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

Submission Title: [DBO-CSK Proposal for IEEE802.15.4a]
Date Submitted: [January 2005]
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Re: [Response to Call for Proposal by IEEE802.15.4a]

Abstract: [This document has been submitted for an official proposal in January 2005. DBO-CSK Technology is proposed]

Purpose: [Proposal for the IEEE802.15.4a standard]

Differentially Bi-Orthogonal Chirp-Shift-Keying (DBO-CSK)

Kyung-Kuk Lee
Orthotron Co., Ltd.

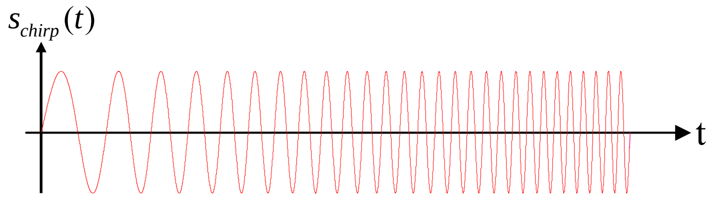
CONTENTS

1. INTRODUCTION

- **Low Power Consumption:**
  - Digital Tx 0.9mW / Rx 1.13mW @ 500Kbps Data-rate
- **Signal Robustness:**
  - Orthogonal / Quasi-Orthogonal Signal Set are deployed
  - Robustness: Applicable in Heavy Multi-path, SOP
  - Low Correlation of Signal with Existing Air-Interfaces
- **Feasibility:** 2.4GHz, 5.2/5.7GHz Band
  - Many existing commercial RF Solutions
- **Ranging:** Based on Chirp Signal (TOA/TDOA)
  - Precision: less then 1m @ Eb/No=24dB
- **Size & Form Factor:** Smaller than SD-Memory size
- **Low Cost / Low Complexity:** Tx +Rx Baseband Digital (58K gates)
- **Advanced Sleep/Wake-up Capability**

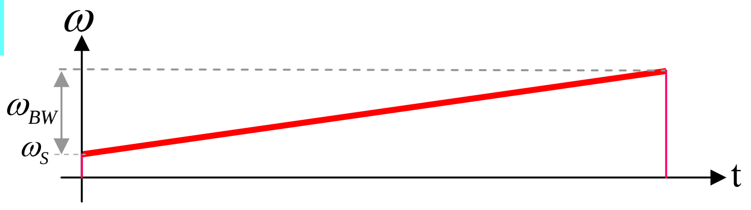
2. M-ary DBO-CSK TECHNOLOGY

Chirp Signal



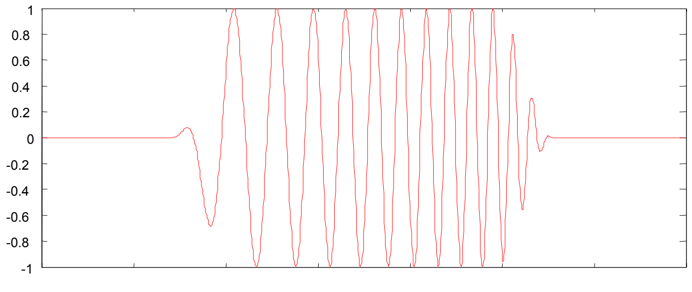
Linear Chirp: Rectangular Window

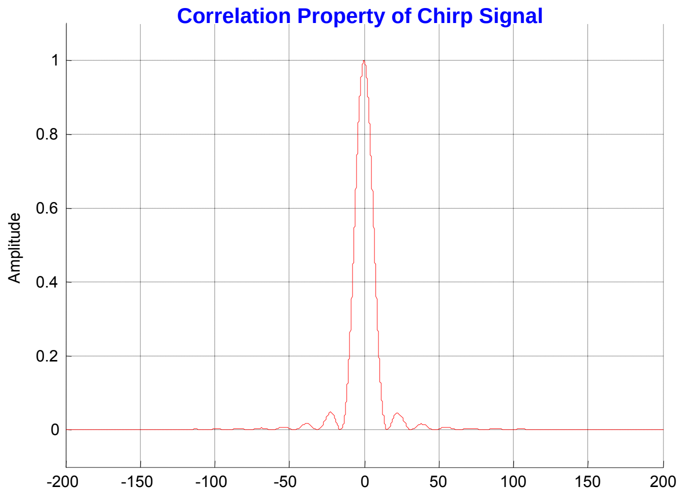
$$s_{chirp}(t) = \mathrm{Re}\left[\exp[(\omega_s + \frac{\omega_{BW}}{2T_{chirp}}t)t + \theta_0] \times [u(t) - u(t - T_{chirp})]\right]$$



Linear Chirp: Raised-Cosine Window

$$s_{chirp}(t) = \mathrm{Re}\left[\exp[(\omega_s + \frac{\omega_{BW}}{2T_{chirp}}t)t + \theta_0] \times p_{RC}(t - T_{chirp})\right]$$

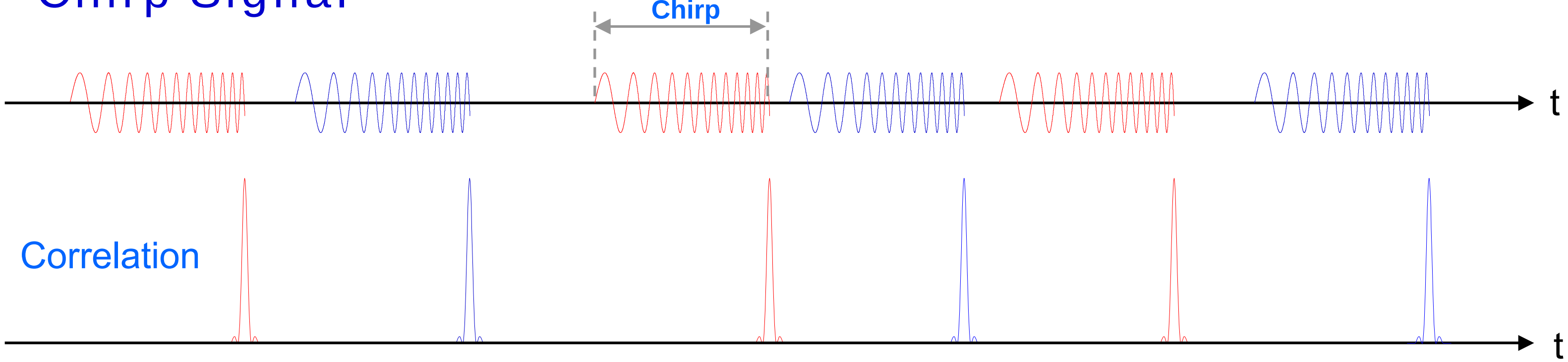




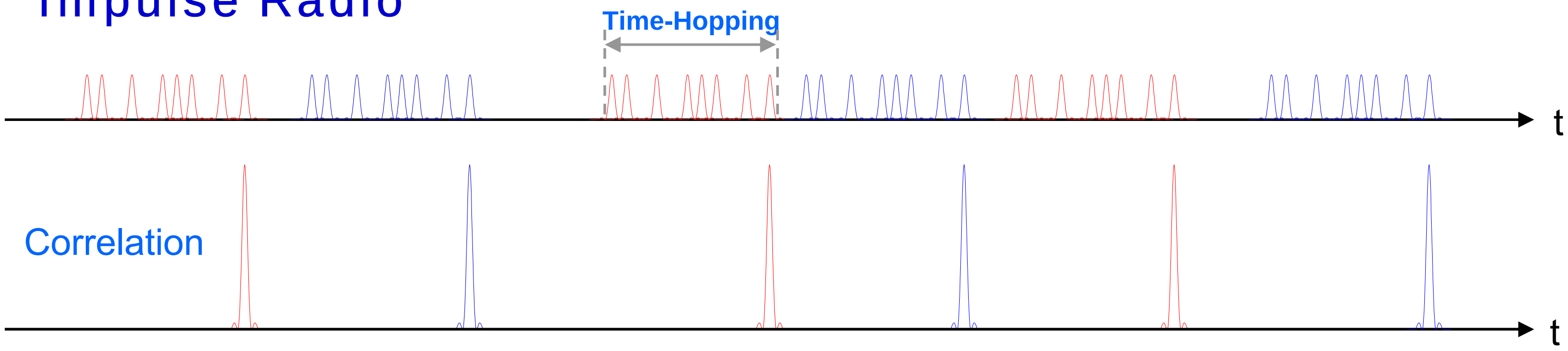
2. M-ary DBO-CSK TECHNOLOGY

Chirp vs Impulse

Chirp Signal



Impulse Radio



2. M-ary DBO-CSK TECHNOLOGY

Chirp vs Impulse

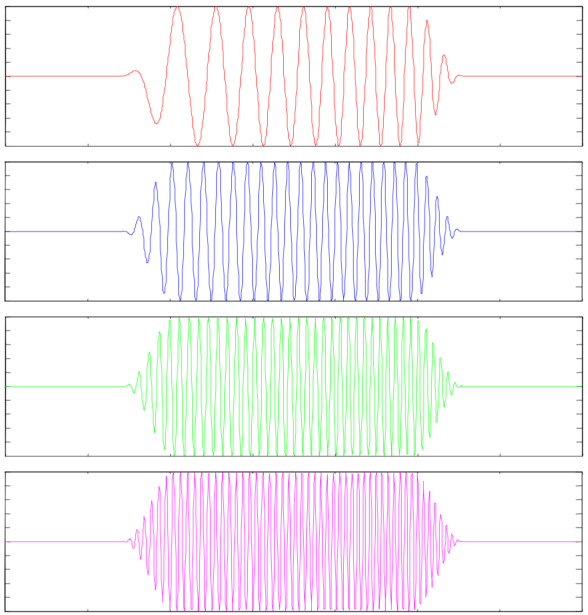
- Similarities
  - Spread-Spectrum: BW >> R_b (De-spreading Gain)
  - High Correlation Peak, Narrow Impulse/Cross-correlation width
  - (Pulse-width of Impulse) = (Pulse-width of Cross-Correlation of Chirp) @ Same BW
  - Great Resolvability of Multi-path

- Differences
  - Cross-correlation Property:
    - Chirp: Inherently very low side-lobe of cross-correlation
    - Impulse: Need very long code-sequence to realize low side-lobe of cross-correlation
  - Signal Voltage for Signal Power: ex. TX 0.1mW ($P = V^2/2R$, R = 50 ohm)
    - Chirp: low peak voltage ----------------------------- 0.1V (Sinusoid)
    - Half-Sinusoid Impulse: higher peak voltage --- 1.0V (duty-cycle 1:100)
  - PAPR:
    - Chirp: PAPR = 3dB (Theoretical Minimum value) → easily achievable Eb
    - Impulse: PAPR = 13dB (ex. Same condition as above)
      very high PAPR → need high-voltage / long pulse sequence for Eb

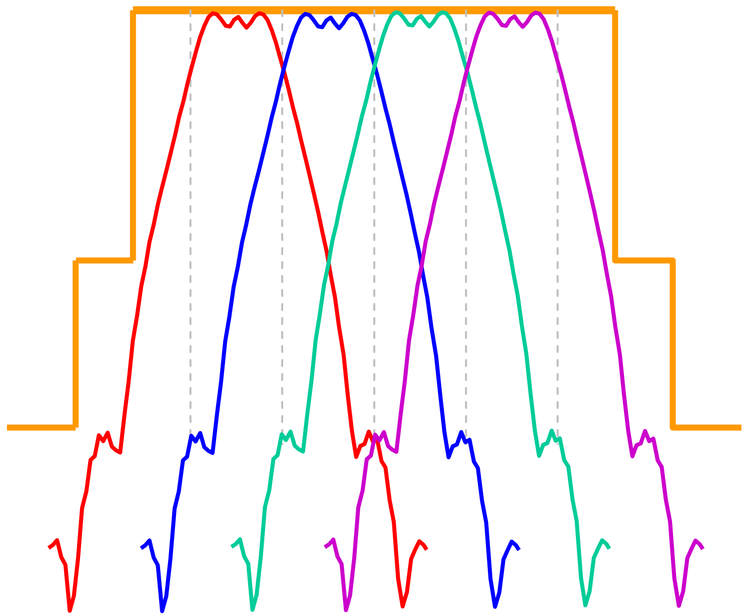
2. M-ary DBO-CSK TECHNOLOGY

Spectrum of Sub-Chirp Signals

Waveform

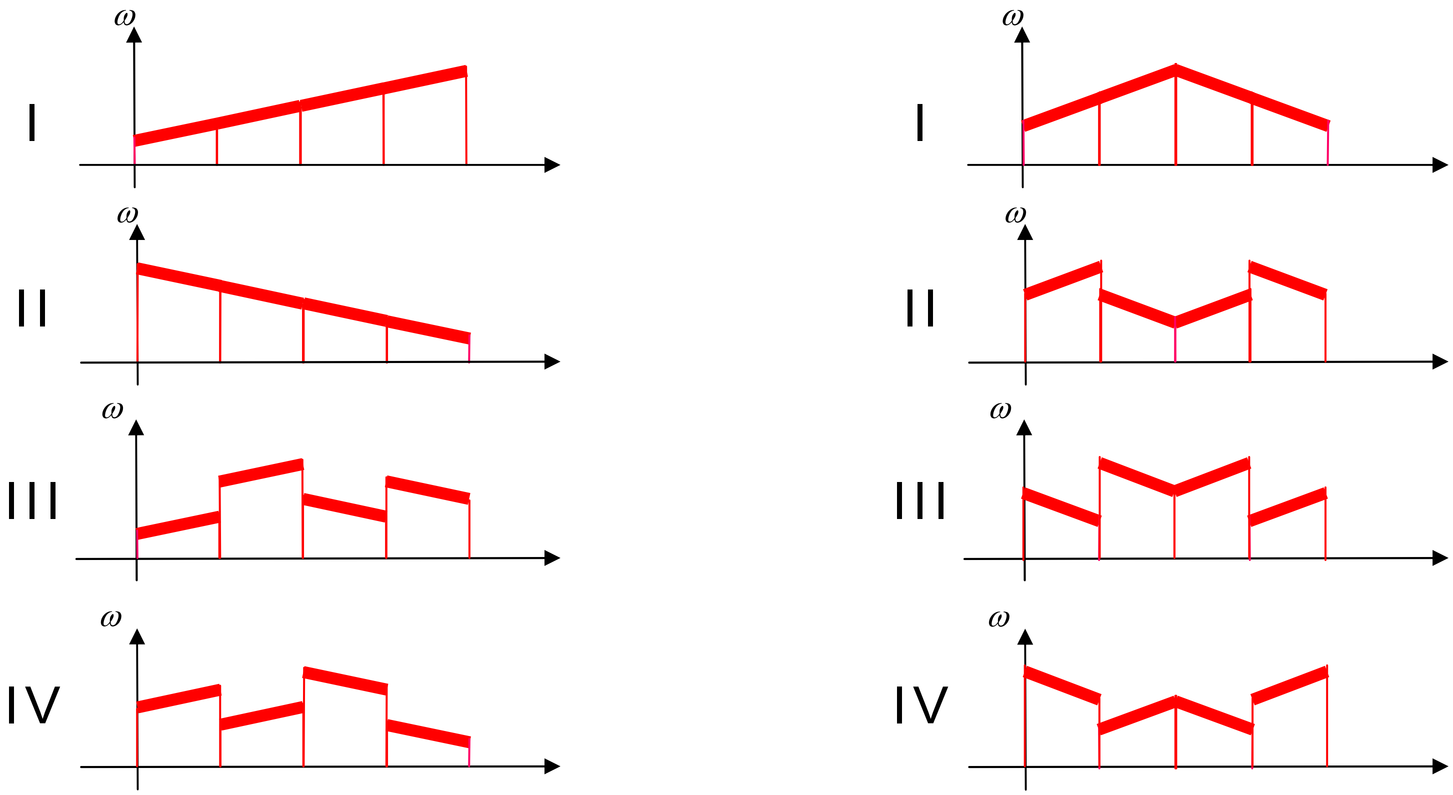


Spectrum



2. M-ary DBO-CSK TECHNOLOGY

Chirp-Shift-Keying (CSK) Signal sets for SOP



Each of CSK Signal consists of 4 sub-chirp signals.

2. M-ary DBO-CSK TECHNOLOGY

Bi-Orthogonal Modulation

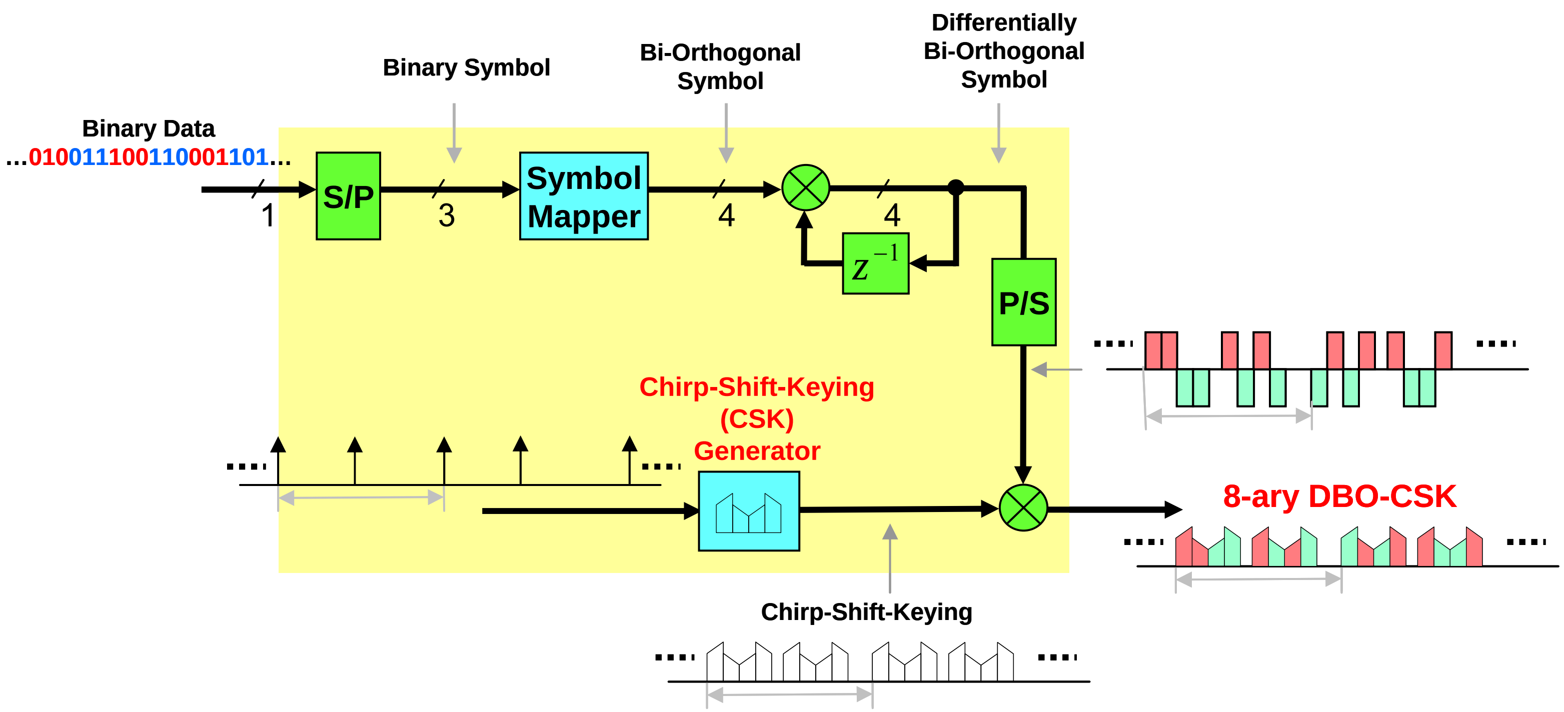
Bi-Orthogonal Symbol Mapping Table (M = 8)

Decimal (m)	Binary (b0,b1,b2)	Bi-Orthogonal Code (01,02,03,04)
0	000	1 1 1 1
1	001	1 -1 1 -1
2	010	1 1 -1 -1
3	011	1 -1 -1 1
4	100	-1 -1 -1 -1
5	101	-1 1 -1 1
6	110	-1 -1 1 1
7	111	-1 1 1 -1

3 bits/symbol

2. M-ary DBO-CSK TECHNOLOGY

8-ary Differentially Bi-Orthogonal Chirp-Shift-Keying(DBO-CSK) Modulator



3. GENERAL SOLUTION CRITERIA

3.1. Unit Manufacturing Cost/Complexity (UMC)

BaseBand Digital		Estimated Complexity 500Kbps / 250Kbps [gates]		Data-Rate 250 Kbps	Data-Rate 500 Kbps
Tx	Scrambler	154	1.5K / 1.6K	O	O
	FEC Encoder (r=1/2)	100		O	X
	Symbol Mapper	13		O	O
	Differential Encoder	56		O	O
	Chirp-pulse Modulator	290		O	O
	Framer & Others	1K		O	O
Rx	Differential Detector	39k	49.4K / 145K	O	O
	Symbol Demapper	200		O	O
	Max Selector	100		O	O
	FEC Decoder (r=1/2)	95K		O	X
	Descrambler	154		O	O
	Deframer & Others	10K		O	O
Common		5K		O	O
Transceiver				152K	56K

3. GENERAL SOLUTION CRITERIA

3.2. General Definitions

- **Payload bit rate and throughput**
  - 500Kbps throughput: 293Kbps
  - 250Kbps throughput: 173.7Kbps
- **Error rate:** see sub-section 5.6
- **Receiver sensitivity:** see sub-section 5.11
- **Antenna gain:** 0dBi
- **Band in use:**
  - 2.4GHz ISM Band (10MHz Overlapping)
  - 5.2/5.7GHz Band (Non-overlapping)
  - 20MHz Bandwidth: Consists of 4 sub-chirp signals per Carrier

3. GENERAL SOLUTION CRITERIA

3.3. Signal Robustness

- **Co-existence / Interference Mitigation Technique**
  - Orthogonal / Quasi-Orthogonal Signal Set
  - High Spectral Processing Gain: Chirp
  - Near-Far Problem: FDM Channels (7ch @2.4GHz, 8ch @5.2GHz, 6ch @5.7GHz)

- **Interference Susceptibility**
  - Low Cross-Correlation property with Existing Signal

- **Robustness:**
  - Heavy Multi-path Environment
  - SOP

- **Low Sensitivity for Component Tolerance**
  - Crystal : ± 40ppm

- **Mobility**
  - Wide-band Chirp: Insensitive for Fading & Doppler Shift
  - Easily Maintaining Timing Sync. of Received Signal

3. GENERAL SOLUTION CRITERIA

3.3. Signal Robustness

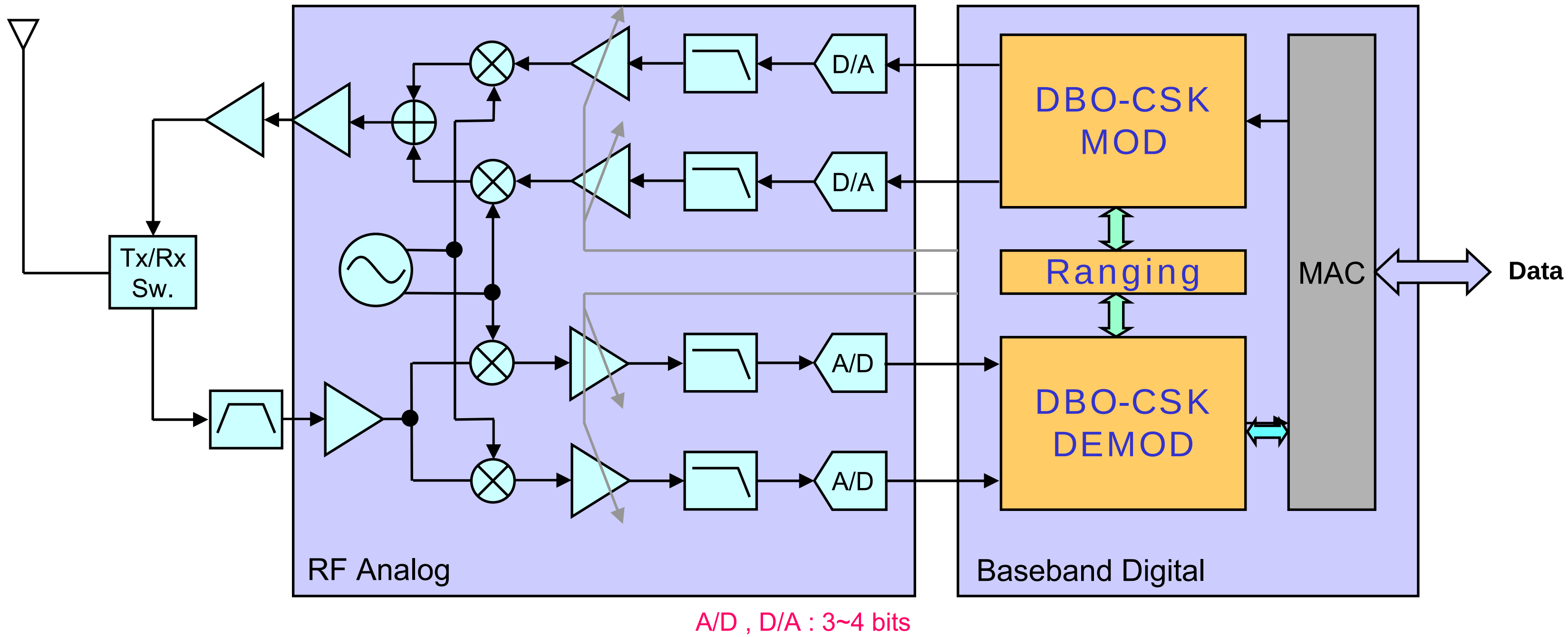
- **Ingress**
  - High Processing Gain (10log(20/.5)=16dB)
  - Addition Processing Gain by DS-Spreading (Optional)
  - Low Cross-Correlation with Existing Air-Interfaces

- **Egress**
  - Same Spectrum Mask with W-LAN @ 2.4GHz, 5.2GHz, 5.7GHz
  - Tx power control: 10mW / 1mW / 0.1mW (use Link Margin to reduce Interference)

3. GENERAL SOLUTION CRITERIA

3.4. Technical Feasibility

Block-diagram of DBO-CSK Transceiver



3. GENERAL SOLUTION CRITERIA

3.4. Technical Feasibility

■ Manufacturability

- Baseband Digital Chip area: 0.75 / 1.64 mm^2 (No FEC / FEC)
  (0.18um Technology)

■ Time-to-Market

- 2005. 5. Proto-type DEMO (FPGA)
- 2006. 1. Digital ASIC

■ Regulatory Impact

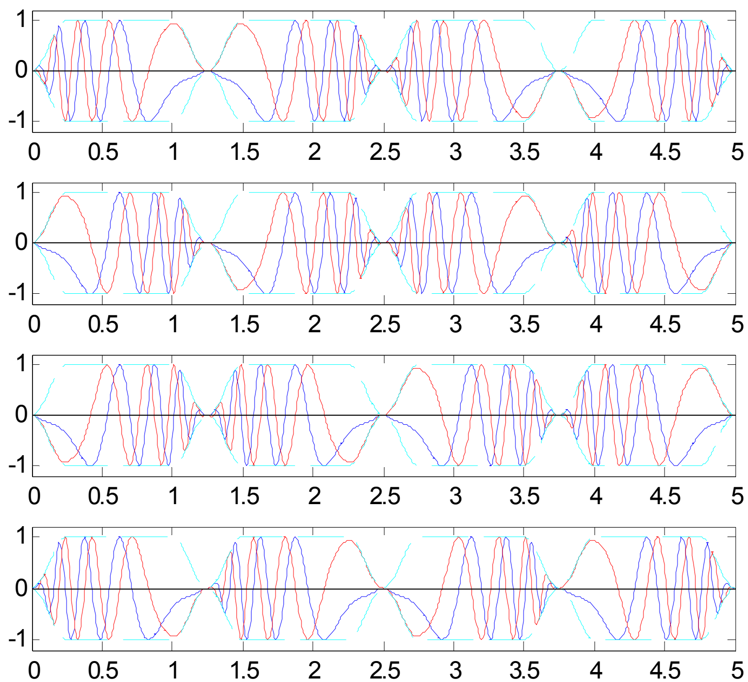
- Availability of Spectrum: 2.4GHz, 5.2/5.7GHz Band
  Globally Allowed to use (Unlicensed)
- Spectrum Availability:
  7 FDM CH. (2.4GHz) , 8 FDM CH. (5.2GHz) , 6 FDM CH. (5.7GHz)
- Tx Power: 0.1mW / 1.0mW / 10mW optional class
- Some Sensitive Frequency Band: Skip Tx Power for that Band (some SNR loss)

3. GENERAL SOLUTION CRITERIA

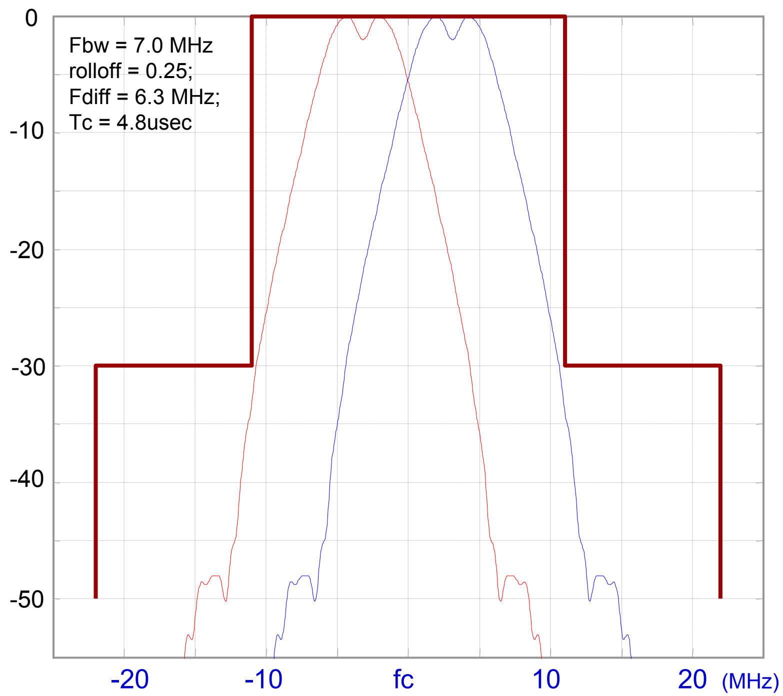
3.4. Technical Feasibility

CSK Signals: 2.4GHz Band (20MHz BW)

Waveform



Spectrum



Same Spectrum with IEEE802.11b

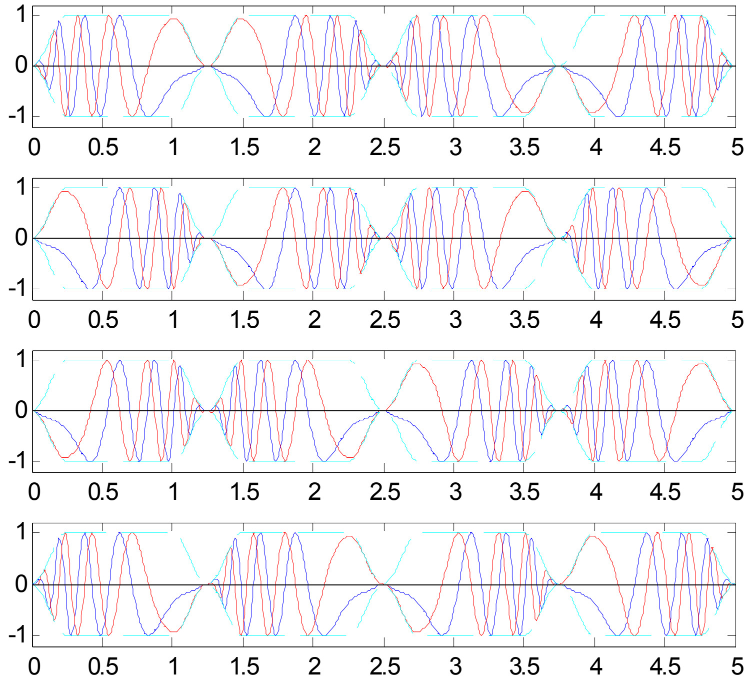
fc = 2.412GHz , 2.422GHz , 2.432GHz , 2.442GHz , 2.452GHz , 2.462GHz , 2.472GHz

3. GENERAL SOLUTION CRITERIA

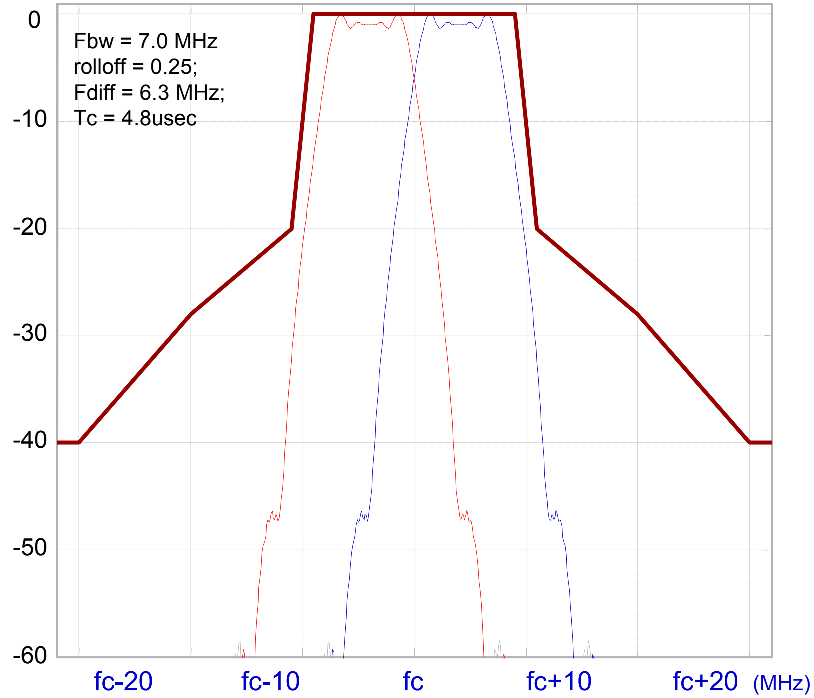
3.4. Technical Feasibility

CSK Signals: 5.2/5.7GHz Band (20MHz BW)

Waveform



Spectrum



Same Spectrum with IEEE802.11a

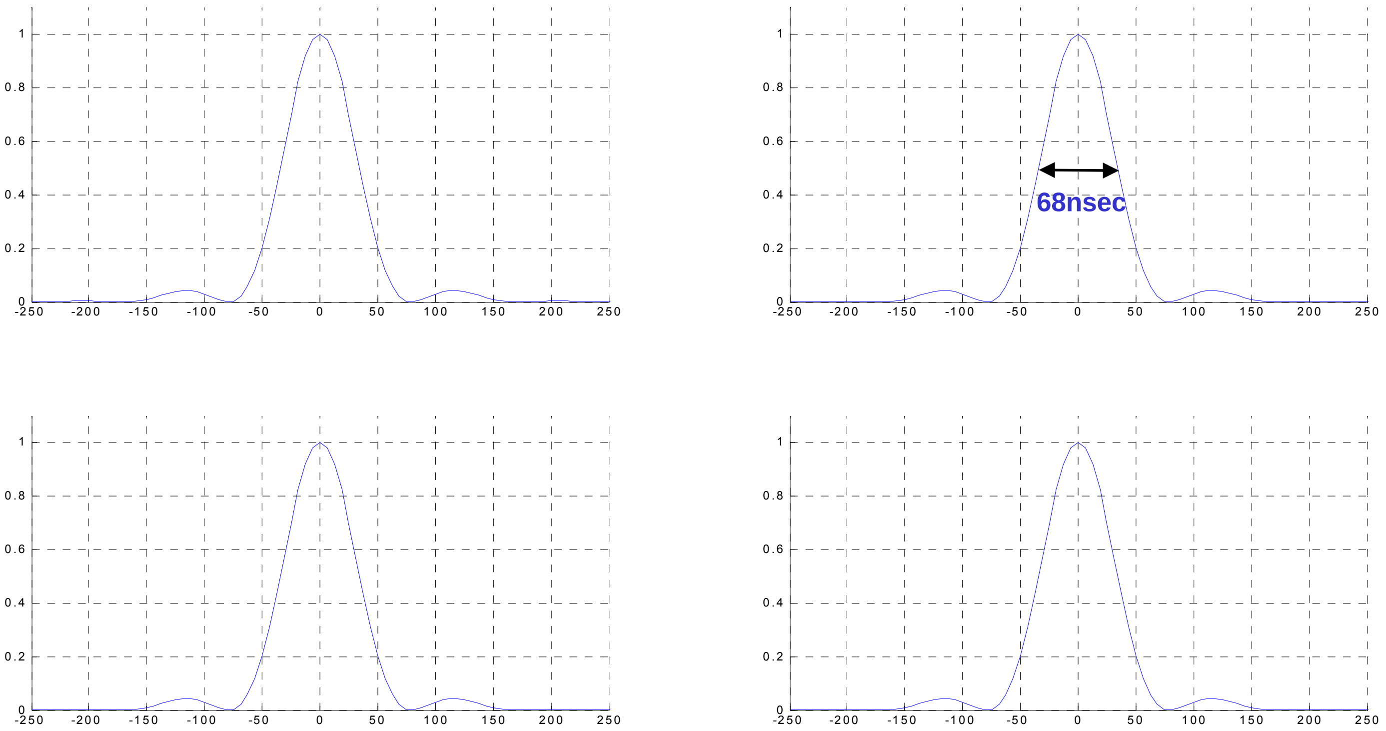
fc = 5180MHz , 5200MHz , 5220MHz , 5240MHz , 5260MHz , 5280MHz , 5300MHz , 5320MHz
fc = 5725MHz , 5745MHz , 5765MHz , 5785MHz , 5805MHz , 5825MHz

3. GENERAL SOLUTION CRITERIA

3.4. Technical Feasibility

CSK Signals: 2.4GHz Band (20MHz BW)

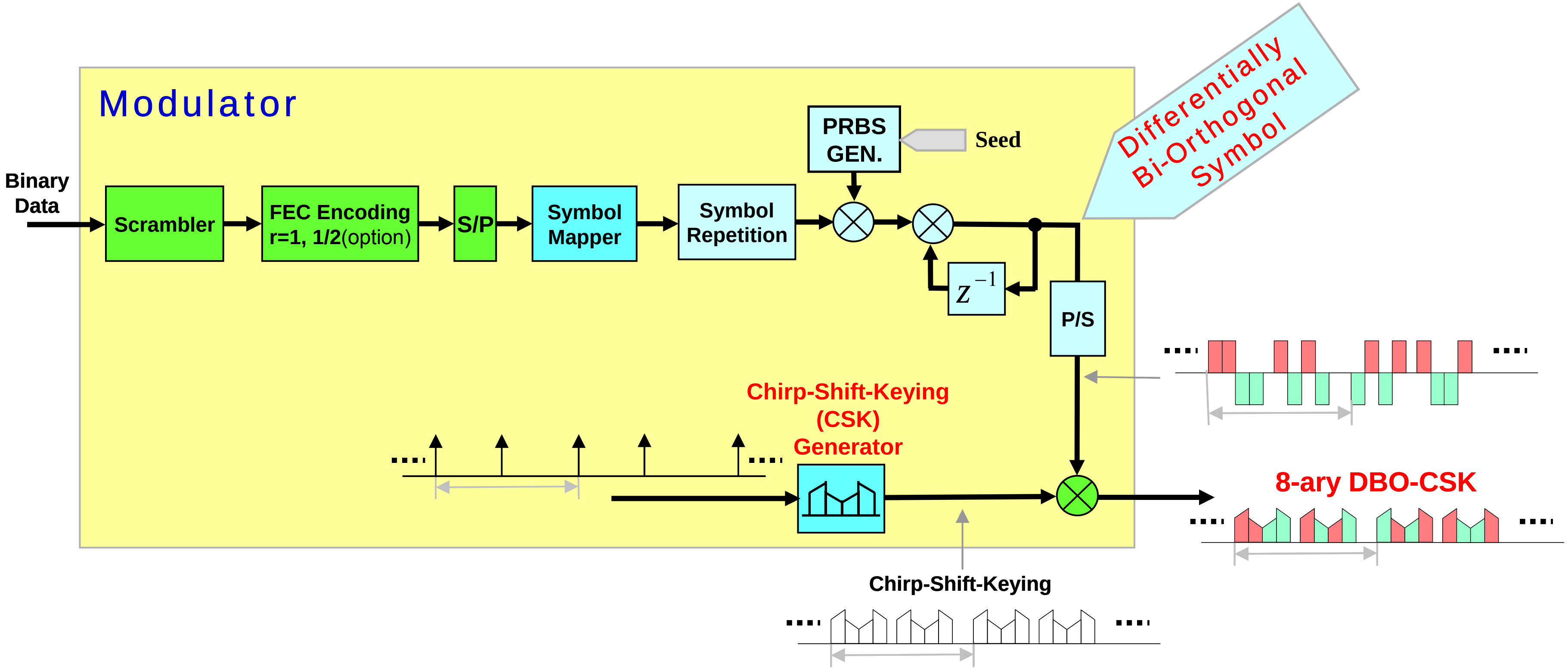
■ **4 piconet CSK Signal: Identical Auto-correlation Property → Same Ranging Accuracy**



3. GENERAL SOLUTION CRITERIA

3.4. Technical Feasibility

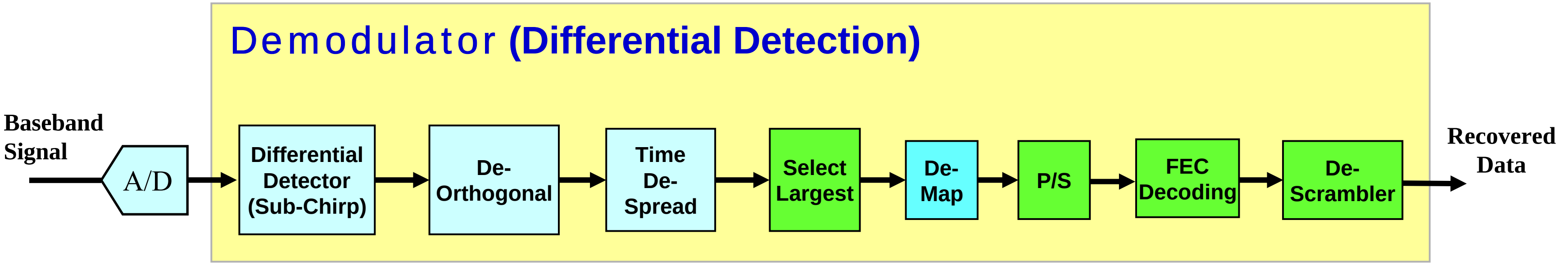
8-ary DBO-CSK Modulator

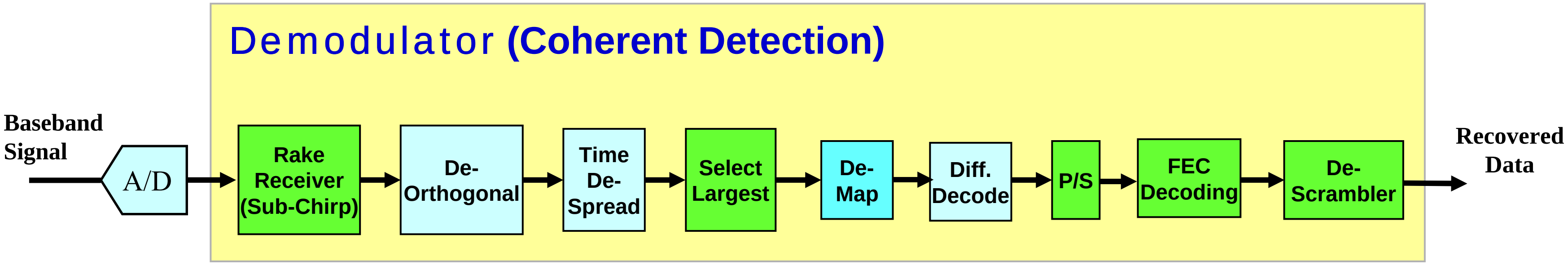


3. GENERAL SOLUTION CRITERIA

3.4. Technical Feasibility

8-ary DBO-CSK Demodulator





3. GENERAL SOLUTION CRITERIA

3.5. Scalability

■ Data-Rate:

- 2 rates: **500Kbps / 250Kbps**

■ RF Tx Power:

- 3 classes: 0.1mW / 1.0mW / 10mW

■ Mobility Value:

- Data: Link Margin >= 34.8dB @ 2.4GHz Band
- Chirp is insensitive for Doppler Shift: very small Ranging error and BER degrade

- Chirp Index: $\mu_f = f_{BW} / T_{chirp}$
- Doppler Shift: $f_d = f_c \times v / c = \mu_f \times \Delta T$
- Ranging Error: $\Delta d = \Delta T \times c = f_c \times v / \mu_f = f_c \times v \times T_{chirp} / f_{BW}$

Ex) $f_{BW} = 14MHz,\ T_{chirp} = 4.8\mu\sec,\ f_c = 2.4GHz \quad \Rightarrow \quad \Delta d = 8.23 \times 10^{-4} \times v$

$v = 50Km/h \ : \ \Delta d = 8.23 \times 10^{-4} \times 50 \times 10^3 / 3600 = 1.14\ [cm]$

4. MAC PROTOCOL SUPPLEMENT

4.1. MAC Enhancements and Modifications

- **Supplement for Scalability**
  - The proposed PHY has scalability for channelization
  - Scalability which is included in PHY may be added to MAC for 15.4a PHY layer (Data-rate / Tx Power / Ranging)

- **Wake-up Mode for Power Consumption Consideration**
  - Power consumption is of significant concern
  - Needing supplement to 15.4 MAC to support wake-up mode for low-power consumption

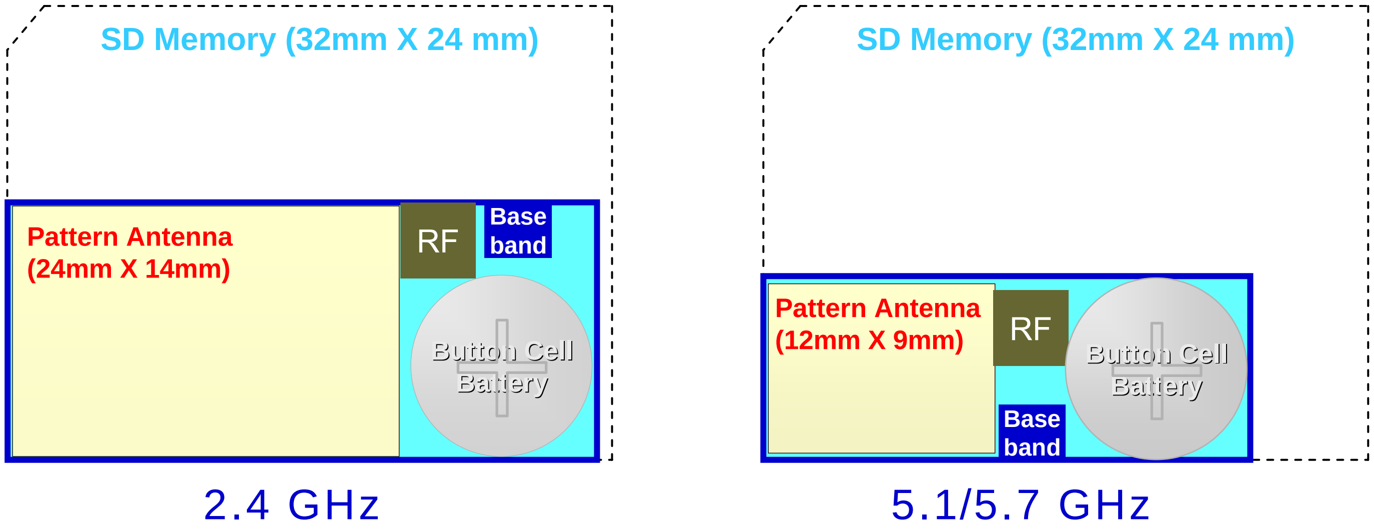
5. PHY LAYER CRITERIA

5.1. Channel models and payload data

- **Channel models and payload data**
  - See sub-section 5.4 in this Document
  - Payload Data: 32bytes per Packet
  - Data-rate: 500Kbps / 250Kbps

5. PHY LAYER CRITERIA

5.2. Size and Form Factor



Ex)
- Battery Capacity: 3V x 30mAh (324Joule)
- Dimension: 10 x 2.5 (Dia. x Ht. mm)

5. PHY LAYER CRITERIA

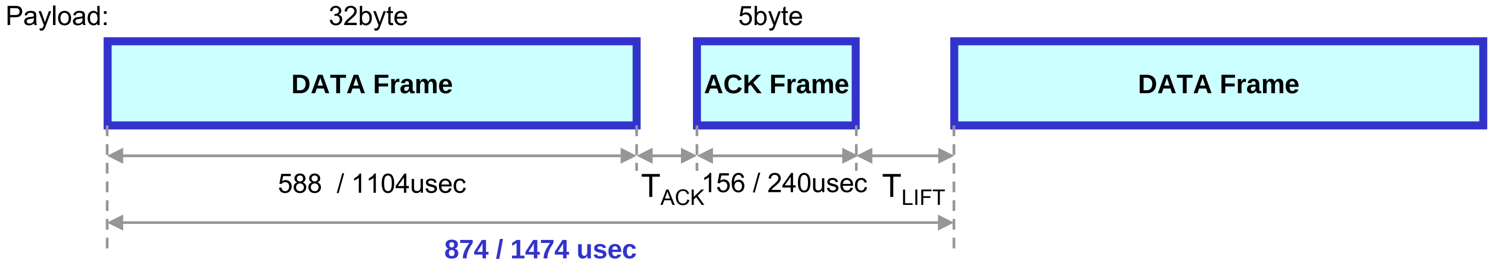
5.3. PHY-SAP Payload Bit Rate and Data Throughput

Payload Bit-rate:

- **Data-rate: 500Kbps / 250Kbps per piconet**
- **Aggregated Data-rate: Max. 2Mbps (4 X 500Kbps) per FDM Channel**
- **FDM Channels: 7 CH. (2.4GHz), 8 CH. (5.2GHz), 6 CH. (5.7GHz)**

Data Throughput:

- **Payload bit-rate 500Kbps : Throughput 293 Kbps**
- **Payload bit-rate 250Kbps : Throughput 173.7 Kbps**



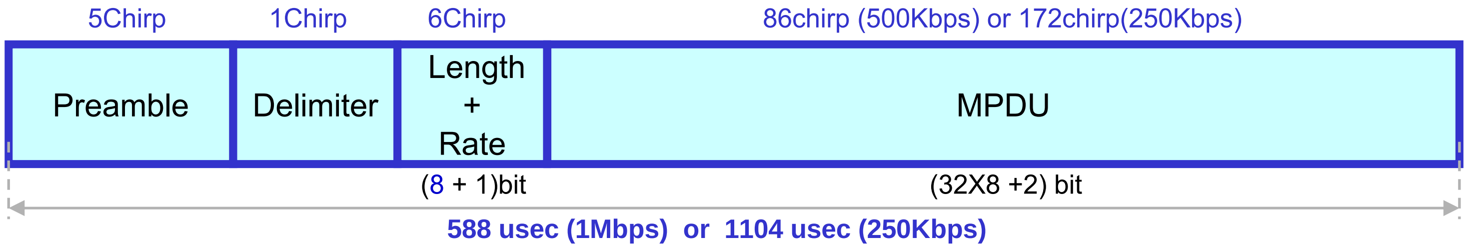
$T_{ACK} + T_{LIFT}$ = 130usec

5. PHY LAYER CRITERIA

5.3. PHY-SAP Payload Bit Rate and Data Throughput

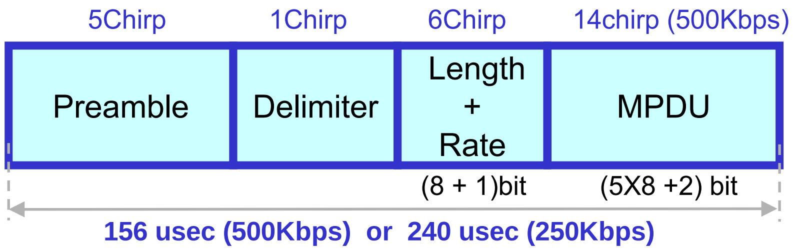
Data Frame:

Payload bit-rate : 500Kbps (No FEC) / 250Kbps (FEC r=1/2)



ACK Frame:

Payload bit-rate : 500Kbps (No FEC) / 250Kbps (FEC r=1/2)

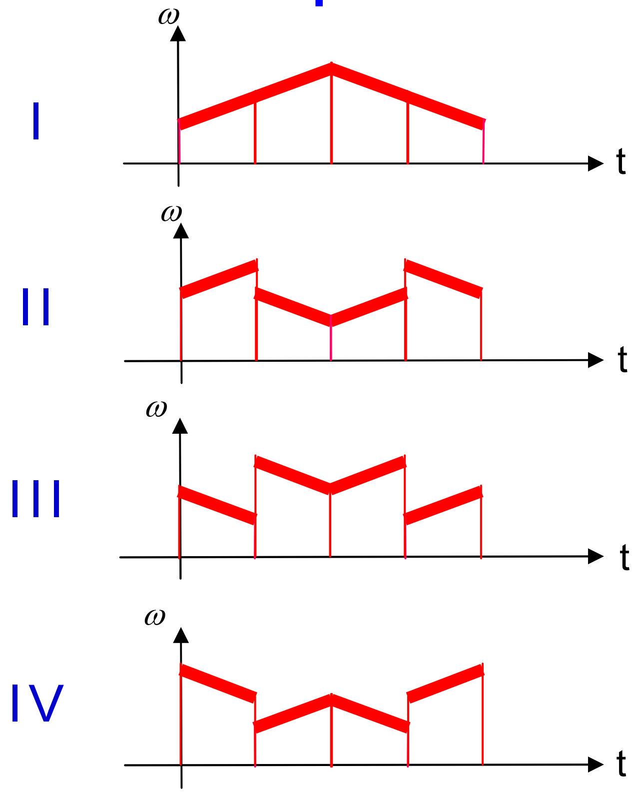


5. PHY LAYER CRITERIA

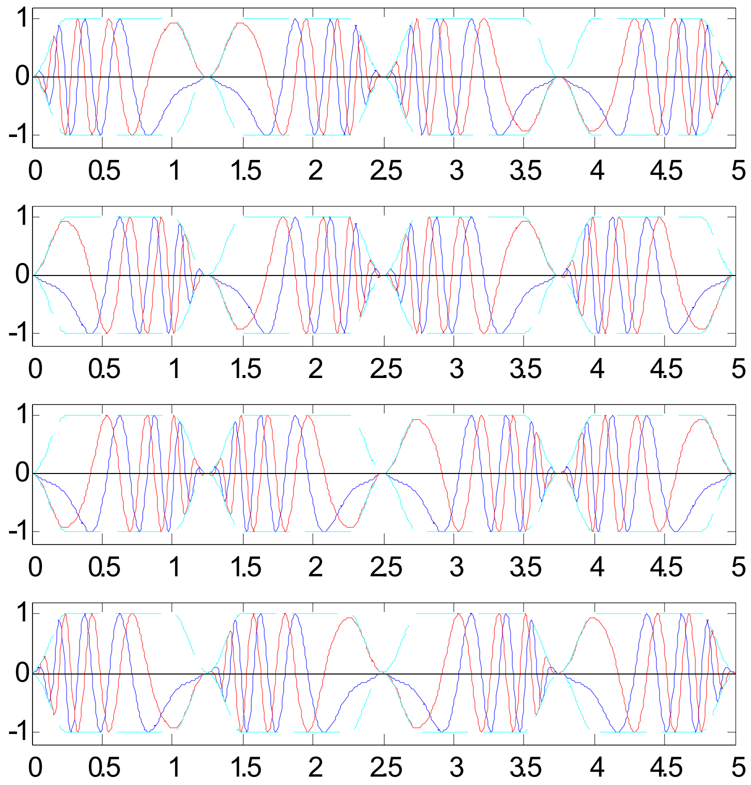
5.4. Simultaneously Operating Piconets

Multiple piconet

Freq. - Time



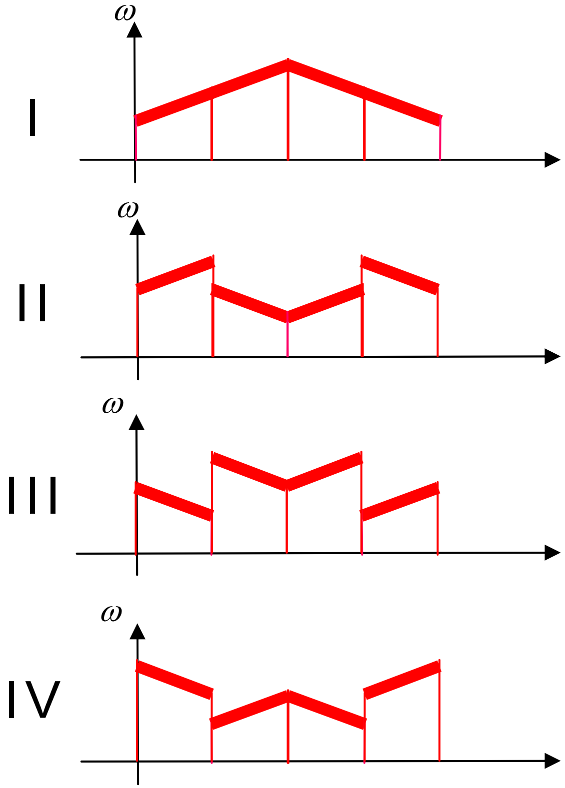
Waveform



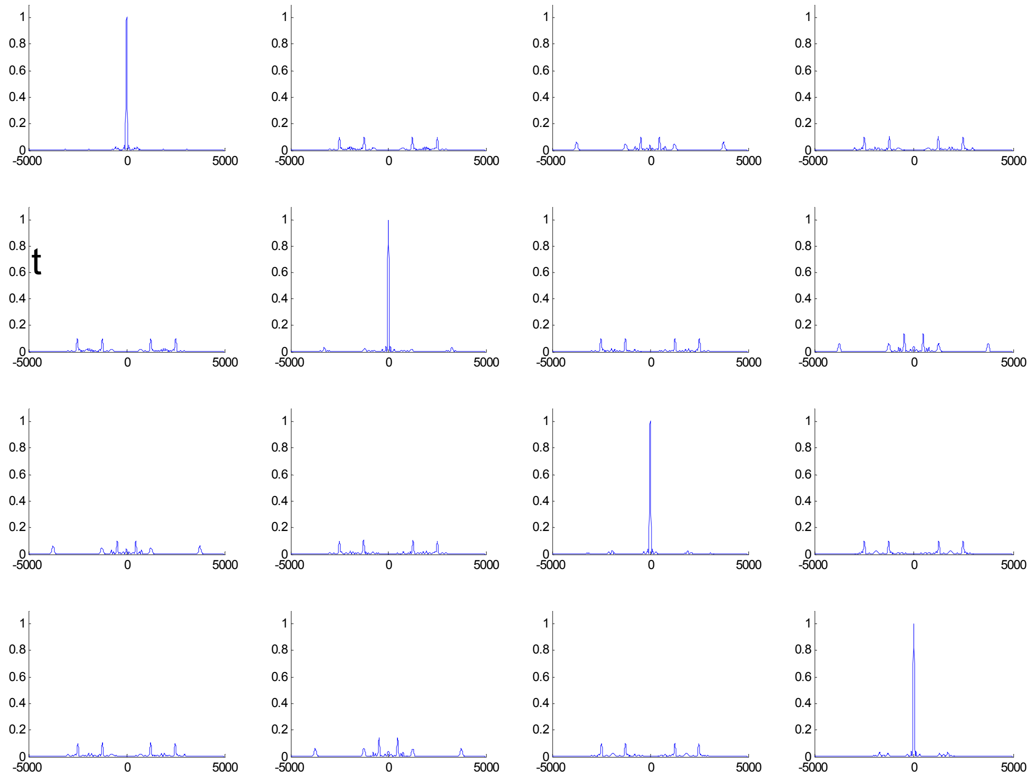
5. PHY LAYER CRITERIA

5.4. Simultaneously Operating Piconets

Multiple piconet



Correlation Power (For Preamble Detection)



CSK Signal : Quasi-Orthogonal Property

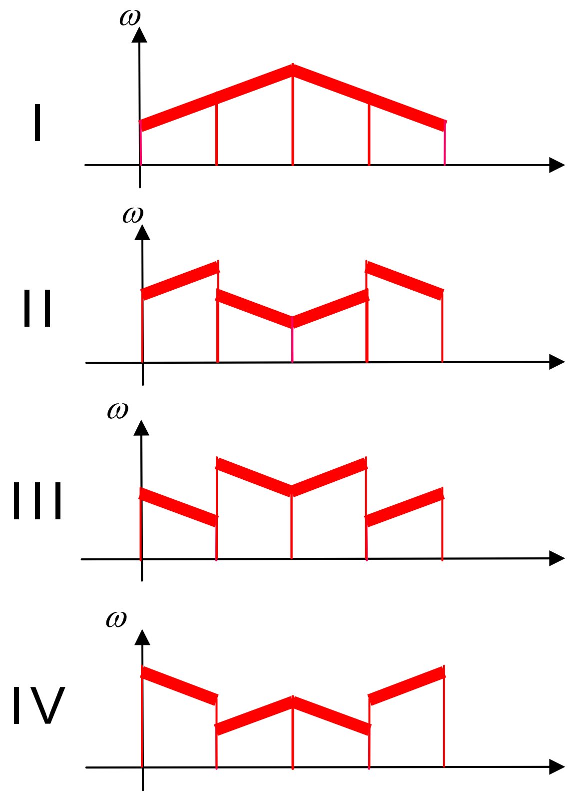
Correlation Property between the piconet
Does not need Synchronization inter-piconet

Each of CSK Signal consists of 4 sub-chirp signals.

5. PHY LAYER CRITERIA

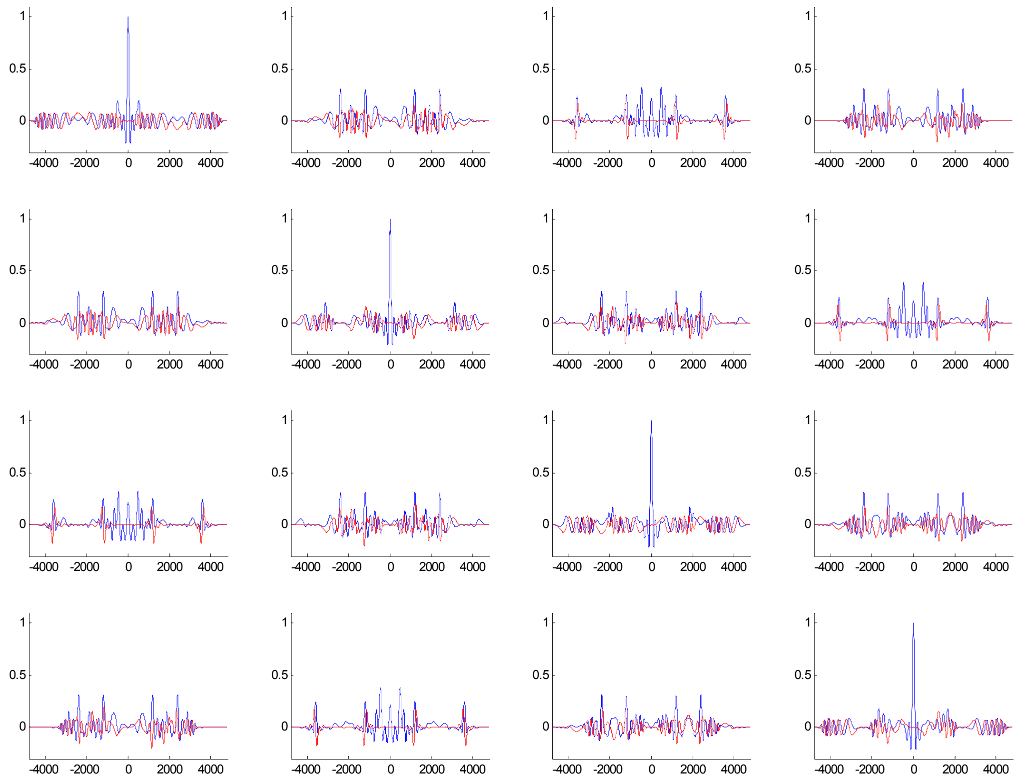
5.4. Simultaneously Operating Piconets

Multiple piconet



CSK Signal : Quasi-Orthogonal Property

Complex Amplitude (for Data Demod)



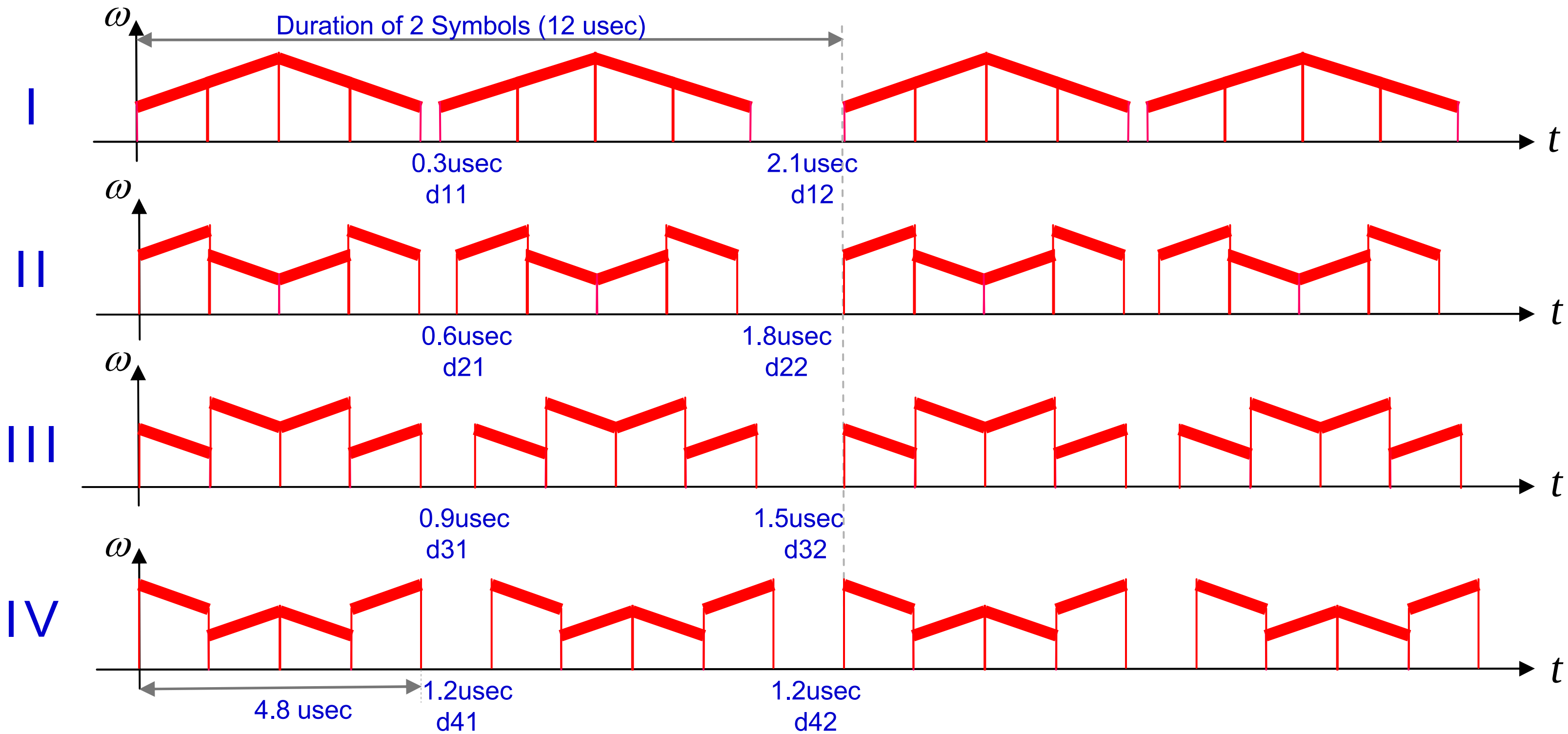
Correlation Property between piconet

Each of CSK Signal consists of 4 sub-chirp signals.

5. PHY LAYER CRITERIA

5.4. Simultaneously Operating Piconets

Multiple piconet

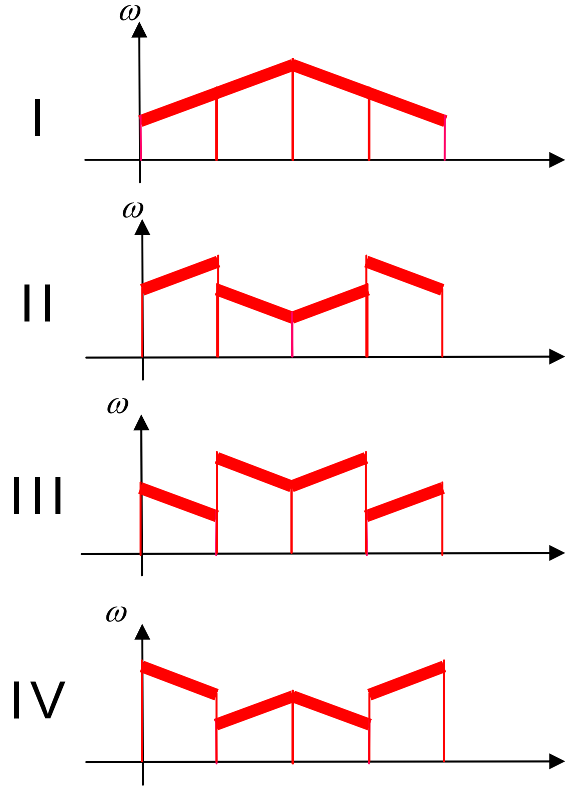


- SOP: Assigning **Different Time-Gap** between the Chirp-Shift-Keying Signal
- **Minimize ISI** for CM8 NLOS: Assign the Time-Gap between symbol more then 200nsec

5. PHY LAYER CRITERIA

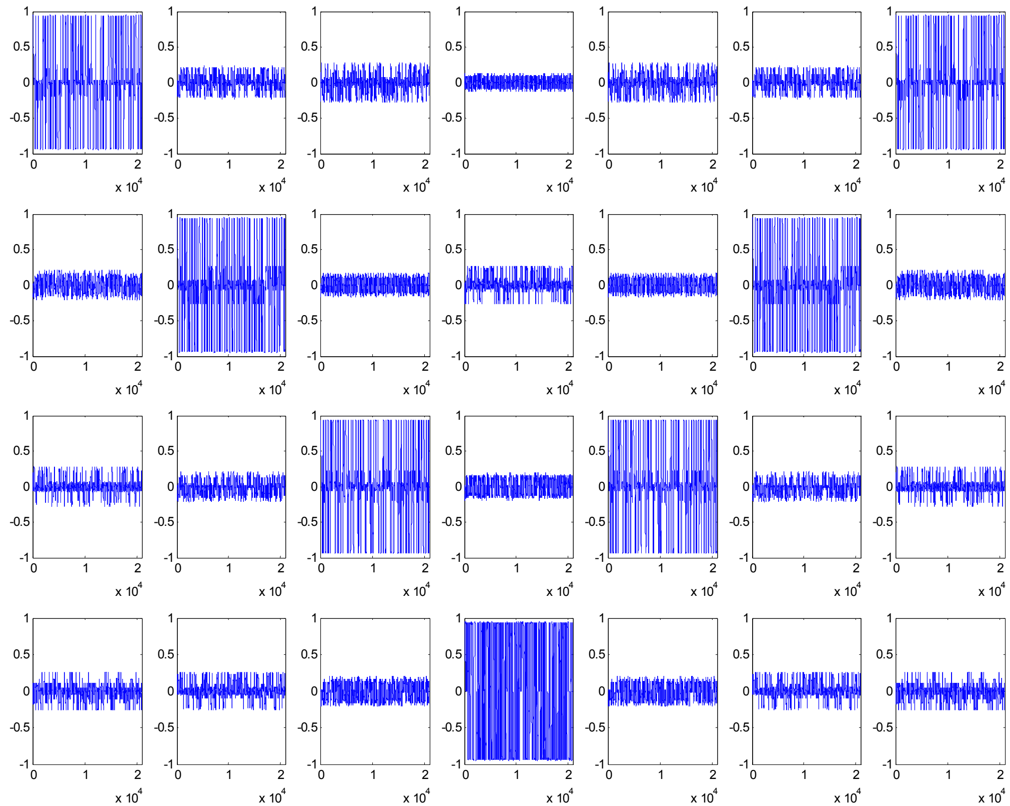
5.4. Simultaneously Operating Piconets

Multiple piconet



Each of CSK Signal consists of 4 sub-chirp signals.

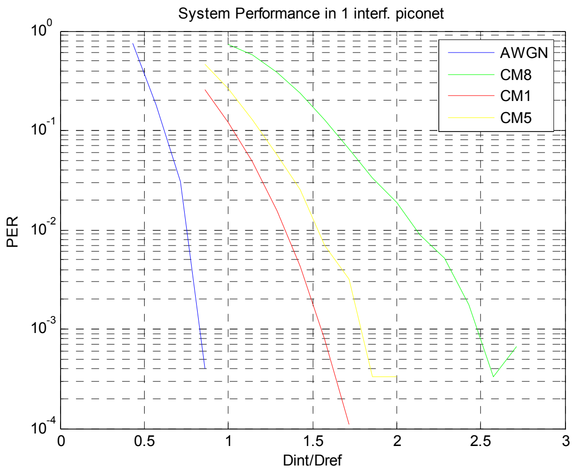
Interference Tested by Packet (32 bytes Random Data)

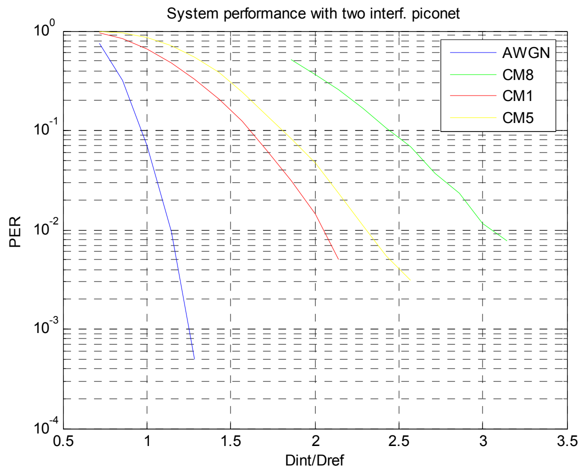


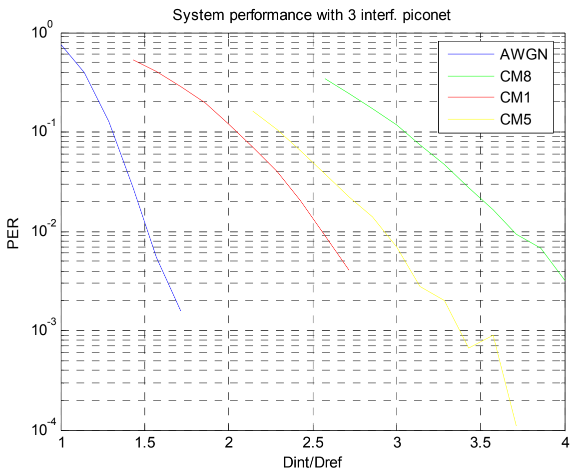
Differential Detection Property between piconet

5. PHY LAYER CRITERIA

5.4. Simultaneously Operating Piconets







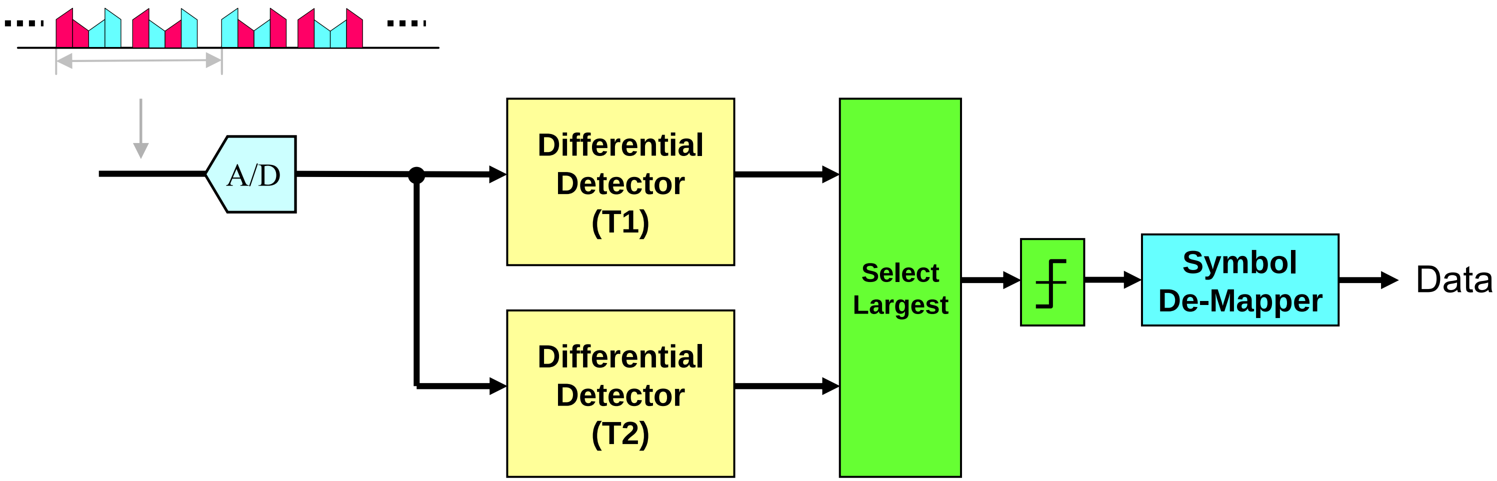
Available SOPs

- 2.4GHz: 4[piconets/FDM Ch.] x 7[FDM Ch.] = 28 SOPs
- 5.2GHz: 4[piconets/FDM Ch.] x 8[FDM Ch.] = 32 SOPs
- 5.7GHz: 4[piconets/FDM Ch.] x 6[FDM Ch.] = 24 SOPs

5. PHY LAYER CRITERIA

5.5. Signal Acquisition

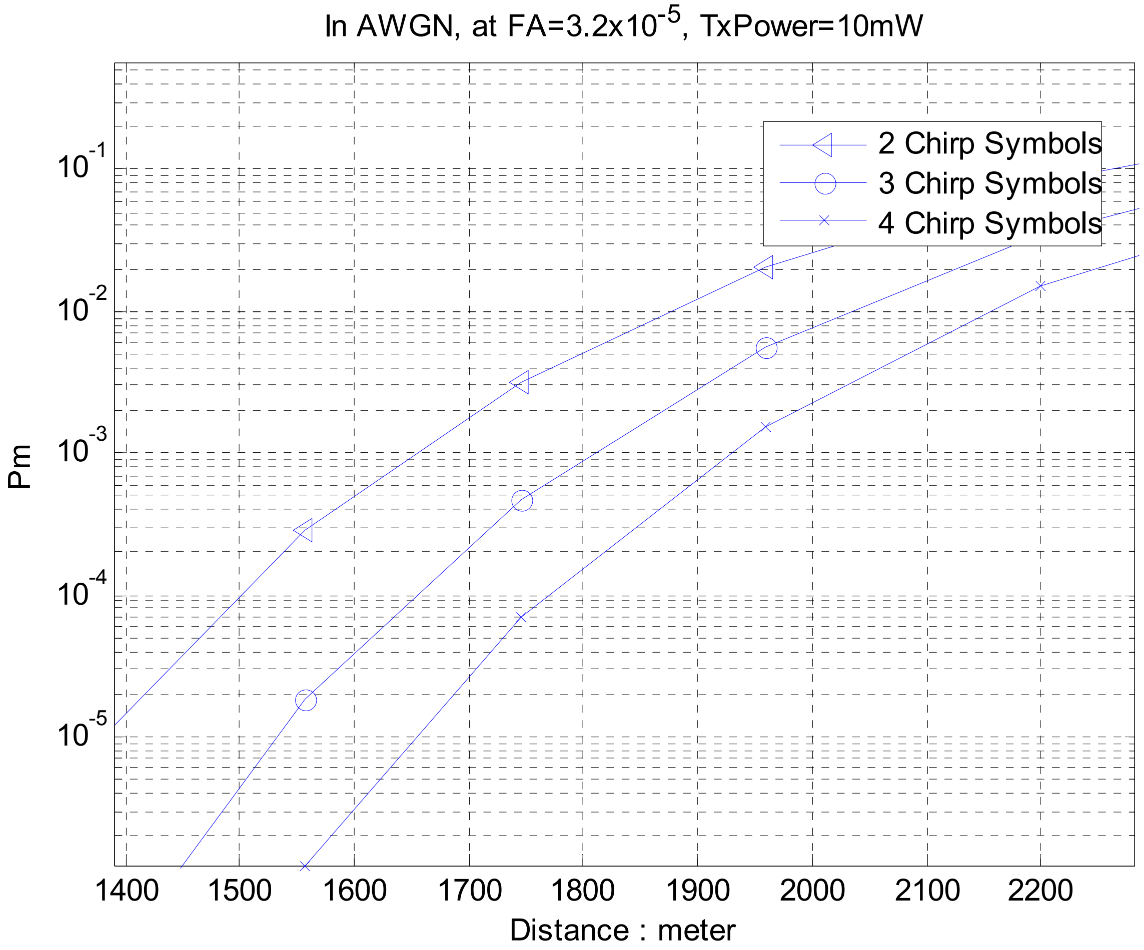
Signal Acquisition



5. PHY LAYER CRITERIA

5.5. Signal Acquisition

Miss Detection Probability

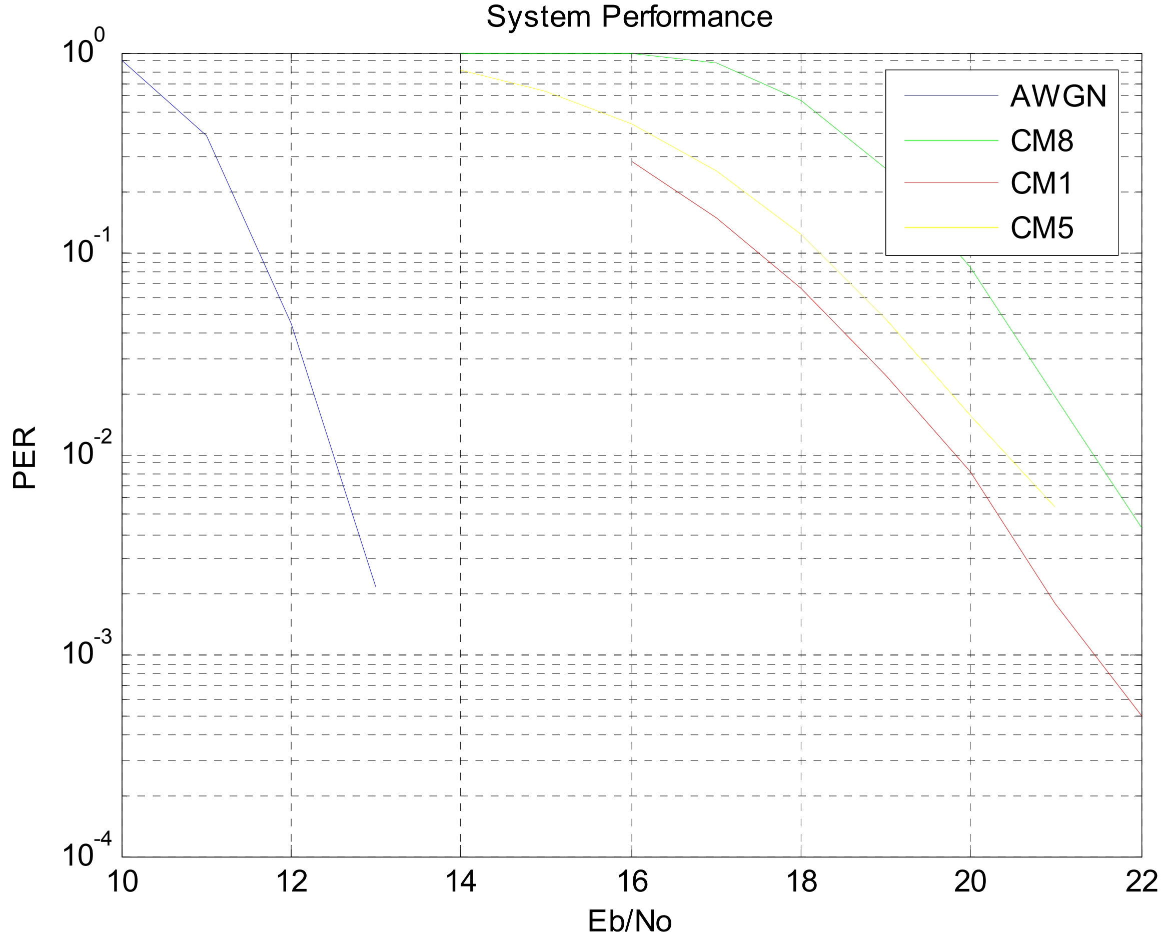


Preamble Detection

5. PHY LAYER CRITERIA

5.6. System Performance

Data Rate : 500kbps



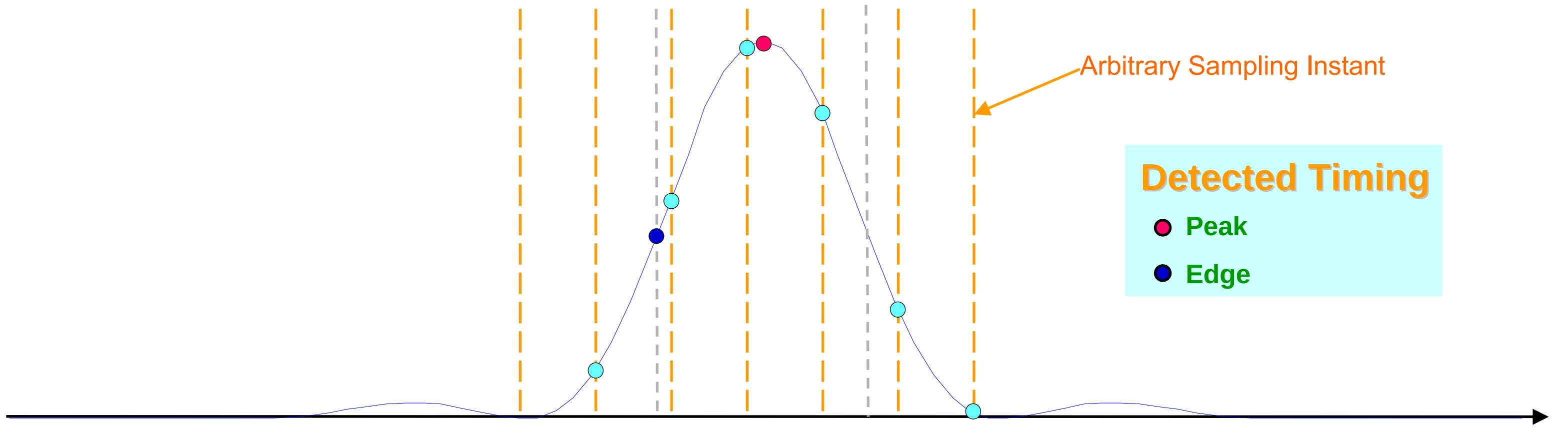
5. PHY LAYER CRITERIA

5.7. Ranging

Timing Detection

- **Coarse Timing Detection**
  - Peak of Differential Detection (Averaging over 4 or more Symbols)

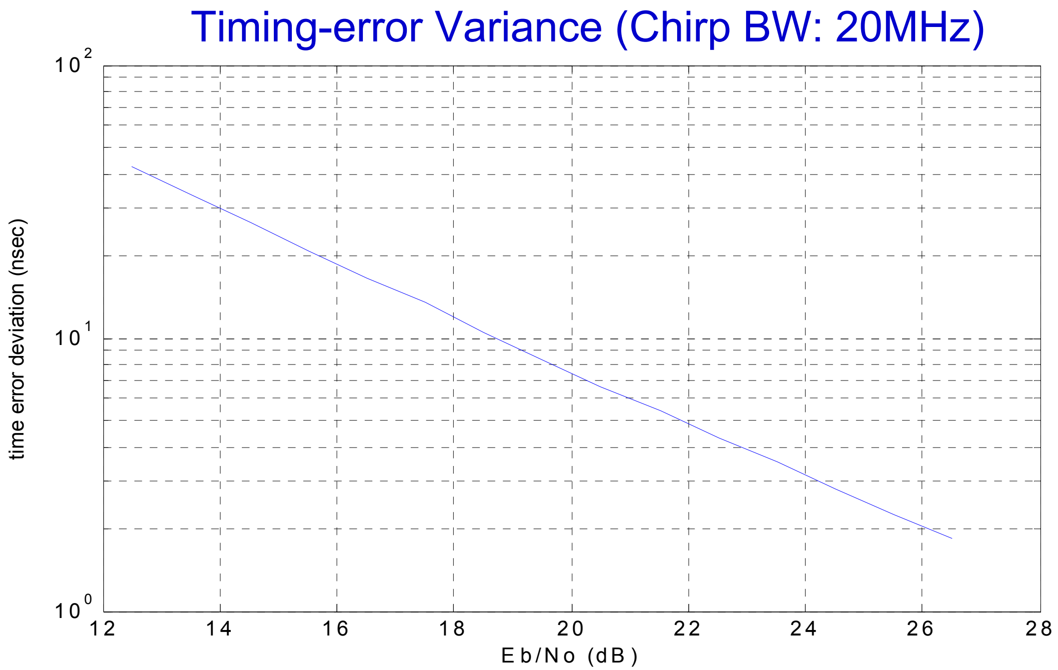
- **Fine Timing Detection**
  - Cross-Correlation of Sampled Input Signal
  - Fine Timing by Interpolation (Fraction of Sampling-Clock Resolution < 1nsec)
  - Averaging over 4 or more Symbols
  - Less than 1m Ranging Resolution @ Eb/No >= 24dB



5. PHY LAYER CRITERIA

5.7. Ranging

- **TDA / TDOA Based Ranging with Chirp Signal**
- **Estimation Precision: < 1m** @ Eb/No greater than 24dB



5. PHY LAYER CRITERIA

5.8. Link Budget

Parameter	ISM(2.4GHz)	UNII(5.2GHz)	UNII(5.7GHz)	
peak payload bit rate(Rb)	500	500	500	kbps
Average Tx Power(Pt)	10	10	10	mW
Average Tx Power(Pt)	10	10	10	dBm
Tx antenna gain(Gt)	0	0	0	dBi
fc' = sqrt(fminfmax) -10dB	2.44	5.20	5.7	GHz
Path loss at 1meter(L1=20log10(4pifc'/c))	40.2	46.8	47.6	dB
distance	30	30	30	m
path loss at d m(L2=20log10(d))	29.5	29.5	29.5	dB
Rx antenna gain(Gr)	0	0	0	dBi
Rx power(Pr = Pt+Gt+Gr-L1-L2(dB))	-59.7	-66.3	-67.1	dBm
Average noise power per bit	-117.0	-117.0	-117.0	dBm
Rx Noise Figure(Nf)	7	7	7	dB
Average noise power per bit(Pn=N+Nf)	-110.0	-110.0	-110.0	dBm
Minimum Eb/No(S)	12.5	12.5	12.5	dB
Implementation Loss(I)	3	3	3	dB
Link Margin (M=Pr-Pn-S-I) @ 30m	34.8	28.2	27.4	dB
Proposed Min. Rx Sensitivity Level	-94.5	-94.5	-94.5	dBm

5. PHY LAYER CRITERIA

5.9. Sensitivity

Bandwidth: 20MHz (2.4GHz Band)

	Rx Sensitivity level (500kbps)
AWGN	-94.5dBm
CM8	-85.5dBm
CM1	-87dBm
CM5	-86.5dBm

5. PHY LAYER CRITERIA

5.10. Power Management Modes

■ Low-power Mode with Advanced Wake-up

- The proposed PHY has differentially bi-orthogonal detection and correlatively independent chirp-pulse waveform for multiple piconet

  => Low-power is achieved by *advanced wake-up* that the only desired group of nodes are called and the other nodes can estimate wake-up time from sleep state

  => Reducing Duty-Cycle and Extending Battery-life
- This is compliant to “power consumption considerations” of 802.15.4 standard, and the mode of operation for advanced wake-up may be added to this standard

5. PHY LAYER CRITERIA

5.11. Power Consumption

- **RF: 140mW for Tx (@10mW RF Power), 35mW for Rx**
- **Baseband (BB) Digital: 0.9mW for Tx , 1.13mW for Rx**
- **RF part consume lot more power than Baseband Digital**
  - Power Reduction of RF ASIC is Essential (C-MOS)
- **Idea for Operating Power Saving:**
  - Use Max. Data-rate mode: shorter time for Tx Data
  - Sleeping: Longer Time
  - Save Power: by reducing active time of RF
- **Further Reduction of Power Consumption**
  - Apply 0.13um / 0.09um Technology for ASIC (RF / Baseband)

5. PHY LAYER CRITERIA

5.11. Power Consumption

		500Kbps (No FEC)			250Kbps (FEC: r=1/2)		
		Logic	Die Area	Power	Logic	Die Area	Power
RF @ Tx Power: 10mW	Tx + D/A	-	1.7 mm^2	130 mW	-	1.7 mm^2	130 mW
	Rx + A/D	-	1.6 mm^2	25 mW	-	1.6 mm^2	25 mW
	Common	-	0.3 mm^2	10 mW	-	0.3 mm^2	10 mW
Baseband @ Sampling-rate: 40MHz	Tx	1.5K	0.04 mm^2	0.48 mW	1.6K	0.06 mm^2	0.52 mW
	Rx	49.4K	0.63 mm^2	0.71 mW	145K	1.5 mm^2	2.08 mW
	Common	5K	0.08 mm^2	0.42 mW	5K	0.08 mm^2	0.42 mW
Total	Tx	56K	**4.35 mm^2**	141 mW	152K	**5.24 mm^2**	141 mW
	Rx			36.1 mW			37.5 mW
Deep Sleep				5 uW			5 uW

Target Library : 0.18 um Technology

- Power Consumption for Average Throughput 1 Kbps (w/o FEC)
  - P_{TX} : 141[mW] / 293 = 481 [uW]
  - P_{RX} : 36.1[mW] /293 = 123 [uW]

- Battery: 324[Joule] for Button Cell (10mm D. X 2.5mm H) / 12,000[Joules] for AA Alkaline Cell
  - (P_{TX} + 50 X P_{RX})/51 = 130[uW] ----- (Assume T_{TX} : T_{RX} = 1:50 duty-cycle for sensor node)
  - Battery Life T_B = 324/130e-6/3600/24 = 28.8 days Continuously (**Button Cell**)
  - Battery Life TB = 12000/130e-6/3600/24/365 = 2.93 years Continuously (**AA Alkaline Cell**)

5. PHY LAYER CRITERIA

5.12. Antenna Practicality

- **Antenna Size**

  \- less than SD-Memory size: 24mm X 14mm @2.4GHz
  12mm X 9mm @5.2/5.7GHz

- **Frequency / Impulse Response**

  \- Almost Flat Freq. Response: Narrow-band

- **Radiation Characteristics**

  \- Isotropic: 0dBi

6. Conclusion

- **Low Power Consumption:** Digital Baseband Tx 0.9mW, Rx 1.13mW
  - Power Consumption is heavily depend on RF-chip.
- **Signal Robustness:**
  - Orthogonal / Quasi-Orthogonal Signal Set
  - Robustness: Tolerance for Heavy Multi-path / SOP,
  - Low Correlation with Existing Air-Interfaces
- **Feasibility:** 2.4GHz ISM Band
  - Existing commercial RF Solutions
  - 2.4GHz / 5GHz band is allowed for unlicensed operation
  - Low Voltage Operation: Low PAPR
- **Ranging:** Based on Chirp Signal (TDA / TDOA)
  - Precision: less then 1m (Standard Deviation) @Eb/N0 = 24dB
- **Size & Form Factor:** Less than SD-Memory size
- **Low Cost / Low Complexity:** Tx +Rx Baseband Digital (56K gates)
- **Support Advanced Sleep / Wake-up Capability**
- **Orthotron will pursue opportunities for future collaborations and merging**