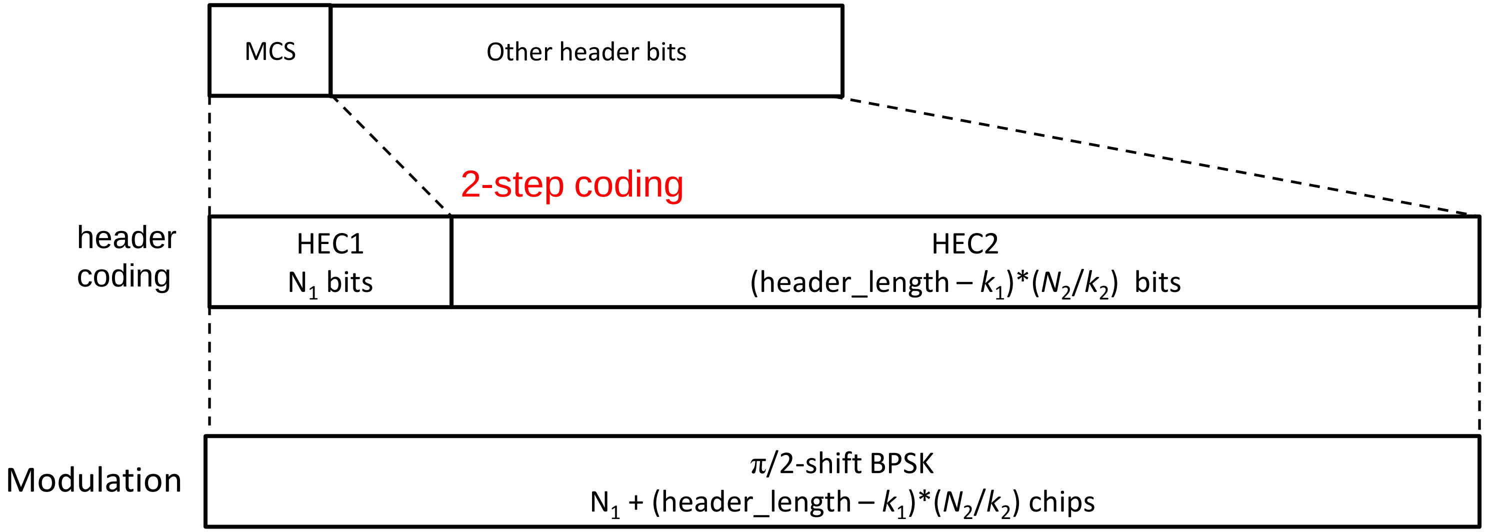


P_{ud}: undetected error probability
P_{md}: miss-detection probability
d_{min}: minimum Hamming distance
code-word length = 51 bits

*CRC: cyclic-redundancy-check code

2-step header coding and modulation scheme

HEC1: first header error-correction, (N_1, k_1) code just for MCS
HEC2: second header error-correction, (N_2, k_2) code for the other header bits



Other PHY Issues

The following PHY issues will be described in the final proposal at the next Sep. Meeting

- ✓ Preamble and pilot word
- ✓ Header coding and a frame-check sequence
- ✓ Coexistence with other systems in the same band when operating without any beamforming technology
- ✓ Antenna form factor small enough for placement and operation inside a mobile device
- ✓ Simulation incorporating RF impairments and channel model
- ✓ Etc.

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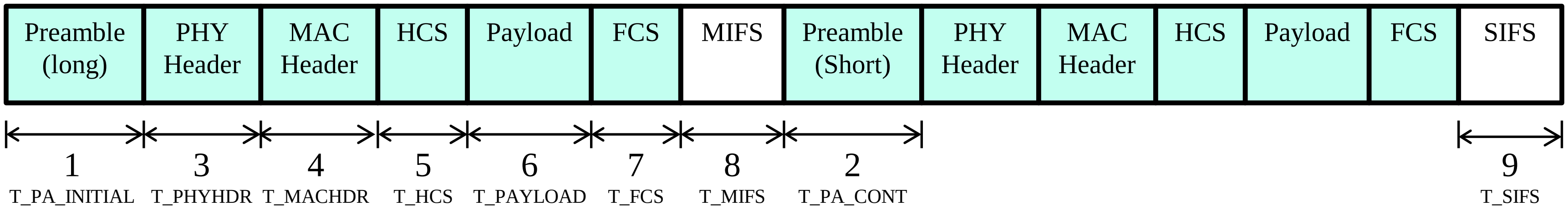
Definition of Packet Overhead

Packet-overhead times are defined as those in 15.3c*



<u>Definition</u>

1. T_PA_INITIAL:	Length of the initial (long) preamble	2 µs
2. T_PA_CONT:	Length of the short preamble	2 µs
3. T_PHYHDR:	Length of the PHY header	0.06 µs
4. T_MACHDR:	Length of the MAC header	0.09 µs
5. T_HCS:	Length of the header checksum	0.02 µs (2B)
6. T_PAYLOAD:	Length of the payload	variable
7. T_FCS:	Length of the frame checksum	depend on MCS (4B)
8. T_MIFS:	Length of the Minimum Inter Frame Space (MIFS)	1 µs
9. T_SIFS:	Length of the Short Inter Frame Space (SIFS)	2 µs

*: A. Seyadi, *et. al*, “TG3c Selection Criteria,” 802.15-05-0493/r27, Mar. 2007

Definition of Data Throughputs

No-ACK mode

Data_Throughput_NO_ACK is defined as the bit rate at which a series of *N* frames each with a payload length in bits (PAYLOAD_bits) are transferred from the MAC to the PHY across the PHY-SAP.

$$\text{Data\_Throughput\_No\_ACK} = \frac{N\text{*PAYLOAD\_bits}}{\text{T\_PA\_INITIAL} + \text{T\_SIFS} + (N-1)(\text{T\_PA\_CONT} + \text{T\_MIFS}) + N\text{*T\_PACKET}}$$

$$\text{T\_PACKET} = \text{T\_PAYLOAD} + \text{T\_MACHDR} + \text{T\_PHYHDR} + \text{T\_HCS} + \text{T\_FCS}$$

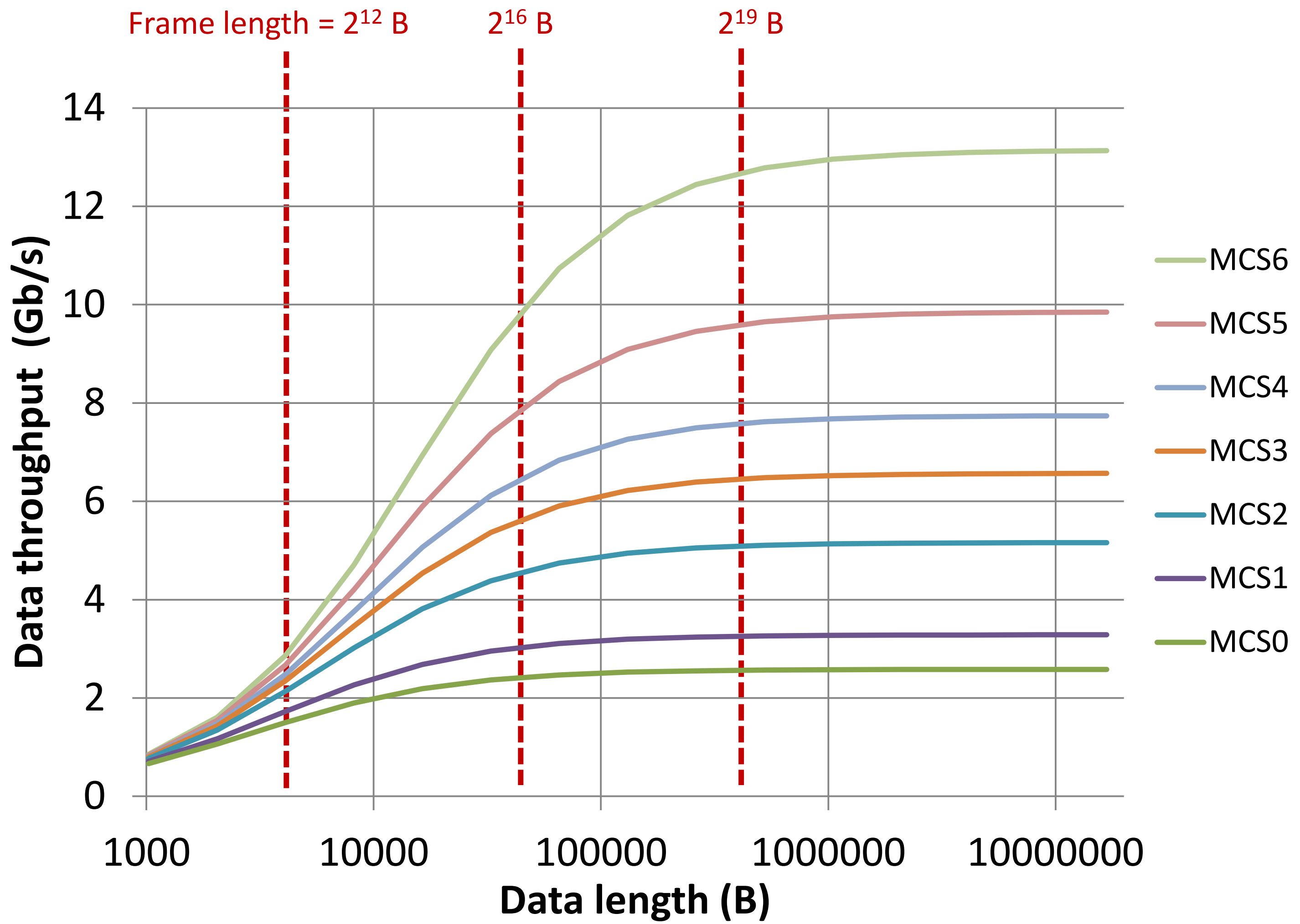
Imm-ACK mode

Data_Throughput_Imm_ACK is defined as the bit rate at which a series of frames each with PAYLOAD_bits are transferred from the MAC to the PHY across the PHY-SAP.

$$\text{Data\_Throughput\_Imm\_ACK} = \frac{\text{PAYLOAD\_bits}}{\text{T\_PAYLOAD} + 2\text{*T\_OVHD}}$$

$$\text{T\_OVHD} = \text{T\_SIFS} + \text{T\_PA\_INITIAL} + \text{T\_MACHDR} + \text{T\_PHYHDR} + \text{T\_HCS} + \text{T\_FCS}$$

Data throughputs in Imm-ACK mode



Other MAC issues

The following MAC issues will be described in the final proposal at the next Sep. Meeting

- ✓ Beacon- and MAC-frame structures
- ✓ Connection setup for point-to-point (P2P) communication without CSMA and PNID with a time less than 2ms
- ✓ No periodic management frames after completion of association
- ✓ Touch action with a trigger distance of 1 cm
- ✓ Prompt disconnection when devices draw apart beyond 10 cm
- ✓ Etc.

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Concept

- PHY and MAC for point-to-point (P2P) and line-of-site (LOS) environment such as the close proximity application should be simpler than those for multi devices and non-LOS (NLOS) environment.
- PHY and MAC in 15.3c is very complicated for such application, *e.g.* a lot of forward-error correction scheme (2 Reed-Solomon codes, 5 LDPC codes, 2 convolutional codes, many spreading, and unequal-error protection).
- State-of-the-art simple forward-error correction technologies in 15.3e enabling a simple and low-power system as well as the high-data rate.
  - ✓ Simple quasi-cyclic LDPC code with a constant column weight of 3
  - ✓ Overlaid-rate-compatible (ORC) LDPC codes
  - ✓ 2-step header coding

Performance comparison of LDPC decoders

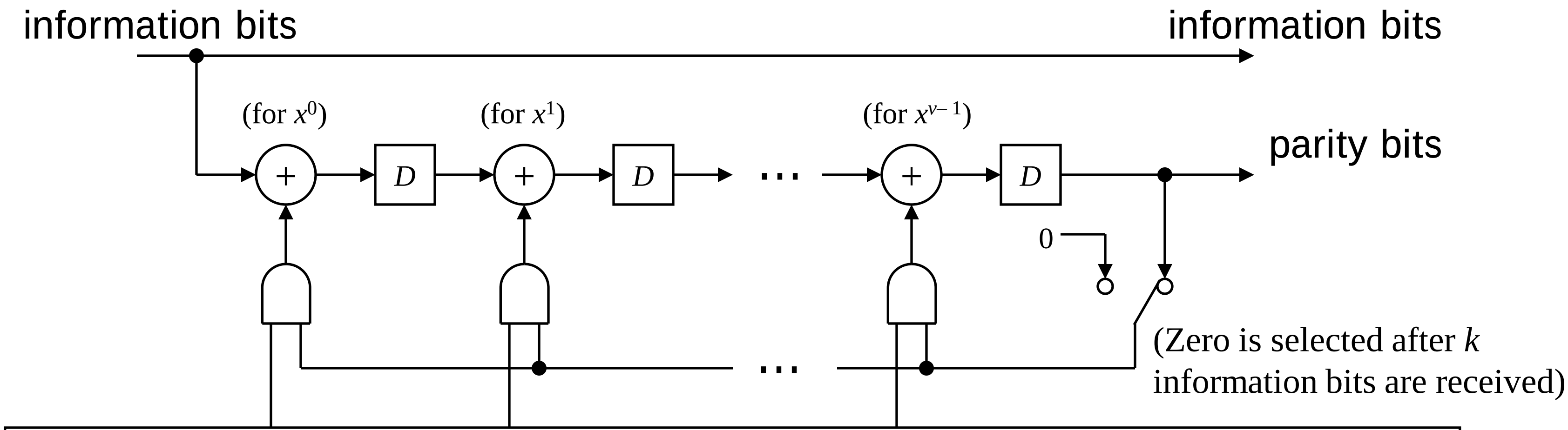
A quasi-cyclic LDPC code with a regular structure simplifies the decoder

	Okada, 2013 [1]	Hung, 2010 [2]	Coz, 2011 [3]
codeword length (bits)	1440	672	1944
IEEE802 standard	15.3c	15.3c	11n
max. user rate (Gb/s)	6.45	5.79	0.693
CMOS process	40nm LP	65nm LP	SOI 65nm LP
core area (mm^2)	0.46	1.56	2
supply voltage (V)	1.1	1.0	1.2
operation frequency (MHz)	288	197	360
power at BER = 10^{-6} (mW)	76	361	288
energy efficiency (pJ/bit)	11.8	62.4 (1/5)	416 (1/35)
error floor at BER = 10^{-11}	none	not confirmed	not confirmed
chip configuration	all BB	LDPC only	LDPC only

[1] K. Okada, *et al.*, IEEE J. Solid State Circuits, vol. 48, no.1, pp. 46-65, Jan. 2013
[2] S-Y. Hung, *et al.*, Proc. IEEE (ASSCC), Nov. 2010.
[3] J.L. Coz, *et al.*, ISSCC Dig, pp.336-337, Feb. 2011

A Simple LDPC encoder

A systematic (n, k) quasi-cyclic code, such that every cyclic shift of a codeword by p symbols yields another codeword, can be encoded by using p generator polynomials and an ($v = n–k+p–1$)-stage shift register*.



Select a generator polynomial $g_{(n-i-1)\mathrm{mod}p}*x^{p-1-\{(n-i-1)\mathrm{mod}p\}}$ at time i, where $i = 0$ is defined as the time that the first v information bits are stored in the v-stage shift registers; v = 96+15–1 = 110 for a rate-14/15 LDPC code and v = 96*4+15–1 = 398 for a rate-11/15 LDPC code.

* H. Yamagishi and M. Noda, Proc. IEEE, pp.78-83, Sep. 2008

Proposed Overlaid-rate-compatible (ORC) LDPC Codes

A check matrix of a high-rate code composed of overlay of sub-matrices in a check matrix of a low-rate code. This structure enables to share a belief-propagation decoder for the high-rate and low-rate LDPC codes.

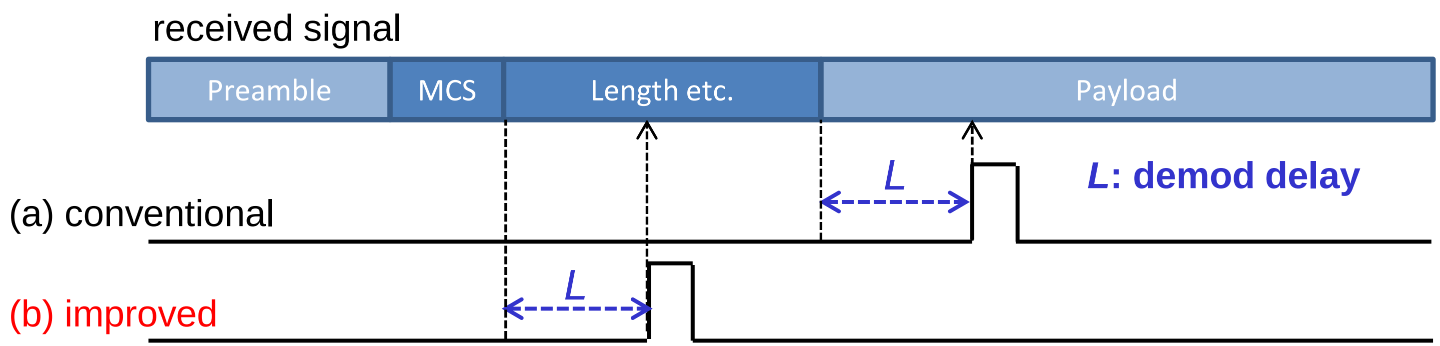
1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0
0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0

A low-rate parity-check matrix, as a simplified example of an 11/15 LDPC code

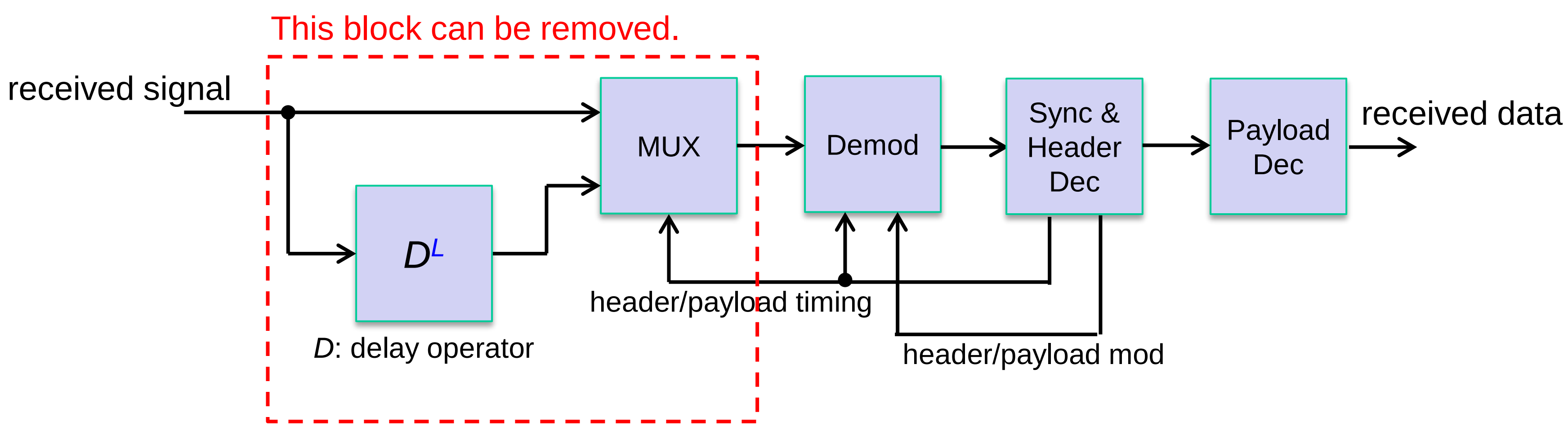
1	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	1	0	1	0	1	0	0	0	1	0
1	1	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	1	0	0	0	1	0	0	0	1
0	1	1	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	1	1	0	0	1	0	0	0
0	0	1	1	0	0	0	1	0	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0	0
0	0	0	1	1	0	0	0	1	0	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0
0	0	0	0	1	1	0	0	0	1	0	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	1
0	0	0	0	0	1	1	0	0	0	1	0	0	1	0	0	0	1	0	1	0	1	0	0	0	1	0	0

A high-rate parity-check matrix, as a simplified example of a 14/15 LDPC code

Simple receiver: advantage of the 2-step header coding



Timing diagram of header/payload mod



A block diagram of a receiver

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Response to Evaluation Criteria in TGD (0109/r6)

	#	criteria	Slide #
PHY	1	Communication distance: Must demonstrate link budget values at a distance of 10 cm based on simulation. Refer to Annex A of this document for the simulation conditions.	10
	2	Frequency: Shall operate within the 60GHz unlicensed band	5
	3	Interference: Shall be able to operate in dense environments without mutual interference among 3e devices	6
	4	Coexistence: Shall be able to coexist with other systems in the same band when operating without any beamforming technology	14
	5	Calculated data rate at the PHY SAP: At least one mode shall be capable of achieving 100 Gbps satisfying the common frequency regulations of US, EU, Korea, and Japan	7
	6	Antenna form factor: The antenna used for satisfying the other PHY criteria shall be small enough for placement and operation inside a mobile device, including smartphones.	14
MAC	1	Connection setup time: less than 2 ms	19
	2	Definition of "Connection setup time": time from first successful reception of all necessary information from the management frame(s) to completion of association by both devices.	19
	3	P2P: Operation shall be limited to point-to-point connection between two devices only	19
	4	No identifiers: Connection setup shall be performed without exchanging network identifiers (PNID) for each session	19
	5	NO CSMA: No Listen before Talk (or CSMA) shall be used prior to transmission	19
	6	Management frames: No periodic management frames shall be transmitted after completion of association	19
	7	Data throughput: Shall be calculated at the MAC SAP	18
	8	Error detection and correction: In the presence of random and burst errors, there shall not be serious throughput degradation nor falling into unstable states	8, 9, 12, 13, 18
System	1	Touch action: Bringing the antennas to within about 1 cm shall trigger the two devices to establish connection. Accurate spatial alignment shall not be required.	19
	2	Disconnection: Shall be able to disconnect promptly when devices draw apart beyond 10 cm	19
	3	Efficient design: System shall achieve high throughput and low latency using simple design.	21-25
	4	Mobile devices should be energy-efficient.	21-25