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

Submission Title: PSSS proposal – Parallel reuse of 2.4 GHz PHY for the sub-1-GHz bands

Date Submitted: **14th** April 2005

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Re: PSSS mode for more even chiprates, simpler filter, and 250 kbit/s in 868 MHz

Abstract: Ballot comments received indicated interest in the TG4b task group to modify the PSSS mode for 868 MHz to have the same 250 kbit/s bitrate as the 2.4 GHz and the PSSS 915 Mhz modes.

Purpose: Response to ballot comments to discuss potential modifiation of PSSS draft specification

Discussion: 250 kbit/s PSSS for 868 MHz

Key Considerations

- Comments indicated interest in the TG4b task group to provide 250 kbit/s for bot 868 and 915 MHz
  - Marketing benefit of having homogenous bit rate in all bands
- Discussion of implementation complexity due to uneven chip rates
  - Clarifications from chip vendors have shown that 440 kcps is not truly a concern – will not increase implementation size
  - Simply changing to 400 kcps rate in current PSSS specification is not attractive due to bitrate < 200 kbit/s (OEM concern)
  - Modification of PSSS mode to 400 kcps rate at 250 kbit/s possible
- Modified PSSS mode for 250 kbit/s in 868 MHz will even decrease filter complexity
  - Implementation complexity on Tx side[1] (of both COBI and PSSS) is clearly driven by compliance to ETSI PSD mask in 868 MHz

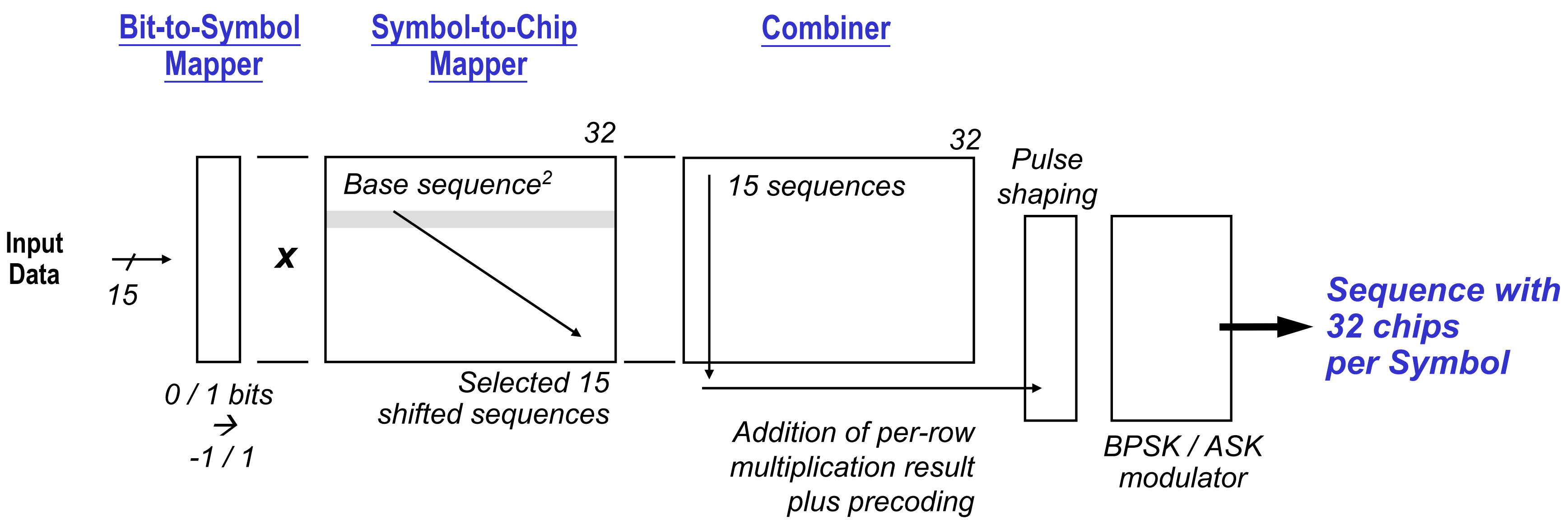
1: Key driver for implementation complexity on Rx side is need to withstand interference (dynamic range, linearity of Rx frontend)

The PSSS mode for 868 MHz could be modified to 250 kbit/s while even *decreasing* implementation complexity

	PSSS 206-440[1] 868 Mhz	**PSSS 250-400[1] 868 Mhz**	**PSSS 250-1600 915 MHz**
Bandwidth	600 kHz	600 kHz	2,400 kHz[2]
Chiprate	440 cps	400 cps	1,6000 cps[2]
Bitrate	206 kit/s	250 kit/s	250 kbit/s
Spectral efficiency[3]	15/32 bit/s/Hz	20/32 bit/s/Hz	5/32 bit/s/Hz
Spreading	15x 32-chip seq.	20x 32-chip seq.	5x 32-chip seq.
RF backward compatibility	Single BPSK / ASK radio	Single BPSK / ASK radio	Single BPSK/ASK radio
Comments	*Original PSSS mode*	*Enhanced original PSSS mode*	

1: Changed names of modes to be consistent <bit rate>"-"<chip rate>
2: Complies to 915 MHz PSD mask specified in IEEE802.15.4-2003
$|f-f_c|$ > 1.2 Mhz: Relative limit -20 dB; Absolute limit -20 dBm
2: Coding level

IEEE802.15.4b-D1 Specification Draft: PSSS 206-440 868 MHz – BPSK/ASK (15/32 bit/s/Hz)[1]



...addition of multiple parallel sequences instead of selection of single sequence

1: Overview, please see TG4b PHY draft specification text and earlier versions of this document for details
2: Use of single base sequence simplifies implementation in Rx

PSSS 250-400 868 MHz Coding Table: Shifting of sequences by 3 instead of 4 subchips enables addition of sequences to achieve 250 kbit/s and 400 kcps

Sequence number	Chip number																																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	
0	-	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	
1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1
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3	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1
4	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	
5	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1
6	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	
7	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1
8	-	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	
9	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1
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11	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1
12	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	
13	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1
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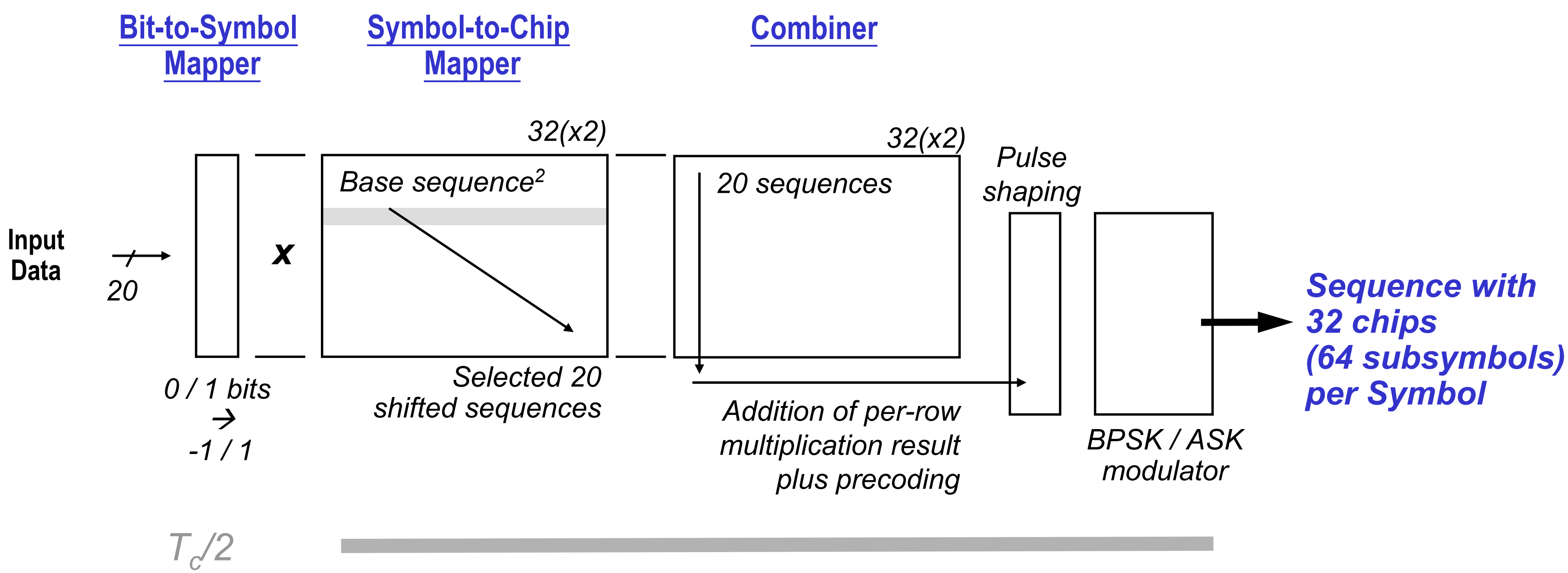
19	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1

Subchip number: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64

- *2 sub-chips per chip – basic chip rate of coding scheme is unchanged*
- *Addition per sub-chip for multivalue encoding – no other changes of PSSS model*

No modification of the basic PSSS model: PSSS 250-400 868 MHz – BPSK/ASK (20/32 bit/s/Hz)



- *No increase of Tx complexity in real-world implementation –*
  - Oversampling used for baseband filtering to achieve PSD compliance anyhow
  - No change in number of chips per symbol – no increase in coding table sizes
- *Simpler baseband filter sufficient due to lower chiprate*
- *No change in Rx processing required*

PSSS Codes form Coding Table in Draft Standard

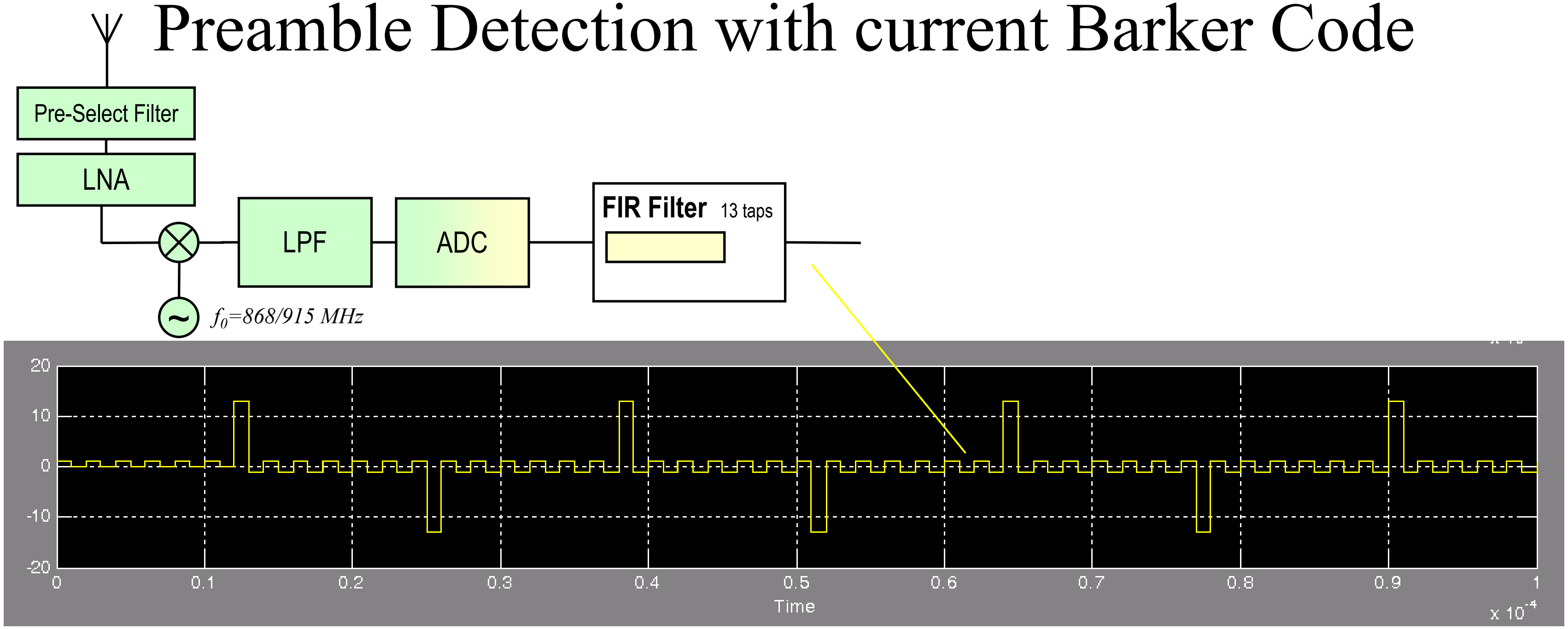
- Sequence 0 is c_0 (m-sequence) plus c_{0ext} (cyclic extension = chip 0)
- Sequence 0 = [$c_{0,}$ c_{0ext}]

Table 27—PSSS Code table used in Symbol-to-Chip mapping for 868 MHz

c_0 c_{0ext}

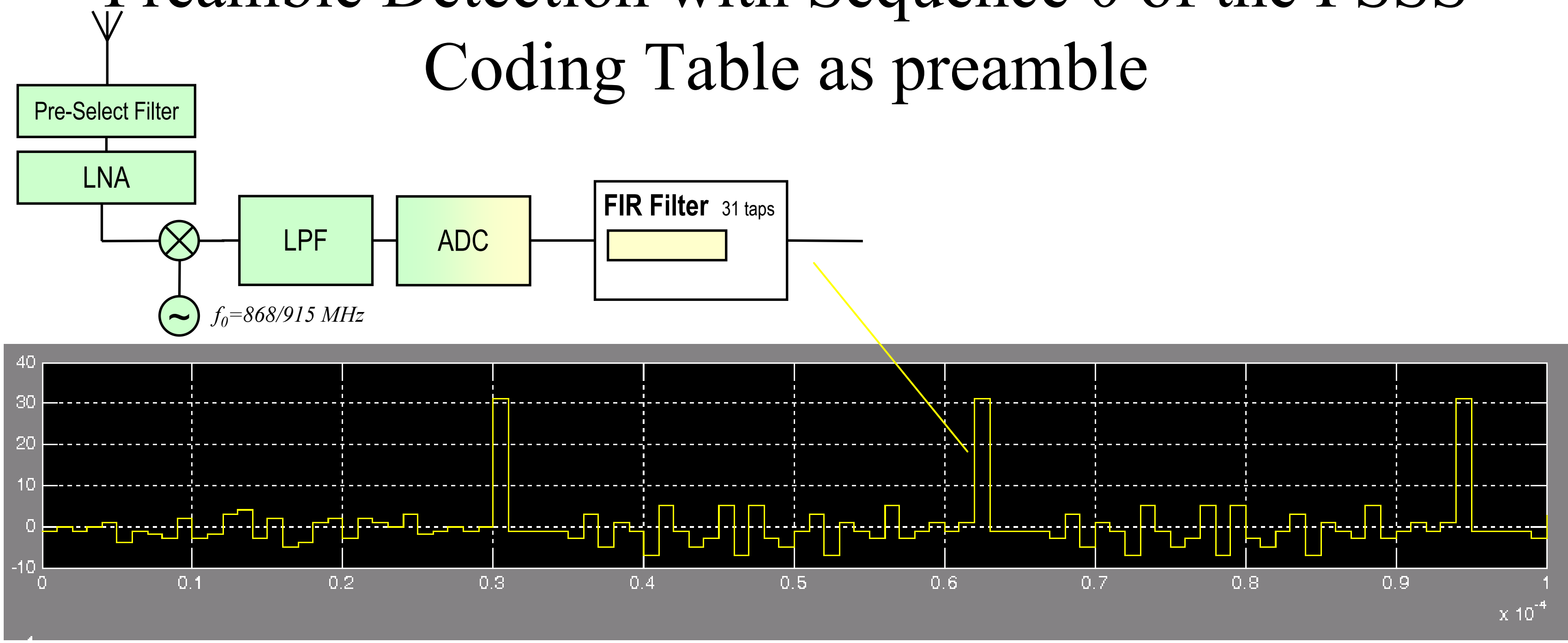
Sequence number	Chip number																															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1
1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1
2	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1
3	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1
4	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1
5	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1
6	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1
7	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1
8	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1
9	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1
10	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1
11	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1
12	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1
13	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1
14	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1

Preamble Detection with current Barker Code



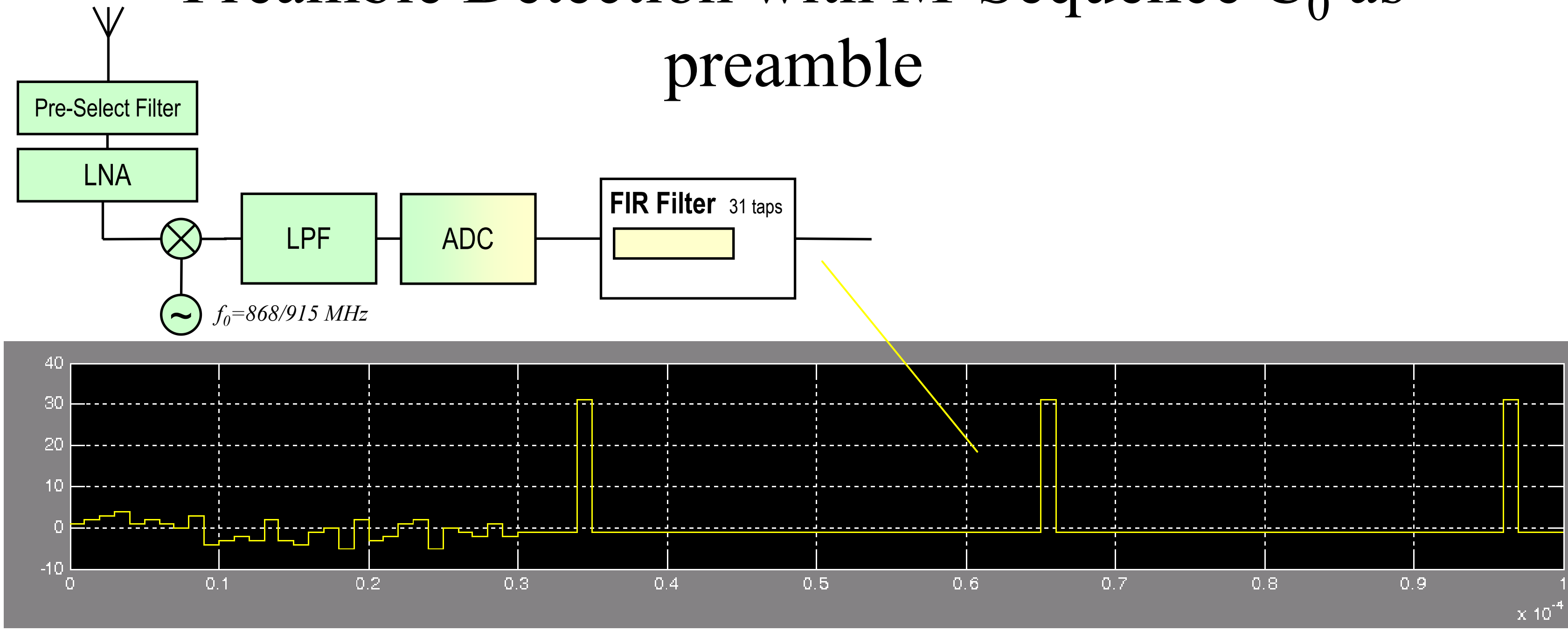
- When detecting the current barker code based preamble with FIR filter, the signal coming out of the FIR filter has side slopes limited to +/- 1.
- Advantages:
  - It is DC free
- Disadvantages:
  - Sides slopes causes a mismatch of the energy maximum detection for multipath fading channels.
  - Two FIR filters needed, one for preamble detection (13 chip barker code), one for PSSS decoding (31 chip m-sequence).

Preamble Detection with Sequence 0 of the PSSS Coding Table as preamble



- When detecting the preamble, base on repeated sequence 0 with FIR filter, the signal coming out of the FIR filter has side slopes limited to +5/-6.
- Advantages:
  - Use of just one FIR filter or correlator for preamble detection and PSSS decoding.
  - 32 chip long preamble code.
  - DC free
- Disadvantages:
  - Sides slopes causes a mismatch of the energy maximum detection for multipath fading channels.

Preamble Detection with M-Sequence C_0 as preamble

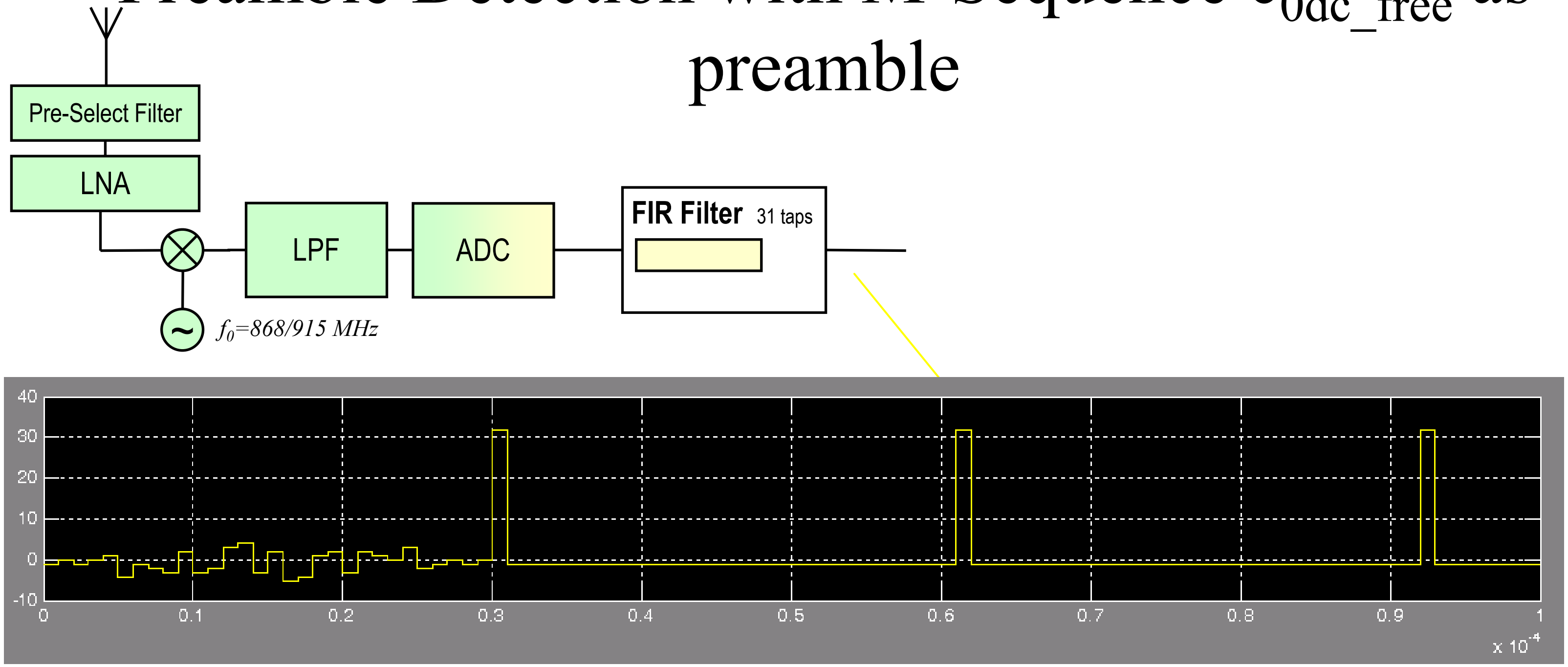


- When detecting the preamble, base on repeated m-sequence c_0 with FIR filter, the signal coming out of the FIR filter has no side slopes, when the first m-sequence c_0 has passed the FIR filter.
- Advantages:
  - Use of just one FIR filter or correlator for preamble detection and PSSS decoding.
  - No side slopes.
  - Optimal maxima detection for multipath fading channels possible.
- Disadvantages:
  - Not DC free.
  - Length of 31 chips instead of 32 chips

Generating of DC-Free 31 chip long M-Sequence

- M-sequence c_0 contains 15 times -1 and 16 times +1. That causes an offset of 1/31.
- If that small DC offset is a real problem, what we don't heard form several chip vendors, it could be eliminated by:
  - Replacing -1 by -1-1/15 = -1,06666666666667 in c_0. That results in DC free shifted m-sequence c_{0dc_free}
- Due to the fact that we have ASK modulation for the payload, it is no problem to send that preamble based on c_{0dc_free}.

Preamble Detection with M-Sequence c_{0dc_free} as preamble



- When detecting the preamble, base on repeated m-sequence c_{0dc_free} with FIR filter, the signal coming out of the FIR filter has no side slopes, when the first m-sequence c_{0dc_free} has passed the FIR filter.
- Advantages:
  - Use of just one FIR filter or correlator for preamble detection and PSSS decoding.
  - No side slopes.
  - DC free.
  - Optimal maxima detection for multipath fading channels possible.
- Disadvantages:
  - 31 chip length instead of 32 chips as for the PSSS codes

Proposed Preamble

	Barker Code	Sequence 0	M-Sequence c0	M-Sequence c0dc_free
Optimal Detection	**no**	**no**	**yes**	**yes**
DC free	**yes**	**yes**	**no**	**yes**
32 Chip long	**no**	**yes**	**no**	**no**
# of needed FIR in Rx	**2**	**1**	**1**	**1**

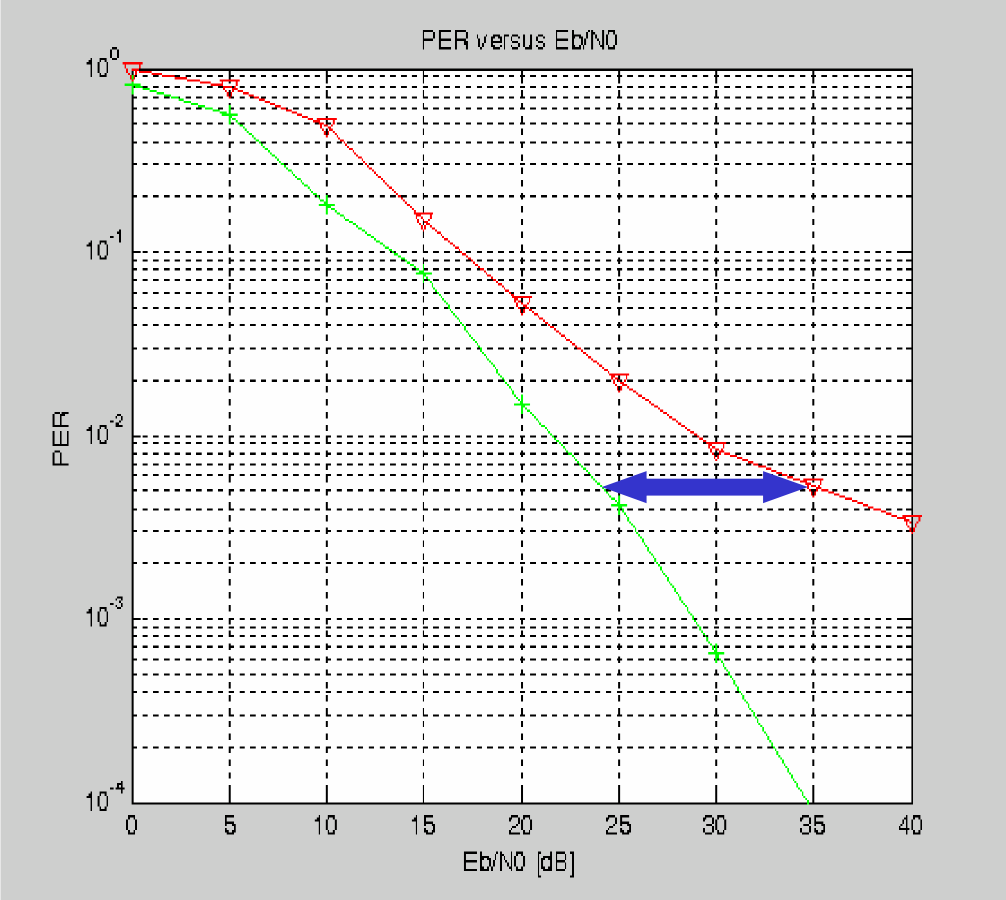
- We propose to use a preamble with repeated Sequence 0 or m-sequence $c_{0/}$ c_{0dc_free} for lowest design complexity and highest performance.
- If length of 32 chips is needed for preamble code the usage of Sequence 0 is the best solution.

Length of Proposed Preamble

	Code length	# of codes	# of repeating	preamble # of chips
Barker Code	**13**	**2**	**8**	**208**
31 chip m-sequence c0 or c0dc_free	**31**	**1**	**6**	**186**
Sequence 0	**32**	**1**	**6**	**192**
Sequence 0	**32**	**1**	**7**	**224**
31 chip m-sequence c0 or c0dc_free	**31**	**1**	**7**	**217**

- The sequence 0 or m-sequence $c_{0/}c_{0dc\_free}$ should be repeated 6 or 7 times for getting nearly same length than the original Barker code base sequence.

PER Performance PSSS 206-440 868 MHz (BPSK/ASK) – Discrete Exponential Channel, 250ns RMS Delay Spread

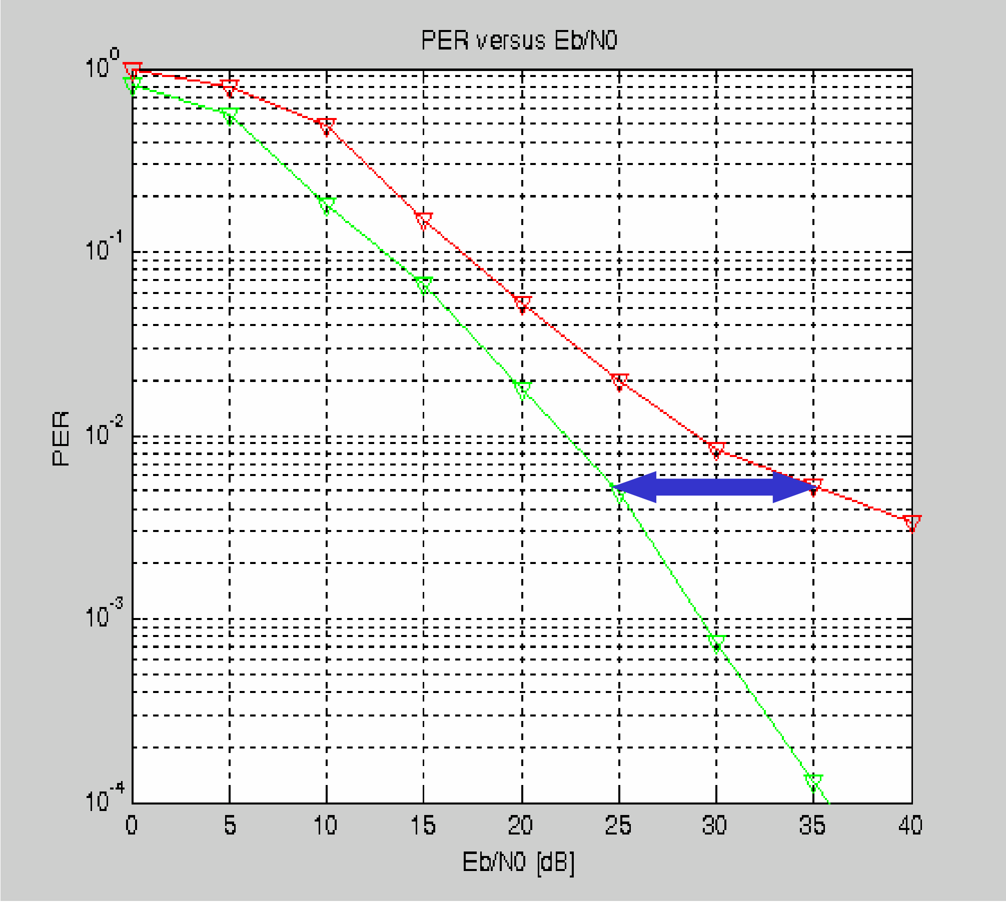


Comparison to COBI:

- Over 11 dB performance benefit over COBI16+1
  - Expected even higher performance benefit against COBI16
- Estimated 15-18 dB performance benefit over COBI8
  - Little if any performance benefit over 868MHz FSK chips for COBI8

– PSSS 206 kbit/s – COBI16+1 235 kbit/s *> 10000 Channel, no Rake receivers*

PER Performance PSSS 250-400 868 MHz (BPSK/ASK) – Discrete Exponential Channel, 250ns RMS Delay Spread

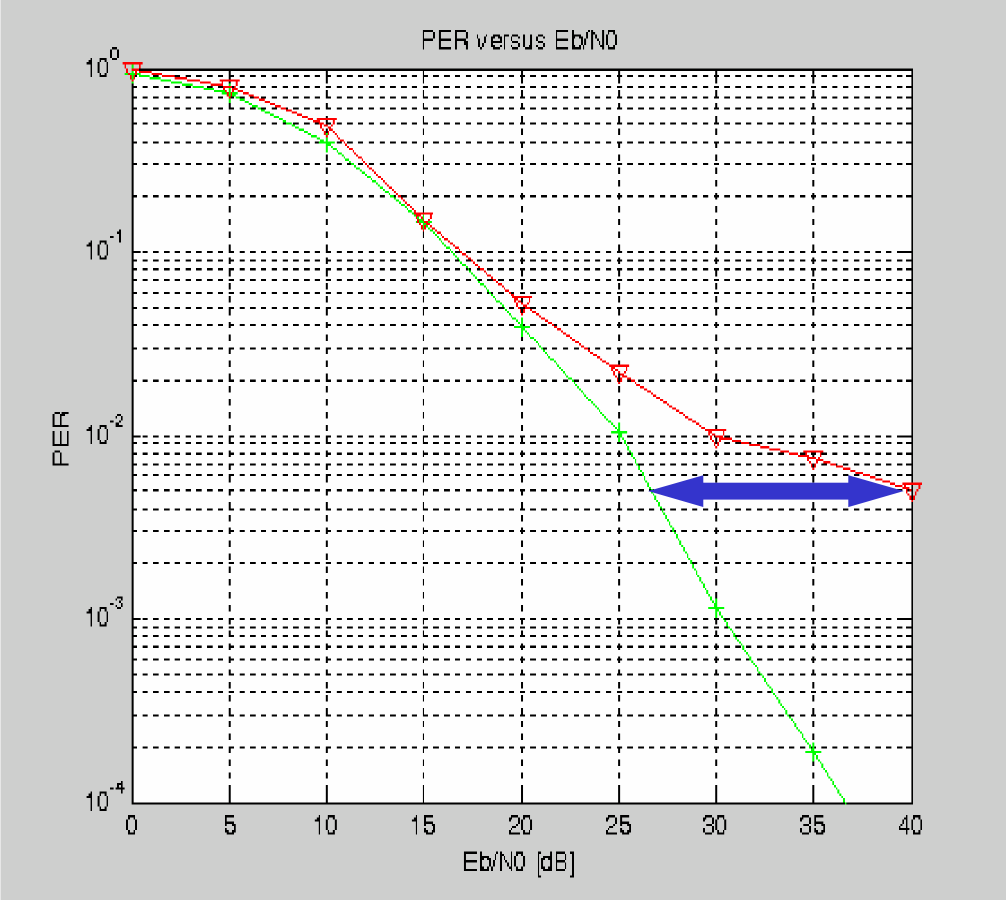


Comparison to PSSS 206-440 868 MHz

- No visible degradation of performance

– PSSS 250 kbit/s – COBI16+1 235 kbit/s *> 10000 Channel, no Rake receivers*

PER Performance PSSS 206-440 868 MHz (BPSK/ASK) – Discrete Exponential Channel, 370ns RMS Delay Spread

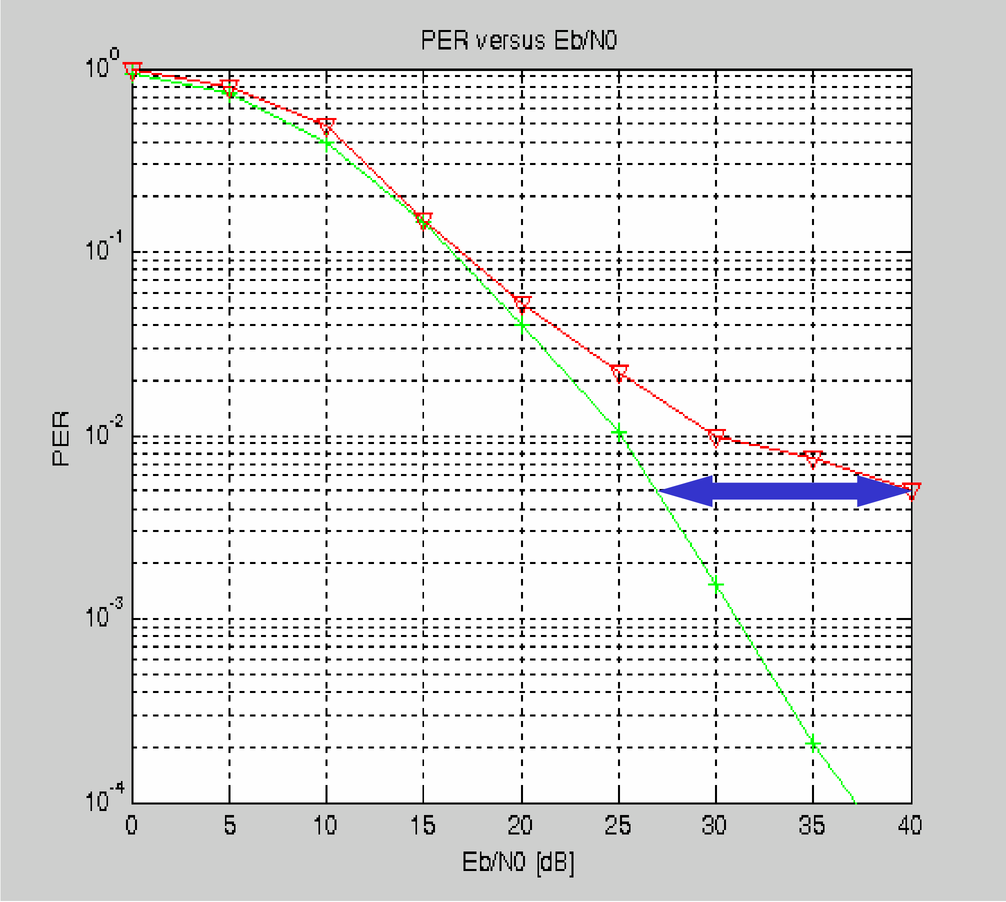


Comparison to COBI:

- Over 14 dB performance benefit over COBI16+1
  - Expected even higher performance benefit against COBI16
- Estimated 18-21 dB performance benefit over COBI8

– PSSS 206 kbit/s – COBI16+1 235 kbit/s *> 10000 Channel, no Rake receivers*

PER Performance PSSS 250-400 868 MHz (BPSK/ASK) – Discrete Exponential Channel, 370ns RMS Delay Spread

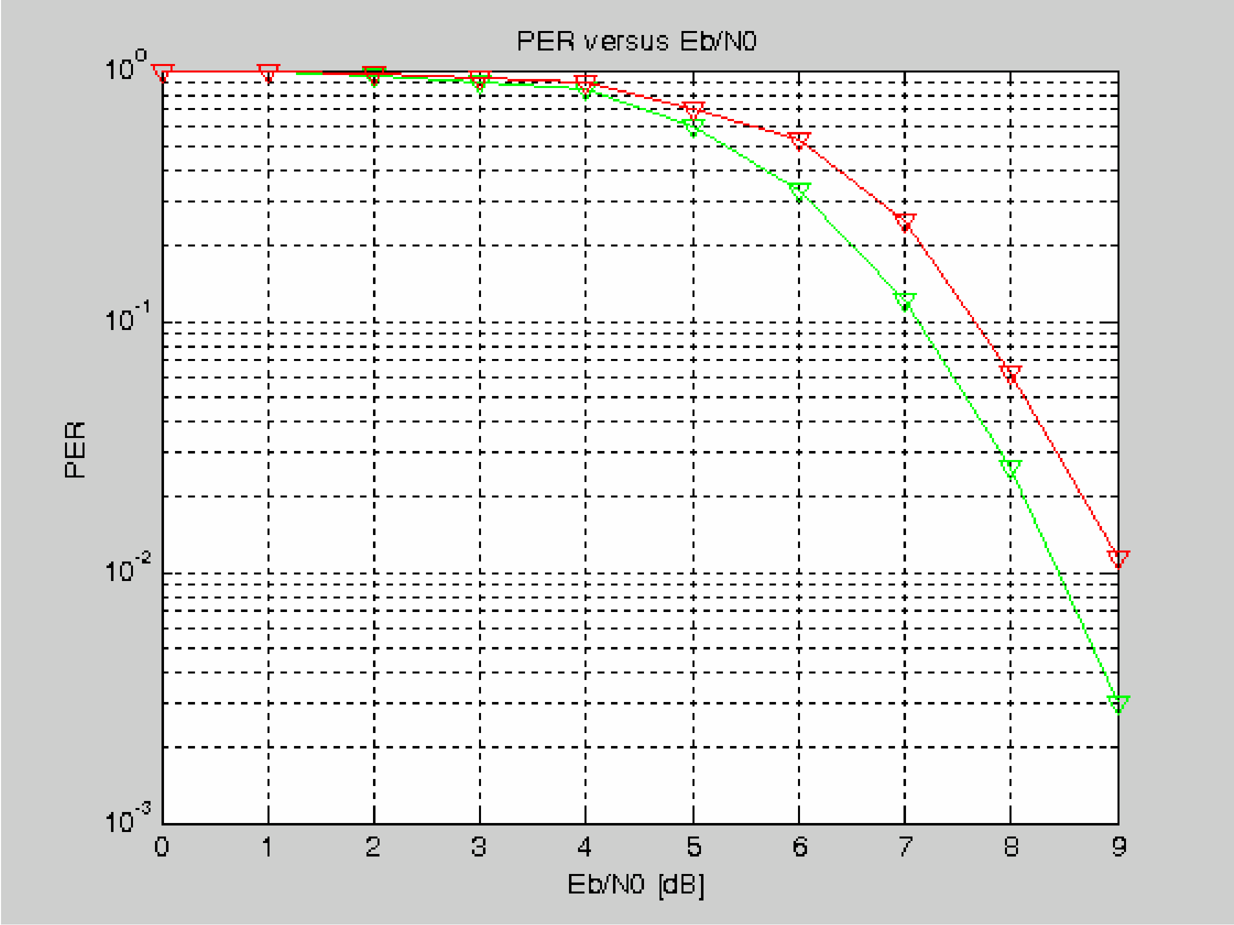


Comparison to PSSS 206-440 868 MHz

- No visible degradation of performance

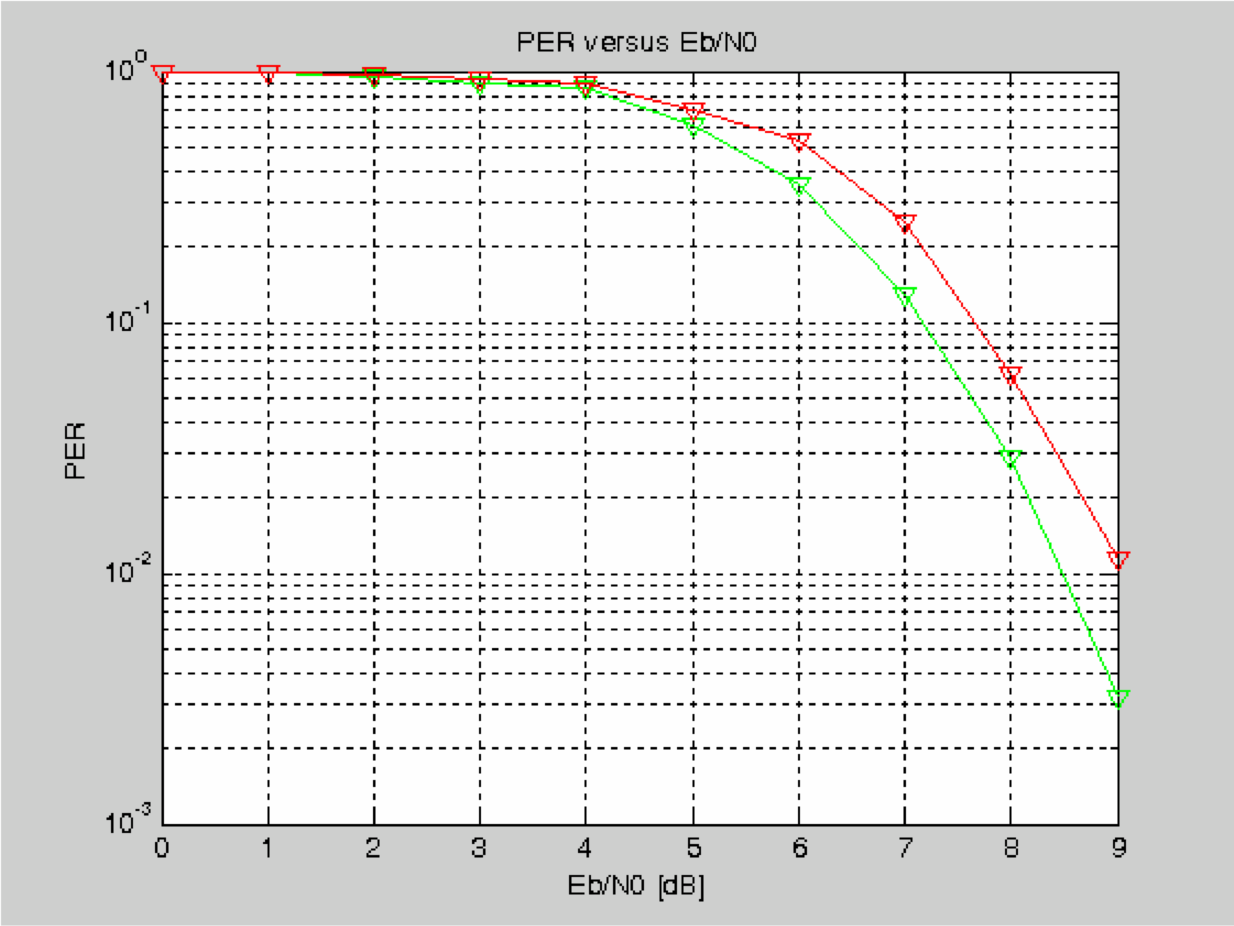
– PSSS 250 kbit/s – COBI16+1 235 kbit/s *> 10000 Channel, no Rake receivers*

AWGN Performance PSSS 206-440 868 MHz



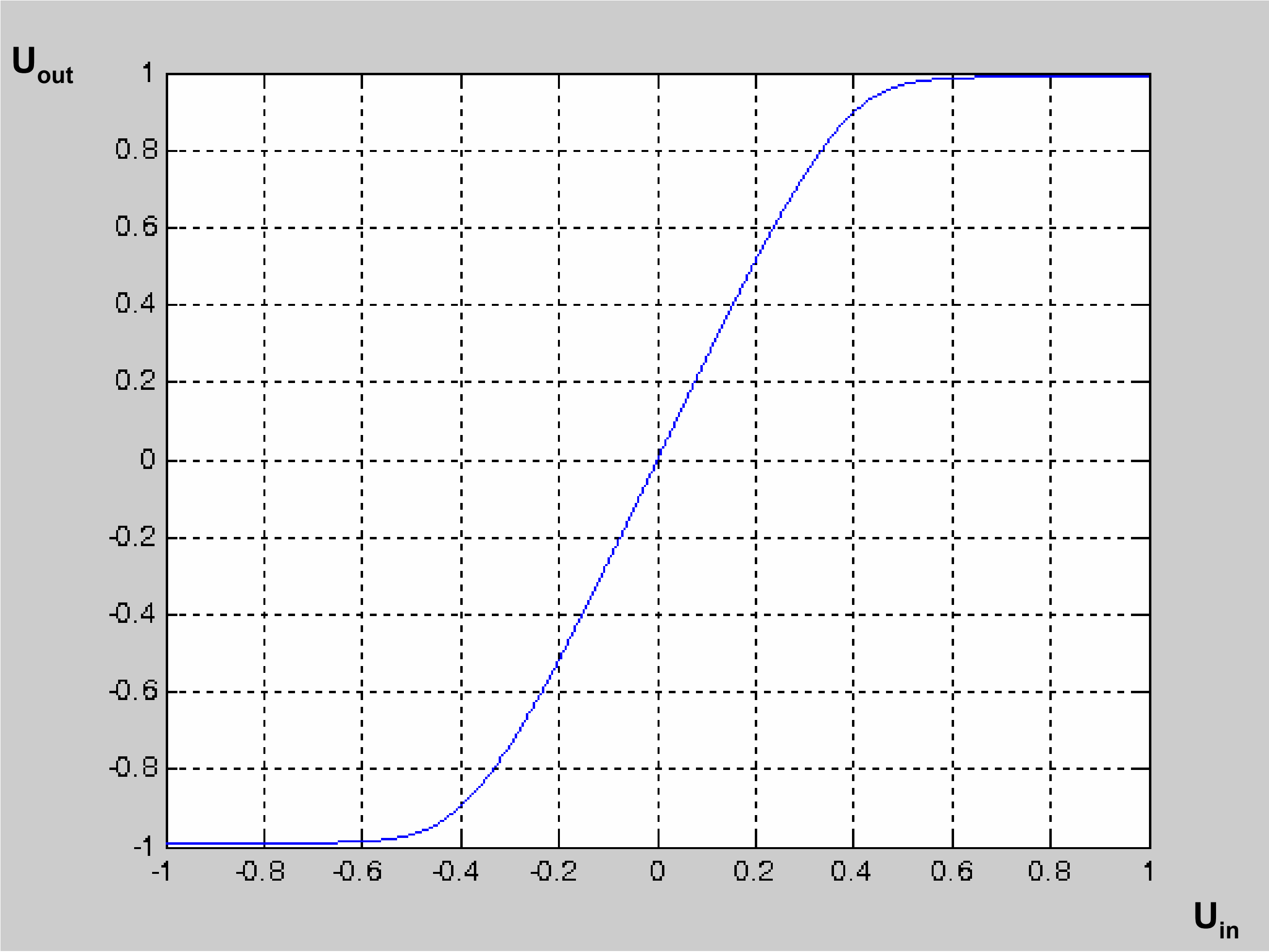
– PSSS206-440 868Mhz 206 kbit/s – COBI8 200 kbit/s

AWGN Performance PSSS 250-400 868 MHz



– PSSS250-400 868 MHz 250 kbit/s – COBI8 200 kbit/s

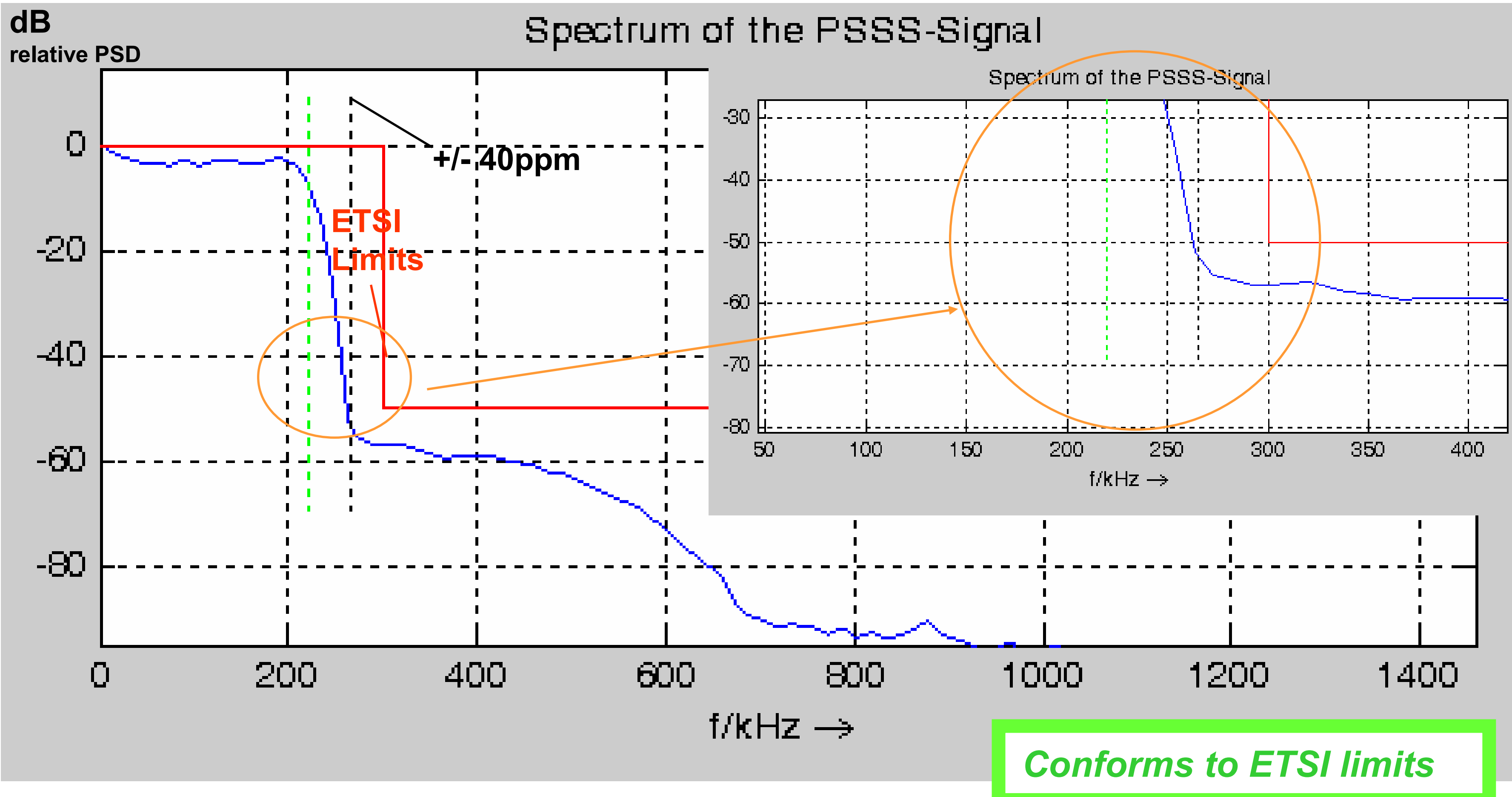
Non Linear Transfer Function of a „Real World PA“



Notes:

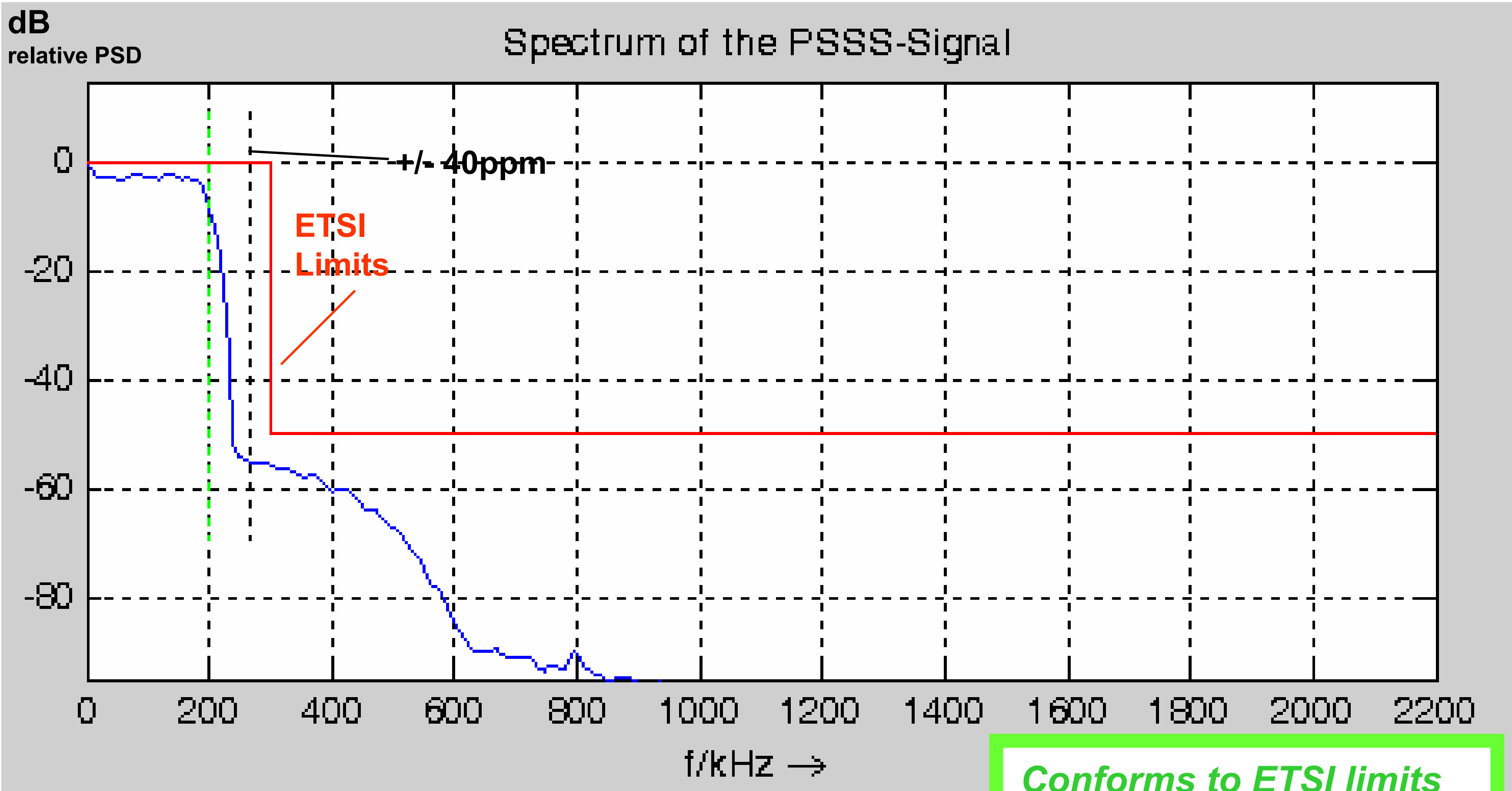
- PA is used in 868/915 MHz high volume, low cost chips today
- Scales are normalized to 1

PSD for PSSS 206-440 868 MHz (in 600 KHz channel) Baseband pulse shaping non-linear "Real World PA"



Simulations of the relative PSD in dB for the PSSS 206-440 signal:
With precoding, at 440 kchip/s, 206 kbit/s, +/- 40ppm, 50% PA drive, as specified in draft TG4b PHY text

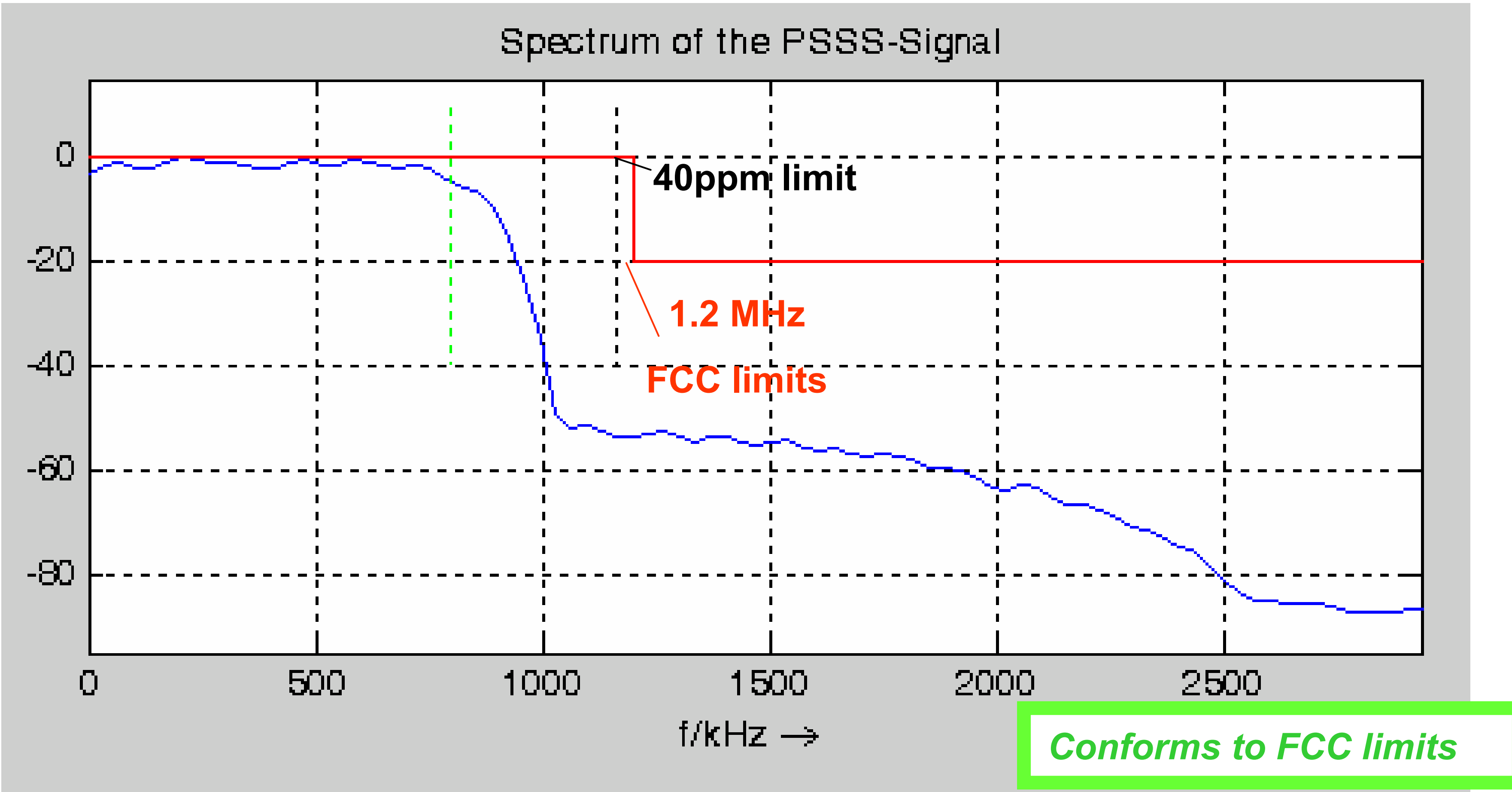
PSD for PSSS 250-400 868 MHz (in 600 KHz channel) Baseband pulse shaping non-linear "Real World PA"



Conforms to ETSI limits

Simulations of the relative PSD in dB for the PSSS 250-400 signal:
With precoding, at 400 kchip/s, 250 kbit/s, +/- 40ppm, 50% PA drive, as specified in draft TG4b PHY text

PSD for PSSS 250-1600 915 MHz (2 MHz channel) Baseband pulse shaping non-linear "Real World PA"



Simulations of the relative PSD in dB for the PSSS 250-1600 signal:
With precoding, at 1,600 kchip/s, 250 kbit/s, +/- 40ppm, 50% PA drive, as specified in draft TG4b PHY text

Comparison of TG4b PHY modes

	PSSS 206-440 868 MHz	PSSS 250-400 868 MHz	PSSS 250-1600 915 MHz	COBI16 915 Mhz	COBI8 868 MHz	E16 868 MHz
Chiprate	440 kcps	400 kcps	1,600 kcps	1,000 kcps	500 kcps	400 kcps
Bitrate	206 kbit/s	250 kbit/s	250 kbit/s	250 kbit/s	250 kbit/s	**100 kbit/s**
Spreading	15x 32-chip seq.	20x 32-chip seq.	5x 32-chip seq.	1x 16-chip seq.	1x 8-chip seq.	1x 8-chip seq.
Pulse shaping	Square root raised cosine, r = 0.1	Square root raised cosine, r = 0.1	Square root raised cosine, r = 0.15	Halfsine	Raised cosine, r = 0.2	Raised cosine, r = 0.6
No. of base sequence	1	1	1	Unclear [4]	2	Unclear [4]
Relative MP performance (PER 1e-2) **- 250 ns RMS** **- 370 ns RMS**	- 15…18 dB - 18…21 dB	- 14.5…17.5 dB - 17.5… 20.5 dB	- 17 … 19 dB - >> 20 dB	*(COBI16+1)* - 4…7 dB	*(Used as reference)* - 0dB - 0dB	***Weaker then COBI8***
Rake	Not required	Not required	Not required	Required [1]	Required [1]	Required
Modulation [3]	BPSK / ASK	BPSK / ASK	BPSK / ASK	OQPSK + BPSK	OQPSK + BPSK	OQPSK + BPSK
Fully simulated in TG4b	Yes	Yes	Yes	No [6]	No [6]	No [6]
Intellectual property	RAND-Z	RAND-Z	RAND-Z	Unclear [4, 5]	Unclear [4, 5]	Unclear [4, 5]
FCC / ETSI compliance	Yes	Yes	Yes	Yes	No [2]	No [2]
Conclusion	Highly Attractive	Highly Attractive	Highly Attractive	Less Attractive	Not Attractive	Not Attractive

Advantage
Disadvantage

1: Proposed by IIR, but not yet fully simulated (current simulation assumes ideal channel estimation)
2: No COBI variant presented in TG4b for 868MHz is ETSI compliant
3: TG4b PHY + IEEE802.15.4-2003 backward compatibility
4: IP for new coding table / correlator unclear
5: Unclear if IP in/from China for 100 kbit/s mode
6: E.g. idealized sync, no FD, change in coding

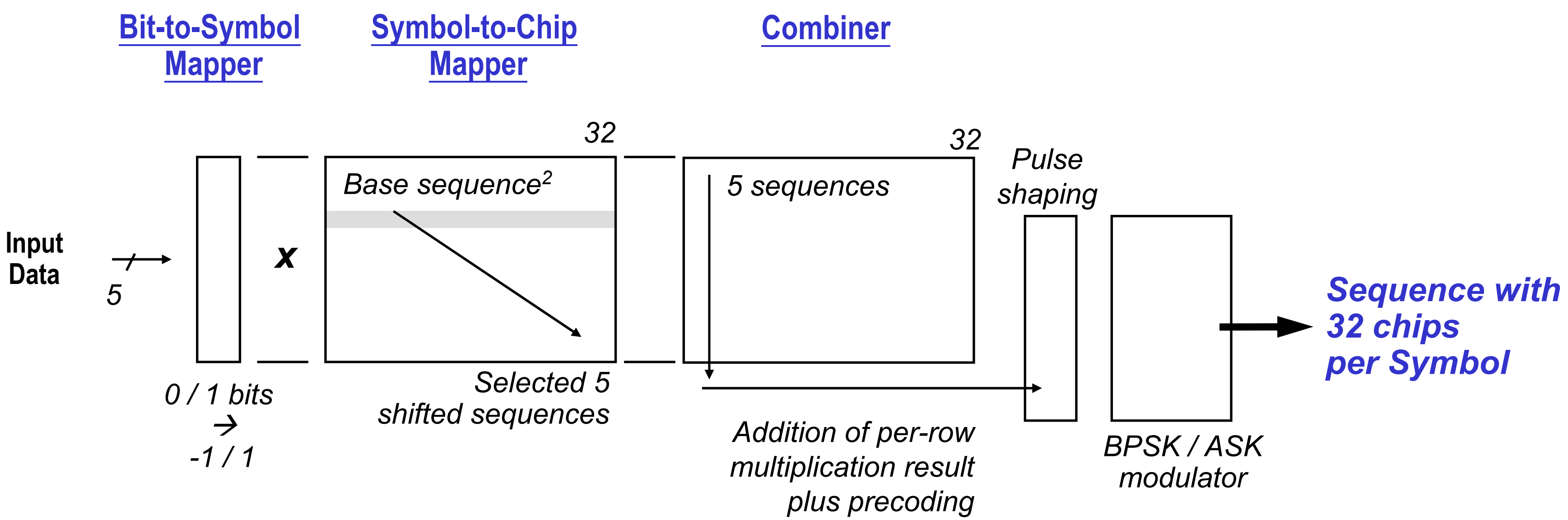
Attachments

Key requirements for sub-1-GHz band PHY

- **Bitrate over 200 kBit/s**
  - Number of permitted transactions/hr is insuffcient in IEEE802.15.4-2003 868 Mhz
    - 1% duty cycle at 20 kbit/s translates into typically only 600-800 transactions/hr
    - With > 200 kbit/s sufficient number of transactions/hr for our targeted applications
    - Disadvantage of 1% duty cycle limit turns into *protection against interference*
  - Extension from 20/40 kbit/s extends total battery lifetime by 15-40%
- **Visibly improved multipath fading robustness over IEEE802.15.4-2003 2.4 GHz**
  - Improve coverage in "challenging" RF environments – Especially commercial, industrial
  - Achieve PER < 10^{-3} at channels with at least 1 µs delay spread (non-exponential channel models)
- **Support of current RF regulatory regimes *plus* enable the use of extended bands**
  - Support 2 MHz wide channels in the USA and other countries were they are permitted
  - Support of current 600 kHz band available at 1% duty cycle in Europe today
  - Allow use of extended European bands and bands in other countries once they become available
    - Allow addition of additional 600 kHz channels as per current ETSI / ECC report (4/6 channels?)
    - Do not expect US-like wide, unrestricted bands or all egulatory domains
  - Support of more flexible channel selection method to flexibly add support for more countries
- **Backward compatibility to IEEE802.15.4-2003 (915/868 MHz)**
  - Interoperability when switched to 15.4-2003 mode
  - No fully transparent backward compatibility as in 802.11b vs. 802.11 or 802.11g vs. 802.11b
- **Low cost and low power consumption (!)**

Source: Danfoss IEEE 15-04-327-01-004b; TG4b discussion in September 2004 meeting

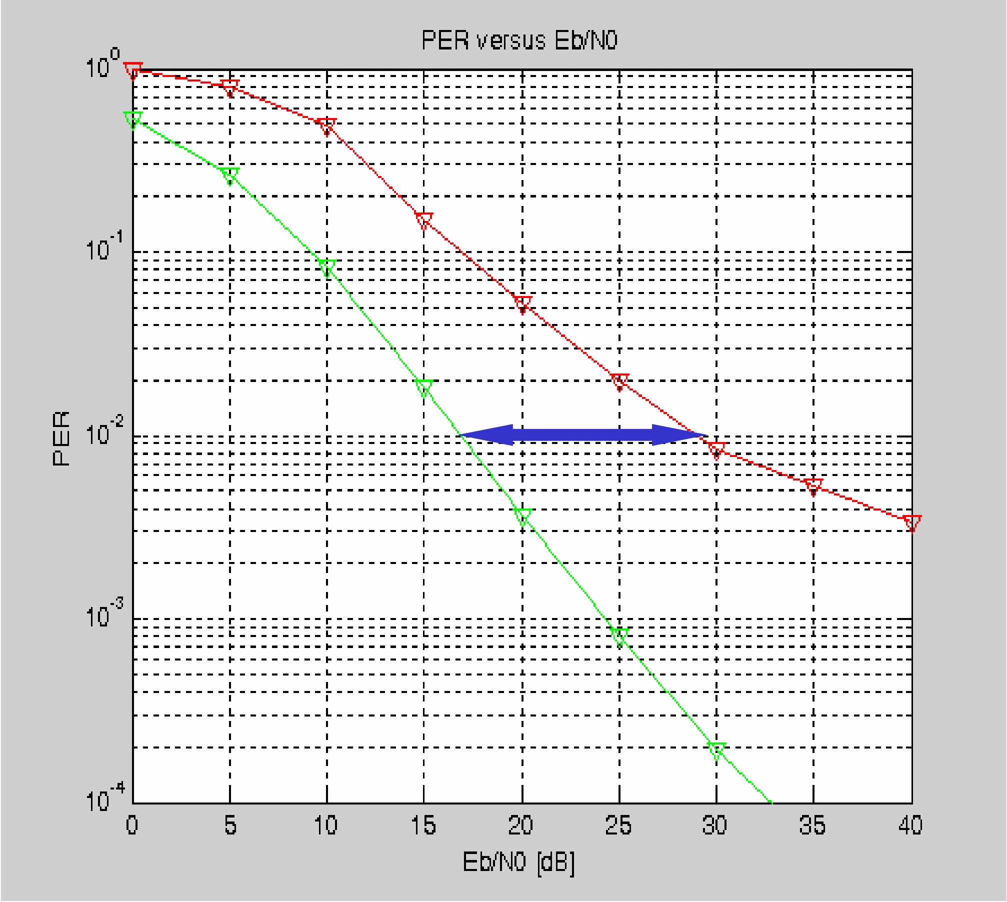
PSSS 250-1600 915 MHz BPSK/ASK (5/32 bit/s/Hz)[1]



...addition of multiple parallel sequences instead of selection of single sequence

1: Overview, please see TG4b PHY draft specification text and earlier versions of this document for details
2: Use of single base sequence simplifies implementation in Rx

PER Performance PSSS 250-1600 915 MHz (BPSK) – Discrete Exponential Channel, 250ns RMS Delay Spread

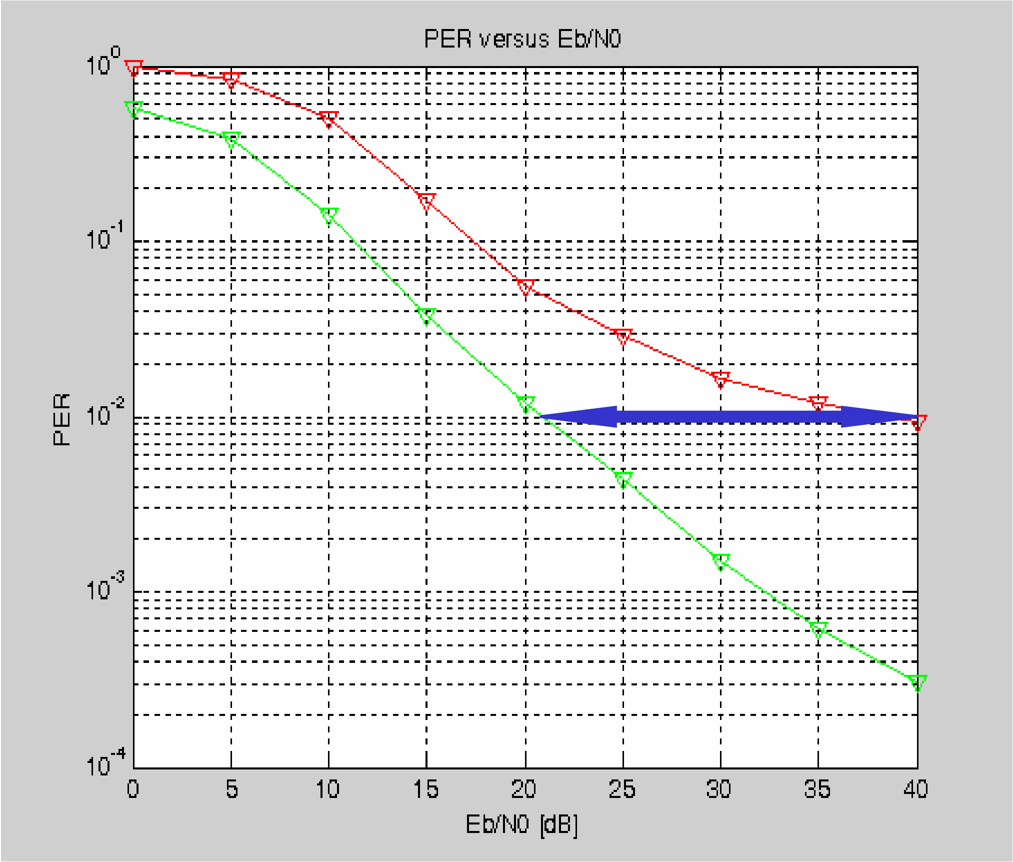


Comparison to COBI:

- Over 13 dB performance benefit over COBI16+1
  - Expected even higher performance benefit against COBI16
- Estimated 17 - 19 dB performance benefit over COBI8

– PSSS 250 kbit/s – COBI16+1 235 kbit/s *> 10000 Channel, no Rake receivers*

PER Performance PSSS 250-1600 915 MHz (BPSK) – Discrete Exponential Channel, 370ns RMS Delay Spread

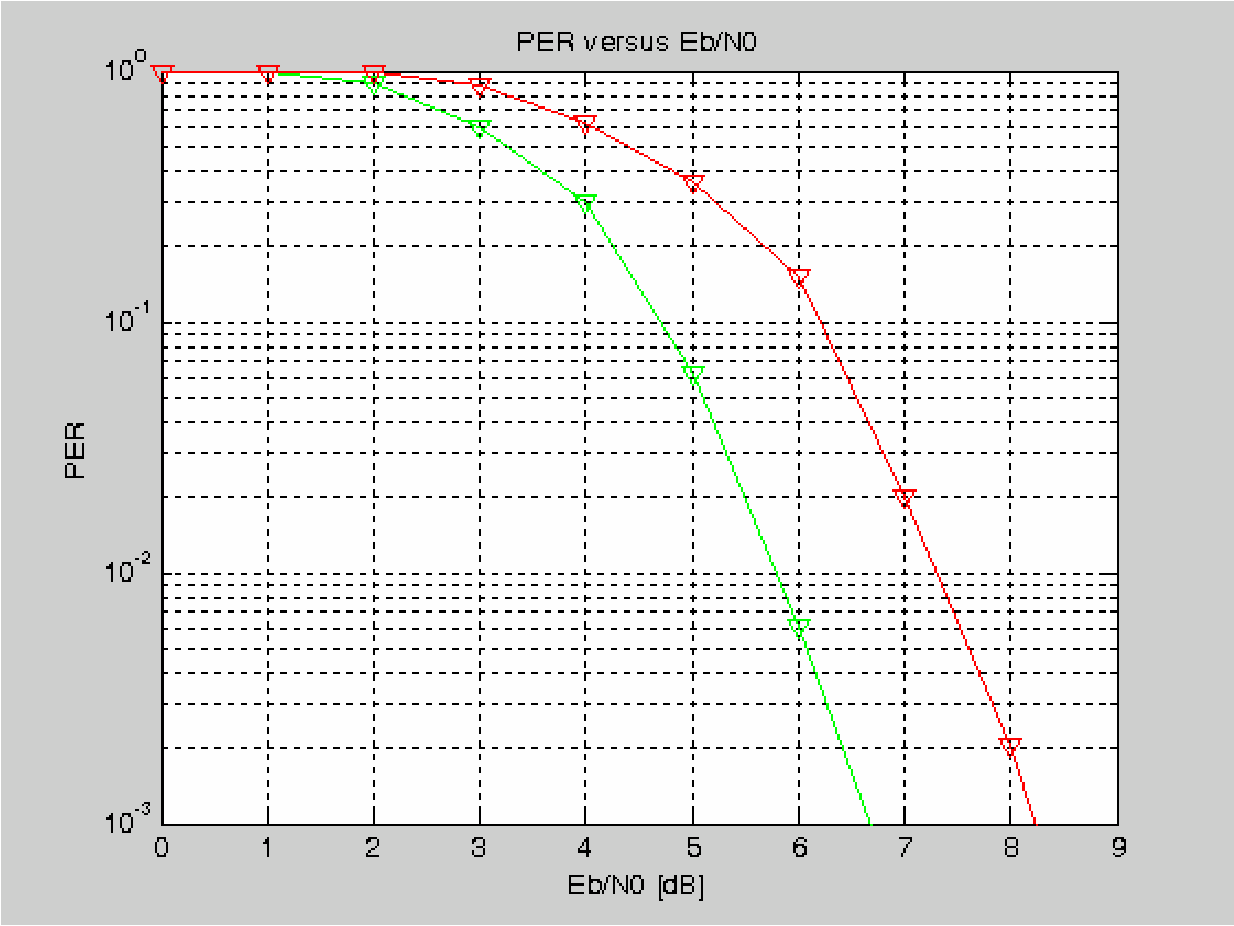


Comparison to COBI:

- Over 18 dB performance benefit over COBI16+1
  - Expected even higher performance benefit against COBI16
- >> 20 dB performance benefit over COBI8

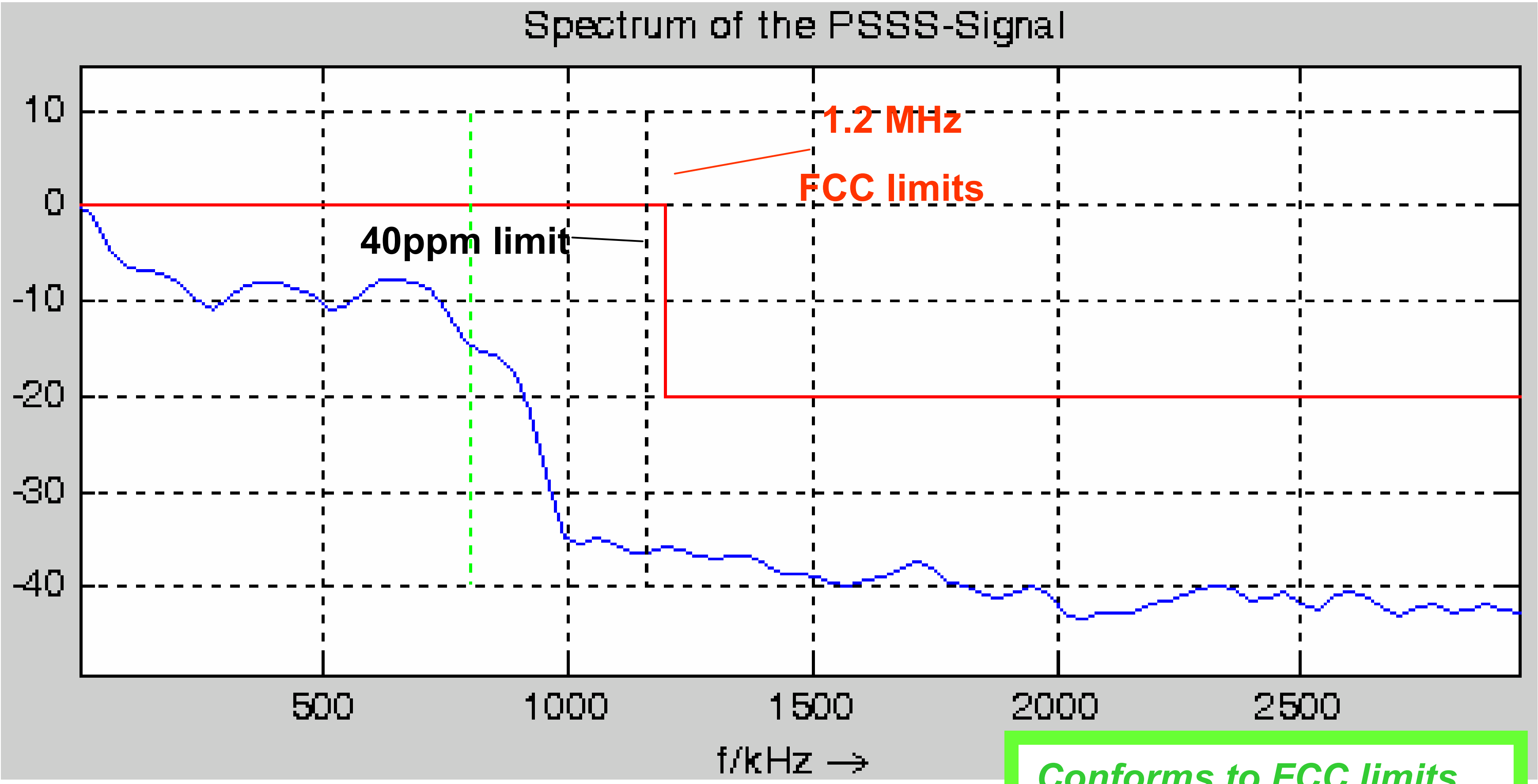
– PSSS 250 kbit/s – COBI16+1 235 kbit/s *> 10000 Channel, no Rake receivers*

AWGN Performance PSSS 250-1600 915 MHz



– PSSS 250-1600 250 kbit/s – COBI8 200 kbit/s

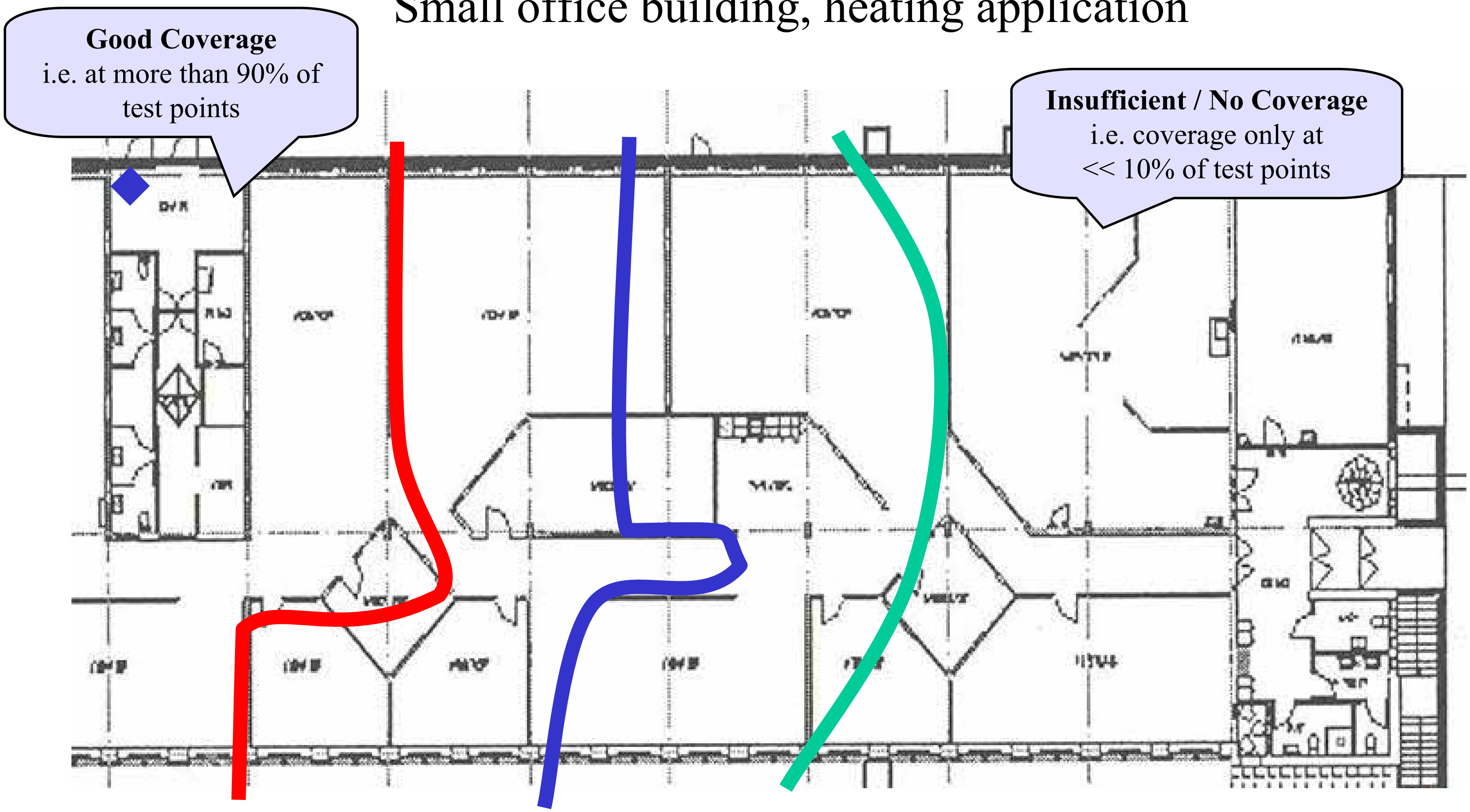
PSD for PSSS 250-1600 915 MHz with Precoding in 2 MHz channel Baseband pulse shaping non-linear RAPP model



Conforms to FCC limits

Simulations of the relative PSD in dB for the PSSS signal:
With precoding, at 1,600 kchip/s, 250 kbit/s, +/- 40ppm, 100% PA drive, as specified in draft TG4b PHY text

Results of first field measurements with PSSS and COBI16: Residential / light commercial environments – Small office building, heating application



- Test site: Office building (brick, sheetrock walls), rms delay spreads typ. 200 ... 400 ns
- Tested RF technology:
  – IEEE802.15.4-2003 (2.4 GHz), 0dBm Tx
  – PSSS 225-600, 225 kbit/s, 600 kHz (2.4 GHz), 0dBm Tx
  – COBI16+1, 235 kbit/s, 600 kHz (2.4 GHz), 0 dBm Tx

◆ Test transmitter