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

Submission Title: [NICT's Wideband PHY Proposal Part 2: IR-UWB]

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Source: [Marco Hernandez, Ryuji Kohno] **Company:** [NICT]

Address: [3-4 Hikarino-oka, Yokosuka, 239-0847, Japan]

Voice: [+81 468475439] **Fax:** [+81 468475431] **Email:** [Marco@nict.go.jp]

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Abstract: [The presentation shows a NICT wideband PHY proposal based on IR-UWB.]

Purpose: [Call for participation for a common wideband architecture for on-body BANs.]

NICT's Wideband PHY Proposal
Part 2: IR-UWB

Marco Hernandez, Ryuji Kohno

NICT, Japan

Motivation

IR-UWB provides advantages for BANs signaling

- Inherent low duty cycle (save battery energy)
  - ▷ *transmitter and receiver are on only when a pulse is present.*
- Inherent safety power levels exposure for human body
  - ▷ *power levels are in the order of those use for the MICS band (around -16 dBm)*
- Due to the low transmitting power and operation in the UWB band
  - ▷ *no interference to medical equipment*
- Coexistence with other wireless systems can be accomplished with DAA mechanisms combined with a multi-band approach

Motivation

BAN requirements like short range communications and data rate up to 10 Mbps

- Allows a feasible low cost, low power UWB radio implementation in the entire UWB band
  - ▹ *in contrast to other very high data rate solutions*
- Respect to the IEEE 802.15.4a standard
  - ▹ *the proposal is intended to operate with lower power consumption and simpler architectures*

Motivation

Call for participants to the present proposal

- We offer a generic design as much as possible and a example of design

The proposal is open for your participation in order to achieve a better solution

BAN Concept

Key requirements:

- long battery life, small form factor, short range communications:
    - *typically up to 1 m. from on-body devices to a coordinator*
    - *and up to 3 m. from coordinator (or special devices) to a gateway or base station.*
- So, BANs are highly power constrain systems

BAN Power Consumption

Power levels set an upper limit on the number of computational operations and radio front-ends design.

Key design objective

- Establishing a *reliable* communication link with the lowest power consumption as possible.
- Obviously, performance needs to be sacrificed for an architecture that allows to operate with very low power consumption.

Why UWB for BAN can be different

A key aspect of the proposal is to have analog front-ends (pulse generation and detection)

- It allows chip implementation for any point of UWB band
  - ▷ *analog technology is mature in the UWB band and it can be optimized to operate with low power consumption.*
- There are not circuits operating with high sampling rates
  - ▷ *weak point of most UWB solutions (implementation and power consumption)*
- In the proposal the fastest clock at receiver is 20 MHz
- As the maximum data rate is 10 Mbps and short range communications
  - ▷ *It is possible to compensate the penalty on performance degradation.*

Motivation

- The proposal is based on IEEE 802.15.4a (with modifications).
- The idea is to have a signal format that can support coherent and non-coherent transceivers to cover a wide range of applications.
- The kth transmitting symbol is given by

$$x^k = (1 - 2g_1^k) \sum_{n=1}^{N_{cpb}} (1 - 2S_{n+kN_{cpb}})\, p(t - g_0^k T_{BPM} - h^k T_{burst} - nT_c)$$

Motivation

- Now focusing on the non-coherent system, then the signaling is on-off (OOK and PPM)
- As the signaling is on-off and the receiver is non-coherent (energy detection), the pulse shape is secondary.
- Hence, the pulse shape can be interchangeable.
- This facilitates low complex implementation of front-ends or the introduction of sophisticated pulse shapes if necessary for coherent transceivers.

Motivation

As an example of design, we present a gated oscillator

- Gated oscillator (oscillator modulated by at least a triangular waveform) (4 triangular waveforms may form a flexible chaotic pulse shape).
- The central frequency can be changed easily.
- A triangular waveform is constructed by the charge and discharge of a capacitor's cycle with duration $T_p = 8$ nsec that sets a 500 MHz bandwidth.
- Fully implementable in a chip with very low power consumption.
- The pulse shape is given by

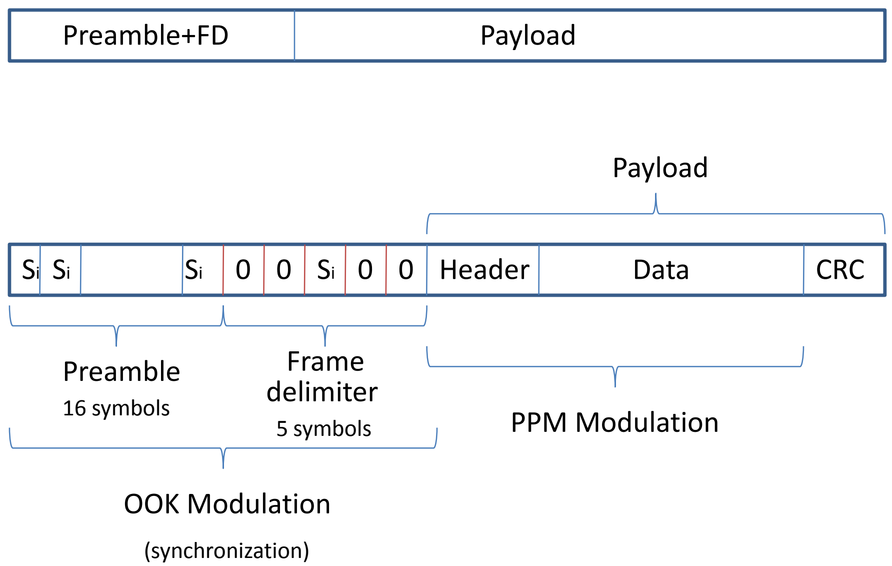
$$p(t) = x_b(t)\ \cos(2\pi f_n t)$$

$$x_b(t) = \begin{cases} 1 - \left|\frac{2t}{T_p} - 1\right| & 0 \leq t < T_p \\ 0 & \text{otherwise} \end{cases}$$

- where f_n is the central frequency of the nth sub-band of the 4a band plan.

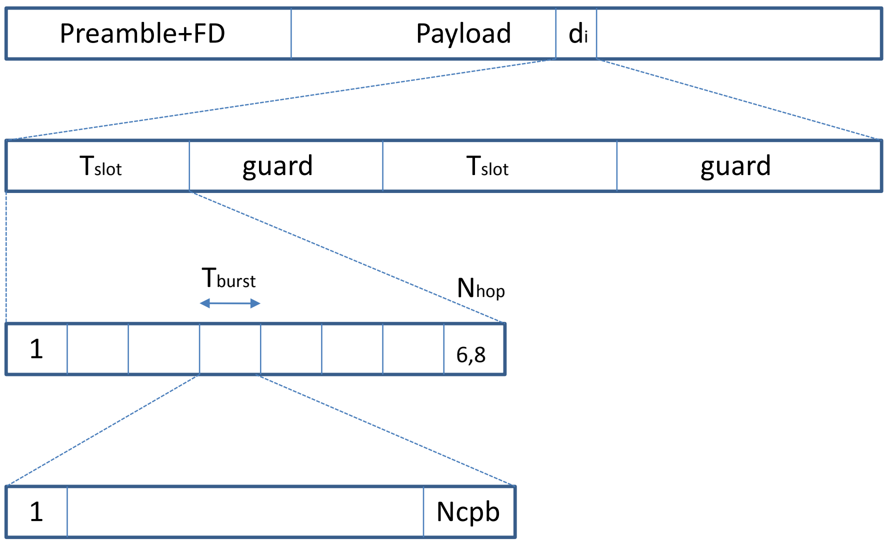
UWB-BAN Transmitter

- Frame format similar to 4a



UWB-BAN Transmitter

- Frame format similar to 4a



UWB-BAN transmitting signal

- Assuming the gated oscillator pulse shape of duration $T_p = 8$ nsec and 2PPM modulation (for the payload):
- $R = 250$ Kbps , $T_{slot} = 2\ \mu$sec
- $R = 1$ Mbps , $T_{slot} = 0.5\ \mu$sec
- $R = 10$ Mbps , $T_{slot} = 50$ nsec

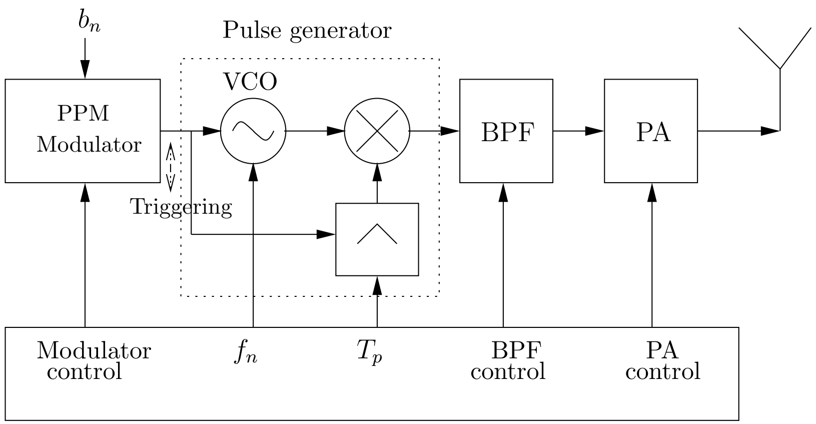
UWB-BAN frame format

- The format characteristics:

R_b (Mbps)	T_{burst} (nsec)	N_{hop}	N_{cpb}	T_p (nsec)
0.250	250	8	31	8
1	62.5	8	7	8
10	8.33	6	1	8

- The guard interval can be 100 to 200 nsec (depending on what the maximum delay spread is considered) to avoid ISI.
- Notice that T_{burst}, N_{hop} and N_{cpb} can be changed depending on the considered pulse shape.

UWB-BAN Transmitter



- The PPM modulator triggers a gated oscillator
  - *The central frequency f_n can be changed easily*
  - *Possible to use slow frequency hopping to combat interference and coexistence*
  - *Fully implementable in a chip with very low power consumption*

Motivation

- The kth symbol of the transmitting signal is given by

$$x^k = (1 - 2g_1^k) \sum_{n=1}^{N_{cpb}} (1 - 2S_{n+kN_{cpb}})\, p(t - g_0^k T_{BPM} - h^k T_{burst} - nT_c)$$

- Payload modulation is PPM (seen by coherent and non-coherent receivers).
- Although g_1^k is seen by coherent receivers only.
- $T_{BPM} = N_{hop} * T_{burst} + guard$ (given in the previous Table)
- S_n is given by the scrambler generator $S_n = S_{n-14} \oplus S_{n-15}$ (like 4a)
- Or unipolar sequences (OOC with sharp autocorrelation function)
- Example OOC(7,3,1) (1101000) for 1 Mbps

TH to support 10 BANs

- Time hopping to support multiple BANs, may be implemented as in 4a from the scrambler generator.
- That is, all BANs use the same TH sequence. The kth symbol is transmitted in the $h^k \in [0, Ncpb - 1]$ hop

$$h^k = S_{kN_{cpb}} + 2\,S_{1+kN_{cpb}} + 2^2\,S_{2+kN_{cpb}}$$

- Unfortunately, the MAI is quite severe for 10 BANs.
- Alternatively, we propose to use TH sequences pre-computed by maximum distance separable codes MDS(n, k, d) over GF(q).
- Example $n = q = 8$ and $k = 2$, there are $q^k = 64$ different codewords.

TH to support 10 BANs

- Table shows 7 codewords. Elements across codewords are not repeated, so MAI is suppressed.

Table 1: MDS codes (8,2)

MDS[0][i]	1	2	4	3	6	7	5	0
MDS[1][i]	0	3	5	2	7	6	4	1
MDS[2][i]	3	0	6	1	4	5	7	2
MDS[3][i]	5	6	0	7	2	3	1	4
MDS[4][i]	2	1	7	0	5	4	6	3
MDS[5][i]	7	4	2	5	0	1	3	6
MDS[6][i]	6	5	3	4	1	0	2	7
MDS[7][i]	4	7	1	6	3	2	0	5
$i = 0, \cdots, 7$								

TH to support 10 BANs

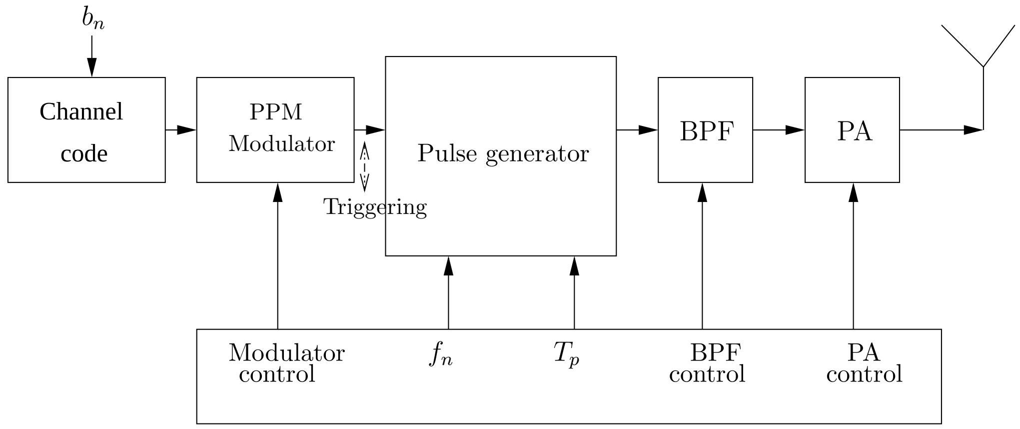
- The kth symbol of the ith BAN is given by

$$x^{k,i} = (1 - 2g_1^{k,i}) \sum_{n=1}^{N_{cpb}} (1 - 2S_{n+kN_{cpb}})\, p(t - g_0^{k,i} T_{BPM} - h^{k,i} T_{burst} - nT_c)$$

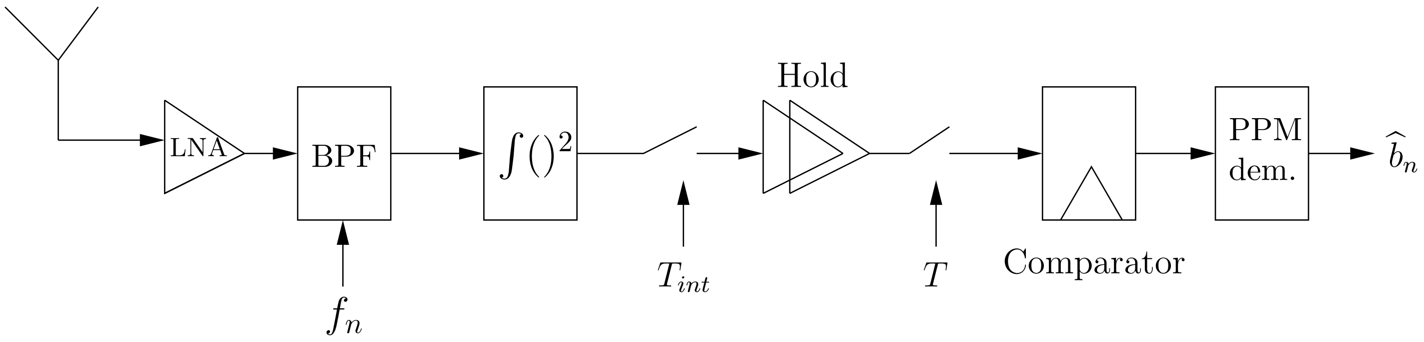
- where $h^{k,i}$ =MSD$[i][k$Mod$N_{hop}]$.
- As elements of $h^{k,i}$ are not repeated across i, so MAI is suppressed and 10 BANs can be supported.

UWB transmitter

Optional channel code

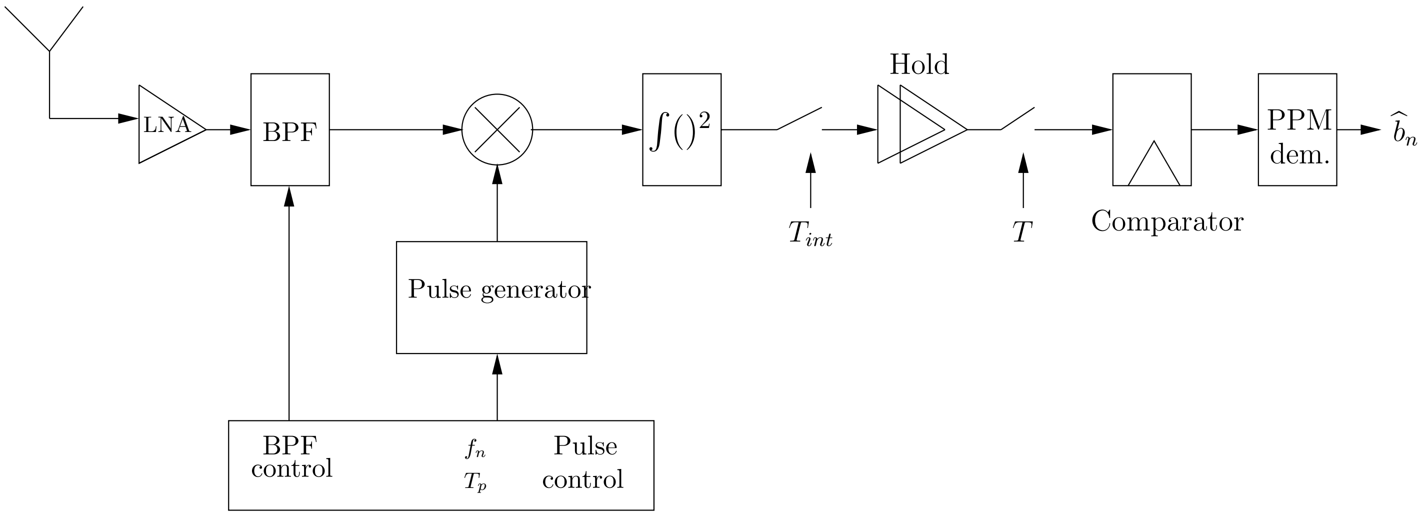


Receiver



- In order to save power consumption a non-coherent architecture is favored.
- Simple energy detection (no required PLL and optional ADC)
- Front-end in the analog domain: integrator's output is sample and hold.
- After a symbol time, hold values are passed to a comparator for symbol/bit evaluation.

Receiver II



- **Non-coherent matched filter (correlation with a locally generated pulse waveform).**
- **Still, no required PLL and optional ADC.**
- **Fastest clock is for $R = 10$ Mbps. So, $T_{int} = T_{burst} = 8.33$ nsec**
- **So $f_{clk} = 1/T_{int} = 120$ MHz**

Multi-band Concept

- The proposal is intended to operate in the high band of UWB (7 - 10 GHz).
- However, by taking advantage that the gated oscillator pulse shape can change its central frequency easily.
- Slow frequency hopping can be introduced to facilitate coexistence and combat interference.
- We adopt the IEEE 802.15.4a frequency band plan.

Multi-band Concept

- Band frequency hopping is performed by special time frequency codes given by MDS(n, k, d) over GF(q) as well. Example $n = q = 16$ and $k = 2$, so $q^k = 256$ different codewords.

Table 2: MDS codes (16,2)

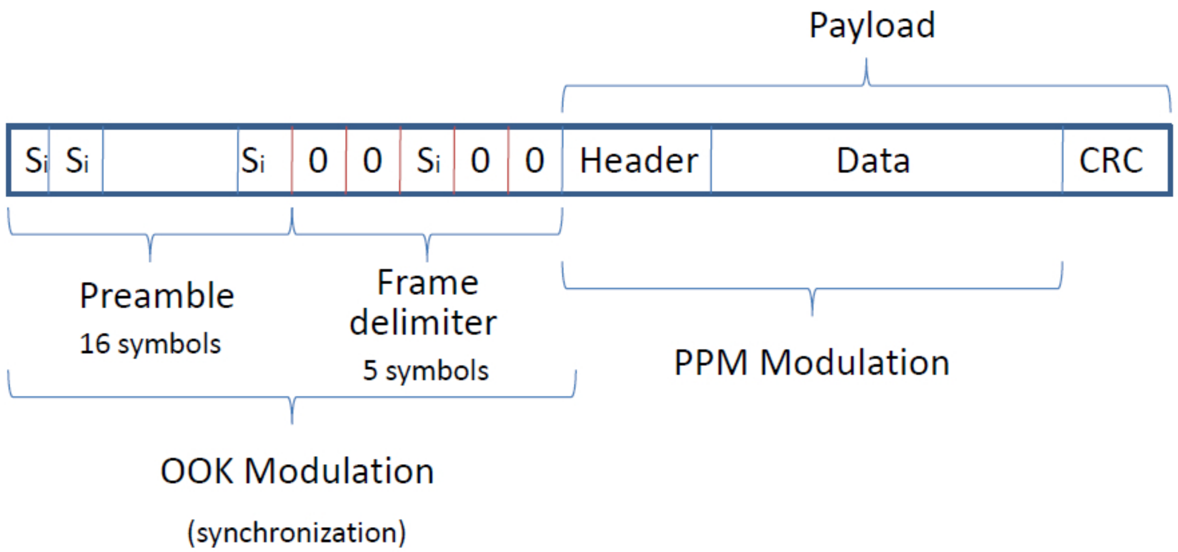
MDS[0][i]	0	1	2	4	8	3	6	12	11	5	10	7	14	15	13	9
MDS[1][i]	1	0	3	5	9	2	7	13	10	4	11	6	15	14	12	8
MDS[2][i]	2	3	0	6	10	1	4	14	9	7	8	5	12	13	15	11
MDS[3][i]	3	2	1	7	11	0	5	15	8	6	9	4	13	12	14	10
MDS[4][i]																
MDS[5][i]																
MDS[6][i]																
MDS[7][i]																
$i = 0, \cdots, 15$																

Multi-band Concept

- A different codeword can be assigned to a different device (components are not repeated across codewords).
- Frequency band = $(i\text{Mod}15)+1$ for the ith codeword component.
- The hopping can be done after the transmission of a set of symbols or in combination with a DAA protocol.
- We present a general example, but we do not intend to cover the entire UWB band necessarily.
- Some frequency bands can be deactivated if needed or change the time-frequency code.
- The idea is to allow coexistence with other wireless systems and robustness against interference from/to other UWB systems and it is optional.

Synchronization

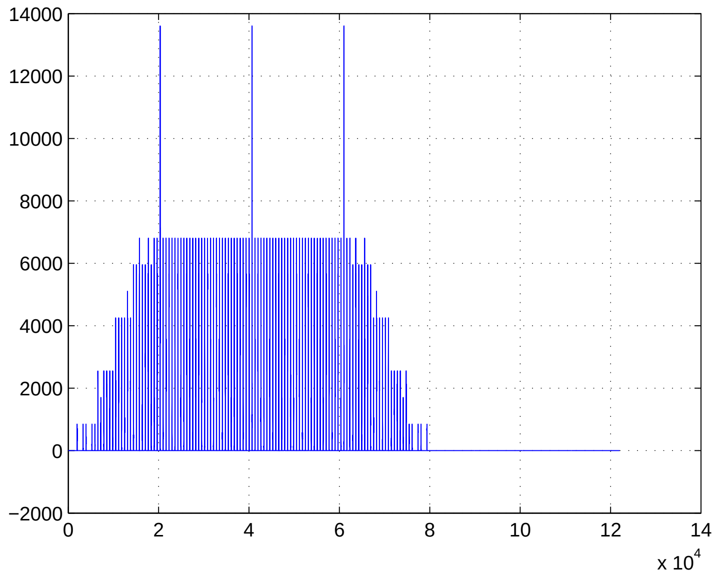
- Preamble similar to 4a (allows coarse acquisition, ranging, channel estimation)



- $S_i = C_i \otimes \delta_L$, where C_i=PBTS of length 31 and $\delta_L = (1, ..., 0)_L$
- Ingenious as PBTS autocorrelation function seen by coherent and non-coherent receivers is proportional to delta.

Synchronization

- Transmission of 3 symbols S_i with C_i of length 31 and $L = 16$ over CM4.
- Correlation of received signal with local template (non-coherent receiver).

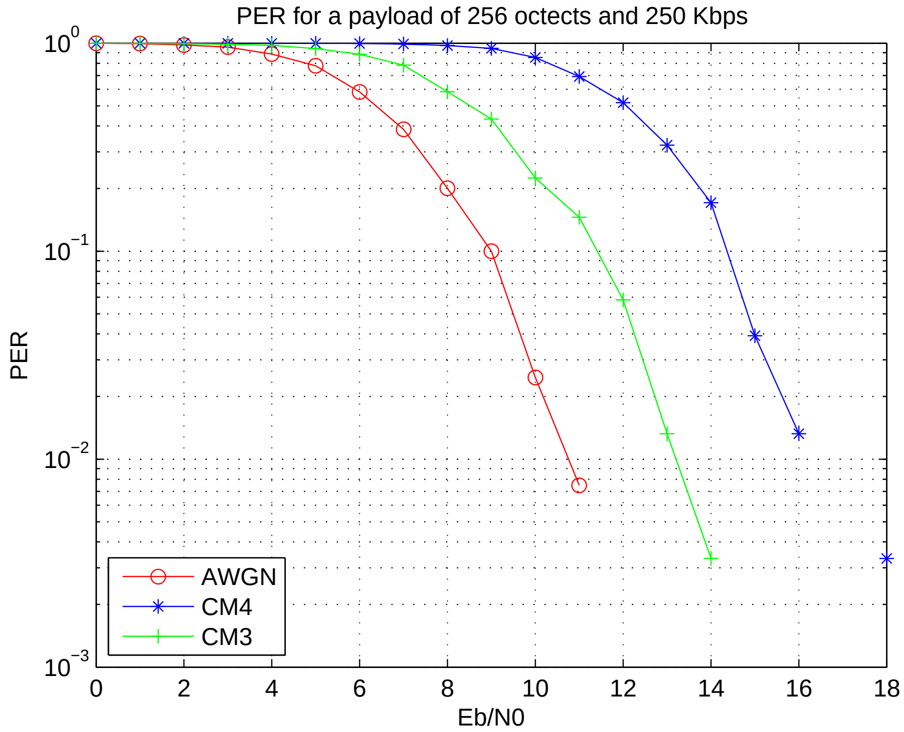


- slot synchronization (around 28 nsec accuracy).

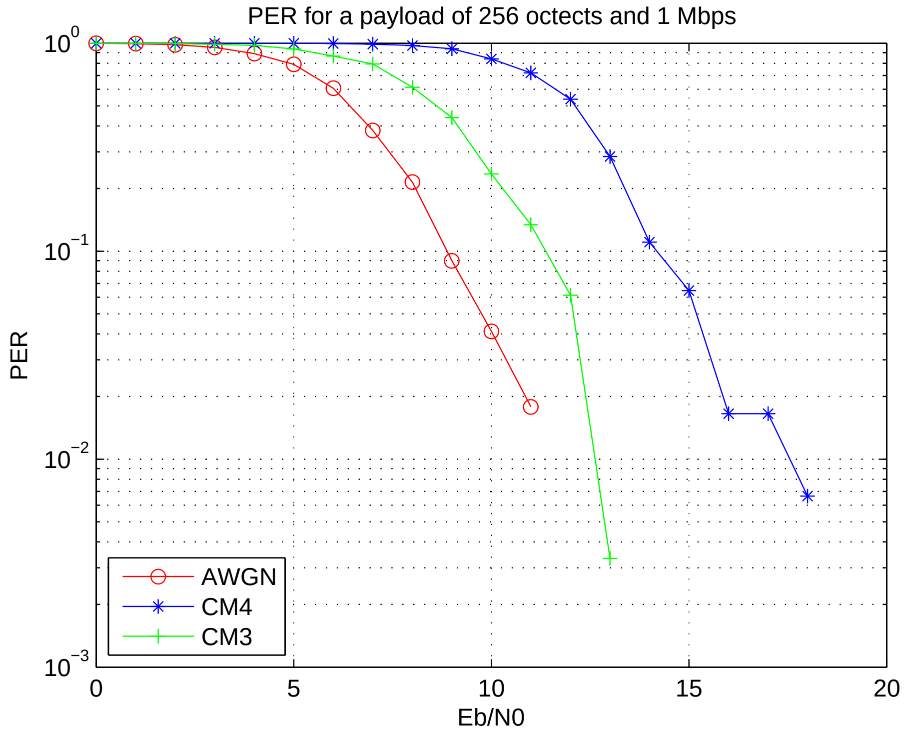
Synchronization

- Thresholding: declare detection if consecutive correlation peaks exceed analytical threshold.
- Fine synchronization by DLL.
- Similar for frame synchronization using the frame delimiter format.

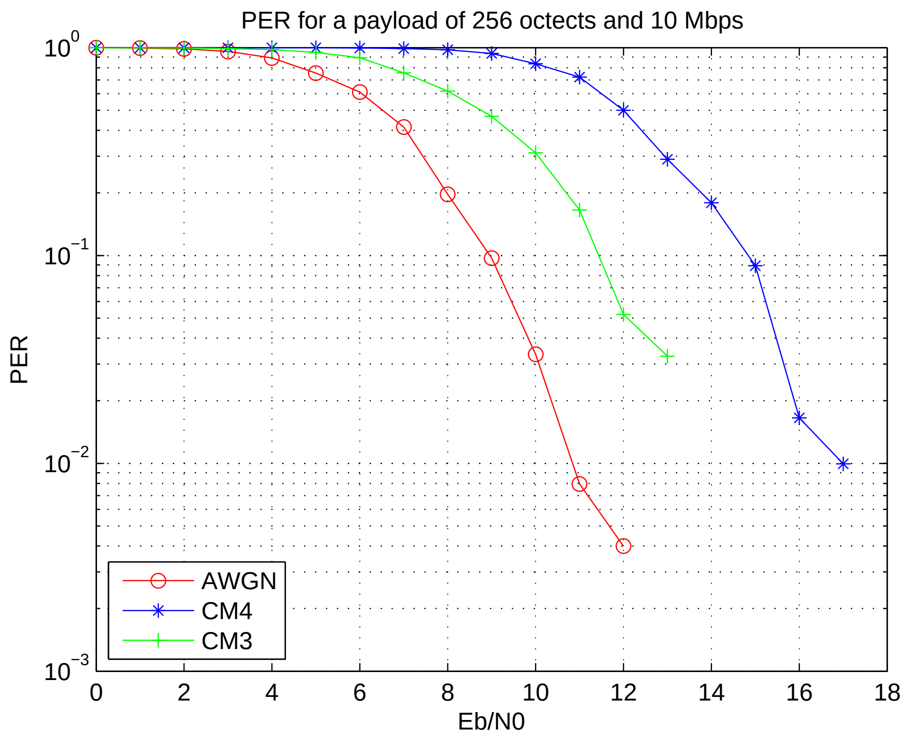
Simulation Performance



Simulation Performance



Simulation Performance



Link Budget

- **Modulation is 2PPM for payload transmitting in the 9th sub-band over CM4 (communication link of 3m) with non-coherent energy detection.**
- **Data rates: 250 kbps, 1 Mbps, 10 Mbps.**
- **Data for antennas, NF, implementation losses taken from state of the art.**

Link Budget

Parameter	*Value*
Data rate (R)	250 Kbps
Average Tx power (P_{Tx})	-16 dBm
Tx antenna gain (G_t)	0 dBi
Rx antenna gain (G_r)	0 dBi
Required ($E_b/N0\|_{\text{req}}$) for BER=10^{-3}	11.5 dB
Rx noise figure (NF)	5 dB
Path loss (free space) at 3 m	59.66 dB
Implementation losses (L_o)	3 dB
Average power at receiver (P_{Rx})	-75.66 dBm
Average noise power per bit (P_N)	-115.02 dBm
Link Margin L_M	**24.85 dB**
Minimum Rx sensitivity S_r	**$-$103.82 dBm**

Link Budget

Parameter	*Value*
Data rate (R)	1 Mbps
Average Tx power (P_{Tx})	-16 dBm
Tx antenna gain (G_t)	0 dBi
Rx antenna gain (G_r)	0 dBi
Required ($E_b/N0\|_{\text{req}}$) for BER=10^{-3}	12.7 dB
Rx noise figure (NF)	5 dB
Path loss (free space) at 3 m	59.66 dB
Implementation losses (L_o)	3 dB
Average power at receiver (P_{Rx})	-75.66 dBm
Average noise power per bit (P_N)	-114 dBm
Link Margin L_M	**17.63 dB**
Minimum Rx sensitivity S_r	**-93.3 dBm**

Link Budget

Parameter	*Value*
Data rate (R)	10 Mbps
Average Tx power (P_{Tx})	-16 dBm
Tx antenna gain (G_t)	0 dBi
Rx antenna gain (G_r)	0 dBi
Required ($E_b/N0\|_{\text{req}}$) for BER=10^{-3}	13.4 dB
Rx noise figure (NF)	5 dB
Path loss (free space) at 3 m	59.66 dB
Implementation losses (L_o)	3 dB
Average power at receiver (P_{Rx})	-75.66 dBm
Average noise power per bit (P_N)	-99 dBm
Link Margin L_M	**6.93 dB**
Minimum Rx sensitivity S_r	**-82.6 dBm**

Power consumption at receiver

- Advantage of IR-UWB: power consumption is duty cycled.
- By switching on the receiver only during $2\ T_{burst}$ over a PPM symbol, large energy savings are possible by duty-cycling the receiver (all stages) during payload.
- duty cycle: $\eta = \frac{T_{burst}}{T_{slot}+T_{guard}}$
- $T_{guard} = 200$ nsec.
- From data of available components in 90nm CMOS [1]
- Turn on time: 2 nsec, supply voltage: 1.3 v.

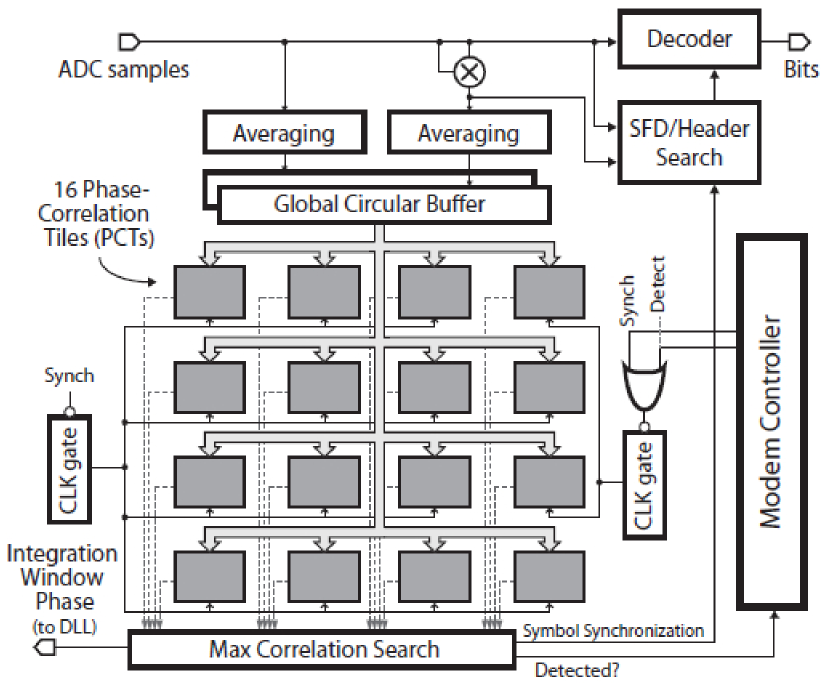
Power consumption at receiver

- Analog power consumption (including transients)
  - *LNA + BPF + passive self-mixer + BB integrator:* 16.5 *mW*
- Digital power consumption (including transients)
  - *Flash ADC of* 5 *bit (*120 *MHz):* 1.5 *mW*
  - *Sample and hold + comparator (latch):* 1 *mW*
- Total instantaneous power 19 mW during payload.
- Average power P:

$R_b = 250$ kbps $\eta = 11\%$ $P = 2$ mW	$R_b = 1$ Mbps $\eta = 9\%$ $P = 1.7$ mW	$R_b = 10$ Mbps $\eta = 3\%$ $P = 0.57$ mW

Power consumption for synchronization

- Non-coherent synchronization (OOK modulation)
- Correlations of preamble S_i with incoming signal based on 16 phase correlation tiles (PCT)
- Every PCT consists of 8 parallel quadratic correlators (QCORRs)



Power consumption for synchronization

- Implemented in 90nm CMOS [2].
- At clock frequency of 32 MHz a preamble is processed in 14 μsec with 1.6 mW average power.
- Synchronization accuracy: 1 nsec.

Conclusions

- A simple an robust UWB solution for BANs
- The proposed design allows:
    - *low power consumption*
    - *low cost radios*
    - *implementation in any sub-band of the UWB band*
    - *coexistence with other wireless systems*
    - *safety power levels exposure to the human body*

References

[1] Ivan Lai, M. Fujishima, ”Design and Modeling of Millimeter-wave CMOS Circuits for Wireless Transceivers”, Springer, April 2008, ISBN-10: 1402069987.

[2]

[3] J. Ryckaert, et al., ”A 0.65-to-1.4nJ/burst 3-to-10GHz UWB Digital TX in 90nm CMOS for IEEE 802.15.4a”, ISSCC, Feb. 2007, pp. 120-121.