IEEE P802.15

Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)	
Title	**Proposal for an Ultra-Low Power GFSK PHY**	
Date Submitted	4 November 2013	
Source	Henk de Ruijter Ping Xiong	Voice: +14087021235 E-mail: hendricus.deruijter@silabs.com ping.xiong@silabs.com
Re:	PHY proposal for TG15.4q	
Abstract	This document describes a PHY proposal for TG15.4q	
Purpose	To provide direction towards a low power PHY specification for the IEEE802.15.4 standard	
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Release		

1 Introduction

This proposal is aimed to work with 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.

Power is being saved by:

1. Selecting FSK with low power solutions already available.
    - Constant envelope → high efficiency PA
2. Increase data rate to reduce the receiver and transmitter ON time.
    - Double Data Rate mode (DDR) without re-sync required
3. 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)

In this document the PHY proposed is called ULP-FSK PHY.

In section 2 the proposal is specified. In section 3 the proposal is evaluated using the TGD [2].

2 ULP-FSK PHY proposal

2.1 PPDU

The ULP-FSK PPDU shall support the format as shown in Figure 112 [1].

		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)

The synchronization header (SHR), PHY header (PHR), and PHY payload components are treated as bit strings of length *n*, numbered b0 on the left and bn-1 on the right. When transmitted, they are processed b0 first to bn-1 last, without regard to their content or structure.

2.2 Preamble

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.

To save power the minimum preamble for the ULP-FSK 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.

2.3 Synchronization Frame Delimiter (SFD)

The SFD in ULP-FSK is specified the same as for MR-FSK. See section 18.1.1.2 in 802.15.4g-2012 [1].

2.4 PHY Header (PHR)

The ULP-FSK PHY shall support the PHY Header as shown in Figure 114 [1]. In addition the Short PHY Header (SPH) as shown in FIG. 1 may be supported as well as the Mode Switching PHY Header as described in section 18.1.1.4 [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

The reserved bits (R1-R0) are used in the ULP-FSK PHY as follows:

- **R0 = SPH** = Short PHY Header. When this bit is set while MS=”0”, the PHY Header shown in FIG. 1 shall be used.
- **R1 = DDR** = Double Data Rate. When this bit is set the data rate across the PSDU will 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 to PSDU.

The Short PHY Header is shown in FIG. 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

FIG. 1 – Format of the Short PHY Header for ULP-FSK

TABLE 1 lists the MS, SPH and DDR functionality related to PHR, Modulation on PSDU, FCS and DW. This table also shows the compatibility with the MR-FSK PHY [1].

MS	SPH	DDR	PHY Header	Modulation on PSDU	FCS	DW
0	0	0	ULP-FSK = MR-FSK no MS, see Figure 114	Same as SHR and PHR	Selected by FCS bit in PHR	Selected by DW bit in PHR
1	X	X	MR-FSK with MS enabled, see Figure 115	Same as SHR and PHR	Selected by FCS bit in PHR	Selected by DW bit in PHR
0	1	0	ULP-FSK, see FIG. 1	Same as SHR and PHR	FCS = 16 bit	DW enabled
0	1	1	ULP-FSK, see FIG. 1	4GFSK, same symbol rate as SHR and PHR	FCS = 16 bit	DW enabled
0	0	1	ULP-FSK = MR-FSK no MS, see Figure 114	4GFSK, same symbol rate as SHR and PHR	Selected by FCS bit is PHR	Selected by DW bit in PHR

TABLE 1 – MS, SPH and DDR functionality

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

2.5 Modulation and coding for ULP-FSK

TABLE 2 shows the operating modes of the ULP-FSK PHY:

ULP-FSK Operating Mode	Data Rate [kbps]	Channel Spacing [kHz]	Mod type	Mod-index/BT	20dB BW	Adjacent channel leakage (dB)	Sensitivity PER=1% [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

TABLE 2 – Operating Modes of the ULP-FSK

A ULP-FSK device shall support any of the 2GFSK operating modes (OM 4, or 6 or 8 or 10) and may support any other mode listed in TABLE 2.

In addition a ULP-FSK device may also support any of the MR-FSK operation modes (OM 1, 2 and 3).

TABLE 3, 4, 6 and 6 shows the modulation and channel parameters for each frequency band.

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

TABLE 3 – ULP-FSK modulation and channel parameters for 12.5kHz channel spacing

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

TABLE 4 – ULP-FSK modulation and channel parameters for 25 kHz channel spacing

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
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

TABLE 5 – ULP-FSK modulation and channel parameters for channel spacing 200-400 kHz

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
	Data rate (kbps)	400	800
2400-2483.5	Modulation	2GFSK	4GFSK
(Worldwide)	Modulation index	1	1/3
	Channel spacing (kHz)	1000	1000

TABLE 6 – ULP-FSK modulation and channel parameters for channel spacing ≥ 400 kHz

2.6 Reference Modulator Diagram

The Reference Modulator Diagram for ULP-FSK is the same as for MR-FSK, see Figure 117 [1].

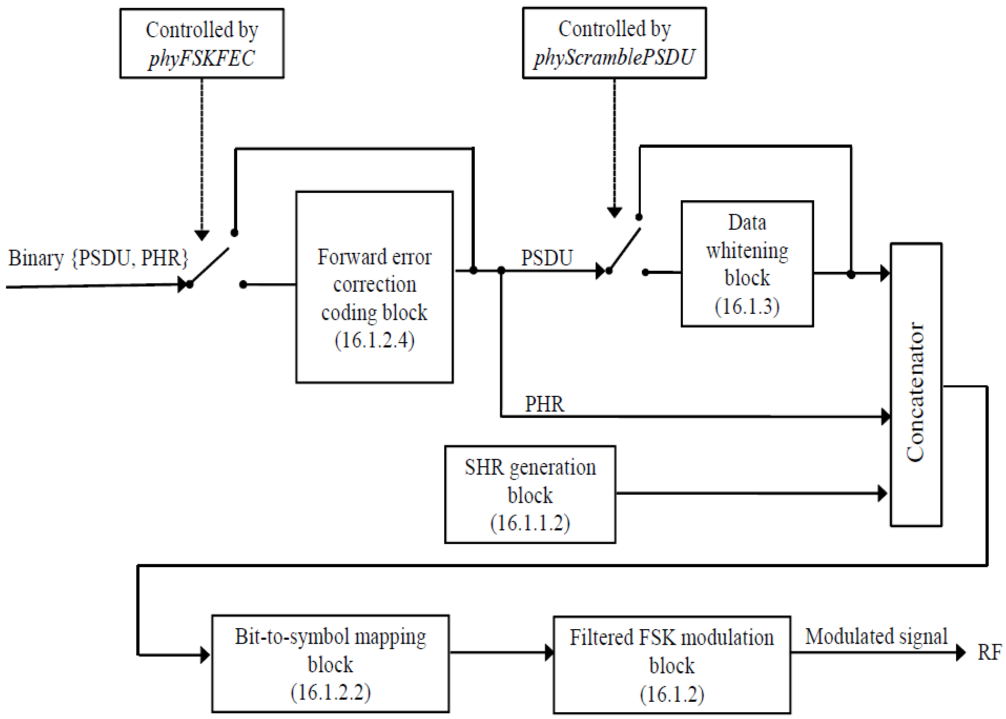


Figure 117—MR-FSK FEC, data whitening, and modulator functions

2.7 Bit to Symbol mapping, modulation quality and zero crossing tolerance

The Bit to Symbol mapping and modulation quality of ULP-FSK is the same as specified for MR-FSK, see section 18.1.2.2, 18.1.2.3 and 18.1.2.3.2 [1].

2.8 Forward Error Correction (FEC), code symbol interleaving, data whitening and mode switching

Forward Error Correction (FEC), code symbol interleaving, data whitening and mode switching in ULP-FSK is the same as specified for MR-FSK, see section 18.1.2.4, 18.1.2.5, 18.1.3 and 18.1.4 [1].

2.9 ULP-FSK RF requirements

The RF requirements of the ULP-FSK PHY shall comply with the RF requirements as defined in the MR-FSK PHY specification in section 18.1.5 [1]

3 Evaluation using Technical Guidance Document.

In this section the TGD document [2] is used as a guide.

3.1 Link budget and impact of channel models

3.1.1 Sensitivity

The sensitivity numbers listed in this section are under AWGN conditions with a receiver noise figure of 10dB.

- Sens_FSK = -174dBm + NF + Eb/No + 10log(Rb)
- Sens_2GFSK = -174dBm + 10 + 11 + 10log(Rb) @ BER =10^{-3}
- Sens_4GFSK = -174dBm + 10 + 14 + 10log(Rb) @ BER =10^{-3}

The Eb/No numbers are measured on a non-coherent demodulator.

ULP-FSK Operating Mode	Data Rate [kbps]	Mod type	Mod-index/BT	Channel Spacing [kHz]	20dB BW	Adj channel leakage (dB)	Sensitivity BER=0.1% [dBm]
4	4.8	2GFSK	1/0.5	12.5	10	-42	-116
5	9.6	4GFSK	0.333/0.5	12.5	8.8	-44	-110
6	9.6	2GFSK	1/0.5	25	20	-42	-113
7	19.2	4GFSK	0.333/0.5	25	18	-44	-107
8	50	2GFSK	1/0.5	200	104	-68	-106
9	100	4GFSK	0.333/0.5	200	92	-73	-100
10	150	2GFSK	1/0.5	400	312	-42	-101
11	300	4GFSK	0.333/0.5	400	276	-45	-95
12	400	2GFSK	1/0.5	1000	836	-41	-97
13	800	4GFSK	0.333/0.5	1000	740	-42	-91

3.1.2 Large scale path loss

The Path loss models as described in the channel model document are used here:

LOS path loss model:

d=	30 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	57.0	46.5	57.0	-12	-5	-74.0
460	2	2	0.65	24.5	47.5	57.0	55.2	57.0	-12	-5	-74.0
780	2	2	0.38	41.6	56.6	57.0	59.8	59.8	-12	-5	-76.8
870	2	2	0.34	46.4	58.5	57.0	60.7	60.7	-12	-5	-77.7
915	2	2	0.33	48.8	59.4	57.0	61.2	61.2	-12	-5	-78.2
2450	2	2	0.12	130.7	76.5	57.0	69.7	69.7	-12	-5	-86.7

Indoor NLOS:

d=	10	m
n=	3	floor(s)
Ptx=	-5	dBm
Ant gain TX=	-6	dB
Ant gain RX=	-6	dB

	N	f MHz	d meter	Lf(n) dB	Ltot dB	Ant gain TX & RX dB	RX power dBm
Residential - 900MHz	33	900	10	24	88.1	-12	-105.1
Office - 900MHz	33	900	10	24	88.1	-12	-105.1
Commercial - 900MHz	20	900	10			-12	
Residential - 2.4GHz	28	2400	10	30	97.6	-12	-114.6
Office - 2.4GHz	30	2400	10	42	111.6	-12	-128.6
Commercial - 2.4GHz		2400	10			-12	

N= Distance power loss coefficient
f= Frequency in MHz
d= Separation distance between base station and portable terminal (d > 1m)
Lf= Floor penetration loss
n= Number of floors between the base station and the portable terminal (n = 1, 2 or 3)

3.1.3 Small scale fading

In this section a small scale fading model is used from the 15.4q channel models document ([4] section 3.3):

In this case the channel impulse response model is assumed to be wide sense stationary with uncorrelated scatters (WSSUS). The many scattered paths that may exist in a real channel are replaced with only a few *N* multi-path components in the model. Then a complex Gaussian time variant process $g_n(t)$ models the super-position of unresolved multipath components arriving from different angles with delays close to the delay $\tau_n$of the n −th model multipath component and a Doppler spectrum of $S_k(f)$. Then, the impulse response $h(t)$ is given by

$$h(t) = \sum_{n=1}^{N} \sqrt{p_n}\, g_n(t)\delta(t - t_n) \tag{19}$$

Where p_n is the received power from the n −th model multipath component. Such a statistical model such as this requires appropriate parameters for each component. Since the mobility is at the most pedestrian and there are many scenarios for fixed wireless channels the Doppler spectrum is either flat or classical.

The flat Doppler spectrum is given by

$$S(f) = \frac{1}{2f_d} \qquad |f| < f_d \tag{20}$$

The classic Doppler spectrum is given by

$$S(f) = \frac{1}{\pi f_d \sqrt{1 - \left(\frac{f}{f_d}\right)^2}}, \qquad |f| < f_d, f_d = \frac{v f_c}{c} \tag{21}$$

The power p_n for each realization of (19) may be chosen from the ITU power delay profiles below. These are applicable to both 900 MHz and 2.4 GHz frequency bands.

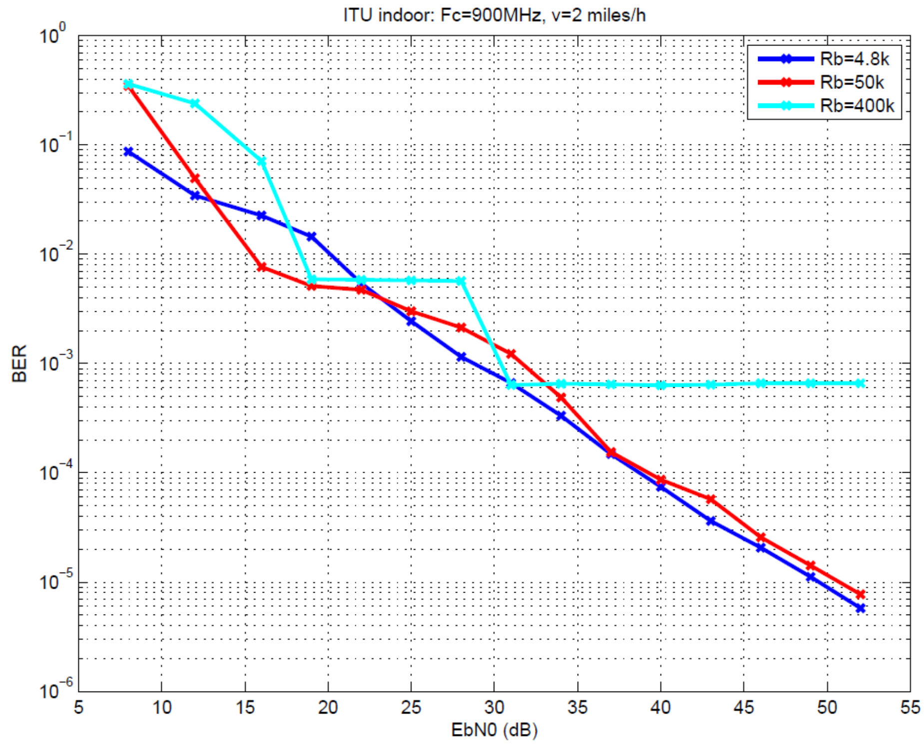
ITU Indoor office

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

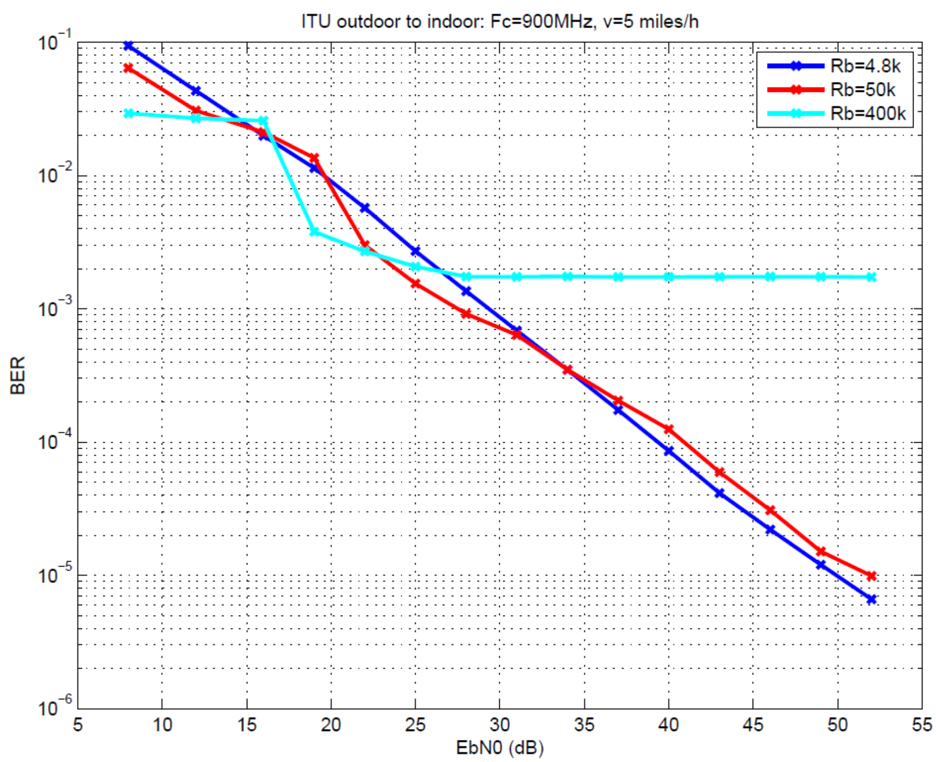
ITU outdoor to indoor and pedestrian

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

The BER vs Eb/No simulation below uses the ITU indoor office profile:



The BER vs Eb/No simulation below uses the ITU indoor to outdoor and pedestrian profile:



3.1.4 Range

In this section the 10m range is demonstrated (see requirement in Technical Guidance document [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

At 915MHz the received signal without small scale fading is -68.6dBm. The large scale fading adds about 30dB attenuation → Receive power at 10 meters including small scale fading = -98.6dBm. This is demonstrated to work at data rates of 50kbps and lower. (see sensitivity listed in section 3.1.1)

3.2 Bit Rate

The bit rates (data rates) are listed in TABLE 2.

3.2.1 PSDU efficiency

The efficiency of the PSDU transfer is defined as:

$$\eta_{PSDU} = \frac{\mathrm{PSDU}}{\mathrm{PSDU + Preamble + SFD + PHR + FCS}}$$

PSDU = length of PSDU, 40 Byte per TGD

Preamble = preamble length, 2 Byte (minimum)

SFD = length of synchronization frame delimiter, 2 Byte

PHR = PHU header length, 2 Byte (ULP-FSK PHY supports 1 Byte PHR up to 32 Byte PSDU size)

FCS = Frame Check Sum, 2 Byte

$$\eta_{PSDU} = 0.833$$

3.2.2 PSDU efficiency of acknowledgement compared to MR-FSK

An acknowledgement frame transfer may yield the following power savings: The number of Bytes for a short acknowledgement in 15.4g is 4 (preamble) + 2 (SFD) + 2 (PHR) + 3 (PSDU) + 2 (FCS)= 13 Bytes total. This proposal provides options to reduce the preamble length to 2 Bytes and the PHY header (PHR) to 1 Byte which will save energy by **23 %**.

Further savings can be obtained by doubling the data rate of the PSDU which will increase the total savings for this example to over **46%**. This data rate doubling can be achieved by setting the DDR bit in the PHR and does not require re-synchronization.

3.3 Interference rejection capability in Adjacent and Alternate channels

The inference rejection capability depends on LO phase noise, channel filter and the 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

Alternate channel rejection ratio can be calculated in a similar fashion.

3.4 Channel availability

Frequency band (MHz)	Channel Spacing (kHz)	# channels
169.400-169.475 (Europe)	12.5	6
	25	3
450-470 (US FCC Part 22/90)	12.5	16
470-510 (China)	200	200
	400	100
779-787 (China)	200	40
	400	20
863-876 (Europe)	200	64
	400	32
915-921 (Europe)	200	30
	400	15
896-901 (US FCC Part 90)	12.5	400
901-902 (US FCC Part 24)	12.5	80
902-928 (US – ISM)	200	130
	400	65
	1000	26
917-923.5 (Korea)	200	32
	400	16
	1000	6
2400-2483.5 (Worldwide)	200	416
	400	208
	1000	82

3.5 Coexistence

Coexistence is obtained by existing 802.15.4 channel access mechanisms like LBT and CCA [3].

3.6 PSD and Adjacent channel leakage

2GFSK – BT=0.5 – Rb=4.8kbps – h=1

Accumulative power in [4.900000e+00, 5.100000e+00]kHz = -35.69 dBm

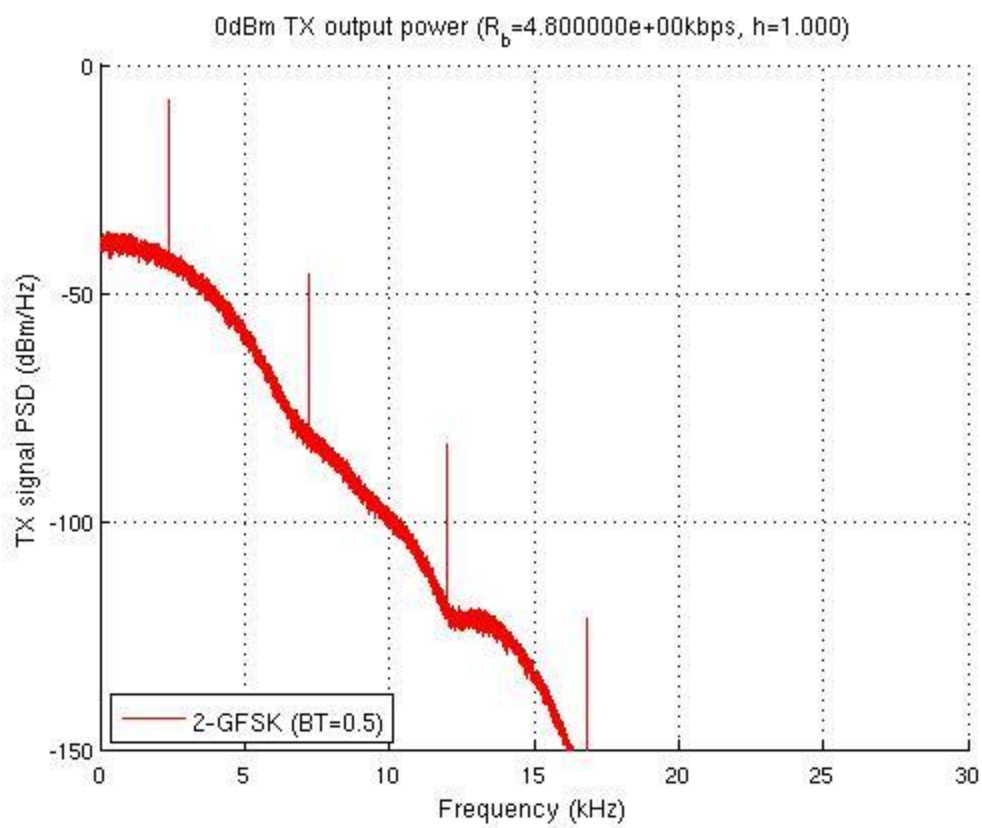
Accumulative power in [0, 2.000000e-01]kHz = -15.66 dBm

Power difference at 5 kHz = 20.03 dBm

Double sided BW = 10 kHz, power = 0.9988

Adjacent channel leakage in [7.500000e+00, 1.750000e+01]kHz = -54.43 dB

Adjacent channel leakage in [6.250000e+00, 1.875000e+01]kHz = -42.15 dB



4GFSK – BT=0.5 – Rb=9.6kbps – h=0.333

Accumulative power in [4.300000e+00, 4.500000e+00]kHz = -33.58 dBm

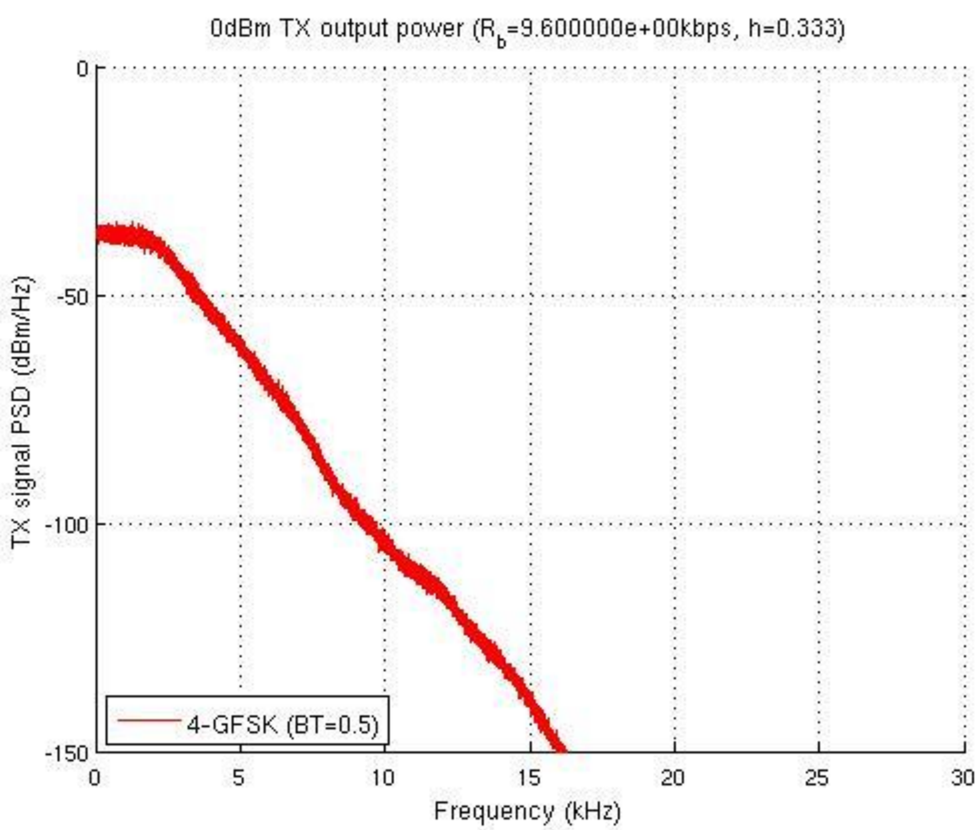
Accumulative power in [0, 2.000000e-01]kHz = -13.43 dBm

Power difference at 4.400000e+00 kHz = 20.15 dBm

Double sided BW = 8.800000e+00 kHz, power = 0.9976

Adjacent channel leakage in [8.100000e+00, 1.690000e+01]kHz = -62.70 dB

Adjacent channel leakage in [6.250000e+00, 1.875000e+01]kHz = -44.23 dB



2GFSK – BT=0.5 – Rb=50kbps – h=1

Accumulative power in [51, 53]kHz = -35.81 dBm

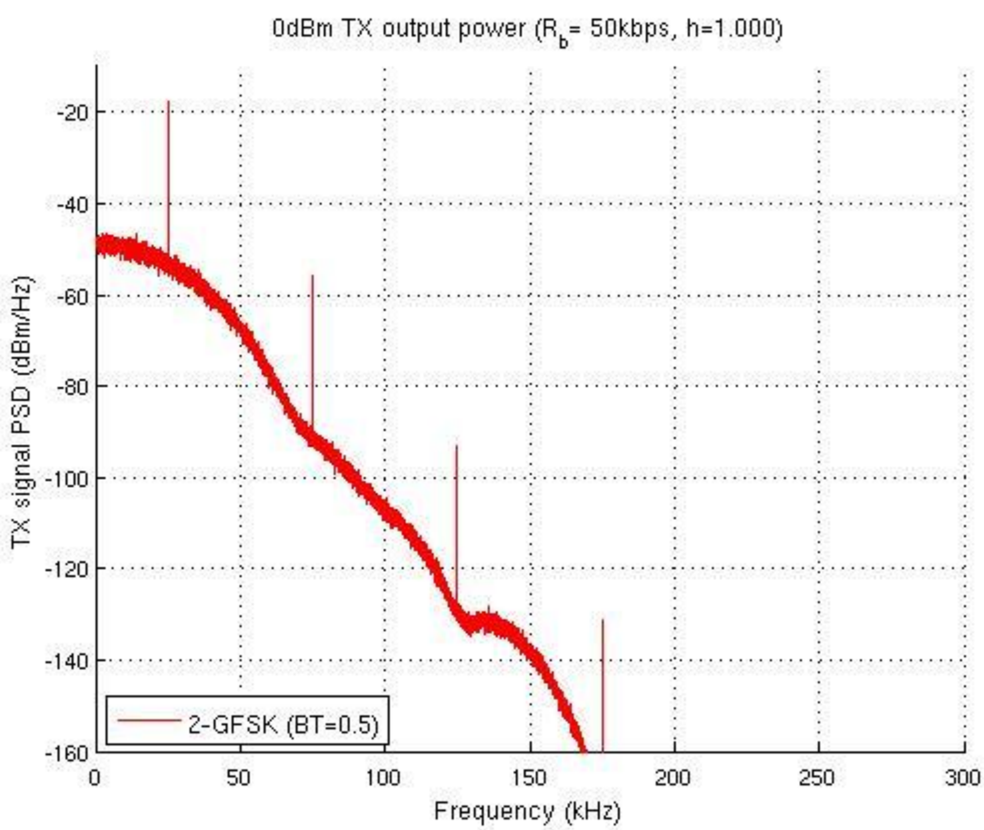
Accumulative power in [0, 2]kHz = -15.82 dBm

Power difference at 52 kHz = 19.99 dBm

Double sided BW = 104 kHz, power = 0.9988

Adjacent channel leakage in [150, 250]kHz = -101.06 dB

Adjacent channel leakage in [100, 300]kHz = -68.54 dB



4GFSK – BT=0.5 – Rb=100kbps – h=0.333

Accumulative power in [45, 47]kHz = -34.01 dBm

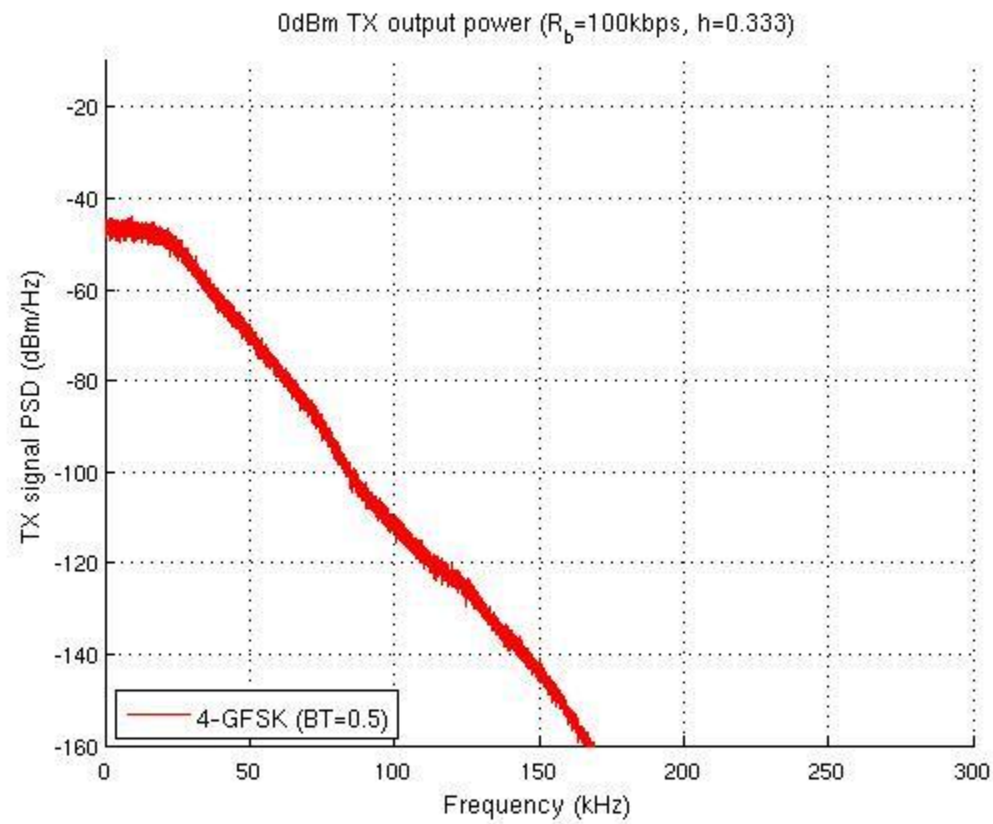
Accumulative power in [0, 2]kHz = -13.42 dBm

Power difference at 46 kHz = 20.59 dBm

Double sided BW = 92 kHz, power = 0.9977

Adjacent channel leakage in [150, 250]kHz = -106.63 dB

Adjacent channel leakage in [100, 300]kHz = -73.14 dB



2GFSK – BT=0.5 – Rb=150kbps – h=1

Accumulative power in [154, 158]kHz = -37.54 dBm

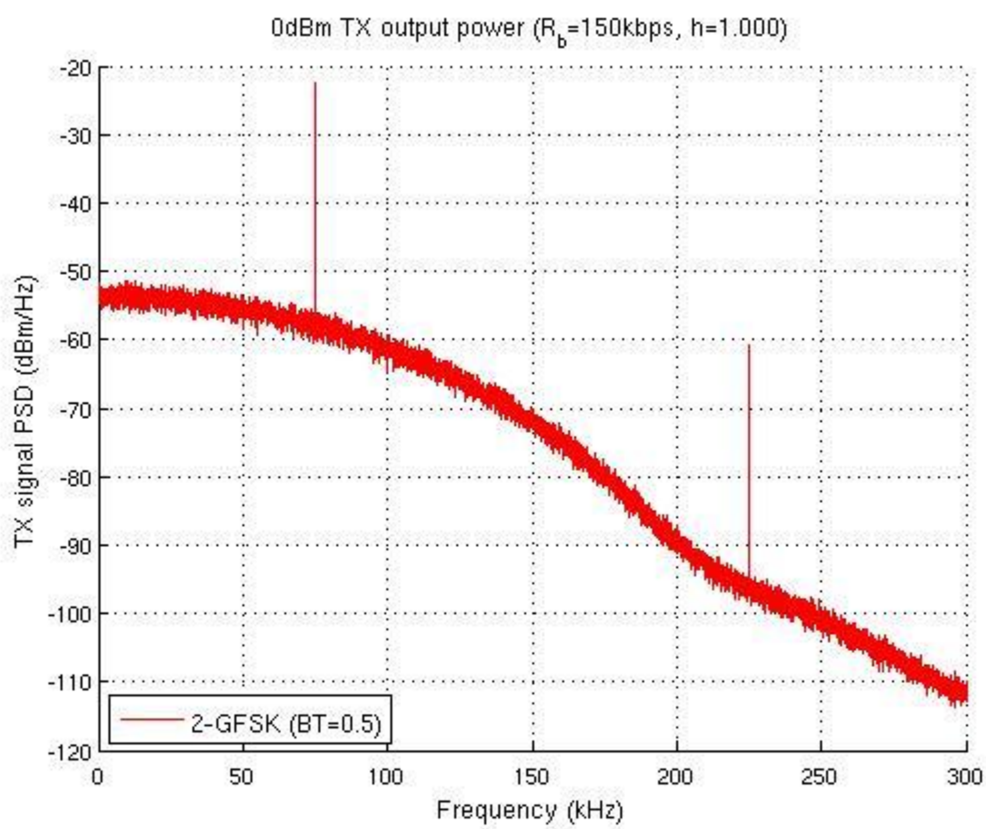
Accumulative power in [0, 4]kHz = -17.55 dBm

Power difference at 156 kHz = 19.99 dBm

Double sided BW = 312 kHz, power = 0.9988

Adjacent channel leakage in [244, 556]kHz = -56.46 dB

Adjacent channel leakage in [200, 600]kHz = -42.64 dB



4GFSK – BT=0.5 – Rb=300kbps – h=0.333

Accumulative power in [136, 140]kHz = -35.70 dBm

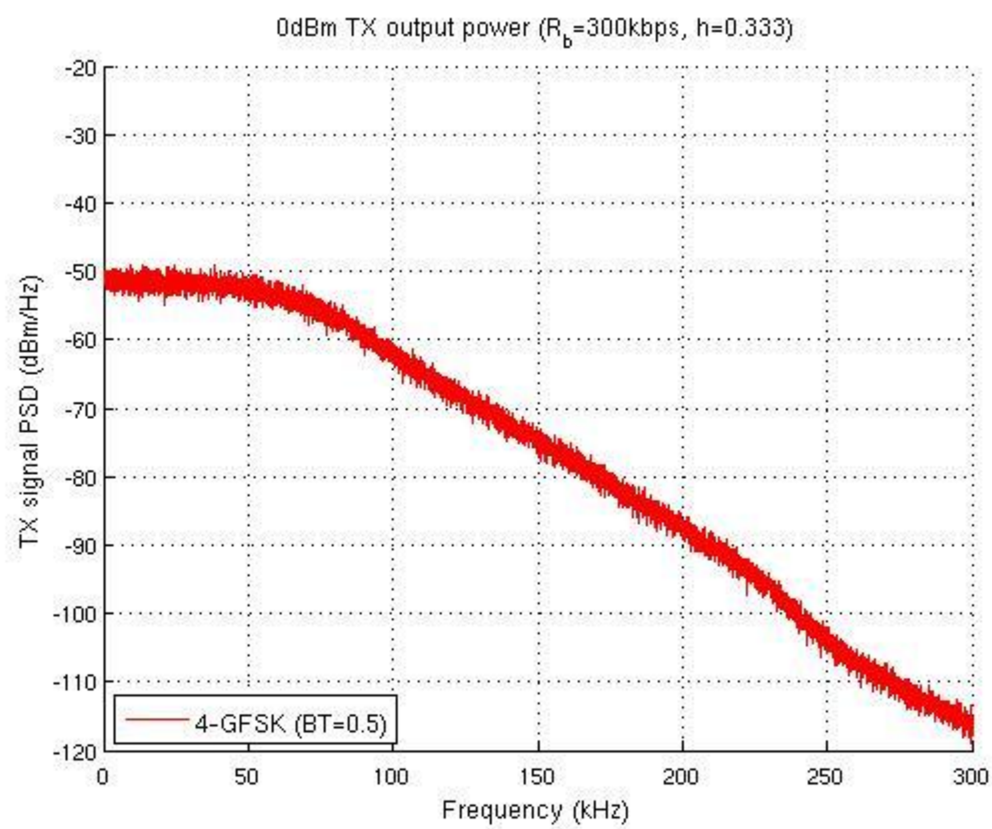
Accumulative power in [0, 4]kHz = -15.41 dBm

Power difference at 138 kHz = 20.29 dBm

Double sided BW = 276 kHz, power = 0.9976

Adjacent channel leakage in [262, 538]kHz = -64.80 dB

Adjacent channel leakage in [200, 600]kHz = -45.61 dB



2GFSK – BT=0.5 – Rb=400kbps – h=1

Accumulative power in [416, 420]kHz = -42.15 dBm

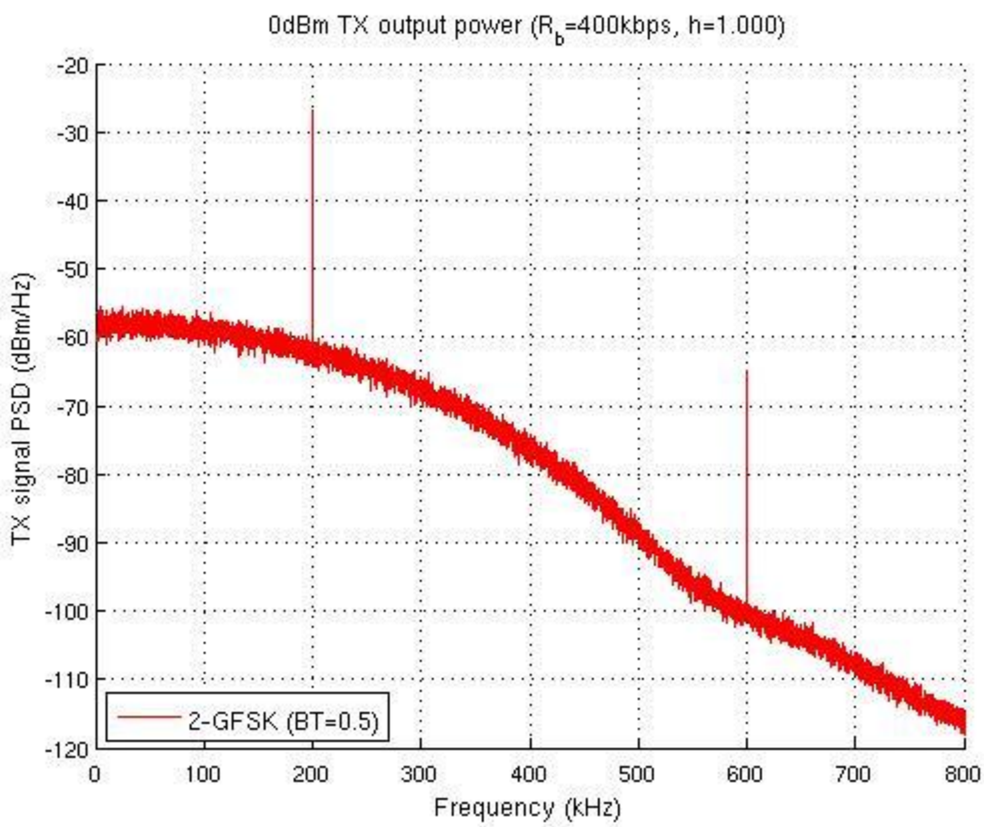
Accumulative power in [0, 4]kHz = -21.97 dBm

Power difference at 418 kHz = 20.18 dBm

Double sided BW = 836 kHz, power = 0.9989

Adjacent channel leakage in [582, 1418]kHz = -43.69 dB

Adjacent channel leakage in [500, 1500]kHz = -40.95 dB



4GFSK – BT=0.5 – Rb=800kbps – h=0.333

Accumulative power in [416, 420]kHz = -39.98 dBm

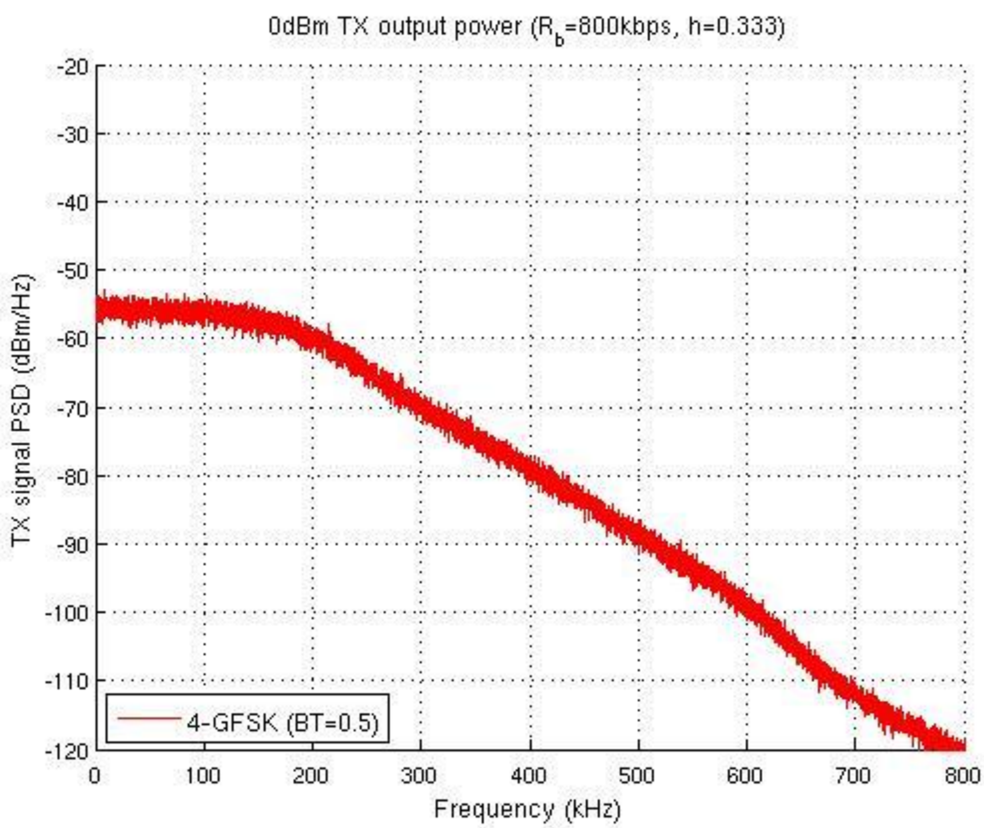
Accumulative power in [0, 4]kHz = -19.77 dBm

Power difference at 418 kHz = 20.21 dBm

Double sided BW = 836 kHz, power = 0.9977

Adjacent channel leakage in [630, 1370]kHz = -57.62 dB

Adjacent channel leakage in [500, 1500]kHz = -42.20 dB



4 Appendix:

4.1 FCC 15.247 – 20dB bandwidth:

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.

5 Abbreviations:

DDR	Double Data Rate
DW	Data Whitening
FCS	Frame Check Sum
FSK	Frequency Shift Keying
GFSK	Gaussian Frequency Shift Keying
MS	Mode Switching
NF	Noise Figure
OM	Operating Mode(s)
PER	Packet Error Rate
PSD	Power Spectral Density
PHR	PHY Header
SNR	Signal to Noise Ratio
SPH	Short PHY Header
ULP	Ultra Low Power

6 Bibliography

[1] IEEE Std 802.15.4g, 2012.

[2] 15-13-0341-03-004q-tg4q-tgd-draft.

[3] IEEE802.15.4-2011.

[4] 15-13-0329-01-004q-channel-models-for-ieee-802-15-4q-draft.