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

Submission Title: Presentation on ULP GFSK PHY proposal

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Abstract: Presentation on ULP GFSK PHY proposal

Purpose: Providing direction towards a ULP PHY standard

Ultra Low Power GFSK PHY proposal

(presentation on draft proposal 15-13-0630-00-ULP-FSK-PHY-proposal)

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November, 2013

Outline:

- Introduction
- ULP-GFSK proposal
- Evaluation using TGD

- Abbreviations
- References
- Appendix

Introduction

Summary:

This proposal, ULP-GFSK PHY, can be considered as an extension, adding low power options, to the MR-FSK PHY as defined in the 802.15.4g amendment [1]

This will have the following benefits:

- The similarities to the MR_FSK PHY will reduce development cost for implementers as well as chip vendors.
- Piggyback on an existing and successful PHY standard will help to expedite industrial acceptance.

MR-FSK PHY for Energy efficient links for SUN:

PRO's:

- Constant envelop → high efficiency PA
- Industry acceptance: ZigBee-NAN, Wi-SUN, ETSI

Short comings for ULP applications:

- **Excessive overhead in PPDU for ULP applications**
- **Data rates not high enough for short transmissions**

Addressed by this proposal

Power savings of this proposal:

Power is being saved by:

- Increase data rate to reduce the receiver and transmitter ON time.
- Double Data Rate mode (DDR) without re-sync required

Additional power is being saved by reducing overhead:

- 1 octet PHY header (vs 2 octet in MR-FSK PHY)
- Optional 2 octet preamble (vs 4 octet in MR-FSK PHY)

ULP-GFSK PHY proposal

PPDU format:

Same as MR-FSK:

		Octets	
		2	**Variable**
Preamble	SFD	As defined in 18.1.1.3	PSDU
SHR		PHR	PHY payload

Figure 112—Format of the MR-FSK PPDU (without mode switch)

Preamble:

To reduce overhead (and save power):

- The minimum preamble for the ULP-GFSK PHY is reduced to 2 octet.
- The PHY PIB attribute "*phyFSKPreambleLength*" will be made available for ULP-FSK. The description in table 71 needs to reflect that and describe the related value range of 2 – 1000 for ULP-FSK.

Common with MR-FSK:

- The Preamble field shall contain *phyFSKPreambleLength* (as defined in 9.3, see 802.15.4g-2012 [1]) multiples of the 8-bit sequence "01010101" for filtered 2FSK.

SFD:

The SFD in ULP-GFSK is specified the same as for MR-FSK. See section 18.1.1.2 [1].

Table 131—MR-FSK PHY SFD values for filtered 2FSK

	SFD value for coded (PHR + PSDU) (b_0–b_{15})	SFD value for uncoded (PHR + PSDU) (b_0–b_{15})
phyMRFSKSFD = 0	0110 1111 0100 1110	1001 0000 0100 1110
phyMRFSKSFD = 1	0110 0011 0010 1101	0111 1010 0000 1110

Mandatory PHY Header (PHR):

The ULP-FSK PHY shall support the PHY Header as shown in Figure 114 [1].

Bit string index	0	1–2	3	4	5–15
Bit mapping	MS	R_1–R_0	FCS	DW	L_{10}–L_0
Field name	Mode Switch	Reserved	FCS Type	Data Whitening	Frame Length

Figure 114—Format of the PHR (without mode switching) for MR-FSK

- This PHY Header is also mandatory for MR-FSK
- In MR-FSK: "*All reserved fields shall be set to zero upon transmission and shall be ignored upon reception*"
- R1-R0 are used by the ULP-GFSK PHY

Resevered bits R1-R0:

R1-R0 are used in the ULP-FSK PHY as follows:

- **R0 = SPH**

  Short PHR. When this bit is set while MS=”0”, the PHY Header (PHR) shown on the next slide shall be used.

- **R1 = DDR**

  Double **D**ata **R**ate. When this bit is set the data rate across the PSDU shall be doubled by applying 4GFSK modulation as appose to 2GFSK which is used during SHR and PHR. One symbol rate is maintained across the entire PPDU and the outer deviation of the 4GFSK is equal to the 2GFSK deviation to support seamless transition from PHR in 2GFSK to PSDU in 4GFSK.

Short PHR:

In addition to the mandatory PHR the Short PHR as shown below may be supported as well as the Mode Switching PHR as described in section 18.1.1.4 [1]

Bit string index	0	1	2	3-7
Bit mapping	MS	SPH	DDR	L_4-L_0
Field name	Mode Switch	Short PHY Header	Double Data Rate	Frame Length

The short PHR supports packet lengths up to 32 Bytes.

Specification of MS/SPH and DDR:

MS	SPH	DDR	PHY Header	Modulation on PSDU	Frame Check Sum	Data Whitening
0	0	0	Mandatory PHR, see slide 11	Same as SHR and PHR	Selected by FCS bit in PHR	Selected by DW bit in PHR
1	X	X	Mode Switch PHR, see Figure 115 [1]	Same as SHR and PHR	Selected by FCS bit in PHR	Selected by DW bit in PHR
0	1	0	Short PHR, see slide 13.	Same as SHR and PHR	FCS = 16 bit	DW enabled
0	1	1	Short PHR, see slide 13	4GFSK, same symbol rate as SHR and PHR	FCS = 16 bit	DW enabled
0	0	1	Mandatory PHR, see slide 11	4GFSK, same symbol rate as SHR and PHR	Selected by FCS bit in PHR	Selected by DW bit in PHR

Note: The DDR bit will be ignored when 4(G)FSK is used across the entire PPDU.

Modulation:

= also used in MR_FSK

ULP-FSK Operating Mode	Data Rate [kbps]	Channel Spacing [kHz]	Mod type	Mod-index/BT	20dB BW	Adjacent channel leakage (dB)	Sensitivity PER=1% NF=10dB [dBm]
4	4.8	12.5	2GFSK	1/0.5	10	-42	-115
5	9.6	12.5	4GFSK	0.333/0.5	8.8	-44	-109
6	9.6	25	2GFSK	1/0.5	20	-42	-112
7	19.2	25	4GFSK	0.333/0.5	18	-44	-106
8	50	200	2GFSK	1/0.5	104	-68	-105
9	100	200	4GFSK	0.333/0.5	92	-73	-99
10	150	400	2GFSK	1/0.5	312	-42	-100
11	300	400	4GFSK	0.333/0.5	276	-45	-94
12	400	1000	2GFSK	1/0.5	836	-41	-96
13	800	1000	4GFSK	0.333/0.5	740	-42	-90

Gaussian shapping:

Impulse response:

$$h(t) = B \cdot \sqrt{\frac{2\pi}{ln(2)}} \cdot e^{-\frac{2\pi^2 B^2 t^2}{ln(2)}}$$

Frequency response:

$$H(f) = e^{-\frac{f^2 \cdot ln(2)}{2B^2}}$$

BT factor for ULP-GFSK:

$$BT_s = 0.5$$

Where ***Ts*** is the symbol period

ULP-GFSK in 12.5kHz channels:

Frequency band (MHz)	Parameter	Operating mode #4	Operating mode #5
169.400-169.475 (Europe)	Data rate (kbps)	4.8	9.6
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	12.5	12.5
450-470 (US FCC Part 22/90)	Data rate (kbps)	4.8	9.6
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	12.5	12.5
896-901 (US FCC Part 90)	Data rate (kbps)	4.8	9.6
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	12.5	12.5
901-902 (US FCC Part 24)	Data rate (kbps)	4.8	9.6
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	12.5	12.5

ULP-GFSK in 25kHz channels:

Frequency band (MHz)	Parameter	Operating mode #6	Operating mode #7
169.400-169.475 (Europe)	Data rate (kbps)	9.6	19.2
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	25	25
928-960 (US FCC Part 22/24/90/101)	Data rate (kbps)	9.6	19.2
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	25	25
1427-1518 (US FCC Part 90) (Canada SRSP 301.4)	Data rate (kbps)	9.6	19.2
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	25	25

ULP-GFSK in 200 – 400 kHz channels (1):

Frequency band (MHz)	Parameter	Operating mode #8	Operating mode #9	Operating mode #10	Operating mode #11
470-510 (China)	Data rate (kbps)	50	100	150	300
	Modulation	2GFSK	4GFSK	2GFSK	4GFSK
	Modulation index	1	1/3	1	1/3
	Channel spacing (kHz)	200	200	400	400
779-787 (China)	Data rate (kbps)	50	100	150	300
	Modulation	2GFSK	4GFSK	2GFSK	4GFSK
	Modulation index	1	1/3	1	1/3
	Channel spacing (kHz)	200	200	400	400
863-876 915-921 (Europe)	Data rate (kbps)	50	100	150	300
	Modulation	2GFSK	4GFSK	2GFSK	4GFSK
	Modulation index	1	1/3	1	1/3
	Channel spacing (kHz)	200	200	400	400

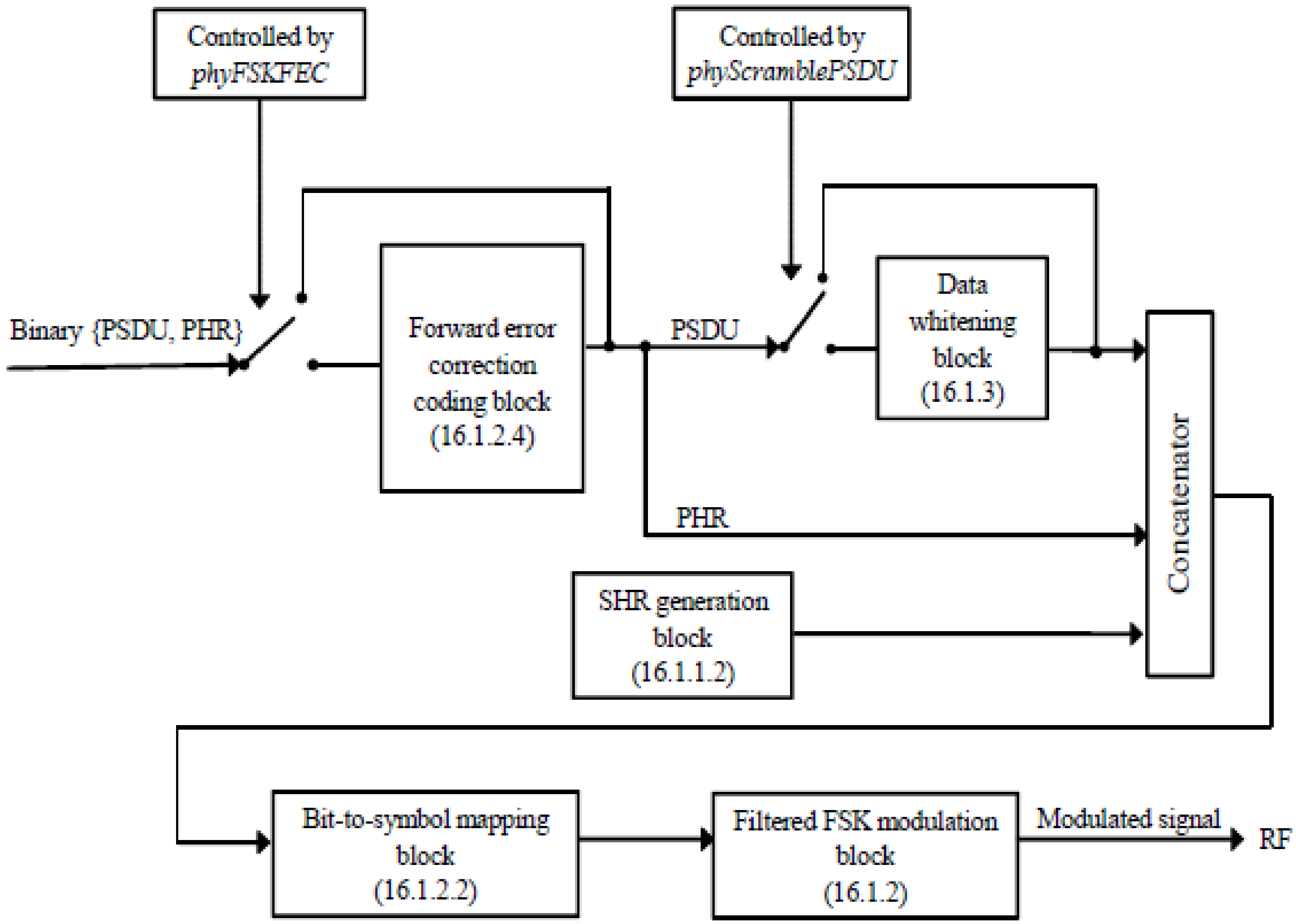
ULP-GFSK in 200 – 400 kHz channels (2):

Frequency band (MHz)	Parameter	Operating mode #8	Operating mode #9	Operating mode #10	Operating mode #11
902-928 (US-ISM)	Data rate (kbps)	50	100	150	300
	Modulation	2GFSK	4GFSK	2GFSK	4GFSK
	Modulation index	1	1/3	1	1/3
	Channel spacing (kHz)	200	200	400	400
917-923.5 (Korea)	Data rate (kbps)	50	100	150	300
	Modulation	2GFSK	4GFSK	2GFSK	4GFSK
	Modulation index	1	1/3	1	1/3
	Channel spacing (kHz)	200	200	400	400
920-928 950-958 (Japan)	Data rate (kbps)	50	100	100	200
	Modulation	2GFSK	4GFSK	2GFSK	4GFSK
	Modulation index	1	1/3	1	1/3
	Channel spacing (kHz)	200	200	400	400
2400-2483.5 (Worldwide)	Data rate (kbps)	50	100	150	300
	Modulation	2GFSK	4GFSK	2GFSK	4GFSK
	Modulation index	1	1/3	1	1/3
	Channel spacing (kHz)	200	200	400	400

ULP-GFSK in 1MHz channels (2):

Frequency band (MHz)	Parameter	Operating mode #12	Operating mode #13
902-928 (US-ISM)	Data rate (kbps)	400	800
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	1000	1000
917-923.5 (Korea)	Data rate (kbps)	400	800
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	1000	1000
920-928 950-958 (Japan)	Data rate (kbps)	400	800
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	1000	1000
2400-2483.5 (Worldwide)	Data rate (kbps)	400	800
	Modulation	2GFSK	4GFSK
	Modulation index	1	1/3
	Channel spacing (kHz)	1000	1000

Reference modulator block diagram [1]:



Radio frequency tolerance, same as in MR-FSK [1]:

18.1.5.3 Radio frequency tolerance

The single-sided clock frequency tolerance T at the transmitter, in ppm, shall be as follows:

$$T \le \min\left(\frac{T_0 \times R \times h \times F_0}{R_0 \times h_0 \times F}, 50 \text{ ppm}\right)$$

for all combinations of R, h, and F and for each mode supported by the device, where

- R is the symbol rate in ksymbol/s
- h is the modulation index
- F is the carrier frequency in MHz
- R_0 is 50 ksymbol/s
- h_0 is 1
- F_0 is 915 MHz
- T_0 is 30 ppm for modes in all bands, except at 2450 MHz for which the value of T_0 is 40 ppm

Leveraging MR-FSK [1]:

The ULP-GFSK PHY is using identical specifications for:

- Bit to Symbol Mapping
- Modulation quality
- Zero crossing tolerance
- Forward Error Correction (Convolution coding, K=4)
- Symbol interleaving
- Data Whitening
- Mode switching
- RF specification

Evaluation of ULP-GFSK PHY proposal

PSDU efficiency:

Definition used here: $$\eta_{PSDU} = \frac{T_{payload}}{T_{total}}$$

Where: T_{total} = total transmit on time

$T_{payload}$ = time of payload transmission

PSDU # of Bytes	FCS # of Bytes	η_{PSDU}	
		MR-FSK	ULP-GFSK
5	2	0.231	0.300
32	2	0.725	0.783

→ 23% power saving

→ 7.4% power saving

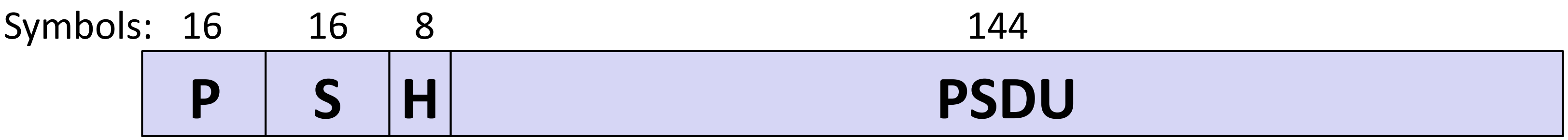
Notes: - ULP-GFSK PHY with 2 Byte preamble, Short PHR and 2 Byte FCS

- A 5 Byte PDSU might be an acknowledgement frame

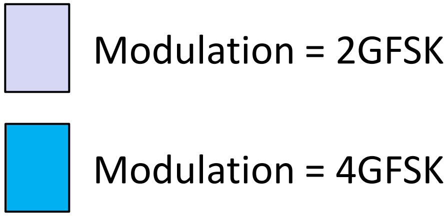
Double Data Rate:

PPDU example with 18 Byte PSDU:

DDR bit not set:

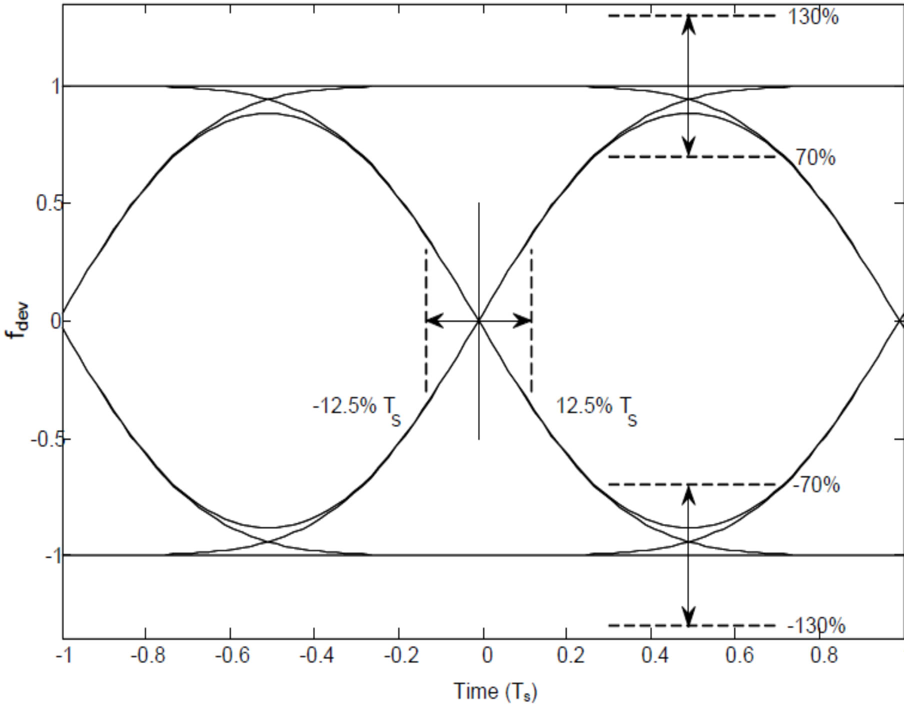


DDR bit set:

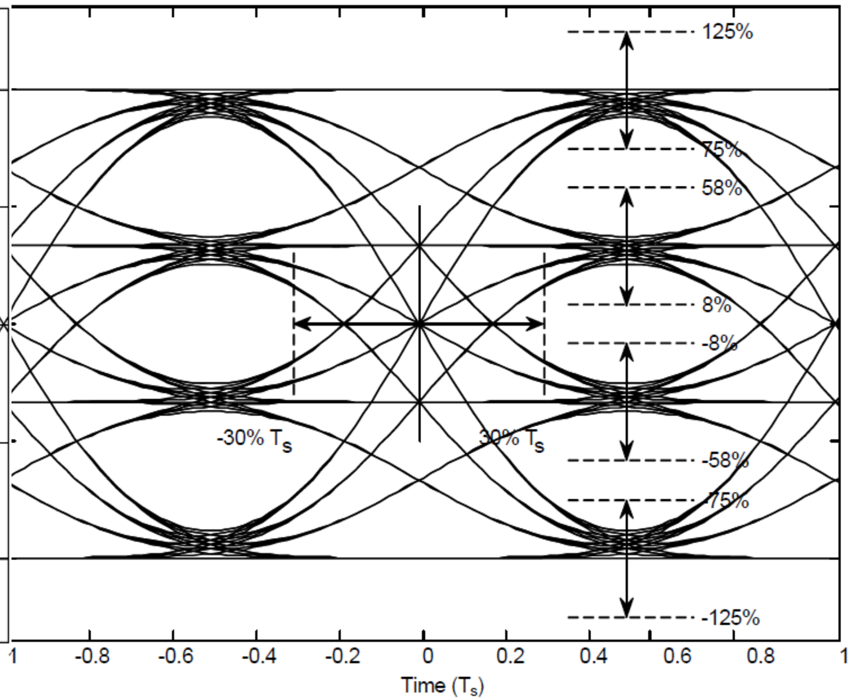


Eye pattern - zero crossing and deviation tolerance spec:

2GFSK h=1

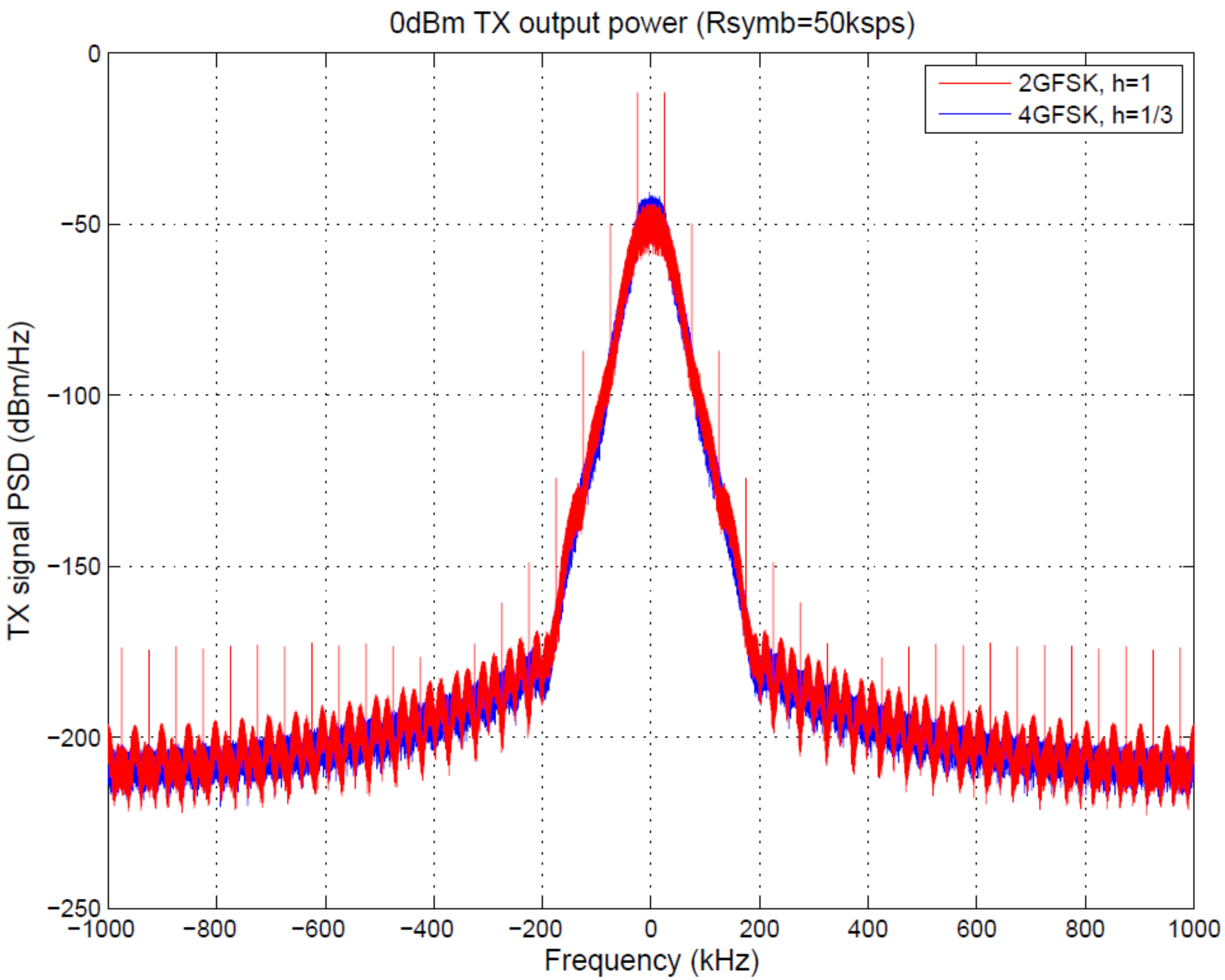


4GFSK h=1/3



Same as MR-FSK

PSD:



PSD of 4GFSK@h=1/3 is very similar to 2GFSK@h=1

Spectral efficiency:

Definition:

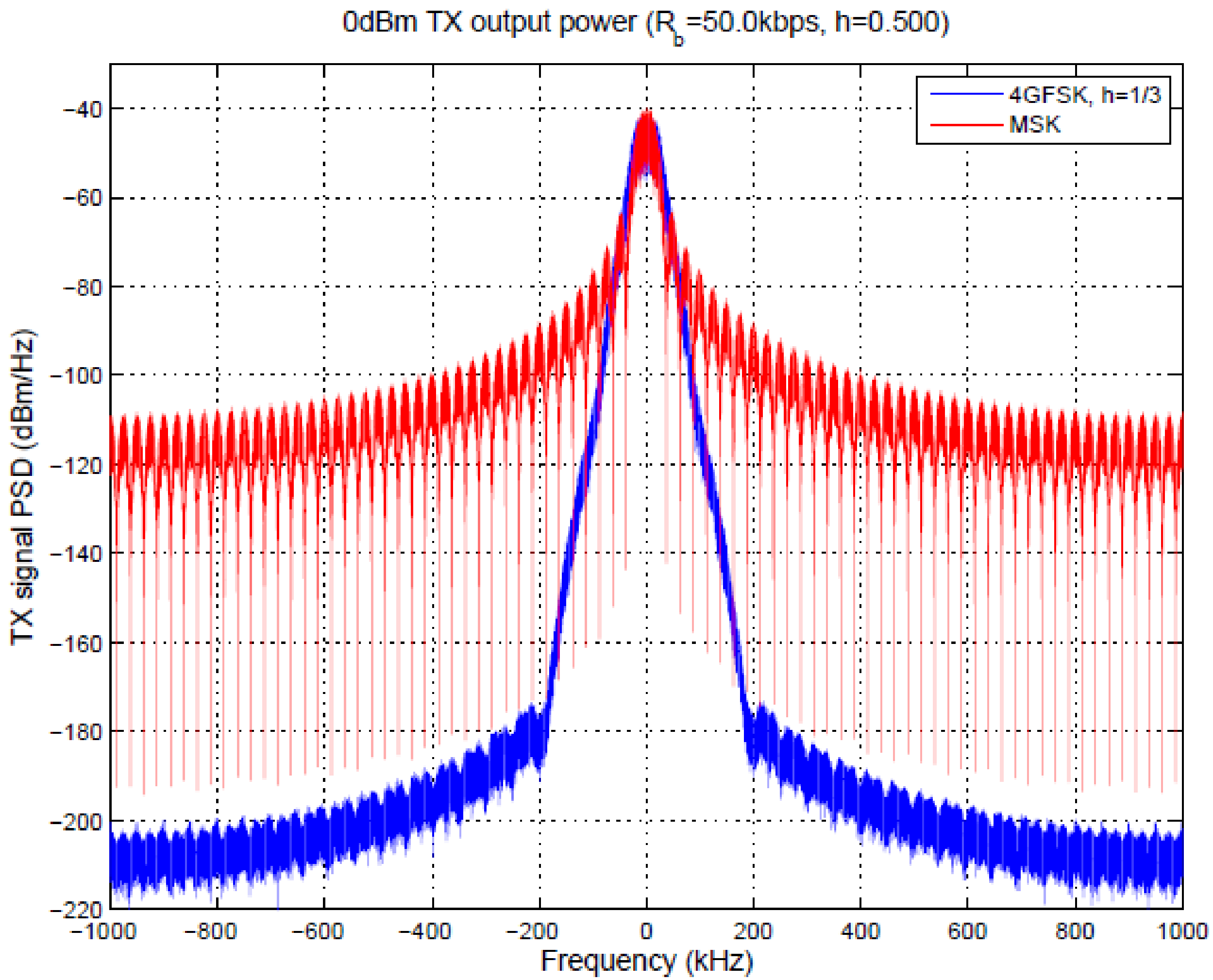
$$\eta_{SA} = \frac{data\_rate}{BW_{-20dB}}$$

2GFSK → η_{SA} = 0.48 (bits/s/Hz)

4GFSK → η_{SA} = 1.09 (bits/s/Hz)

Allows for short packets when BW constrained

PSD of 4GFSK@h=1/3 compared to MSK:



Note: Both MSK and OQPSK(half sine shaped) have significant spectral leakage

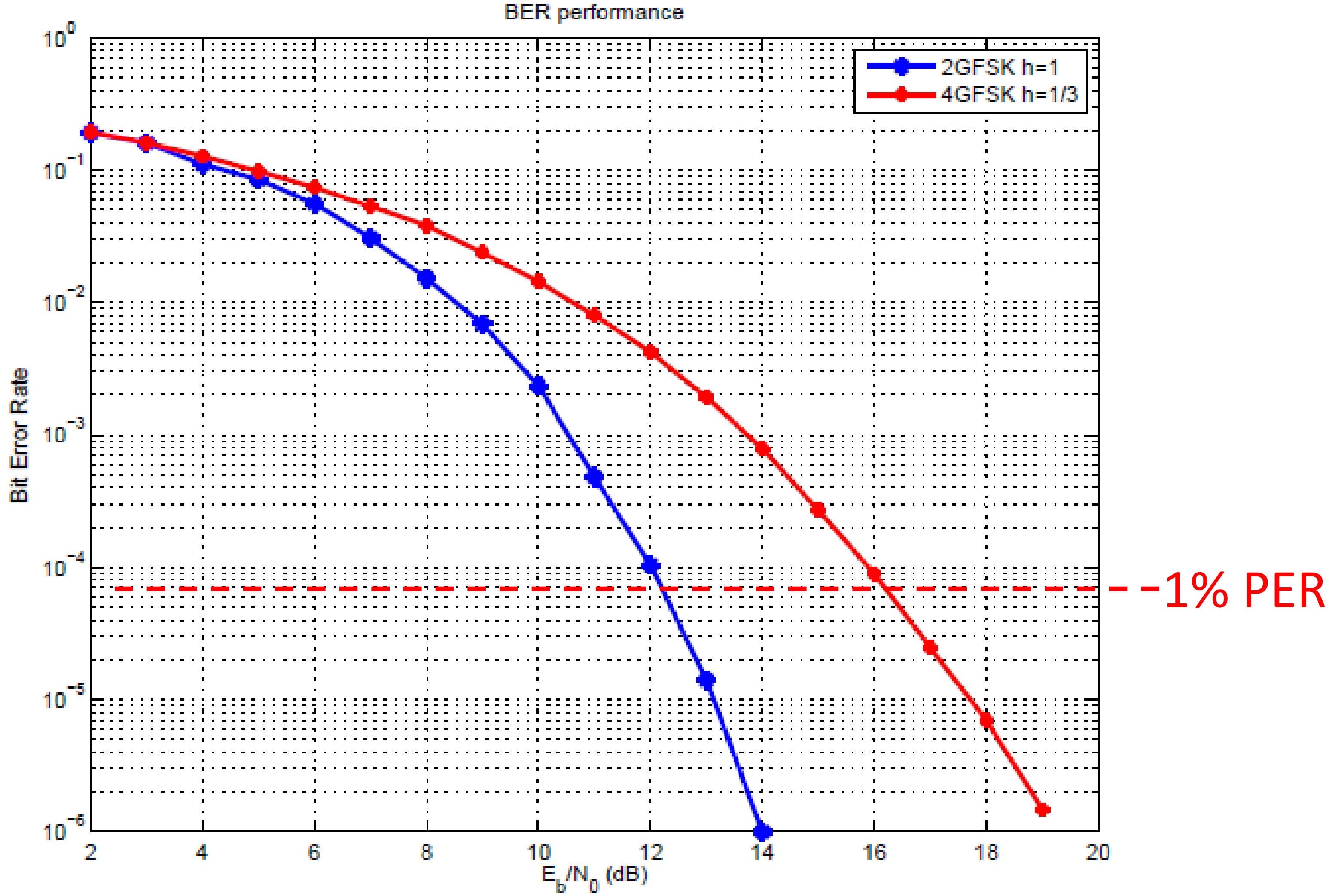
20 dB signal Bandwidth:

ULP-FSK Operating Mode	Data Rate [kbps]	Channel Spacing [kHz]	Mod type	Mod-index/BT	20dB BW (kHz)	Adjacent channel leakage (dB)	Sensitivity PER=1% NF=10dB [dBm]
4	4.8	12.5	2GFSK	1/0.5	10	-42	-115
5	9.6	12.5	4GFSK	0.333/0.5	8.8	-44	-109
6	9.6	25	2GFSK	1/0.5	20	-42	-112
7	19.2	25	4GFSK	0.333/0.5	18	-44	-106
8	50	200	2GFSK	1/0.5	104	-68	-105
9	100	200	4GFSK	0.333/0.5	92	-73	-99
10	150	400	2GFSK	1/0.5	312	-42	-100
11	300	400	4GFSK	0.333/0.5	276	-45	-94
12	400	1000	2GFSK	1/0.5	836	-41	-96
13	800	1000	4GFSK	0.333/0.5	740	-42	-90

Adjacent Channel Leakage:

ULP-FSK Operating Mode	Data Rate [kbps]	Channel Spacing [kHz]	Mod type	Mod-index/BT	20dB BW (kHz)	Adjacent channel leakage (dB)	Sensitivity PER=1% NF=10dB [dBm]
4	4.8	12.5	2GFSK	1/0.5	10	-42	-115
5	9.6	12.5	4GFSK	0.333/0.5	8.8	-44	-109
6	9.6	25	2GFSK	1/0.5	20	-42	-112
7	19.2	25	4GFSK	0.333/0.5	18	-44	-106
8	50	200	2GFSK	1/0.5	104	-68	-105
9	100	200	4GFSK	0.333/0.5	92	-73	-99
10	150	400	2GFSK	1/0.5	312	-42	-100
11	300	400	4GFSK	0.333/0.5	276	-45	-94
12	400	1000	2GFSK	1/0.5	836	-41	-96
13	800	1000	4GFSK	0.333/0.5	740	-42	-90

Eb/No in AWGN:


BER performance
Bit Error Rate
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
2
4
6
8
10
12
14
16
18
20
E_b/N_0 (dB)
2GFSK h=1
4GFSK h=1/3
1% PER

RX sensitivity (non-coherent demodulator, 20B PSDU):

ULP-FSK Operating Mode	Data Rate [kbps]	Channel Spacing [kHz]	Mod type	Mod-index/BT	20dB BW (kHz)	Adjacent channel leakage (dB)	Sensitivity PER=1% NF=10dB [dBm]
4	4.8	12.5	2GFSK	1/0.5	10	-42	-115
5	9.6	12.5	4GFSK	0.333/0.5	8.8	-44	-109
6	9.6	25	2GFSK	1/0.5	20	-42	-112
7	19.2	25	4GFSK	0.333/0.5	18	-44	-106
8	50	200	2GFSK	1/0.5	104	-68	-105
9	100	200	4GFSK	0.333/0.5	92	-73	-99
10	150	400	2GFSK	1/0.5	312	-42	-100
11	300	400	4GFSK	0.333/0.5	276	-45	-94
12	400	1000	2GFSK	1/0.5	836	-41	-96
13	800	1000	4GFSK	0.333/0.5	740	-42	-90

Line of Sight (LOS) path loss @ 10 meters [2]:

d=	10	meter
Ptx=	-5	dBm
Ant gain TX=	-6	dB
Ant gain RX=	-6	dB

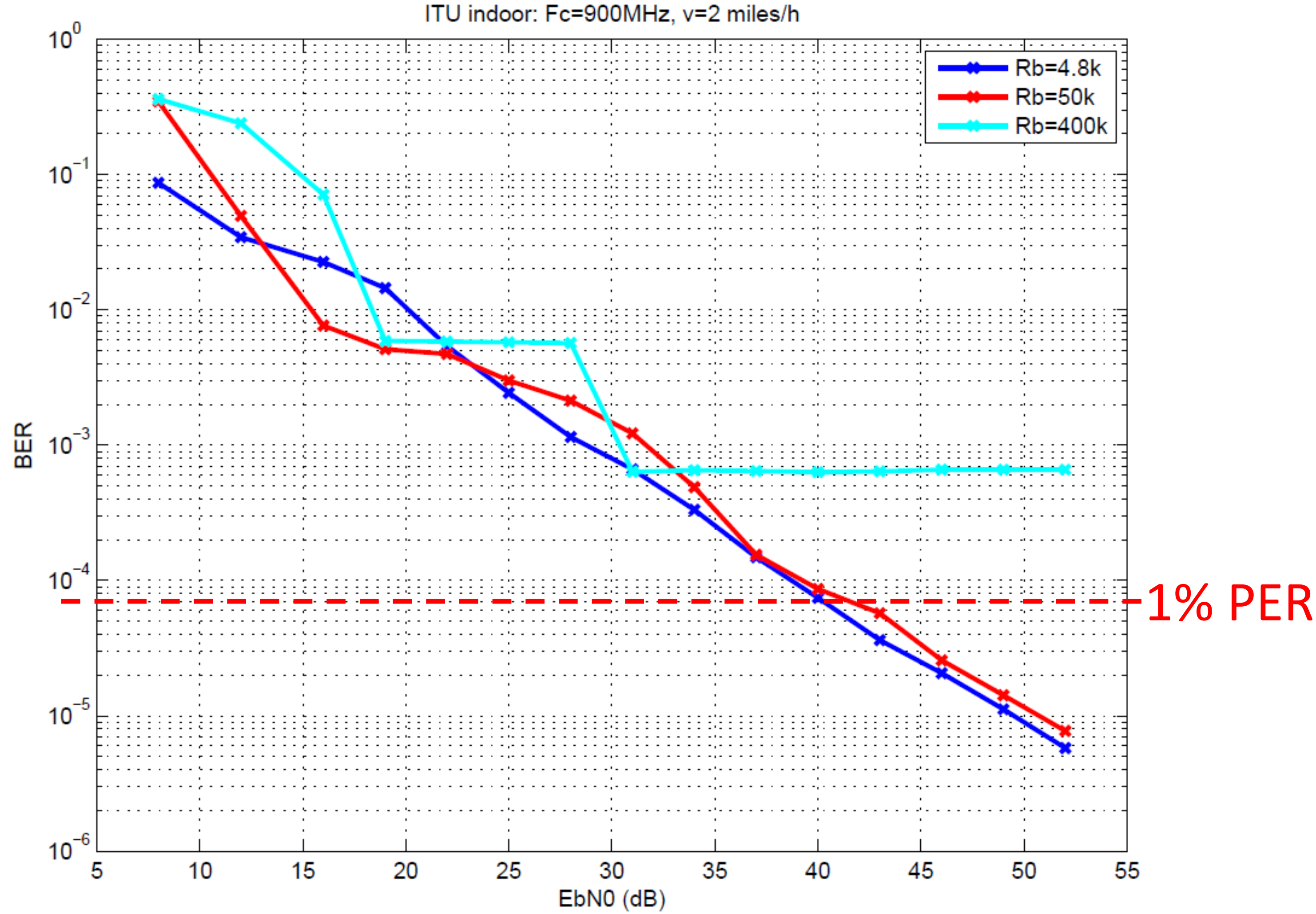
F MHz	hb meter	hm meter	lambda meter	Rbp meter	Lbp dB	Llos @ d>Rbp dB	Llos @ d<Rbp dB	Llos final	Ant gain TX & RX dB	TX power dBm	RX power dBm
169	2	2	1.78	9.0	30.1	37.9	37.0	37.9	-12	-5	-54.9
460	2	2	0.65	24.5	47.5	37.9	45.7	45.7	-12	-5	-62.7
780	2	2	0.38	41.6	56.6	37.9	50.3	50.3	-12	-5	-67.3
870	2	2	0.34	46.4	58.5	37.9	51.2	51.2	-12	-5	-68.2
915	2	2	0.33	48.8	59.4	37.9	51.6	51.6	-12	-5	-68.6
2450	2	2	0.12	130.7	76.5	37.9	60.2	60.2	-12	-5	-77.2

ITU indoor channel model [2]:

Power Delay Profile:

Tap	Relative delay (ns)	Average power (dB)	Doppler spectrum
1	0	0	Flat
2	50	-3	Flat
3	110	-10	Flat
4	170	-18	Flat
5	290	-26	Flat
6	310	-32	Flat

Simulation ITU indoor channel model @ 900MHz:

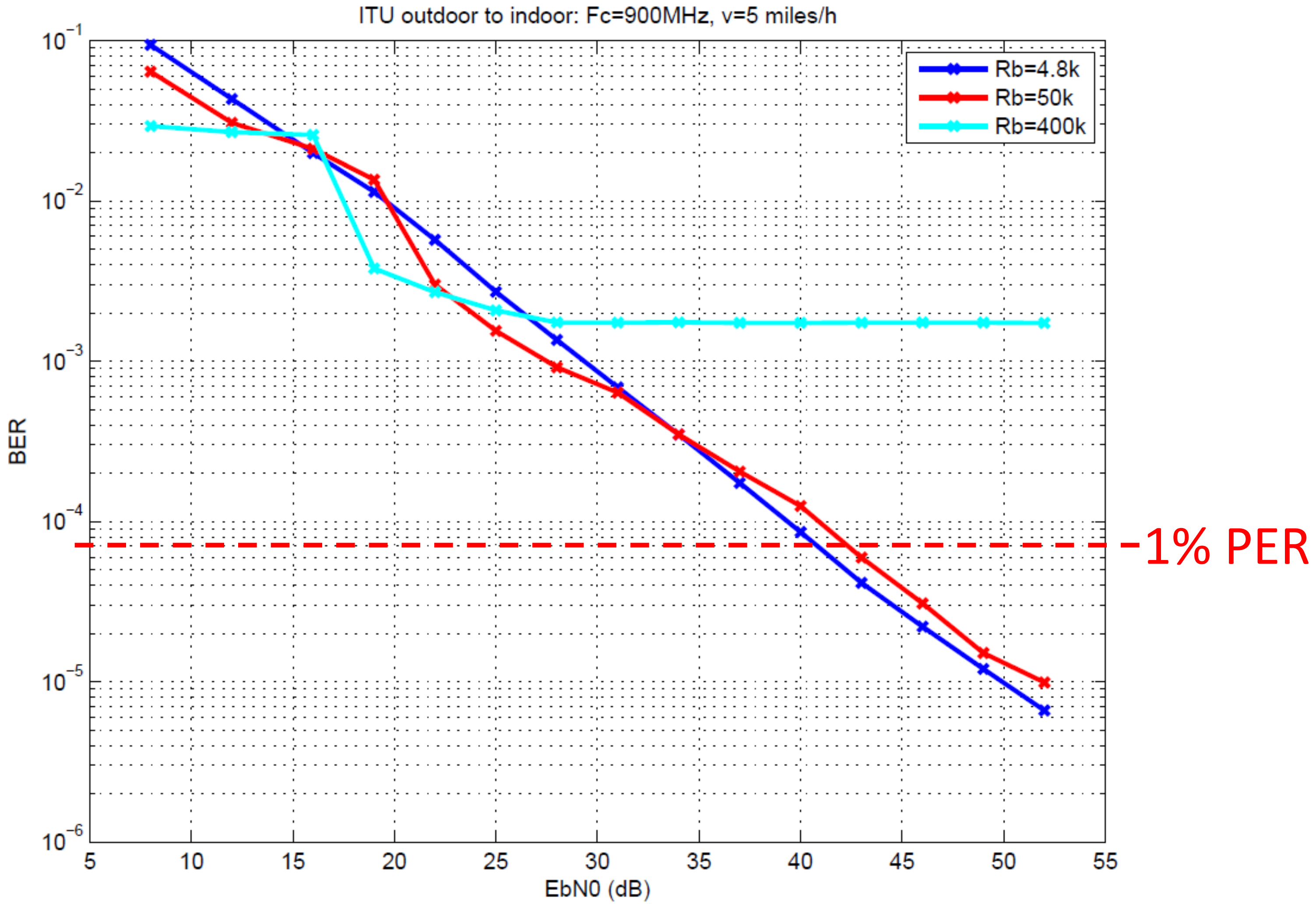


ITU outdoor to indoor channel model and pedestrian [2]:

Power Delay Profile:

Tap	Relative delay (ns)	Average power (dB)	Doppler spectrum
1	0	0	Classic
2	110	-9.7	Classic
3	190	-19.2	Classic
4	410	-22.8	Classic

Simulation ITU indoor channel model @ 900MHz:



Link Budget @ 915MHz:

Parameter	Signal power & Gain
TX power	-5 dBm
TX antenna gain	-6 dBi
Path loss at 10m	-51.6 dB
Receiver antenna gain	-6 dBi
Power at RX input	-68.6 dBm
Receiver noise figure	10 dB
Eb/No under fading conditions – non coherent demod	-43 dB
RX sensitivity* at OM 8 (50kbps)	-74 dBm
Receive power margin	5.4 dB

*RX sensitivity = -174dBm + NF + Eb/No + 10log(Rb)

Receiver power consumption (1):

Power consumption in receiver depends on:

- Noise Figure
- Selectivity and blocking performance
- Demodulator sensitivity

E.g. the adjacent channel selectivity can be calculated as follows:

$$AdjCR = 10 * \log_{10}\left(10^{\frac{(PN_{AdjCh}+SNR)}{10}} + 10^{\frac{(CF_{AdjCh}+SNR)}{10}}\right)$$

Where:

PN_{AdjCh} is the LO phase noise power integrated over the adjacent channel in dBc

CF_{AdjCh} is the suppression of the adjacent channel relative to the pass band in dB

SNR is the signal to noise ratio required at the demodulator input for the specified PER in dB

Receiver power consumption (2):

Based on silicon available today:

- PLL tuning system ~ 11mW
- LNA/Mixer + demod ~ 7mW
- Total consumed power: ~18mW
- Higher performance than needed for ULP applications:
  - NF = 8dB, ULP TGD specifies 10dB
  - Adjacent Channel selectivity = -56dB

Down scaled performance is likely to meet the TG4q requirement of 15mW.

Transmitter power consumption:

Power consumption in transmitter depends on:

- PA efficiency
- Spurious emission requirements
  - ➢ Phase Noise on RF signal

From existing silicon:

- PA power consumption < 1mW at -5dBm RF power
- RF carrier generation ~12mW
  - For high performance / low phase noise carrier
- Already lower than TG4q requirement (15mW)

Conclusions:

- ULP-GFSK file meets range requirements including small scale fading @ 50kbps
- Power savings by
  - ➢ Reduction in overhead in Preamble and PHR
  - ➢ Higher data rates (shorter TX/RX on time)
  - ➢ Double Data Rate without re-sync
- Meeting 4q PAR requirements (<15mW)
- Clean spectrum by employing Gaussian filter

Abbreviations:

FCS	Frame Check Sequence
FEC	Forward Error Correction
GFSK	Gaussian Frequency Shift Keying
OM	Operating Mode
PHR	PHY header
PPDU	PHY Protocol Data Unit
PSDU	PHY Service Data Unit
SFD	Synchronization Frame Delimiter
SHR	Synchronization header
SUN	Smart Utility Network
ULP	Ultra Low Power

REFERENCES:

[1] IEEE802.15.4g-2012

[2] 15-13-0329-01-004q-channel-models-for-IEEE-802-15-4q

[3] 15-13-0341-03-004q-tg4q-tgd-draft

[4] IEEE802.15.4-2011

[5] 15-13-0630-01-ULP-FSK-PHY-proposal.pdf

APPENDIX A – Frame structures – 802.15.4-2011:

Frame control field:

Bits :	0-2	3	4	5	6	7-9	10-11	12-13	14-15
	Frame Type	Security enabled	Frame Pending	Ack. request	Intra PAN	Reserved	Dest. addressing mode	Reserved	Source addressing mode

Address information:

Bytes :	0/2	0/2/8	0/2	0/2/8
	Destination PAN identifier	Destination Address	Source PAN identifier	Source Address

MAC data frame:

Bytes :	2	1	4 - 20	0 - 122	2
	Frame Control	Data Sequence Number	Address Information	Data Payload	Frame Check Sequence

Acknowledgement frame:

Bytes :	2	1	2
	Frame Control	Data Sequence Number	Frame Check Sequence

APPENDIX B -20dB signal BW definition:

Use the following spectrum analyzer settings:

- Span = approximately 2 to 3 times the 20 dB bandwidth, centered on a hopping channel
- RBW ³ 1% of the 20 dB bandwidth
- VBW ³ RBW
- Sweep = auto
- Detector function = peak
- Trace = max hold

The EUT should be transmitting at its maximum data rate. Allow the trace to stabilize. Use the marker-to-peak function to set the marker to the peak of the emission. Use the marker-delta function to measure 20 dB down one side of the emission. Reset the marker-delta function, and move the marker to the other side of the emission, until it is (as close as possible to) even with the reference marker level. The marker-delta reading at this point is the 20 dB bandwidth of the emission.