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

Submission Title: [IMEC Narrowband PHY Proposal]
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Abstract: [This presentation is the first part of IMEC's narrowband proposal for IEEE 802.15.6. It focuses on the PHY proposal.]

Purpose: [For discussion by the group in order to provide applications scenarios, develop channel models and discuss radio architectures for IEEE P802.15.6.]

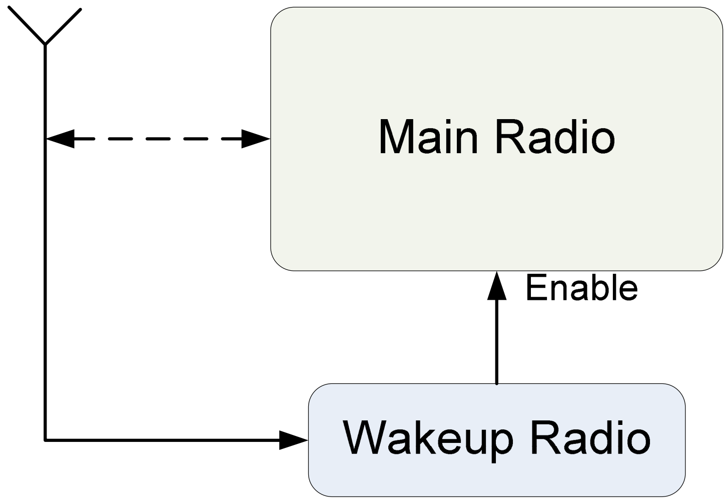
Outline

- WBAN PHY proposal
  - <u>Dual-Radio Overview</u>
  - PHY Proposal Overview
  - PHY Proposal Description
  - PHY Proposal Characteristics

802.15.6 Technical Requirements

- Miniaturized sensor nodes – small form factor
- Limited range (3 meters, extendable to 5 meters)
- Significant path loss
- Energy scavenging / battery-less operation
- Scalable data rate: 10 kbps - 10 Mbps
- Extremely low consumption power (0.1 to 1 mW)
- Different classes of QoS for high reliability, low latency, asymmetric traffic
- Energy efficient, low complexity MAC and upper layers
- High security/privacy required for certain applications

Dual-Radio System



Typical application scenarios of dual-radio system:

- Emergent/on-demand communication
- Low traffic activity
- Ultra low power consumption

IMEC’s Dual Radio Proposal

- **IMEC’s Narrowband Proposal:**
  - Main radio and wakeup radio in the ISM band 2.4 – 2.485 GHz with possible 2.36 – 2.4 GHz MBAN extension.
  - Hardware of two radios can be shared.
  - Wakeup radio overrules the MAC of the main radio in case of strict latency and/or high energy efficiency requirements.
- **Part 1 of the proposal**
  - PHY proposal in the main radio.
- **Part 2 of the proposal**
  - MAC proposal in the main radio.
  - Wakeup radio proposal.

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Overview

- **Proposal PHY operation: duty-cycled main radio with reliable wake-up scheme for achieving key requirements of IEEE 802.15.6 WBAN**
- **Frequency band: ISM band 2.4 – 2.485 GHz with possible 2.36 – 2.4 GHz MBAN extension**
- **Transmit power should be below 1 mW to satisfy local specific absorption rate (SAR) regulation**
- **Scalable date rate ranged from 16 kbps to 16 Mbps**
- **Receiver sensitivity should be better than -75 dBm**
- **19 channels are assigned in the ISM band and 40 channels are allocated in the 2.36 – 2.4 GHz band to support the coexistence of piconets**
- **OOK/GFSK transmission supporting direct sequence spreading spectrum (DSSS)**
- **Root raised cosine or Gaussian is used as the reference pulse shaper**
- **Optional error correction is used to achieve flexibility and reliability**
- **Cyclic redundancy check (CRC) is used to verify the packet integrity**

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Packet Structure

SHR Preamble	PHY Header	Data Field

- **SHR preamble includes synchronization header (SHR) and start frame delimiter (SFD)**
- **Data field includes MAC header, payload, and the cyclic redundancy check (CRC)**
  - Systematic block codes are used, which allows for optional decoding
    - The (15,10) shortened Hamming code is proposed to use
    - This code can correct all single errors and detect all double errors in each code word
    - We are open to other systematic codes
  - CRC is used to check whether the packet has been correctively received
    - CRC-16-CCITT is proposed to use
    - Widely used in 802.15.4, X.25, V.41, CDMA, Bluetooth, XMODEM, HDLC, PPP, IrDA, BACnet

Table 1. Length of different parts in the packet.

	SHR	SFD	Data field (uncoded)	Data field (coded)	CRC
Length (in bits)	32	8	0~1016	0~1530	16

Channel Number

- **40 channels in 2.36-2.4 GHz band with 1 MHz bandwidth**

$$F_c = (2360.5 + k - 1)\text{MHz, for } k = 1, 2, ..., 40$$

  - Normally low-data rate applications are operated
  - Current frequency band proposal limits the bandwidth of 1 MHz

- **19 channels in 2.4 GHz ISM band with 4 MHz bandwidth**

$$F_c = (2404 + 4 \times (k - 41))\text{MHz, for } k = 41, 42, ..., 59$$

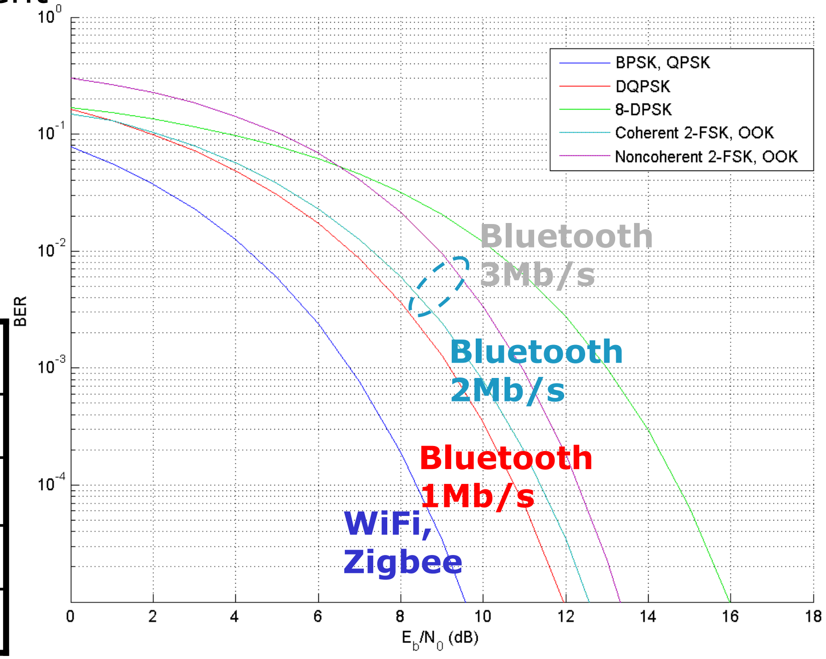
  - Higher bandwidth to support higher data rate
  - Lower guardband (2400-2402 MHz) and higher guard band (2482-2483.5 MHz) to avoid interferences with other bands

Modulation

- **Choosing modulation scheme is a trade off between bandwidth efficiency and energy per bit requirement**
  - Low power design desires low energy per bit requirement
  - Low power design desires simple implementation

- **<u>We propose to use OOK or GFSK</u>**
  - It has reasonable energy per bit requirement
    - ➢ This requirement is proved to be valid in successful standards (Bluetooth 2Mb/s)
  - It has been proved to facilitate ultra-low power receiver design
    - ➢ Current commercial low power receivers consume more than 30mW
    - ➢ With OOK, it is shown that the receiver could consume less than 1mW [4]-[6]

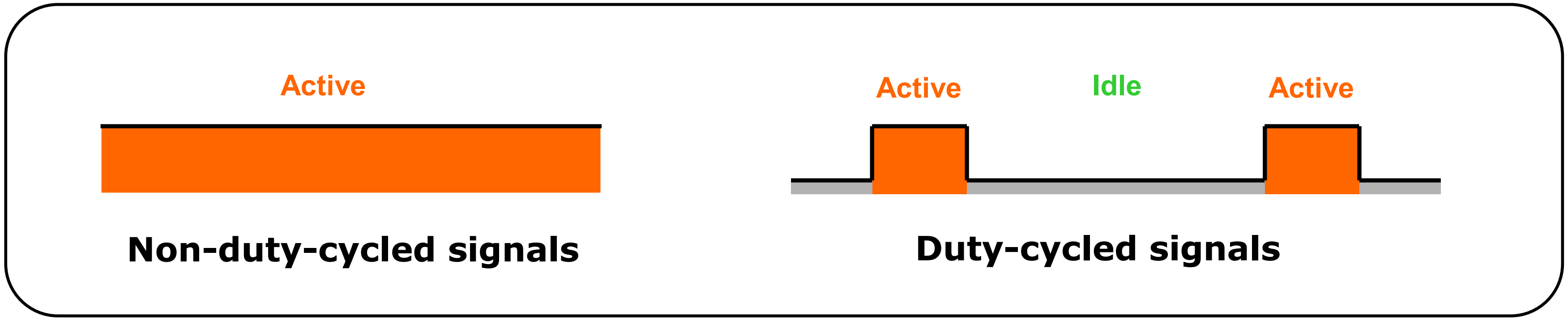
Standard	Proprietary	Zigbee		Bluetooth
Manufacturer	Nordic	Ti	Freescale	Skyworks
Product Number	RF24L01	CC2420	MC13192	CX72303
RX power [mW]	33.3	33.8	99.9	43.2
TX power [mW]	33.9	31.3	82.0	34.2



Direct-Sequence Spread Spectrum (DSSS)

- **Our proposed bandwidth is normally wider than the minimum required bandwidth for the 802.15.6 supported data rate**
  - Satisfy the condition to achieve DSSS
- **The use of DSSS is desirable to achieve scalability**
  - Scalable data rate: for a given bandwidth and modulation scheme, the change of the length of spreading code could result in the change of data rate
  - Scalable processing gain: the longer length of spreading code could result in higher processing gain
- **DSSS is widely used in different systems and standards, e.g.**
  - Cordless phones operating in the 900 MHz, 2.4 GHZ and 5.8 GHz bands
  - IEEE 802.11b
  - 802.15.4
  - 802.15.4a
- **We limit the maximum length of spread code to be 64**
  - See our PHR Data Rate part for details

Duty-Cycling



- **Our proposed bandwidth is normally wider than the minimum required bandwidth for the 802.15.6 supported data rate**
  - Allow the use of duty cycling

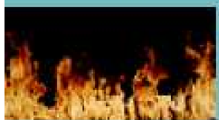
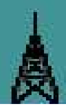
- **The use of duty cycling is desirable to achieve scalability**
  - Scalable data rate: the change of the duty cycle results in the change of data rate

- **Duty cycling is suitable to achieve ultra low power**
  - Switch on the radio front-ends only when pulses must be transmitted or received

- **We can achieve the duty cycle as low as 0.39%**
  - Desirable for ultra-low power design
  - Energy scavenging could be used to achieve autonomous system

Power Consumption

- **The power consumption of 1 mW is a reasonable target [4]-[6].**
- **Energy scavenging could be used to achieve autonomous system.**

Energy Source		Source Characteristics	Efficiency	Harvested Power
Photovoltaic (PV) 	Indoor	0.1 mW/cm²	10-24 %	10 μW/cm²
	Outdoor	100 mW/cm²		10 mW/cm²
Vibration/Motion 	Human	0.5m @1Hz 1 m/s² @50 Hz	Max. Power is source dependent	4 μW/cm²
	Machine	1m @5 Hz 10m/s² @1kHz		100 μW/cm²
Thermal Energy 	Human	20 mW/cm²	± 0.1 %	25 μW/cm²
	Machine	100 mW/cm²	±3 %	1-10 mW/cm²
RF 	GSM 900 MHz 1800 MHz	0.3 0.1 μW/cm²	± 50 %	0.1 μW/cm²

Pulse-shaping (1)

- **For narrowband communication systems, efficient use of frequency spectrum is important;**
- **Pure OOK/FSK modulation is poor in spectrum efficiency: modulated signal exhibits high level side-lobe and slow roll-off;**
- **Pulse-shaping techniques help to improve spectrum efficiency by smoothening the transitions between bit "0" and "1";**
- **Practical pulse shapes:**
  - Trapezoidal, including rectangular and triangular;
  - Exponential;
  - Gaussian;
  - Raised cosine;
  - …
- **They feature different spectrum efficiency and hardware complexity;**

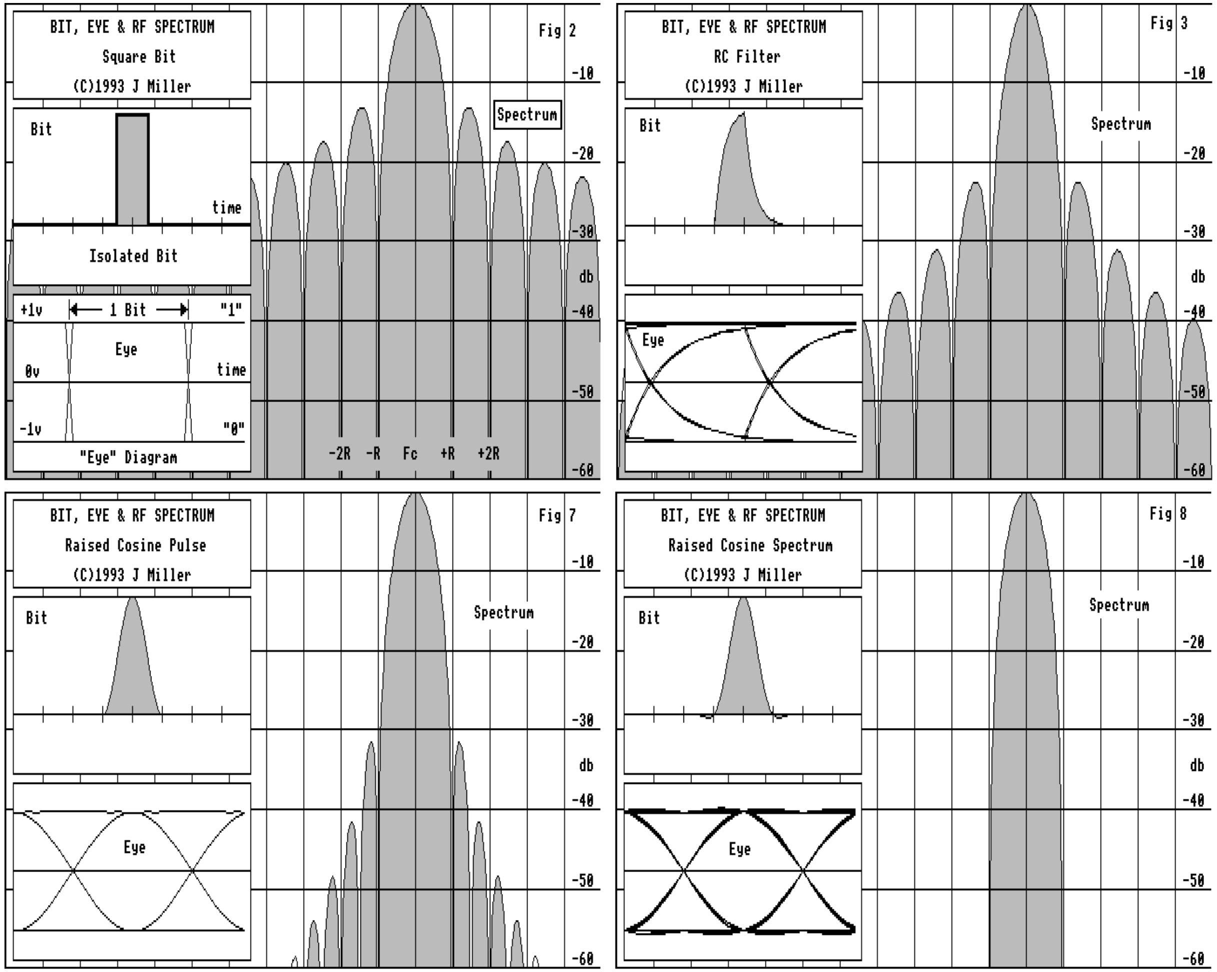
Pulse-shaping (2)

- **Trapezoidal pulse shapes are easy to generate, however they suffer from slow roll-off and high sideband level:**
  - Triangular pulse offers better spectrum efficiency compared to rectangular pulse, but still poorer than other pulse shapes;
- **Exponential pulse shapes can be generated in analog domain conveniently (RC filtering):**
  - Envelope becomes asymmetric;
  - Faster roll-off and lower sideband compared to trapezoidal pulses;
  - Trade-off between ISI and sideband suppression;
- **Gaussian pulse-shaping is mainly used in frequency/phase modulation instead of OOK/amplitude modulation:**
  - Suppress sideband in GFSK and GMSK modulations;
  - Degrade ISI performance;
- **Raised-cosine filtering is widely used pulse-shaping:**
  - Definitive bandwidth and minimized sidebands;
  - Immunity to ISI;
  - Realizable in digital domain with moderate complexity;

Pulse-shaping (3)

No ISI, poor spectrum efficiency

ISI, good spectrum efficiency



No ISI, better spectrum efficiency

No ISI, best spectrum efficiency

* http://www.amsat.org/amsat/articles/g3ruh/108.html

Pulse-shaping (4)

- **Pulse shaping is desirable to achieve spectrum efficiency and minimize interference to other systems**
- **We propose different reference pulse shapes in different modulations**
- **We propose to use <u>raised-cosine shape in OOK modulation</u>**
  - Roll-off factor = 0.2, small leakage outside of the bandwidth
  - Used in 802.15.4
- **We propose to use <u>Gaussian shape in FSK modulation</u>**
  - Bandwidth time is 0.5
  - The modulation index is 0.3
  - Used in 802.15.1
- **A standard compliant transmitter should make the cross-correlation function of the transmitted pulse shape and the reference pulse shape**
  - The main lobe is greater or equal to 0.8 for one fourth of the chip duration
  - Any sidelobe is no greater than 0.3

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Raw PHY Data Rate (1)

- **The duty cycle and DSSS could achieve scalable data rate for a fixed bandwidth**
  - Low duty cycle could save power consumption
  - Long length of PN will increase the reliability of the receiver
- **Scalable data rate: <u>16 Mbps, 4 Mbps, 1 Mbps, 256 Kbps, 64 Kbps, 16 Kbps</u>**
- **Each channel has a bandwidth of 4 MHz in 2.4 GHz band and 1 MHz in 2.36-2.4 GHz band**
  - Channel bonding is used to support high data rate (only one mode)
  - Simultaneously use four separate channels to transmit data in 2.4 GHz
  - Channel bonding is also supported in 802.11n

Table 1. Operating modes at high and mid data rates

Data Rate	Bandwidth	Length of PN	Duty Cycle	Mode Index
16 Mbps	4 MHz + channel bonding	1	100%	1.a1
4 Mbps	4 MHz	1	100%	2.a1
1 Mbps	4 MHz	1	25%	3.a1
		2	50%	3.a2
		4	100%	3.a3
	1 MHz	1	100%	3.b1

Raw PHY Data Rate (2)

Table 2. Operating modes at low data rate

Data Rate	Bandwidth	Length of PN	Duty Cycle	Mode
256 Kbps	4 MHz	1	6.25%	4.a1
		4	25%	4.a2
		16	100%	4.a3
	1 MHz	1	25%	4.b1
		2	50%	4.b2
		4	100%	4.b3
64 Kbps	4 MHz	1	1.5625%	5.a1
		4	6.25%	5.a2
		16	25%	5.a3
		64	100%	5.a4
	1 MHz	1	6.25%	5.b1
		4	25%	5.b2
		16	100%	5.b3

Raw PHY Data Rate (3)

- **Scalable power consumption: 0.39%~100%**
- **Scalable processing + duty cycling gain: up to 24dB**

Table 3. Operating modes at very low data rate

Data Rate	Bandwidth	Length of PN	Duty Cycle	Mode
16 Kbps	4 MHz	1	0.39%	6.a1
		4	1.5625%	6.a2
		16	6.25%	6.a3
		64	25%	6.a4
	1 MHz	1	1.5625%	6.b1
		4	6.25%	6.b2
		16	25%	6.b3
		64	100%	6.b4

Power Emission Level

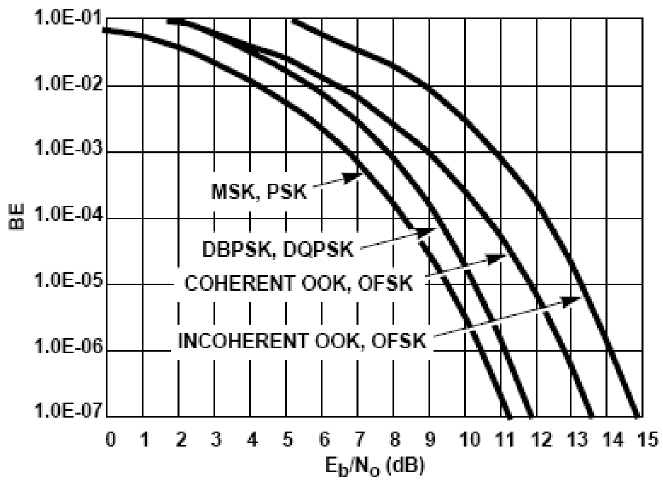
- **Maximum 1 mW for effective radiated power**
  - Under the local specific absorption rate (SAR) regulation
  - Tx power should be in US < 1.6 mW and in EU < 20 mW [1]
  - GE’s proposed band limits the power to below 1 mW

- **Pulse shape is used to reduce power leakage to adjacent channels**

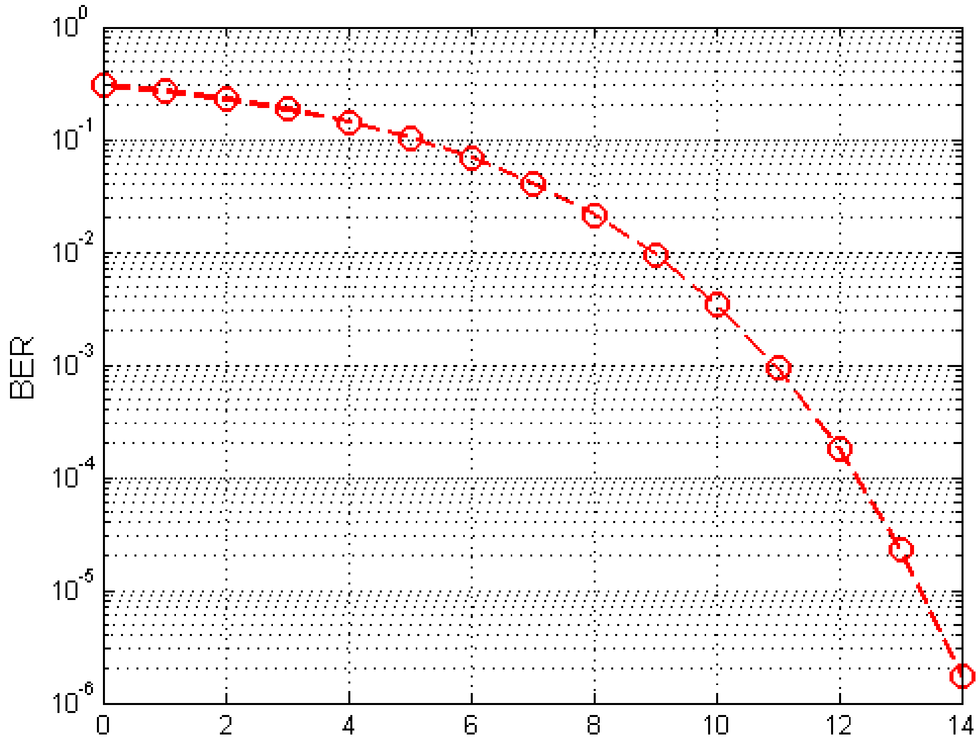
Link Budget Analysis (1)

Receiver sensitivity $P_r = Noisefloor + SNR + NF$

- For PER=0.1 with a 256 octet PSDU [3], BER=5.1444e-005 for uncoded systems
- Incoherent OOK/GFSK modulation, Eb/No=13 dB
- Required signal to noise ratio: SNR = (Eb/No)*(R/B)
  - Scalable B/R in our proposal: 0, 6, 12, 18, 24 dB
  - Scalable SNR: 13, 7, 1, -5, -11 dB
- Noise floor: *Noisefloor* = -174 dBm + 10log(B)
  - Two possible bandwidths in our proposal: 1 and 4 MHz
- Noise figure: a value of 20 dB is achievable
- In the worst case, receiver sensitivity is -75 dBm
- **<u>We propose a receiver sensitivity of -75 dBm for IEEE 802.15.6</u>**



Link Budget Analysis (2)



Bit-error-rate (BER) versus Eb/No of OOK with non-coherent detector

Link Budget Analysis (3)

Tolerable Pathloss $$P_l = P_t - P_r + P_p + P_d$$

- **Transmit power P_t is 0 dBm**
- **Receiver sensitivity P_r is -75 dBm**
- **Scalable processing gain (P_p) + duty cycling gain (P_d)**

P_p +P_d (in dB)	**0**	**6**	**12**	**18**	**24**
Data rate	16Mbps, 4Mbps, 1Mbps,	1Mbps, 256 Kbps	256 Kbps, 64 Kbps	64 Kbps, 16 Kbps	16 Kbps
Mode	1.X, 2.X, 3.bX	3.aX, 4.bX	4.aX, 5.bX	5.aX, 6.bX	6.aX
P_l (in dB)	75	81	87	93	99

- **Considered scenario is CM4 2.4 GHz channel at a distance of 3m [3]**

Scenario	**LOS/standing**	**LOS/walking**	**NLOS/standing**	**NLOS/walking**
Pathloss	56.04	52.14	63.12	63.98
Data Rate	<= 16Mbps	<= 16Mbps	<= 16Mbps	<= 16Mbps

Packet Error Rate: Computation Method

- **Each packet has a length of 256 octet payload [2]**
- **A link success probability of 95% is used [1]**
  - The small-scale fading is considered
  - Pathloss is changed every packet
  - Ignore the packets when the pathloss exceeds the 5% largest point
  - With the probability density function of pathloss, we can compute a PER averaged over different pathlosses

$$SNR = P_t + P_a + P_p + P_d - P_l - Noisefloor - NF - L$$

- Transmit power P_t: 0 dBm
- Antenna gain P_a: 3 dBi
- Processing gain (P_p) + duty cycling gain (P_d): ranging from 0 to 24 dB
- Pathloss (P_l): changed every packet
- Noise floor: -114 or -108 dBm
- Noise figure (NF): 20 dB
- Additional Losses (L) - matched filter loss, board/digital losses: 7 dB

Packet Error Rate: Results (1)

- **Considered scenario is CM4 2.4 GHz channel (Section 8.2.9 in [3])**
- **We assume the worst case: Rayleigh fading**
  - The Ricean factor in LOS is not provided in the channel model report

High data rate modes (4 Mbps or 16 Mbps)

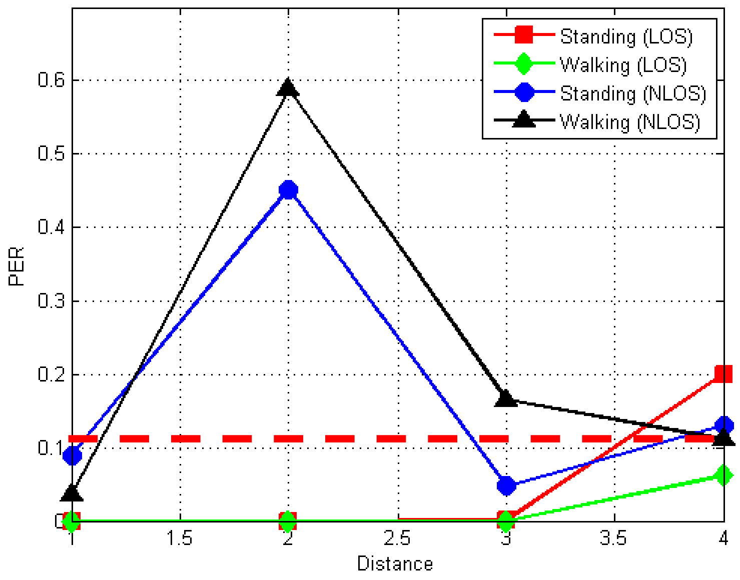


Fig1. Uncoded PER for different scenarios.

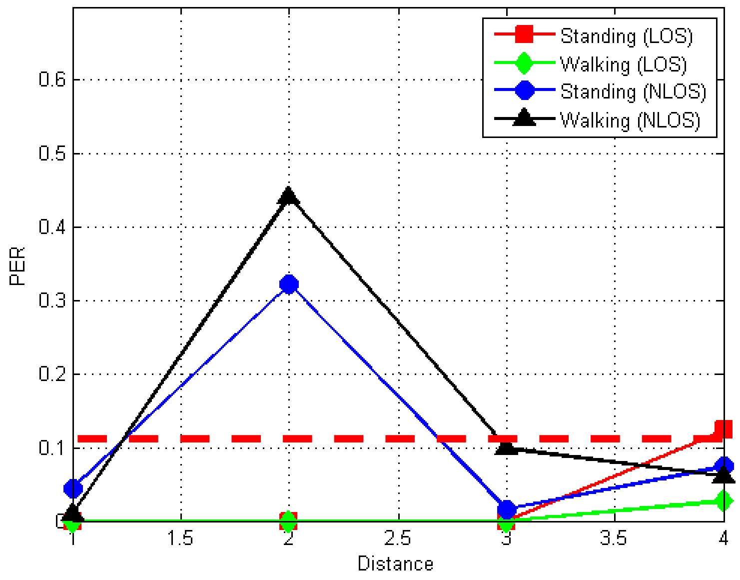


Fig2. Coded PER for different scenarios.

Packet Error Rate: Results (2)

Mid data rate modes (1 Mbps)

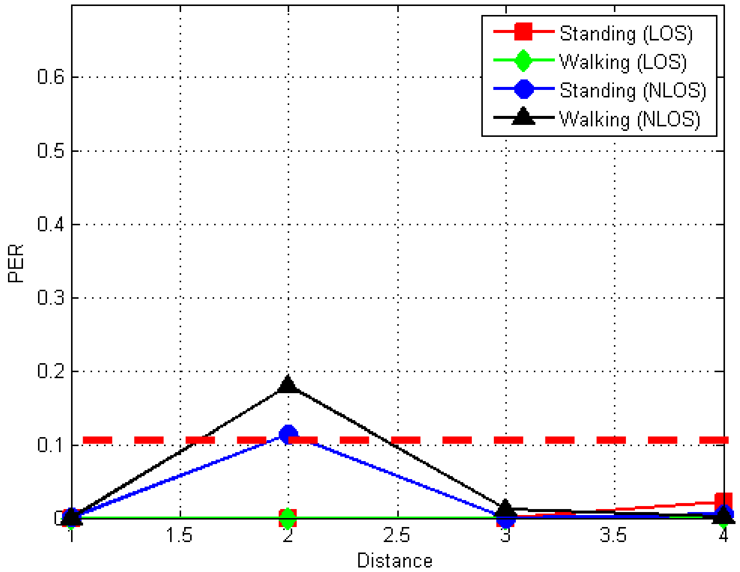


Fig1. Uncoded PER for different scenarios.

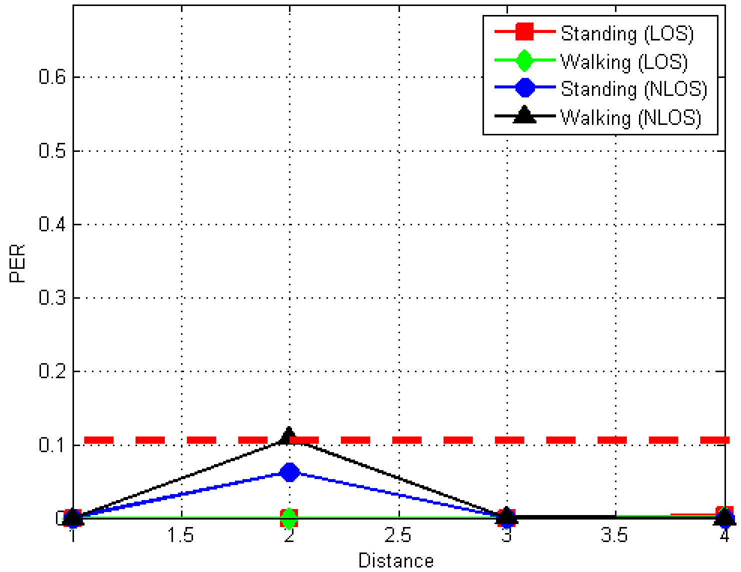


Fig2. Coded PER for different scenarios.

- **High data rate modes (> 1Mbps) can cover most of the cases**
- **Mid data rate modes (1Mbps) can cover almost all the cases**
- **Low data rate modes (<1Mbps) can cover all the cases**

Interference & Coexistance

- **The DSSS is used to**
  - provide processing gain to protect interferences from other systems
  - reduce the interference to narrowband systems
- **The duty cycling is used to**
  - provide duty cycling gain
  - reduce the interference to and from continuous-time systems
- **Pulse shaping is used to reduce interferences to adjacent channels**
- **Low transmission power can avoid interferences to other systems**
- **Sufficient channels are assigned to allow the coexistence of 10 piconets**
  - 19 channels in 2.4 GHz ISM band
  - 40 channels in 2.36-2.4 GHz
- **Block codes are optionally used to improve the performance**
  - Link budget calculation shows that interference will be the main factor to degrade performance
  - SIR (P_d/P_i) should be above 13 dB for uncoded systems
  - SIR (P_d/P_i) should be above 10 dB for coded systems

Reliability

- **The duty cycling could achieve duty-cycling gain**
- **The DSSS could achieve processing gain**
- **Optional error correction**

Scalability

- **The duty cycling and DSSS is used to achieve**
  - scalable data rate
  - scalable processing gain
  - scalable duty cycling gain
- **Channel bonding is used to support higher data rate**

Quality of Service & Topology

- **Please see Part 2 of the proposal.**

Power Consumption

- **The scalable duty cycling allows different power consumption in different modes: 0.39%~100%**

Bonus Point

- **The proposed PHY could be supported by the superregenarative receiver**
  - **Pros: high gain, few components, simple, low cost, low power**
  - **It can achieve a power consumption of 380 μW [4]**

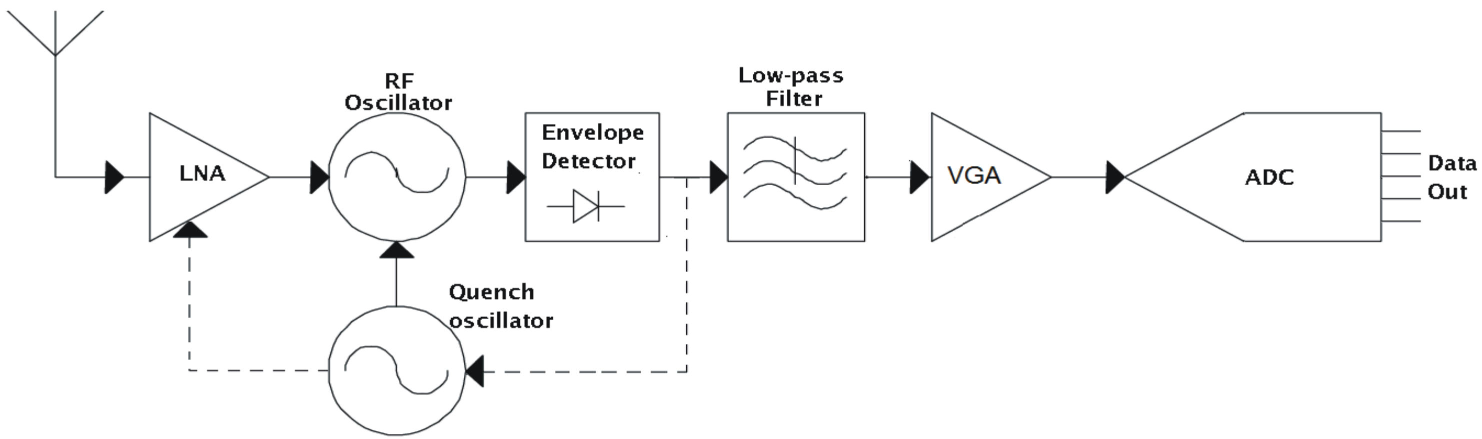


Figure. Architecture of a super-regenerative receiver.

References

[1] B. Zhen, M. Patel, S. Lee, E. Won, and A. Astrin. (2008, Nov.). TG6 Technical Requirements Document. Available: https://mentor.ieee.org/802.15/dcn/08/15-08-0644-06-0006-tg6-technical-requirements-document.doc.

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[3] K. Y. Yazdandoost and K. S.-Pour. (2009, Apr.). Channel Model for Body Area Network. [Online]. Available: https://mentor.ieee.org/802.15/dcn/08/15-08-0780-08-0006-tg6-channel-model.pdf.

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[5] B.P. Otis, J.M. Rabaey - "Ultra-low power wireless technologies for sensor networks" – Springer, 2007.

[6] F.X. Moncunill-Geniz, P.Palà-Schönwälder, C. Dehollain, N. Joehl, M. Declercq – "An 11 Mb/s 2.1 mW synchronous superregenerative receiver at 2.4 GHz" – IEEE Transactions on Microwave Theory and Techniques, vol. 55, no. 6, June 2007.