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

**Submission Title:** Samsung's Physical Layer Proposal
**Date Submitted:** Nov, 2013
**Source:** Kiran Bynam, Young-Jun Hong, Jinesh Nair, Chandrashekhar Thejaswi, Sujit Jos, Changsoon Park, Youngsoo Kim, Chunhui Zhu, Ashutosh Gore, Jongae Park, Manoj Choudhary
E-Mail: kiran.bynam@samsung.com
**Abstract:** Samsung's PHY proposal as response to IEEE 802.15.4q CFP

**Purpose:** Response to Call for Proposals

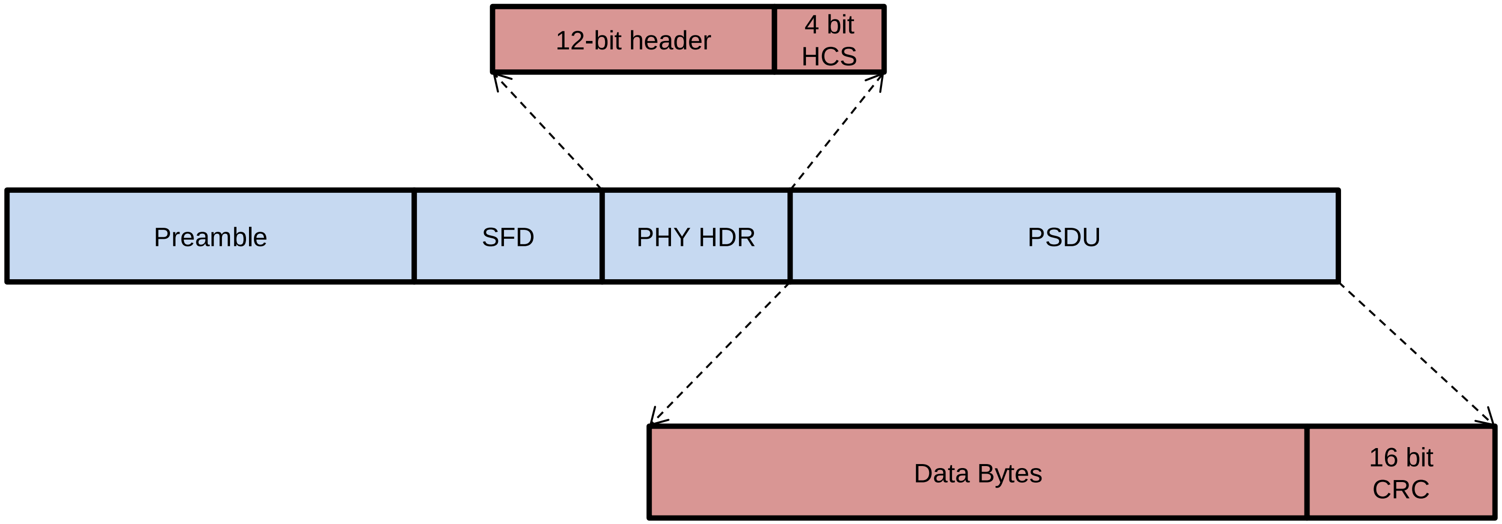
# Objective

- Proposal for Physical Layer amendment as response to CFP of IEEE 8021.5.4q TG
  - With power consumption less than 15 mW
  - With receiver sensitivity less than -85 dBm
- To operate in both coherent/non-coherent mode
  - With Rx power as low as 2 mW in non-coherent mode
  - With sensivity below -90 dBm in coherent mode

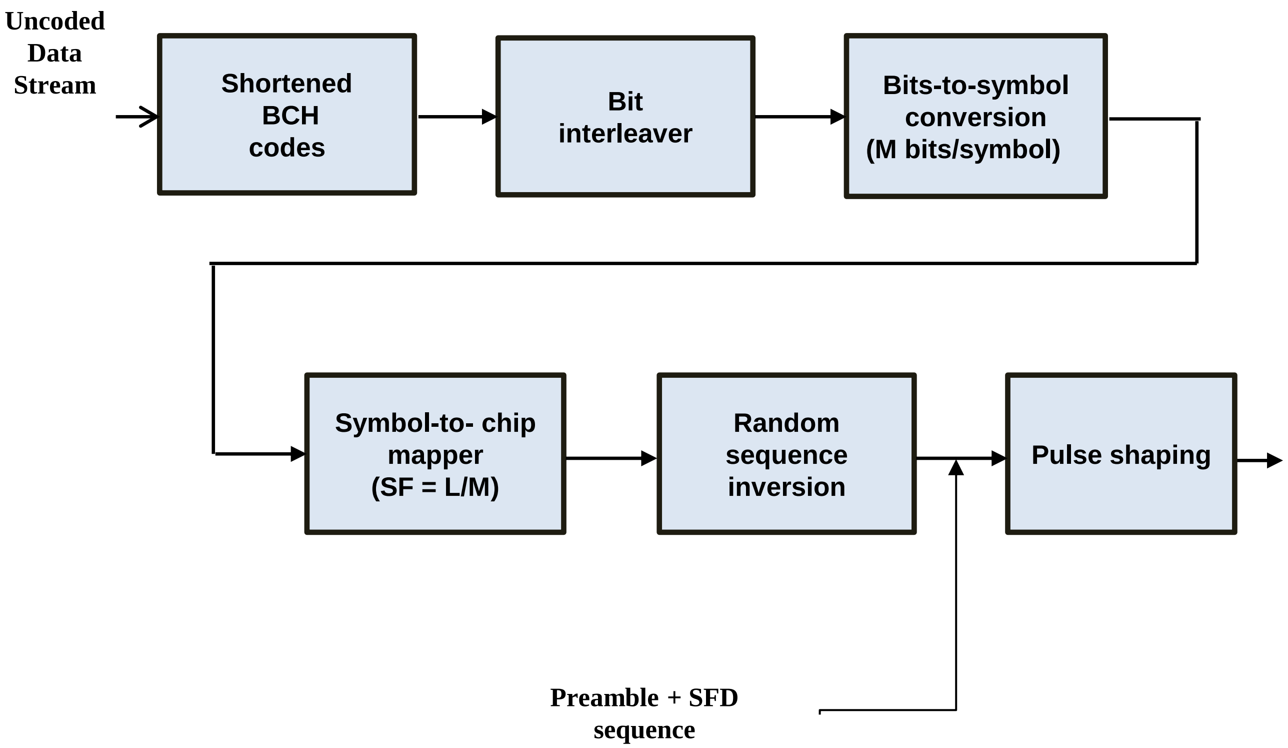
# PPDU Format

- Quite Synonymous with IEEE 802.15.4
  - Header is protected with 4 bit HCS
  - 4 bits for indicating modulation format

| Header Bits | PHY Parameter |
|---|---|
| 0-7 | Length of Payload (0-127 bytes) |
| 8-11 | Modulation Format |



# Transmitter Block Diagram



# FEC-BCH codes

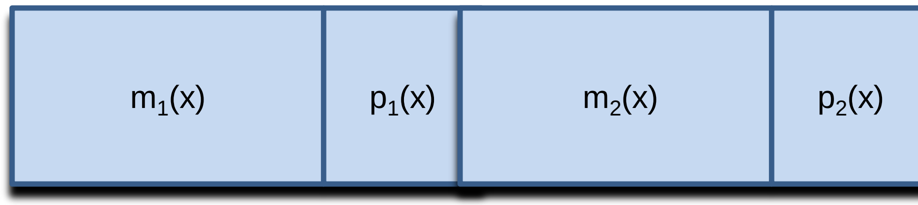
- BCH (63,51) codes are employed for error correction capability of 2 bits

❑ **Generator Polynomial**

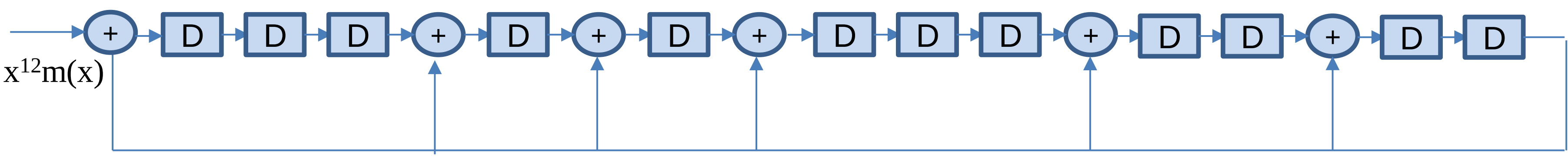
$$g(x) = 1 + x^3 + x^4 + x^5 + x^8 + x^{10} + x^{12}$$

❑ **Parity Bits**

$$p(x) = \mathrm{mod}(x^{12} m(x), g(x))$$




✓ m(x) is the message polynomial




**FEC Encoder**

- Any ‘$\ell$ ‘-bit shortened code BCH $(63-\ell, 51-\ell)$ codes can be obtained from above encoder with error correction capability of 2

# Rate-Matching with shortened BCH codes: $\mathrm{FEC} - BCH(63-\ell, 51-\ell)$

- ✓ Incurs lesser overhead when compared to naïve zero-padding.
- ✓ Improves the performance of the FEC, since more bits can be corrected for a given packet length, and also due to the increased energy/coded bit.
- ✓ Same encoder/decoder pair is used for all combinations (all values of $1 \le \ell < 51$).

| | | |
|---|---|---|
| Total no. of message blocks: | $M_B$ | $= \left\lceil \frac{B}{51} \right\rceil$; $B$– packet length in bits. |
| Length of the new message block: | $K$ | $= \left\lceil \frac{B}{M_B} \right\rceil$; |
| Shortening length of the code: | $\ell$ | $= 51 - K$ |
| Length of the new encoded block: | $N$ | $= 63 - \ell$ |
| Length of the new bit-stream: | $B_{new}$ | $= M_B K$ |
| Required no. of zeros for insertion: | $Z$ | $= B_{new} - B$ |

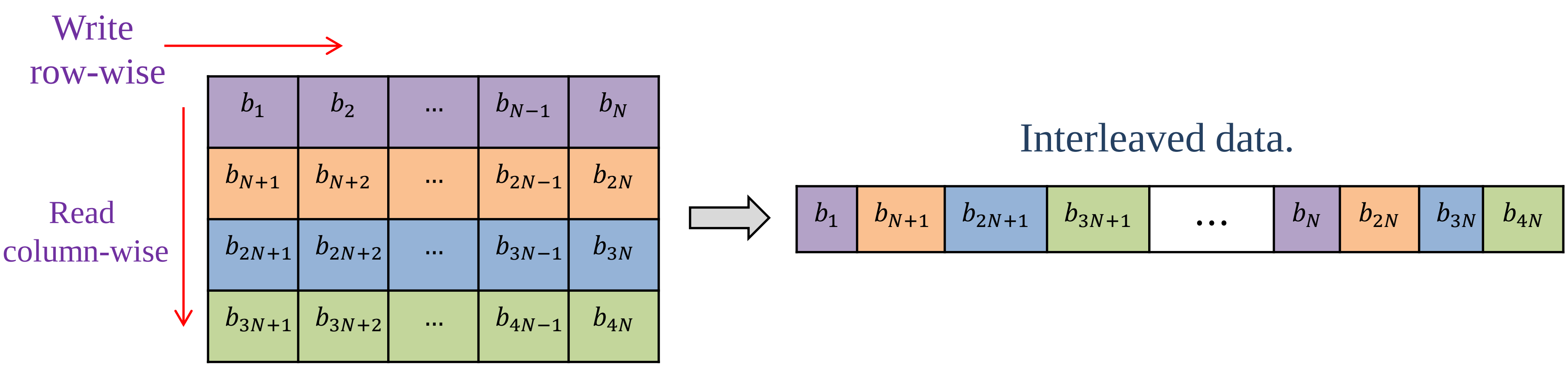
# Interleaving (1/2)

- Allowed depth of interleaving, d = 2,3,4,5

## ❑ Interleaving Procedure

- ✓ Collect $d$ blocks of $N$-length codewords
- ✓ Write them row-wise in a $d \times N$ dimensional array.
- ✓ Read the array column-wise and output the data sequentially.

## Ex: Interleaving for depth d=4



# Interleaving (2/2)

- $M_B$ → number of code words after FEC encoding
- $d$ → depth of the interleaver

$$Q = \left\lfloor \frac{M_B}{d} \right\rfloor$$

$$R = mod\ (M_B, d\ )$$

- Apply depth ‘d’ interleaving for Q blocks
- Apply depth ‘R’ interleaving for last R blocks

# Modulation

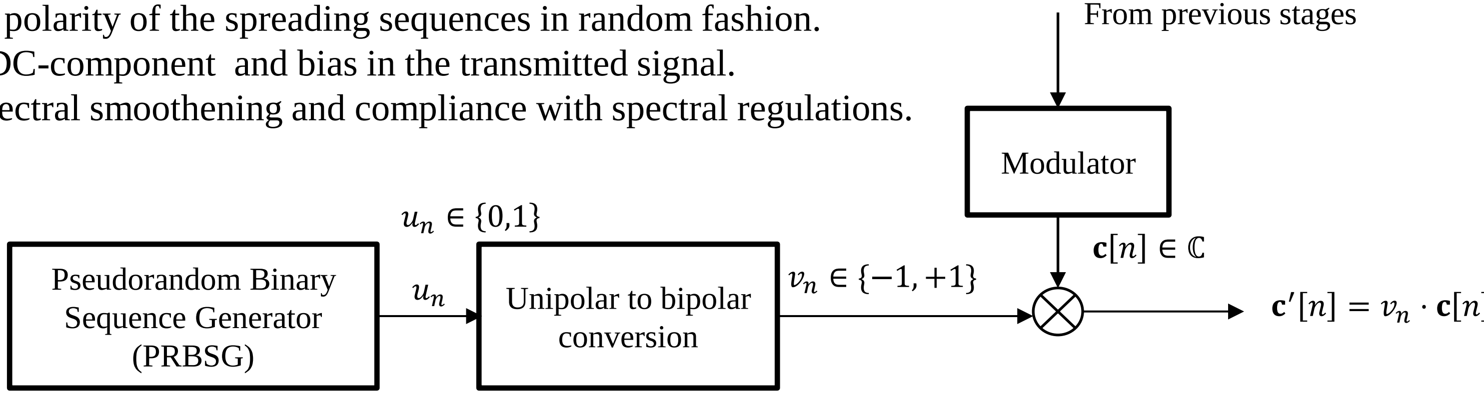
- Variable Spreading factor **Ternary OOK** modulation schemes
- Two types of spreading codes
  - **Orthogonal code:** Perfect Orthogonal sequences to map symbols ‘1’ and ‘0’.
  - **Pseudorandom code :** Set of circularly shifted sequences to map $2^k$ symbols

| M | L | Nomenclature | Orthogonal Sequences (symbols: ‘1’ / ‘0’) |
|---|---|---|---|
| 1 | 1 | 1/1-TOOK | 1/0 |
| | 2 | 1/2-TOOK | 1 0/ 0 -1 |
| | 4 | 1/4 –TOOK | 1 0 0 1/0 -1 -1 0 |
| | 8 | 1/8 –TOOK | 1 0 -1 0 0 -1 0 1 / 0 -1 0 1 1 0 -1 0 |

| M | L | Nomenclature | Basic Pseudorandom Sequence |
|---|---|---|---|
| 2 | 4 | 2/4-TOOK | 1 0 0 0 |
| 3 | 8 | 3/8-TOOK | 0 0 0 1 -1 0 1 1 |
| 4 | 16 | 4/16-TOOK | 1 -1 0 0 0 0 1 0 -1 0 0 1 1 0 1 1 |
| 5 | 32 | 5/32-TOOK | -1 0 0 1 0 1 -1 0 -1 -1 1 -1 0 1 0 1<br>0 0 0 1 0 0 1 1 -1 0 0 0 0 0 1 1 |

# Random Sequence Inverter

- ✓ Inverts the polarity of the spreading sequences in random fashion.
- ✓ Removes DC-component  and bias in the transmitted signal.
- ✓ Enables spectral smoothening and compliance with spectral regulations.




**PRBS Generator:**

Adapted from ITU scrambler with Generator polynomial

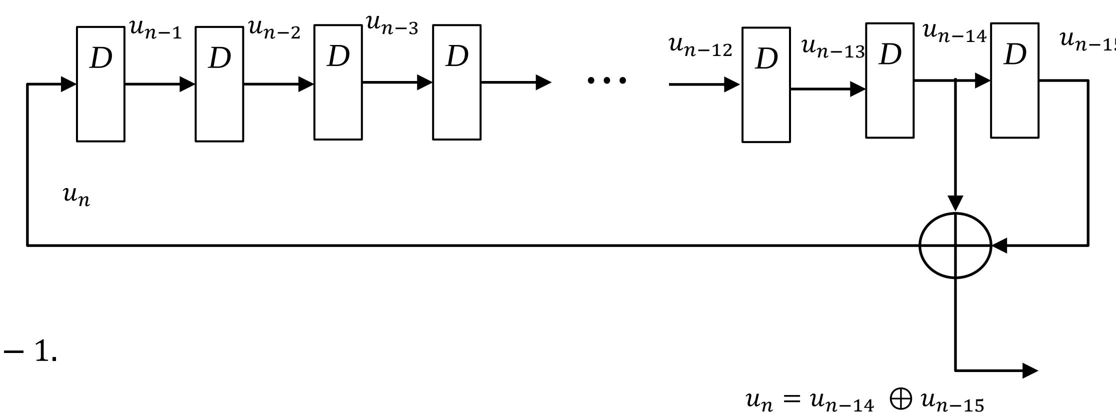
$G(x) = 1 + x^{14} + x^{15}$.

PRBS is generated recursively as

$u_n = u_{n-14} \oplus u_{n-15}, \quad n = 0,1,2,\ldots$

The initialization sequence is defined by

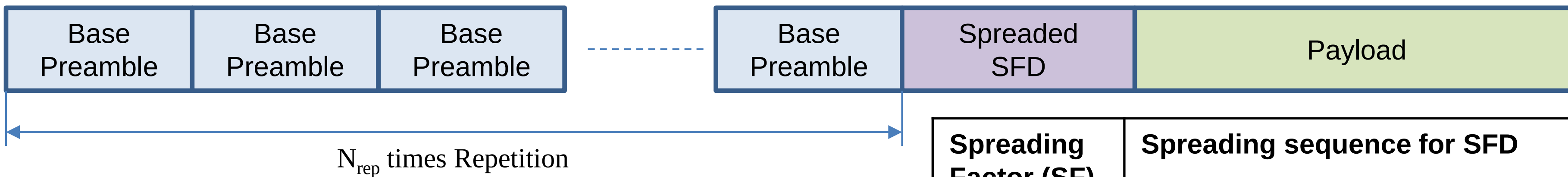
$u_{init} = [u_{-1}, \ldots, u_{-14}, u_{-15}]$




**Unipolar to Bipolar Conversion:** $v_n = 2u_n - 1$.

**Random Sequence inversion**: $\mathbf{c}'[n] = v_n \cdot \mathbf{c}[n]$

# Preamble Structure



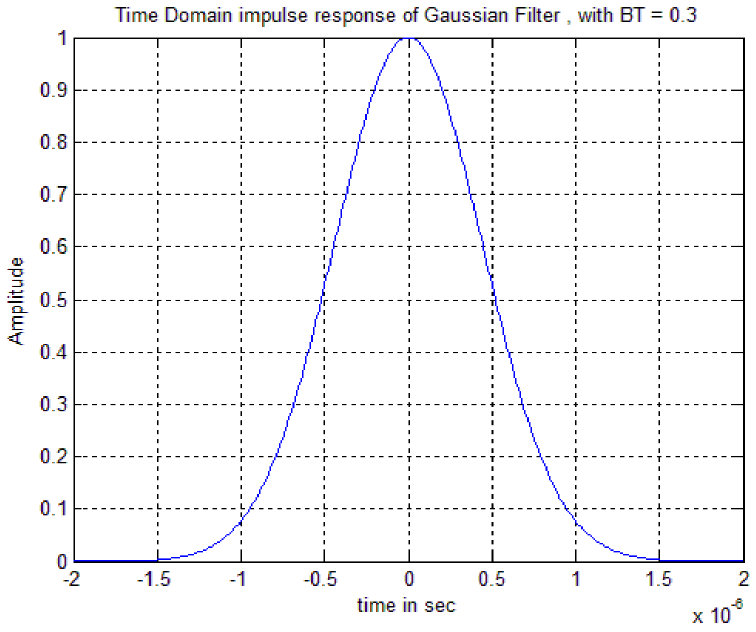


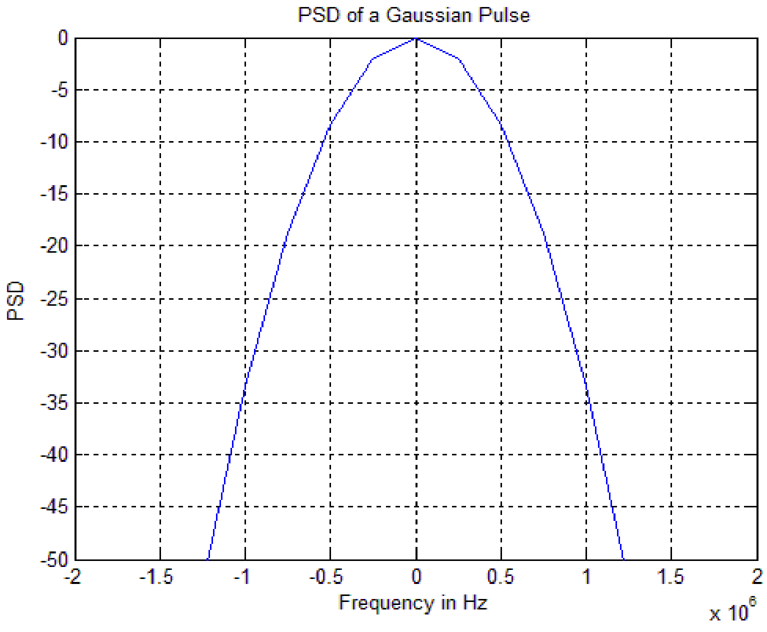
| **Spreading Factor (SF)** | **Spreading sequence for SFD** |
|---|---|
| S1 (2) | 10/0 -1 |
| S2 (4) | 1 0 0 1/ 0 -1 -1 0 |
| S3 (8) | 1 0 -1 0 0 -1 0 1/ 0 -1 0 1 1 0 -1 0 |
| S4 (16) | 1 0 -1 0 -1 0 1 0 0 1 0 -1 0 -1 0 1/<br>0 -1 0 1 0 1 0 -1 -1 0 1 0 1 0 -1 0 |

| **Preamble Def** | **Spreading Factor (SF)** | **Base Preamble Sequence** | **Number of Repetition ($N_{rep}$)** |
|---|---|---|---|
| P1 | 2 | -1 0 -1 0 1 0 1 0 -1 0 -1 0 1 0 -1 0<br>1 0 1 0 1 0 -1 0 -1 0 1 0 -1 0 -1 0 | 2 |
| P2 | 4 | 1 0 0 1 1 0 0 1 1 0 0 1 1 0 0 -1 -<br>1 0 0 1 -1 0 0 1 -1 0 0 1 -1 0 0 -1 | 4 |
| P3 | 8 | 1 0 -1 0 0 -1 0 -1 1 0 1 0 0 -1 0 1<br>1 0 1 0 0 -1 0 1 -1 0 1 0 0 1 0 1 | 8 |
| P4 | 16 | -1 0 -1 0 -1 0 -1 0 0 -1 0 1 0 1 0 -1<br>-1 0 1 0 -1 0 1 0 0 1 0 1 0 -1 0 -1 | 16 |

# Pulse Shaping

- Gaussian Pulse Shape with BT = 0.3
- Symbol Time $T = 1\mu s$.



# Data Rates-Proposal

| Data Rate Number | Code used | Modulation Duty Cycle | Inter-leaver depth (d) | M (bits per Symbol) | L (chips Per Symbol) | Data Rate in 2.4 GHz (kbps) | Data Rate in 900 MHz (kbps) | Preamble used | SFD Spreading used |
|---|---|---|---|---|---|---|---|---|---|
| D1 | 1/1-TOOK | 0.50 | 1 | 1 | 1 | 809.5 | 485.7 | P2 | S2 |
| D2 | 2/4-TOOK | 0.25 | 2 | 2 | 4 | 404.8 | 242.8 | P2 | S2 |
| D3 | 3/8-TOOK | 0.50 | 3 | 3 | 8 | 303.6 | 182.1 | P3 | S3 |
| D4 | 1/4-TOOK | 0.50 | 1 | 1 | 4 | 202.4 | 121.4 | P3 | S3 |
| D5 | 4/16-TOOK | 0.50 | 4 | 4 | 16 | 202.4 | 121.4 | P3 | S3 |
| D6 | 5/32-TOOK | 0.50 | 5 | 5 | 32 | 126.5 | 75.9 | P4 | S4 |
| D7 | 1/8-TOOK | 0.50 | 1 | 1 | 8 | 101.2 | 60.7 | P4 | S4 |

- Chip rate used = 1MHz for 2.4 GHz, 600 KHz for 900 MHz band
- FEC code specified : BCH(63,51)

| Data Rate Number | D1 | D2 | D3 | D4 | D5 | D6 | D7 |
|---|---|---|---|---|---|---|---|
| Payload efficiency for 40 bytes (% ge) | 69.69 | 82.14 | 83.63 | 82.14 | 82.14 | 78.63 | 82.14 |

# Band Plan

- Band plan similar to IEEE 802.15.4 for 2.4 GHz and 900 MHz

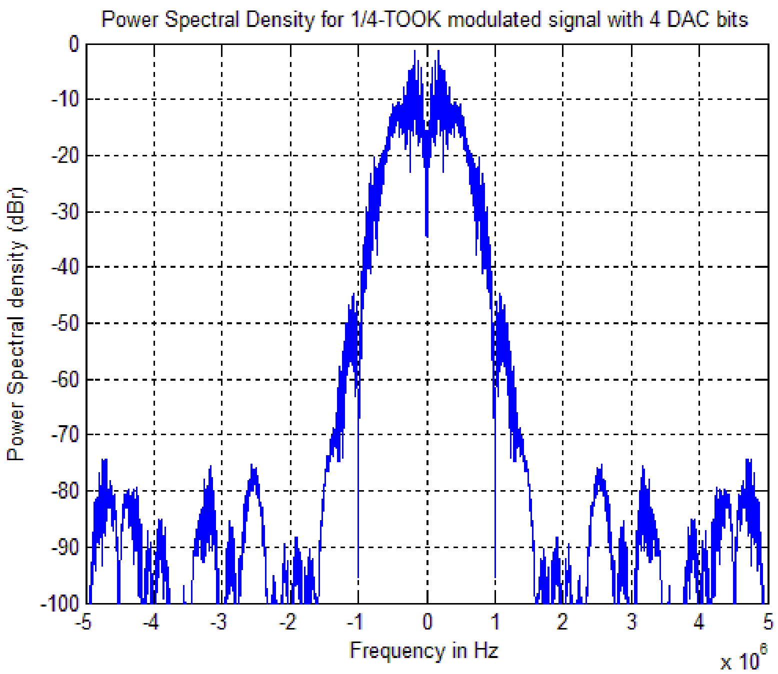
- 2400 MHz

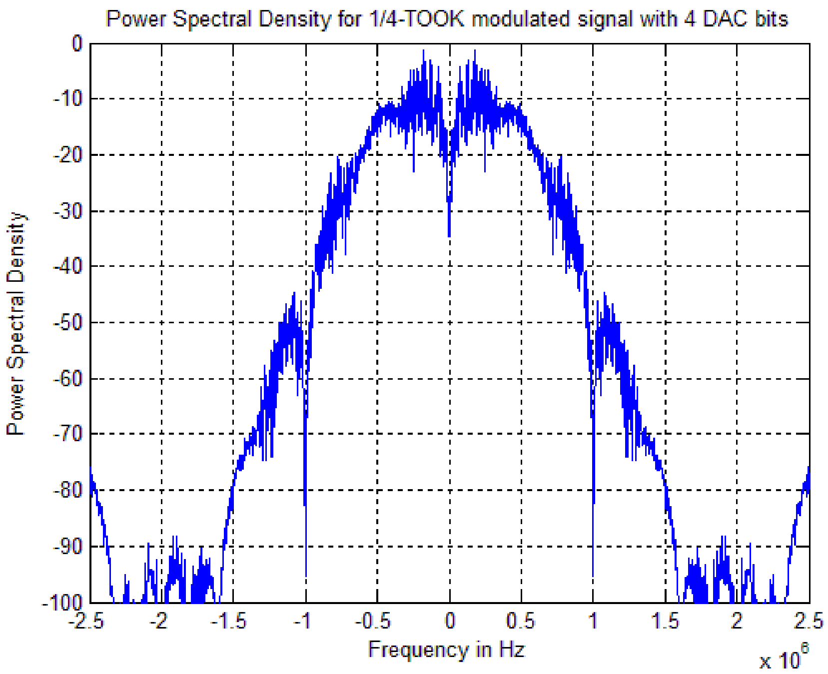
$$F_c = 2405 + 5 * k, \ldots k = 0,1,2 \ldots 15$$

- 900 MHz

$$F_c = 906 + 2 * k, \ldots k = 0,1,2 \ldots 9$$

# Power Spectral Density

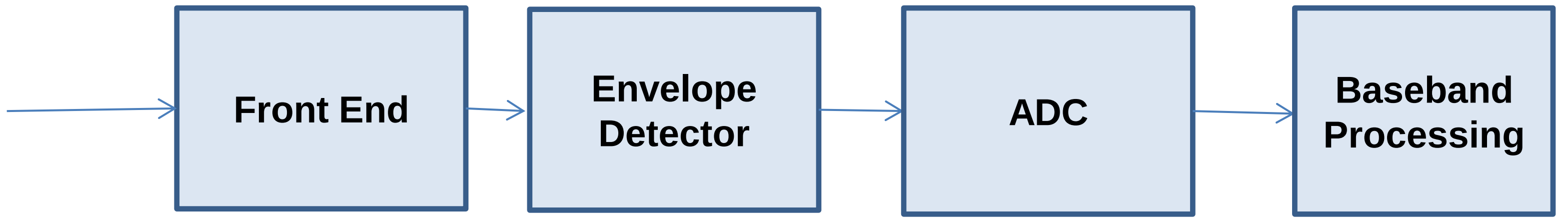


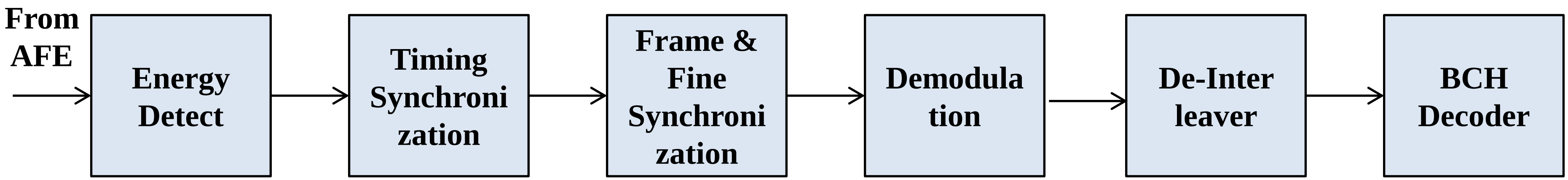

| Power Leakage Ratio | Value |
|---|---|
| Adjacent channel leakage ratio | -69 dB |
| Alternate channel leakage ratio | -72 dB |

# Receiver Architecture

- Super Regeneration based amplification used for OOK demodulation and detection
- 60 dB super regenerative gain
- Baseband processing involves
  - Synchronization
  - Demodulation and Detection



# Baseband Processing (1/2)




- **Timing Synchronization**

Frame timing estimate $\hat{\tau}$

$$\hat{\tau} = \underset{j}{\operatorname{argmax}} \sum_{i=1}^{N_p} x[i]y[i+j]$$

$\left[x[1], \ldots, x\left[N_p\right]\right]$ – preamble template at Rx

$\{y[1], y[2] \ldots, \}$ – baseband samples at Rx

- **Demodulation**

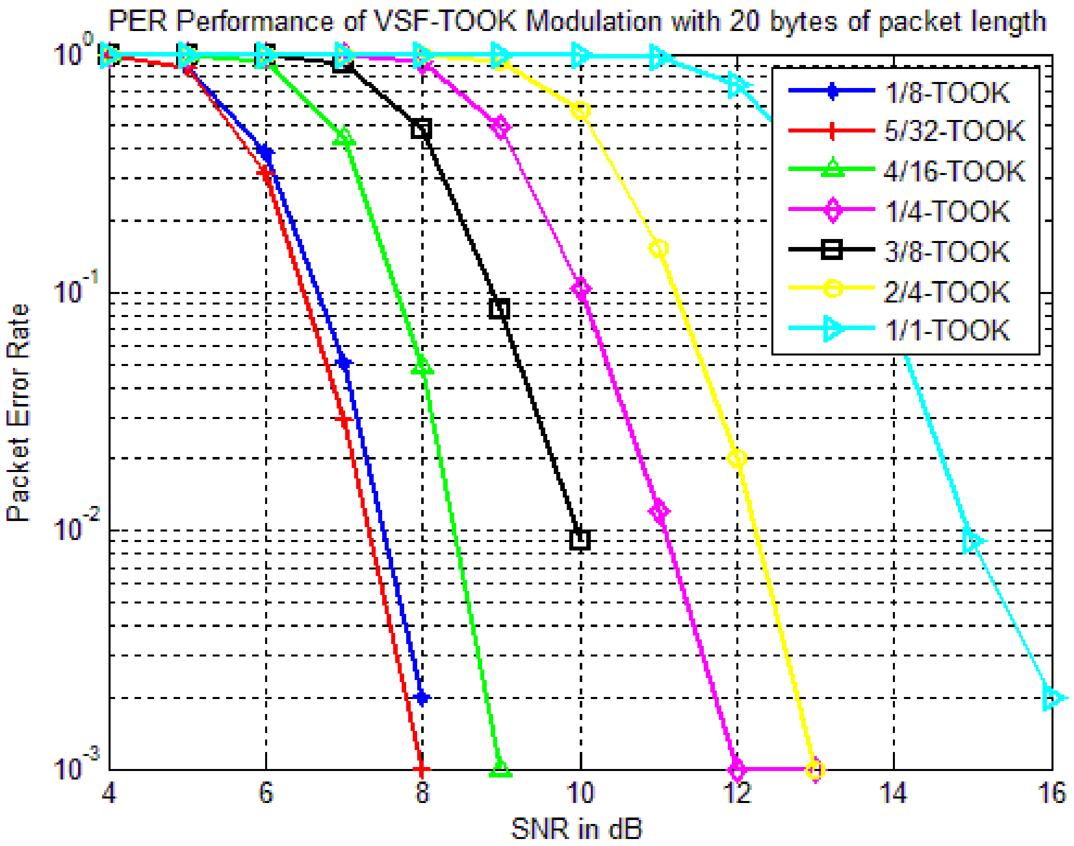
Symbol estimate at epoch $n$, $\widehat{m}_n$

$$\widehat{m}_n = \underset{m \in \{0,\ldots,M-1\}}{\operatorname{argmax}} \mathbf{s}_m^T \mathbf{y}_n$$

$\mathbf{y}_n = [y_n[1], \ldots, y_n[L]]$ – rx samples corresponding to symbol at epoch $n$

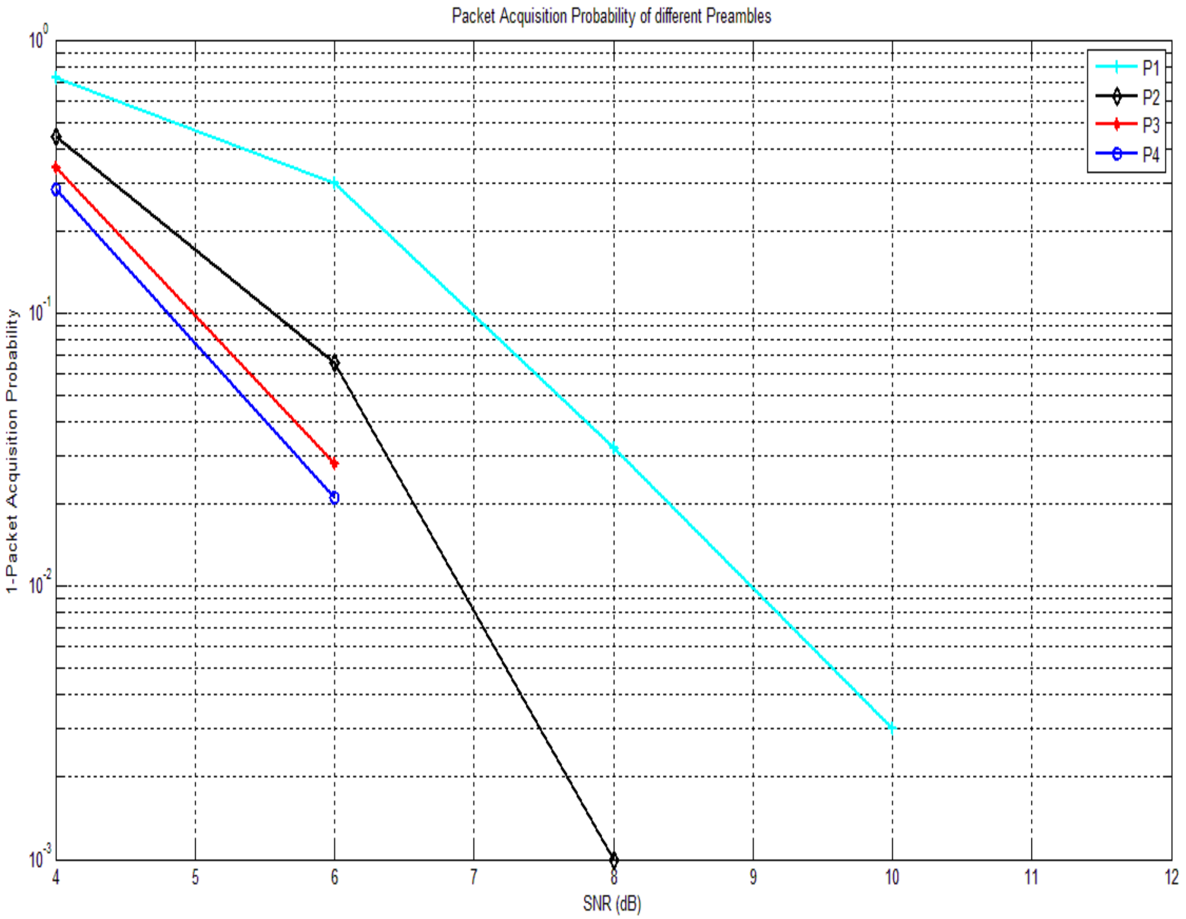
$\mathbf{s}_i^T = [s_i[1], \ldots, s_i[L]]$ - spreading sequence corresponding to symbol $i$.

# Packet Error Rate in AWGN

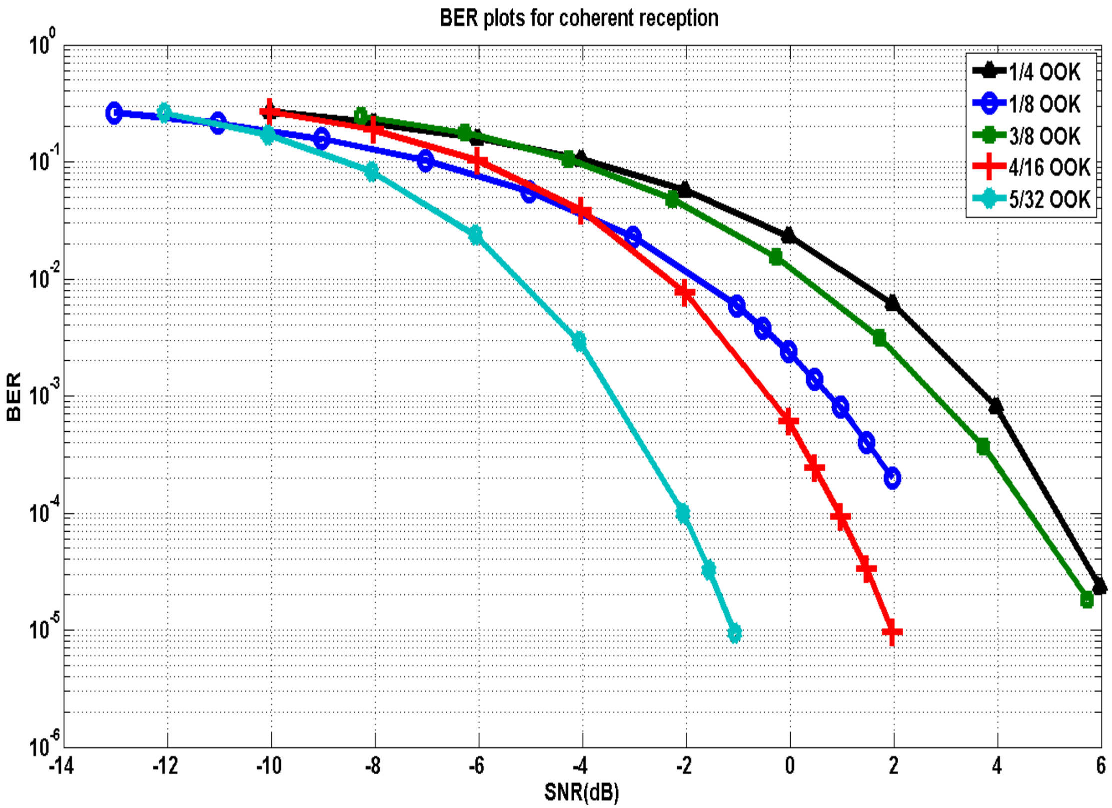



- 20 bytes of packet length assumed for PER measurements

# Synchronization Results



# BER Results for coherent mode in AWGN




- BER of 4e-5 is equivalent to PER of 1% @ 20 bytes of packet length

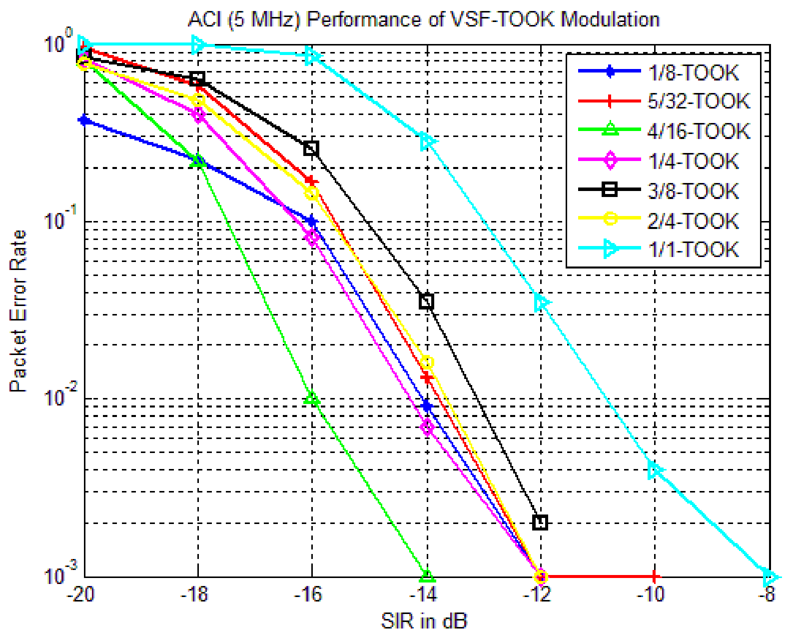
# Link Budget for AWGN

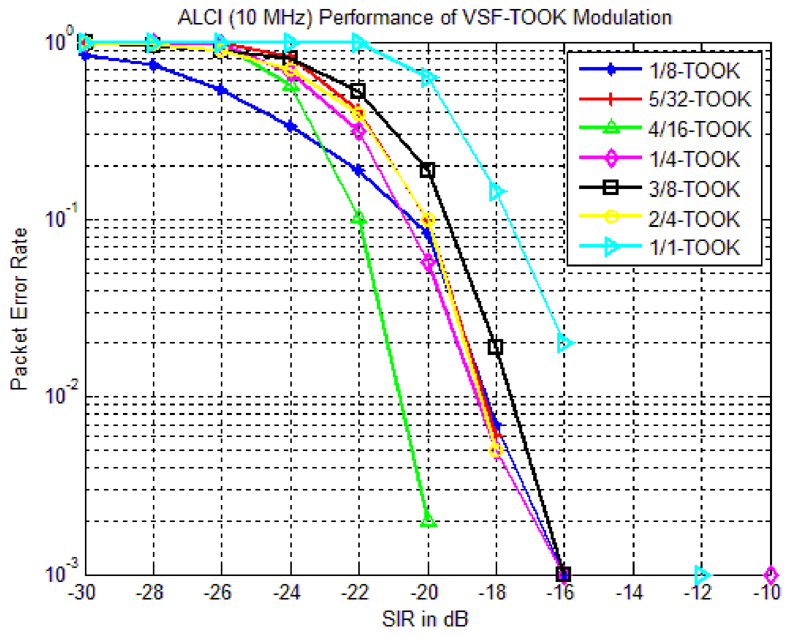
| Parameter | Value for D7 (1/8-TOOK) | Value for D5 (4/16-TOOK ) | Value for D1 (1/1-TOOK) |
|---|---|---|---|
| **Transmitter Budget** | | | |
| Payload Data Rate ($R_b$) in kbps | 101.2 | 202.4 | 809.5 |
| Distance (d) in m | 30 | 30 | 30 |
| Bandwidth (B) in MHz | 1 | 1 | 1 |
| Tx Antenna Gain ($G_T$) in dB | 0 | 0 | 0 |
| Center Frequency ($F_C$ ) in MHz | 2450 | 2450 | 2450 |
| Average Transmit Power ($P_t$) in dBm | -5 | -5 | -5 |
| **Receiver Budget** | | | |
| Path Loss at distance d m | 69.77 | 69.77 | 69.77 |
| Rx Antenna Gain ($G_R$) in dB | 0 | 0 | 0 |
| Received Power ($P_{rx}$) in dBm | -74.77 | -74.77 | -74.77 |
| Average Noise Per bit (N) in dBm | -123.94 | -120.93 | -114.91 |
| System Noise Figure (NF) in dB | 10 | 10 | 10 |
| Minimum Eb/No Required in dB | 14 | 14.5 | 16 |
| Implementation Loss (I) in dB | 3 | 3 | 3 |
| **System Performance** | | | |
| Link Margin (LI) in dB | 22.17 | 18.66 | 11.14 |
| Receiver Sensitivity (S) in dBm | -96.94 | -93.43 | -85.91 |

# Link Budget for Indoor Channels

| Parameter | Value for D7 (1/8- TOOK) | Value for D5 (4/16-TOOK ) | Value for D1 (1/1-TOOK) |
|---|---|---|---|
| **Transmitter Budget** | | | |
| Payload Data Rate ($R_b$) in kbps | 101.2 | 202.4 | 809.5 |
| Distance (d) in m | 10 | 10 | 10 |
| Bandwidth (B) in MHz | 1 | 1 | 1 |
| Tx Antenna Gain ($G_T$) in dB | 0 | 0 | 0 |
| Center Frequency ($F_C$ ) in MHz | 2450 | 2450 | 2450 |
| Average Transmit Power ($P_t$) in dBm | -5 | -5 | -5 |
| **Receiver Budget** | | | |
| Path Loss at distance d m | 69.6 | 69.6 | 69.6 |
| Rx Antenna Gain ($G_R$) in dB | 0 | 0 | 0 |
| Received Power ($P_{rx}$) in dBm | -74.6 | -74.6 | -74.6 |
| Average Noise Per bit (N) in dBm | -123.94 | -120.93 | -114.91 |
| System Noise Figure (NF) in dB | 10 | 10 | 10 |
| Minimum Eb/No Required in dB | 14 | 14.5 | 16 |
| Implementation Loss (I) in dB | 3 | 3 | 3 |
| **System Performance** | | | |
| Link Margin (LI) in dB | 22.34 | 18.83 | 11.31 |
| Receiver Sensitivity (S) in dBm | -96.94 | -93.43 | -85.91 |

# ACI Performance




| Parameter | Value |
|---|---|
| Adjacent Channel Rejection | 13 |
| Alternate Channel Rejection | 20 |

# Power Consumption

| Tx Component | Power (µW) @ -5 dBm |
|---|---|
| Baseband | 1000 |
| VCO | 322 |
| Power Amplifier | 2982 |
| PLL + Freq Synthesizer | 1000 |
| Total | 5304 |

| Rx Component | Power (µW) |
|---|---|
| LNA+SRO | 638 |
| ED+VGA | 33 |
| ADC (8 bit) | 7.5 |
| Baseband | 1500 |
| PLL + Freq Synthesizer | 1000 |
| Total | 3178.5 |

- Total Power consumption less than 5 mW for Receiver
- Total Power consumption of transmitter less than 7 mW @ -5 dBm EIRP
- Meets the 15.4q PAR requirement of less than 15 mW in transmit and receive modes

# Targeted Area of Applications

# Reference Powers for Transmitter and Receiver Circuits

- Transmitter Power Reference: For a 0 dBm Transmit power, and $\eta_T = 0.2$, The transmitter power is 5 mW
- Receiver Power Reference 1: For a median receiver current of 20mA from vendor chipsets the power is 20mA$\times$ 3V$\approx 60mW$
- Receiver Power Reference 2: For a minimum receiver current of 3.5mA from vendor chipsets the power is 3.5mA$\times$ 3V$\approx 10mW$

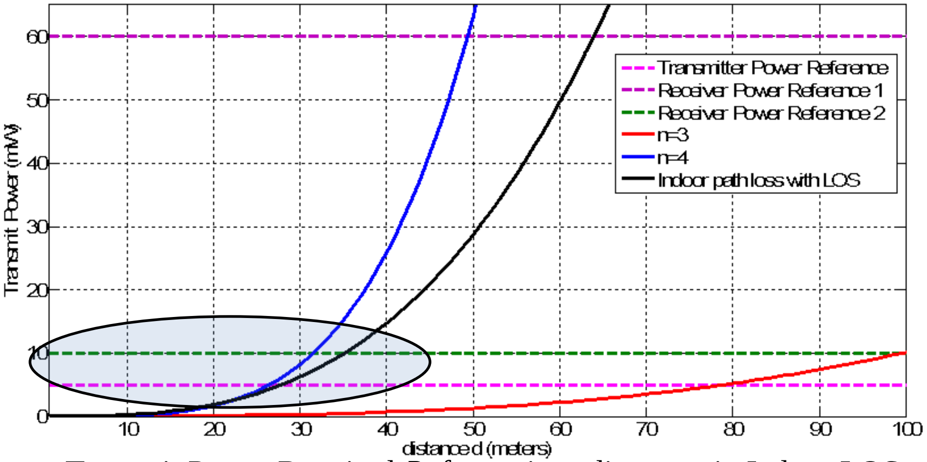
**2.4 GHz IEEE 802.15.4 Commercial Chipsets**

| Chipset | Tx Current | Rx. Current |
|---|---|---|
| Vendor6 | 21 mA (0 dbm) | 21 mA |
| Vendor7 | 19.6 mA (0 dbm) | 19 mA |
| Vendor10 | 17 mA (+3 dbm) | 16 mA |
| Vendor3 | 30 mA (+3 dbm) | 25 mA |
| Vendor13 | 6 mA (0 dbm) | 4 mA |
| Vendor5 | 20 mA (0 dbm) | 22 mA |
| Vendor12 | 15 mA (2.5 dbm) | 17.5 mA |
| Vendor2 | 30 mA (0 dbm) | 37 mA |
| Vendor8 | 19 mA | 20 mA |
| Vendor9 | 18.9 mA | 17.4 mA |
| Vendor11 | 17 mA | 13 mA |
| Vendor1 | 36 mA | 36 mA |
| Vendor4 | 29 mA | 24 mA |
| Vendor14 | 3.6 mA | 3.5 mA |

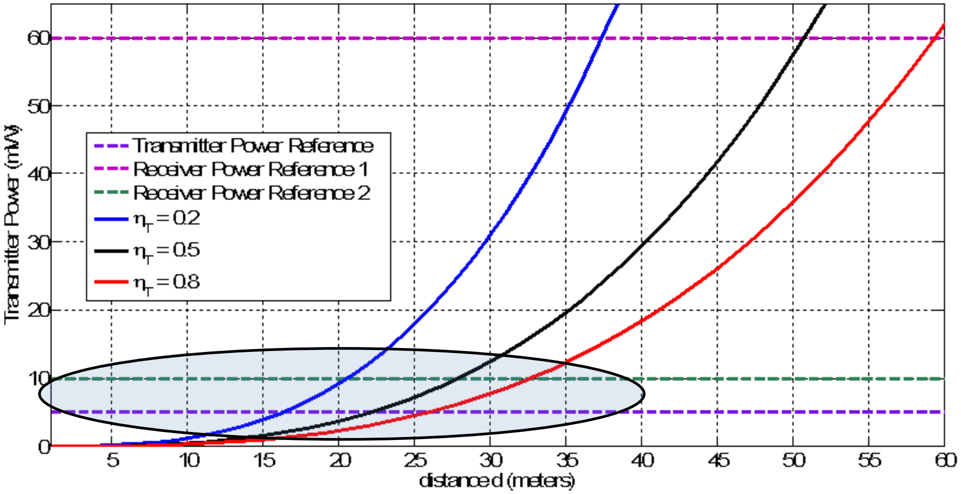
Ref [4]: IEEE902.15-12-0383-0000-4q “A Limitation of Coin Cell Batteries” Shahriar Emami

# Efficiency of Transceiver vs Distance

- For distances of below ~30 m, the reference transmitter and receiver system powers are higher than $P_t$
- For $\eta_T = 0.5$, for distances below ~ 20 m, the transmitter and receiver system powers are higher than $P_{tx}$
- For shorter distances the Transmitter powers and Receiver powers become more important than the Transmit signal power (EIRP)
- *With this protocol, we could support applications with range up to 30 m with greater energy efficiency due to Ultra Low Receiver Power*



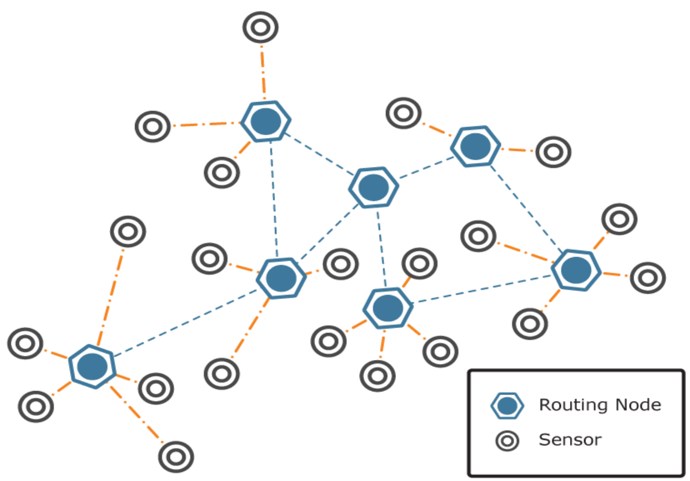

Transmit Power Required $P_t$ for various distances in Indoor LOS, and with Free space path loss model with n=3 and n=4

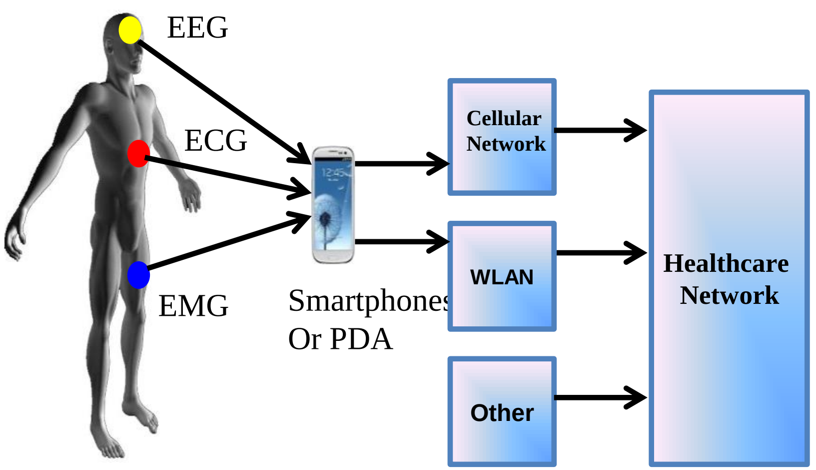



Corresp Transmitter Power $P_{tx}$ for various distances in Indoor LOS

# Applications with Low Rx Power Requirement

- Master nodes are becoming energy constrained
- Collaborating sensor nodes
- Sensors in some applications need continuous sensing
- Power Consumed by the Receiver is *also* important

# TGD Compliance Sheet

| TGD Metric | Evaluation |
|---|---|
| Lowest Mandatory Data Rate | 101.2 kbps |
| Range in AWGN Channel | Link Margin of 22 dB @ 30 m |
| Bit Rate | 101.2 to 809.5 kbps |
| Range in channel model proposed | Link Margin of 22 dB @ 10 m |
| ACI/ALCI Rejection | 13/20 dB |
| ACPR/ALCPR | -69/-72 dB |
| Band Plan and co-existence | Band plan proposed for 2.4 GHz and 900 MHz |
| Evaluation of packet efficiency for 40 bytes | Done |
| Power Consumption for Receiver | 3.2 mW |
| Power Consumption for transmitter | 5.3 mW |

# Summary

- Proposal for air interface for Low range applications requiring ultra low power consumption
- Receiver Power of non-coherent mode less than 5 mw
- Demonstrated the positive link margin for 30 m range in awgn, 10 m range in indoor channels for all data rates proposed
- Coherent sensitivity of much less than -90 dBm
- Range of data rates – 0.1 to 1 Mbps