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

Submission Title: PHY Proposal for the IEEE 802.15.4m by Niigata University
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Source: Shigenobu Sasaki, Takuya Inoko, Yutaro Fukaishi Hiromu Niwano and Bingxuan Zhao
(Niigata University)
Address: 8050 Ikarashi 2-no-cho, Nishi-ku, Niigata, 950-2181, Japan
Voice: 81-25-262-6737, FAX: 81-25-262-6737, E-Mail: shinsasaki@ieee.org

Re: Call for Proposals

Abstract: This contribution presents a PHY proposal from Niigata University for the IEEE 802.15 TG4m.

Purpose: Technical Proposal for discussion in IEEE 802.15.4m

Abstract

- This contribution presents a PHY proposal for the IEEE 802.15.4m which is the amendment for use of TV whitespace (TVWS) in IEEE 802.15.4 standard.
- This PHY proposal contains the updated proposal of
  - Band Plan
  - PHY specifications
    - FSK/FH PHY for low-rate applications
    - OFDM PHY for mid-rate applications

  from the preliminary proposal [1] based on the technical requirements in [2] and link budget analysis

Technical Requirements [2]

- Meet at least one, and as many as practical, TV White Space regulatory requirements.
- Specify operations in TV white space frequency bands under regulatory constraints that can be identified.
- Support PHY data rate of typically 40kbps to 2000kbps. (~10Mbps desired).
- Cover operating range of at least 1km.
- Provide at least one operation mode that supports up to at least 1000 direct neighboring devices.

Key elements on the spectrum mask in TVWS
(FCC Third MO&O [3])

Table 1 Key spectrum mask elements in TVWS (FCC)

Type of TV bands device	**Power limit (6 MHz)**	**PSD limit (100 kHz)**	**Adjacent channel limit (100 kHz)**
Fixed	30 dBm (1 Watt)	12.6 dBm	-42.8 dBm
Personal/portable (adj. channel)	16 dBm (40 mW)	-1.4 dBm	-56.8 dBm
Sensing only	17 dBm (50 mW)	-0.4 dBm	-55.8 dBm
All other personal/portable	20 dBm (100 mW)	2.6 dBm	-52.8 dBm

Preliminary Link Budget Analysis

- Assumptions
  - LOS propagation model [2] is considered.
  - Receiver sensitivity level = -85 dBm
    (Highest level of sensitivity requirements in the IEEE Std. 802.15.4-2006 [4])
  - Transmitter PSD emission limit = 2.6dBm/100kHz
    (FCC 3rd MO&O, personal/portable device)
  - Antenna Gain at the base station: G_B=0dBi
  - Antenna Gain at the terminal station: G_T=0dBi

Link Budget Examples

Table 2 Examples of link budget calculations

Parameter	Case 1	Case 2	Case 3	Remarks
Signal Bandwidth	500 kHz	1 MHz	2 MHz	
Average Tx power	9.6 dBm	12.6 dBm	15.6 dBm	2.6dBm/100kHz
Tx antenna gain (G_B)	0 dBi	0 dBi	0 dBi	(Portable)
Center frequency (f_c)	695 MHz	695 MHz	695 MHz	Channel 51 (US)
Path loss at 1 km (L_1)	89.28 dB	89.28 dB	89.28 dB	LOS channel
Rx power at 1 km	-79.68 dBm	-76.68 dBm	-73.68 dBm	-85 dBm or better
Path loss at d km (L_d)	95.30 dB at d = 2 km	95.30 dB at d = 2 km	98.82 dB at d = 3 km	
Rx power at d km	-85.70 dBm at d = 2 km	-82.70 dBm at d = 2 km	-83.32 dBm at d = 3 km	-85 dBm or better

PHY Proposal

- Based on the preliminary proposal in [1], we propose the following PHY configurations with some modifications
  - Band plan
  - PHY for low-rate applications --- FSK/FH
    - Smart Utility Networks (SUN) , Infrastructure monitoring M2M applications
  - PHY for mid-rate applications --- OFDM
    - Intelligent Transportation Systems, Digital Signage System

Preliminary Band Plan [1]

- 6MHz channel is divided into 4 subchannels with 1.2 MHz bandwidth
- Guard band with 0.6 MHz is reserved at the upper and lower edge of the channel in use
  - To comply with the stringent out-of-band PSD limit

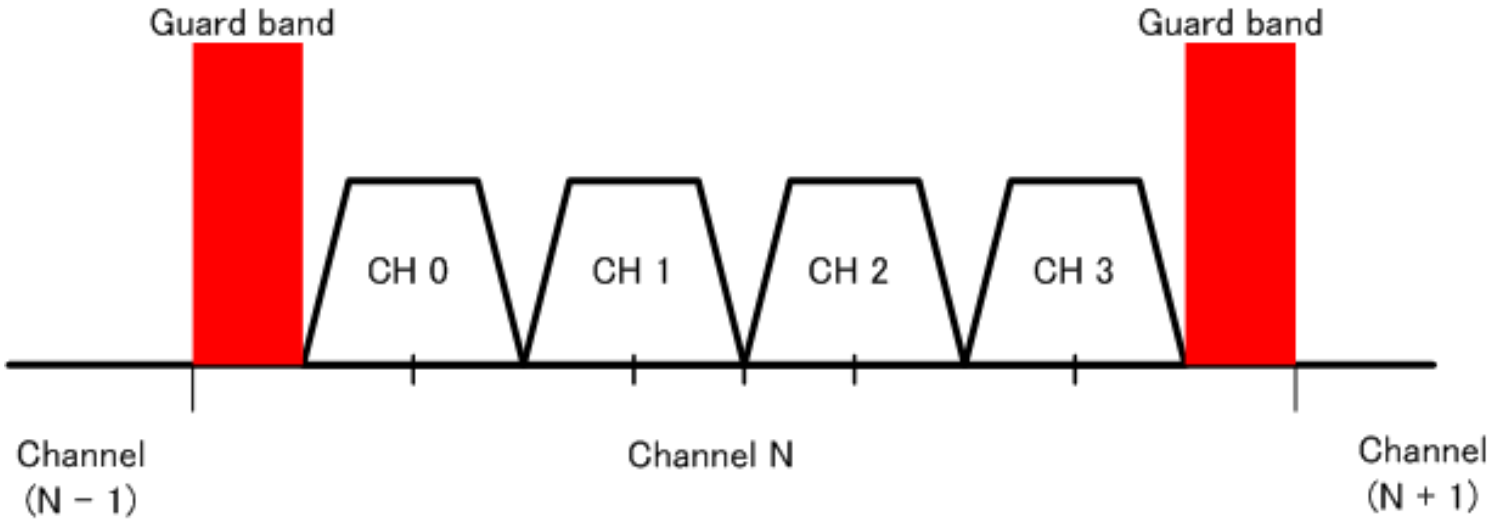


Fig. 1 Preliminary Band Plan (1.2MHz x 4 subchannels and 0.6MHz x 2 guard bands)

Modified Band Plan

- 6MHz channel is divided into 11 subchannels with 400 kHz bandwidth
  - 1.2 MHz bandwidth (in the preliminary proposal) is available by using 3 subchannels
- Guard band with 0.8 MHz is reserved at the upper and lower edge of the channel in use
  - To comply with the stringent out-of-band PSD limit

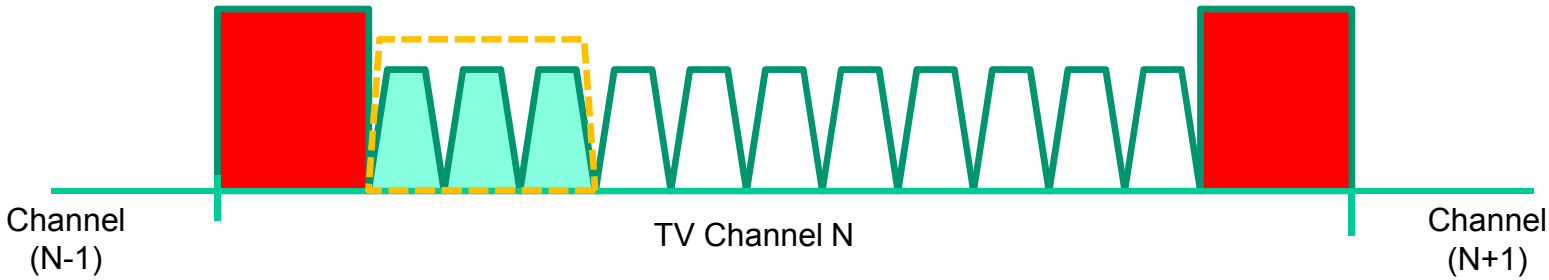
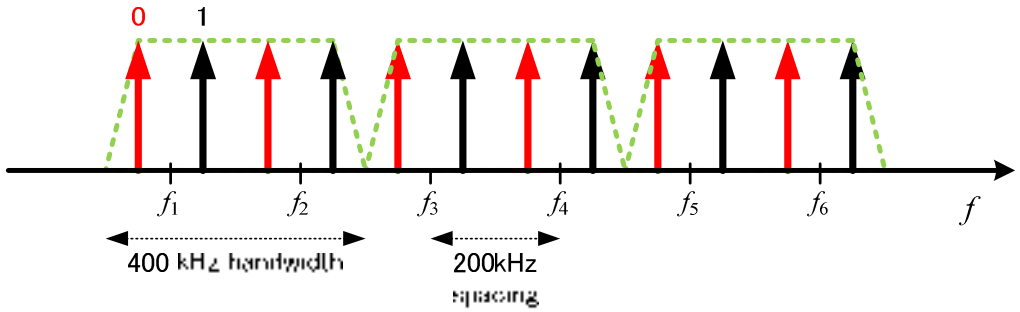


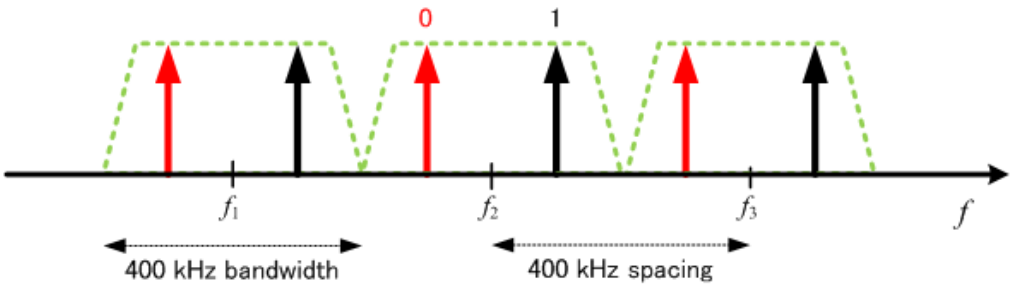
Fig. 2 Modified Band Plan (400kHz x 11 subchannels and 0.8MHz x 2 guard bands)

FSK/FH PHY Proposal

- FSK/FH for low-rate applications
  - Compatible to 802.15.4g FSK mandatory PHY
  - Frequency hopping is applied to occupy more bandwidth so that more emission power is available.



(a) Data rate = 50 (kbps), 6 hops with 3 subchannels



(b) Data rate = 200 (kbps), 3 hops with 3 subchannels

Fig. 3 Carrier allocation of FSK/FH signals

FSK/FH System Model

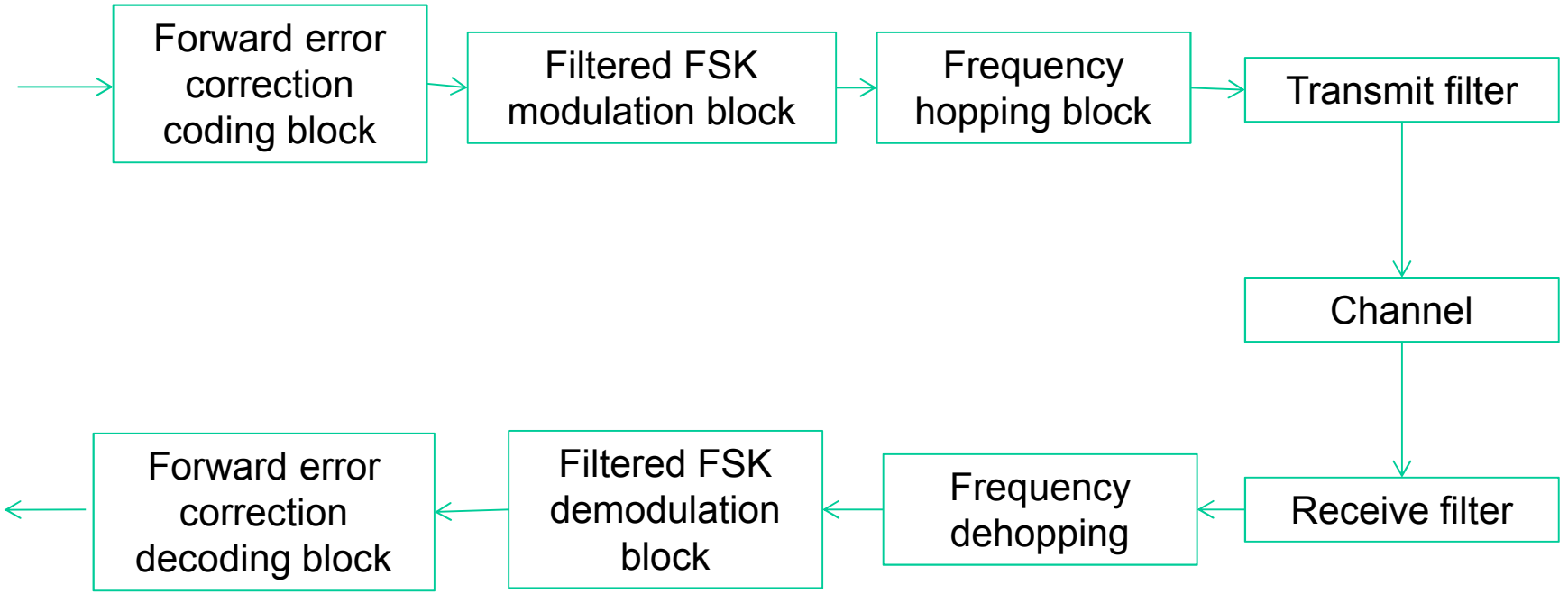


Fig. 4 FSK/FH System Model

FSK /FH parameters

Table 3 FSK/FH parameters (uncoded)

Parameters	Mode 1	Mode 2	Mode 3	Mode 4
Data rate	50kbps	100kbps	200kbps	400kbps
Modulation	2FSK	2FSK	2FSK	4FSK
Modulation index	1.0	1.0	1.0	1/3
Symbol rate	50ksps	100ksps	200ksps	200ksps
Proposed freq. slot spacing	200	200	400	400
# of slot per subchannel	2	2	1	1
Notes				
Minimal freq. slot spacing	100	200	400	400
Max frequency slot per subchannel	4	2	1	1

- Data rate becomes a half when 1/2-rate FEC code is applied

Supporting Multiple Devices

- Multiple devices can be supported by using different subchannels
- Multiple devices can be supported by using different hopping sequences
  - Using multiple subchannels
  - Example: 4 subchannels = 1.6MHz bandwidth

FSK/FH Link Budget Analysis

- Consider various gains and losses as suggested in [2]
  - Path loss (LOS: free space, NOS: Mod. Hata model)
  - Penetration loss, Interference at the receiver input
  - Rx noise figure : 7 (dB)
  - Implementation loss: 3 (dB)

Table 4 FSK/FH parameters for link budget analysis

Paramters	Value	Value	Notes
Data rate (kbps)	50	50	
Modulation	BFSK	BFSK	Noncoherent detection
Symbol rate (ksps)	100	100	with 1/2-rate FEC coding
Symbol duration (s)	1.00E-05	1.00E-05	(sec)
Channel separation (kHz)	200	200	
# of hops	2	6	
Channel bandwidth(kHz)	400	1200	
FEC coding rate	1/2		convolutional code, K=7
Tx PSD limit (dBm/100kHz)	2.6		FCC PSD limit for portable device (EIRP)

Link Budget Example (LOS)

Table 5 FSK/FH Link Budget Example(LOS)

Parameter	Value	Value	Notes
Frequency (MHz)	695	695	
Tx Power (dBm)	8.62	13.39	EIRP (PSD limit * bandwidth)
Tx Antenna Height (m)	10.0	10.0	From Doc. 15-12-223r0
Rx Antenna Height (m)	2.0	2.0	From Doc. 15-12-223r0
Tx Antenna Gain (dBi)	0.0	0.0	
Distance (km)	**1.0**	**1.0**	
Path Loss (dB)	89.28	89.28	LOS (free space)
Penetration Loss (dB)	5.0	5.0	For underground vaults, etc.
Rx Antenna Gain (dBi)	0.0	0.0	Omni antenna
Rx Input Power (dBm)	-85.66	-80.89	Compare against Rx sensitivity
Thermal noise PSD (dBm/Hz)	-174	-174	Noise Tempreture = 290K
Rx Noise Figure (dB)	7.0	7.0	
Total noise PSD level (dBm/Hz)	-167	-167	
Required Eb/No	8.0	8.0	@10^-5 BER
Implementation loss (dB)	3.0	3.0	
Rx Interference (dB)	1.0	1.0	Rise over Thermal Interference
Link Margin (dB)	**19.34**	**24.11**	
Rx Sensivity (dBm)	-105.00	-105.00	Required Rx Input power

Link Budget Example (NLOS)

Table 6 FSK/FH Link Budget Example(NLOS)

Parameter	Value	Value	Notes
Frequency (MHz)	695	695	
Tx Power (dBm)	8.62	13.39	EIRP (PSD limit * bandwidth)
Tx Antenna Height (m)	10.0	10.0	From Doc. 15-12-223r0
Rx Antenna Height (m)	2.0	2.0	From Doc. 15-12-223r0
Tx Antenna Gain (dBi)	0.0	0.0	
Distance (km)	**1.0**	**1.0**	
Path Loss (dB)	104.52	104.52	Mod. Hata model in TGD
Penetration Loss (dB)	5.0	5.0	For underground vaults, etc.
Rx Antenna Gain (dBi)	0.0	0.0	
Rx Input Power (dBm)	-100.90	-96.13	Compare against Rx sensitivity
Thermal noise PSD (dBm/Hz)	-174	-174	Noise Tempreture = 290K
Rx Noise Figure (dB)	7.0	7.0	
Total noise PSD level (dBm/Hz)	-167	-167	
Required Eb/No	8.0	8.0	@10^(-5) BER
Implementation loss (dB)	3.0	3.0	
Rx Interference (dB)	1.0	1.0	Rise over Thermal Interference
Link Margin (dB)	**4.10**	**8.87**	
Rx Sensivity (dBm)	-105.00	-105.00	Required Rx Input Power

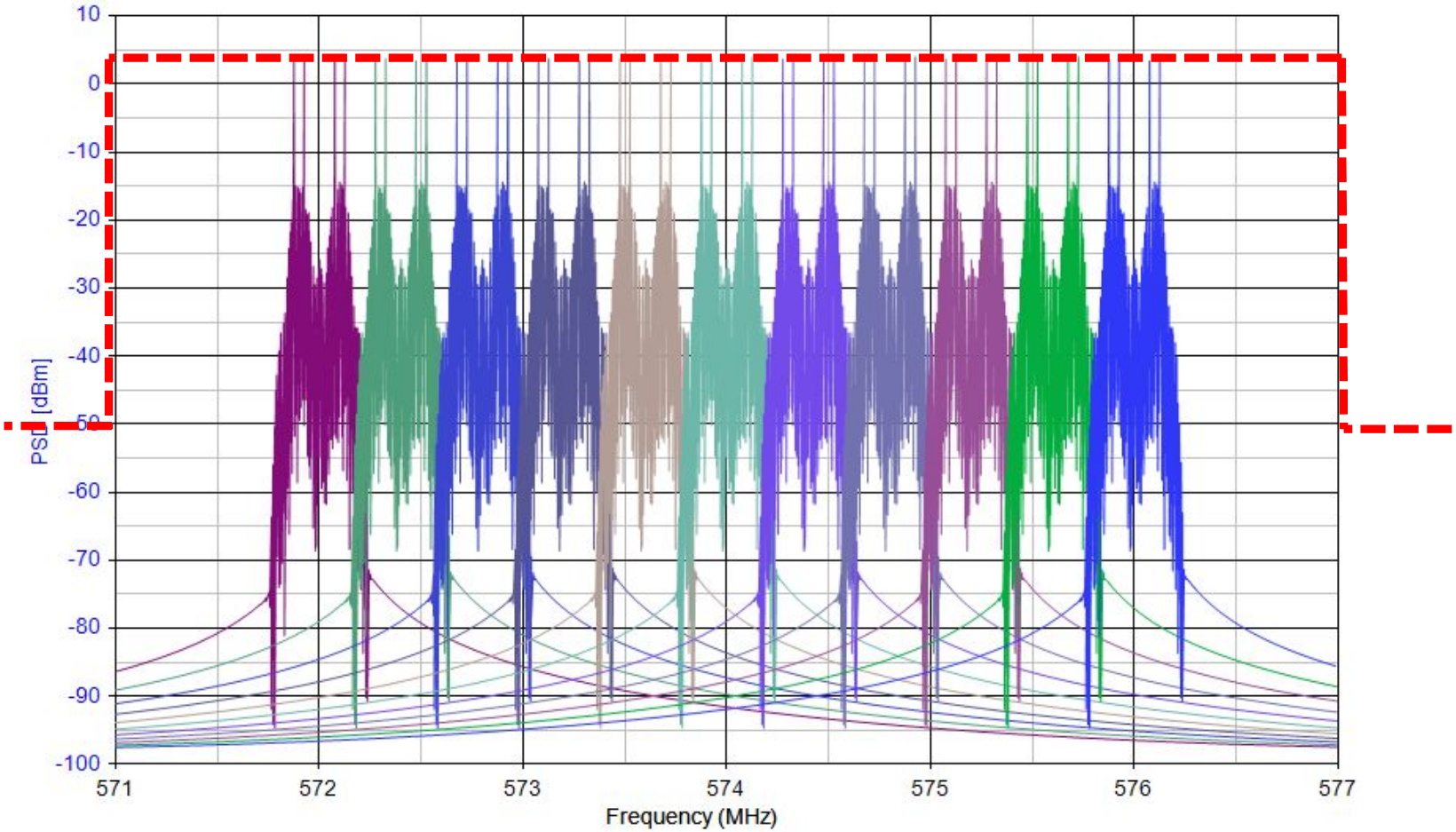


Fig. 5 FSK/FH Spectrum Example
(50kbps data rate, 400kHz x 11 subchannels, 200kHz spacing)

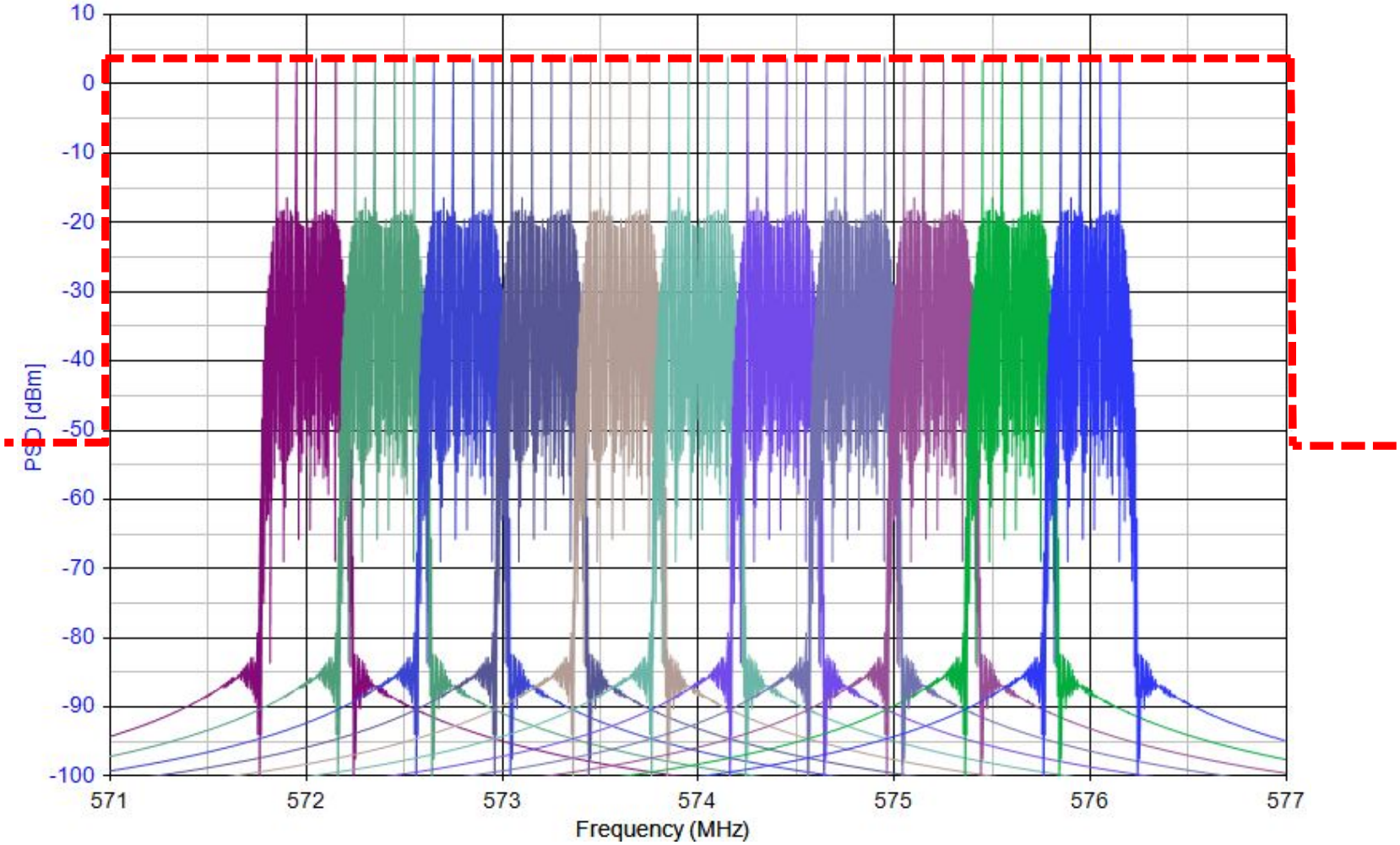


Fig. 6 FSK/FH Spectrum Example
(100kbps data rate, 400kHz x 11 subchannels, 200kHz spacing)

OFDM PHY Proposal

- OFDM for mid-rate applications
  - Based on the 802.15.4g OFDM PHY (mode 1)
- Subchannel spacing : 400kHz
  - We have a couple of potential OFDM parameter sets including:
    - Subcarrier spacing
    - symbol rate
    - Cyclic prefix and data symbol duration

OFDM parameters

Table 7 OFDM parameter options

Parameters	Option 1	Option 2	Remarks
Nominal bandwidth [kHz]	380.95	281	
Subcarrier spacing [Hz]	992.06	10416.7	
Symbol rate [ksymbol/s]	0.99206	10.417	
Symbol duration [μs]	1008	96	
# of effective subcarriers	384	26	
# of Pilot tones	32	2	
# of Data tones	352	24	
Data duration [μs]	882	84	
Cyclic Prefix (1/8) [μs]	126	12	
Subchannel spacing	400 [kHz]	400[kHz]	

Modulation Parameters and Data Rate (1)

Table 8 Modulation and coding parameters and data rate per subchannel (Option 1)

Mode	Modulation	Coding rate	Frequency repetition	Data rate	Remarks
1	QPSK	1/2	1	349.2 kbps	
2	16QAM	1/2	1	698.4 kbps	
3	16QAM	3/4	1	1.0476Mbps	
4	64QAM	1/2	1	1.0476Mbps	
5	64QAM	3/4	1	1.5714Mbps	
6	64QAM	7/8	1	1.8333Mbps	

- It is possible to cover higher data rate up to 20 Mbps by using multiple subchannels
- Frequency repetition by using multiple subchannel is also possible to achieve more Tx power.

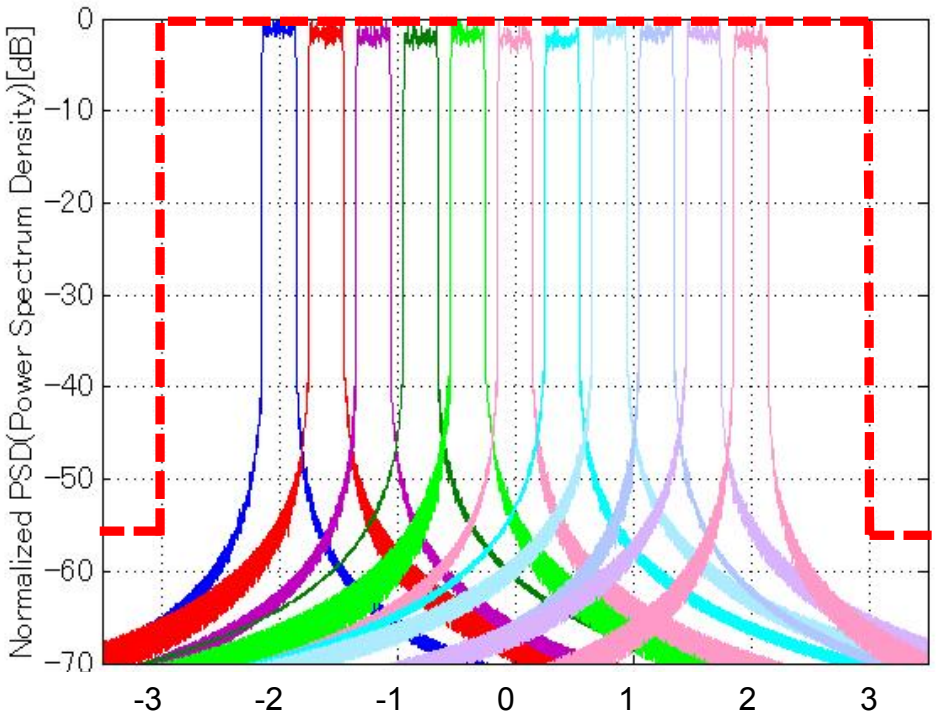
Modulation Parameters and Data Rate (2)

Table 9 Modulation and coding parameters and data rate per subchannel (Option 2)

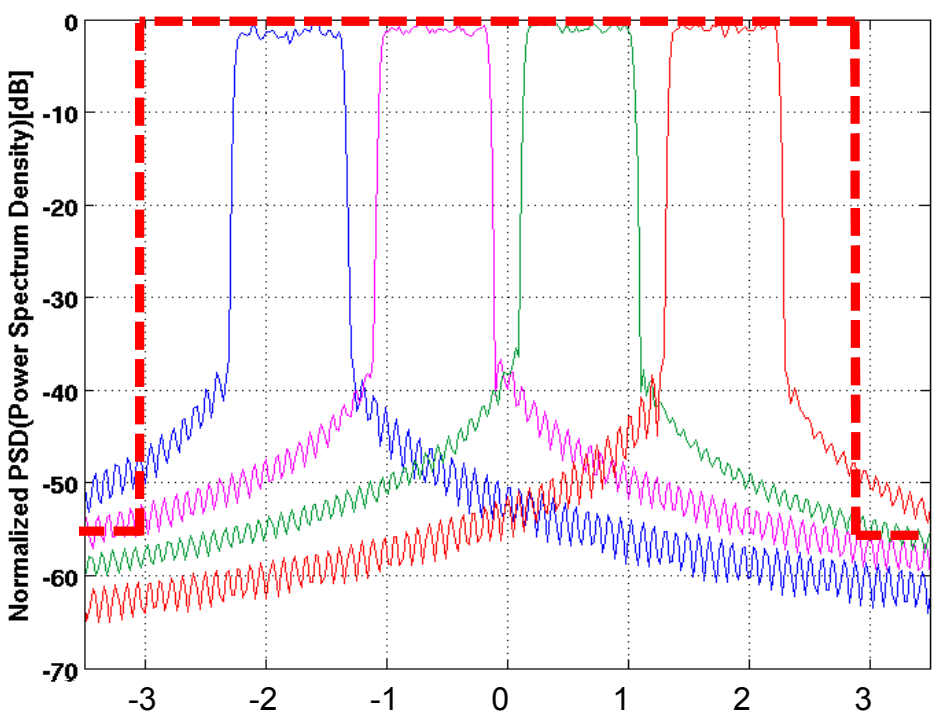
Mode	Modulation	Coding rate	Frequency repetition	Data rate	Remarks
1	QPSK	1/2	1	250 kbps	
2	16QAM	1/2	1	500 kbps	
3	16QAM	3/4	1	750 kbps	
4	64QAM	1/2	1	750 kbps	
5	64QAM	3/4	1	1.125 Mbps	
6	64QAM	7/8	1	1.3125 Mbps	

- It is possible to cover higher data rate up to 14.5 Mbps by using multiple subchannels
- Frequency repetition by using multiple subchannel is also possible to achieve more Tx power.

Spectrum Example



(a) 400kHz spacing 11 channels
(Option 1)



(b) 1200kHz spacing 4 channels
(In the preliminary proposal)

•Fig. 7 Spectrum overview of OFDM PHY

OFDM PHY Link budget Analysis

- Consider various gains and losses as suggested in [2]
  - Path loss (LOS: free space, NOS: Mod. Hata model)
  - Penetration loss, Interference at the receiver input
  - Rx noise figure : 7 (dB)
  - Implementation loss: 3 (dB)

Table 10 OFDM PHY parameters for link budget analysis

Paramters	Case 1	Case 2	Notes
Data rate (kbps)	349.2	1833.3	
Modulation	QPSK	64QAM	Coherent detection
# of data subcarrier	352	352	
Symbol rate (ksps)	0.9920	0.9920	with 1/2-rate FEC coding
Symbol duration (s)	1.008E-03	1.008E-03	
Guard Interval (s)	1.26E-04	1.26E-04	
Effective Data Interval (s)	8.820E-04	8.820E-04	
Channel bandwidth(kHz)	380.95	380.95	
FEC coding rate	1/2	7/8	convolutional code, K=7
Tx PSD limit (dBm/100kHz)	2.6		FCC PSD limit for portable device (EIRP)

Link budget example (LOS)

Table 11 OFDM Link Budget Example (LOS)

Parameter	Value	Value	Notes
Frequency (MHz)	695	695	
Tx Power (dBm)	8.41	8.41	EIRP (PSD limit * bandwidth)
Tx Antenna Height (m)	10.0	10.0	From Doc. 15-12-223r0
Rx Antenna Height (m)	2.0	2.0	From Doc. 15-12-223r0
Tx Antenna Gain (dBi)	0.0	0.0	
Distance (km)	**1.0**	**1.0**	
Path Loss (dB)	89.28	89.28	LOS (free space)
Penetration Loss (dB)	5.0	5.0	For underground vaults, etc.
Rx Antenna Gain (dBi)	0.0	0.0	
Rx Input Power (dBm)	-85.87	-85.87	Compare against Rx sensitivity
Thermal noise PSD (dBm/Hz)	-174	-174	Noise Tempreture = 290K
Rx Noise Figure (dB)	7.0	7.0	
Total noise PSD level (dBm/Hz)	-167	-167	
Required Eb/No	4.1	18.0	@10^-5 BER
Implementation loss (dB)	3.0	3.0	
Rx Interference (dB)	1.0	1.0	Rise over Thermal Interference
Link Margin (dB)	**43.06**	**29.16**	
Rx sensivity (dBm)	-128.93	-115.03	Required Rx Input power

Link budget Example (NLOS)

Table 12 OFDM Link Budget Example (NLOS)

Parameter	Value	Value	Notes
Frequency (MHz)	695	695	
Tx Power (dBm)	8.41	8.41	EIRP (PSD limit * bandwidth)
Tx Antenna Height (m)	10.0	10.0	From Doc. 15-12-223r0
Rx Antenna Height (m)	2.0	2.0	From Doc. 15-12-223r0
Tx Antenna Gain (dBi)	0.0	0.0	
Distance (km)	**1.0**	**1.0**	
Path Loss (dB)	104.52	104.52	Mod. Hata model in TGD
Penetration Loss (dB)	5.0	5.0	For underground vaults, etc.
Rx Antenna Gain (dBi)	0.0	0.0	
Rx Input Power (dBm)	-101.11	-101.11	Compare against Rx sensitivity
Thermal noise PSD (dBm/Hz)	-174	-174	Noise Tempreture = 290K
Rx Noise Figure (dB)	7.0	7.0	
Total noise PSD level (dBm/Hz)	-167	-167	
Required Eb/No	4.1	18.0	@10^(-5) BER
Implementation loss (dB)	3.0	3.0	
Rx Interference (dB)	1.0	1.0	Rise over Thermal Interference
Link Margin (dB)	**27.24**	**13.34**	
Rx sensivity (dBm)	-128.35	-114.45	Required Rx Input power

Summary

- PHY proposal for IEEE 802.15.4m
  - 11 x 400kHz subchannels and guard band
    - 1.2 MHz bandwidth is possible by using 3 subchannels
    - N x 400 kHz bandwidth is available
  - FSK/FH for low-rate applications
  - OFDM for mid-rate applications
- Both PHY proposal can meet the requirement for 1km coverage with some link margin.

References

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