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

Submission Title: [Merged Proposal of Chaotic UWB System for 802.15.4a]
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Re: [Response to IEEE 802.15.4a Call for Proposals (04/380r2)]
Abstract: [Proposal for the IEEE 802.15.4a PHY standard based on the chaotic UWB system technology.]
Purpose: [Proposal for the IEEE 802.15.4a PHY standard.]

Samsung Electronics (SAIT)/IRE/Samsung Electro-Mechanics(SEM),
Samsung Electronics (DM),
Electronics and Telecommunications Research Institute(ETRI)/KAIST/HGU,
Simon Fraser University(SFU)/Inha University,

Chaotic UWB System

Young-Hwan Kim, Jae-Hyon Kim, Chia-Chin Chong, Su Khiong Yong, Seong-Soo Lee A. S. Dmitriev, A. I. Panas, S. O. Starkov, Yu. V. Andreyev, E. V. Efremova, L. V. Kuzmin, Jeongsuk Lee, Haksun Kim, Jaesang Cha, Namhyong Kim, Haksun Kim, Jaesang Cha, Hyung Soo Lee, Cheol Hyo Lee, Dong Jo Park, Dan Keun Sung , Sung Yoon Jung, Chang Yong Jung, Joon Yong Lee, Dong In Kim, Serhat Erküçük, Kyung Sup Kwak

CONTENTS

1. INTRODUCTION

Feature of Proposed System

- **Low Power**

- **Low Hardware Complexity / Low Cost**
  - Chaotic signal can be generated directly into the desired microwave band
  - Simple RF ciucuit
- **Sleep / Wake-up Capability**

- **Robust in Multipath**

- **Flexibility**
  - Chaotic radio pulse with different time duration can have the same bandwidth

2. CHAOTIC COMMUNICATION SYSTEM

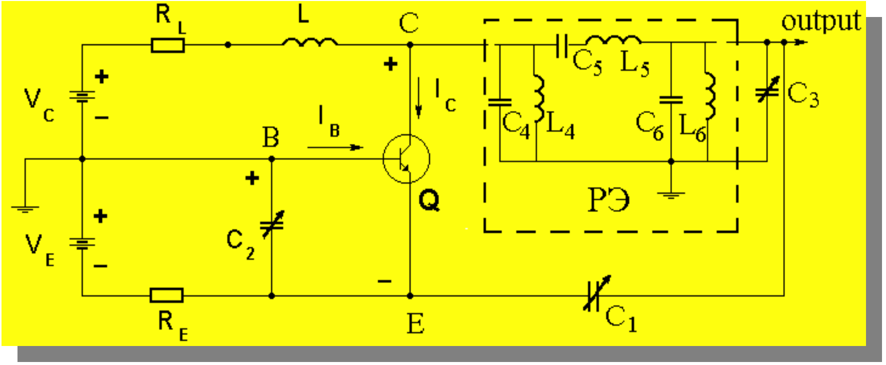
Direct Chaotic Communication (DCC)

- Chaotic source generates oscillations directly in a specified microwave band.
- Information component is put into the chaotic carrier using a stream chaotic radio pulses.
- Information is retrieved from the chaotic radio pulses without intermediate heterodyning.
- Most simple non-coherent receiver is used.

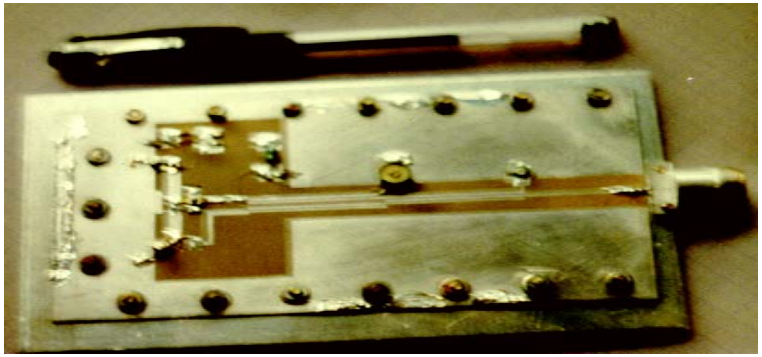
2. CHAOTIC COMMUNICATION SYSTEM

Chaotic Source

Chaotic Source Generator Circuit



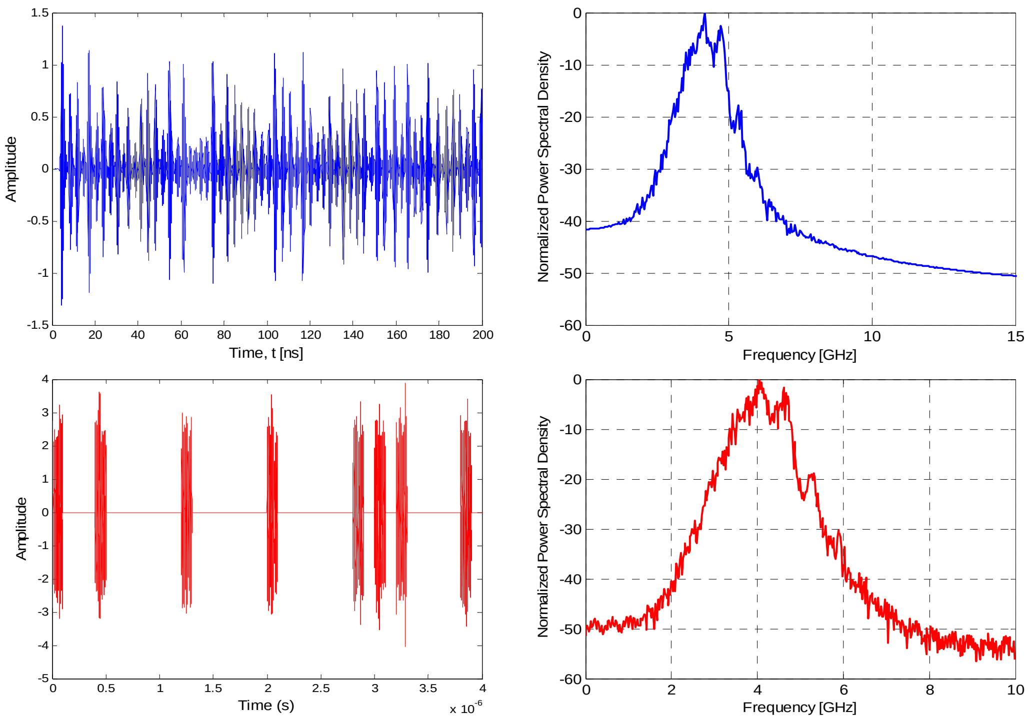
Experiment device



2. CHAOTIC COMMUNICATION SYSTEM

Spectral Properties of Chaotic Signal

- Spectral properties don't change even though the length or duration of the chaotic pulses are varied



Chaotic Signal

Chaotic Pulse (OOK)

2. CHAOTIC COMMUNICATION SYSTEM

Modulation Schemes

- **OOK**
  - Advantages:
    - Lower complexity (TX and RX)
    - 3 dB more energy efficiency that PPM & DCSK
      => battery saving
  - Disadvantages:
    - Requires non-zero detection threshold

3.1. Unit Manufacturing Cost/Complexity

Complexity

RF part of the transceiver:

- Chaotic oscillator in 3.1-5.1 GHz frequency band with 10 dBm output power amplifier (common complexity is equivalent to 4 power amplifiers)
- Switch-modulator
- LNA (amplification 30-35 dB)
- 2 Band Pass Filter with bandwidth 1 GHz (in band 3.1-5.1 GHz)
- Envelope detector
- Antennas
- No mixers, no correlators, no RF VCO

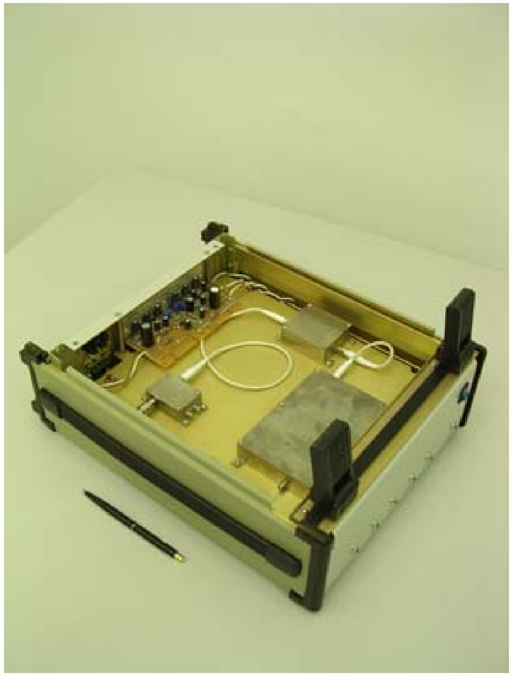
- **Baseband part of the transceiver:**
  - Reference oscillator – 20 MHz
  - Bandpass amplifiers
  - Threshold detector or 4 bit A/D converter
  - Frequency Synthesizer on 2.5125 MHz (for ranging)
  - Digital part with ~ 10K gates

3.4. Technical Feasibility

Prototype

- -

UWB DCC-OOK Test-bed



5.1. Channel models and payload data

Refer to the selection criteria document

- Industrial environment NLOS
- Indoor residential LOS
- Outdoor LOS
- Agricultural areas
- Body area networks

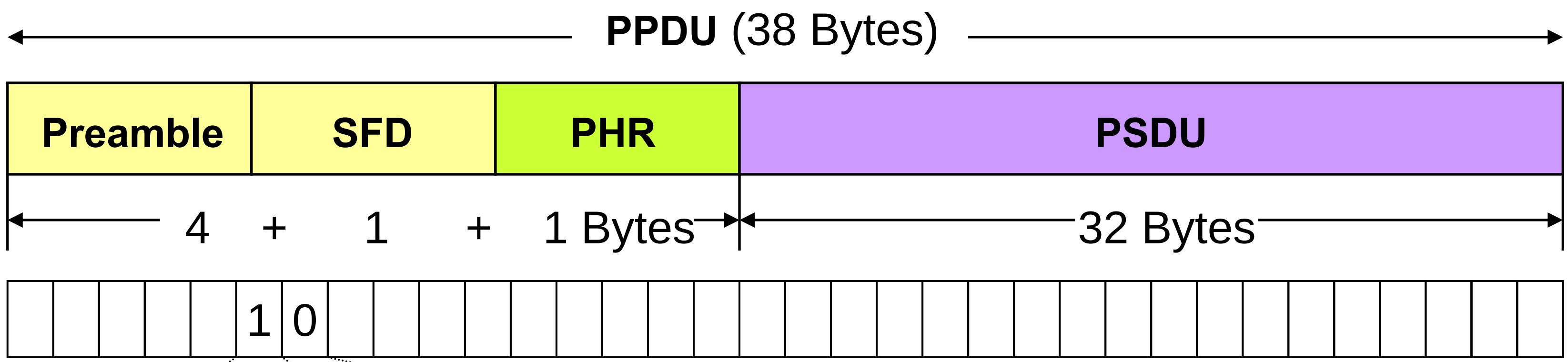
5.2. Size and Form Factor

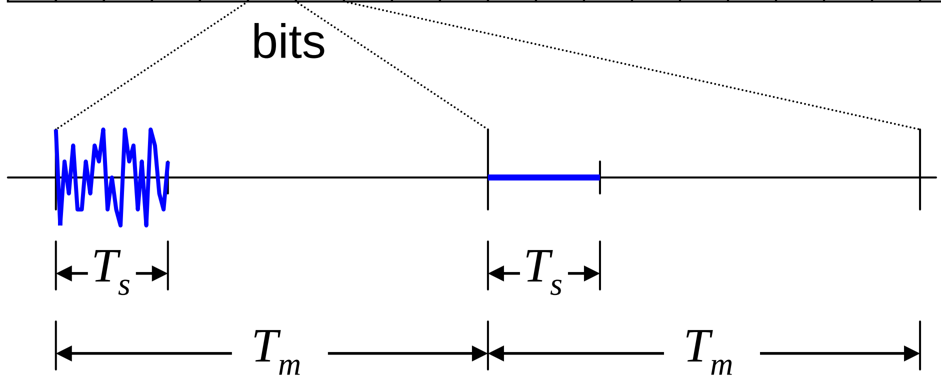
Values

- **PHY–level (130 nm technology)**
  - RF part of transceiver => 0.3 mm^2
  - Analog part of transceiver PHY–level baseband => 0.2 mm^2
  - Digital part of transceiver PHY–level baseband => 0.3 mm^2
  - Common layout square for PHY-level => 1.0 mm^2
  - Antenna: 2.0 x 2.0 cm^2

5.3. PHY-SAP Payload Bit Rate / Throughput

Payload Bit Rate





T_s = 100 ns : Pulse emission time

T_m = 400 ns : Pulse bin width or Bit period

∴ Duty cycle, *D* = 1/4

T_s = 100 ns : Pulse emission time

T_m = 600 ns : Pulse bin width or Bit period

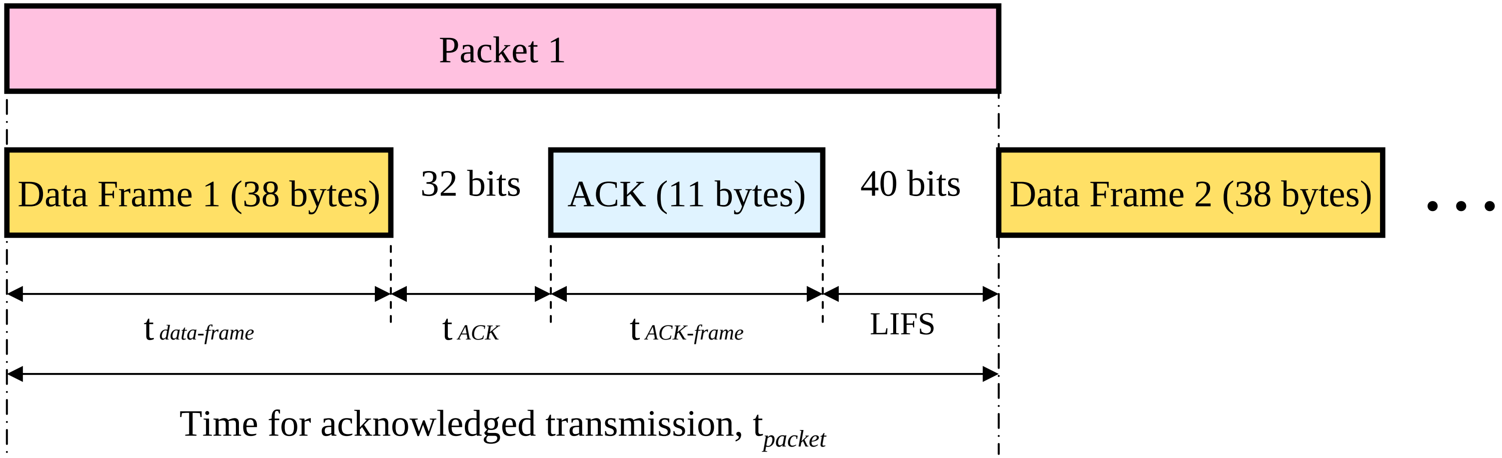
∴ Duty cycle, *D* = 1/6

Nominal PHY-SAP payload bit rate, X_0 = (1/400ns)×(1000/1024) = 2.44Mbps

Optional PHY-SAP payload bit rate, X_i = (1/600ns)×(1000/1024) = 1.63Mbps

5.3. PHY-SAP Payload Bit Rate / Throughput

Throughput



$$t_{packet} = t_{data\text{-}frame} + t_{ACK} + t_{ACK\text{-}frame} + LIFS$$
$$= (38\times8\times400ns) + (32\times400ns) + (11\times8\times400ns) + (40\times400ns)$$
$$= 121.6\mu s + 12.8\mu s + 35.2\mu s + 16\mu s = 185.6\mu s$$

$$t_{packet} = t_{data\text{-}frame} + t_{ACK} + t_{ACK\text{-}frame} + LIFS$$
$$= (38\times8\times600ns) + (32\times600ns) + (11\times8\times600ns) + (40\times600ns)$$
$$= 182.4\mu s + 19.2\mu s + 52.8\mu s + 24\mu s = 278.4\mu s$$

Nominal Data Throughput, $T_0 = (32\times8/185.6\mu s)\times(1000/1024) = 1.35Mbps$

Optional Data Throughput, $T_i = (32\times8/278.4\mu s)\times(1000/1024) = 898kbps$

5.4. Simultaneously Operating Piconets

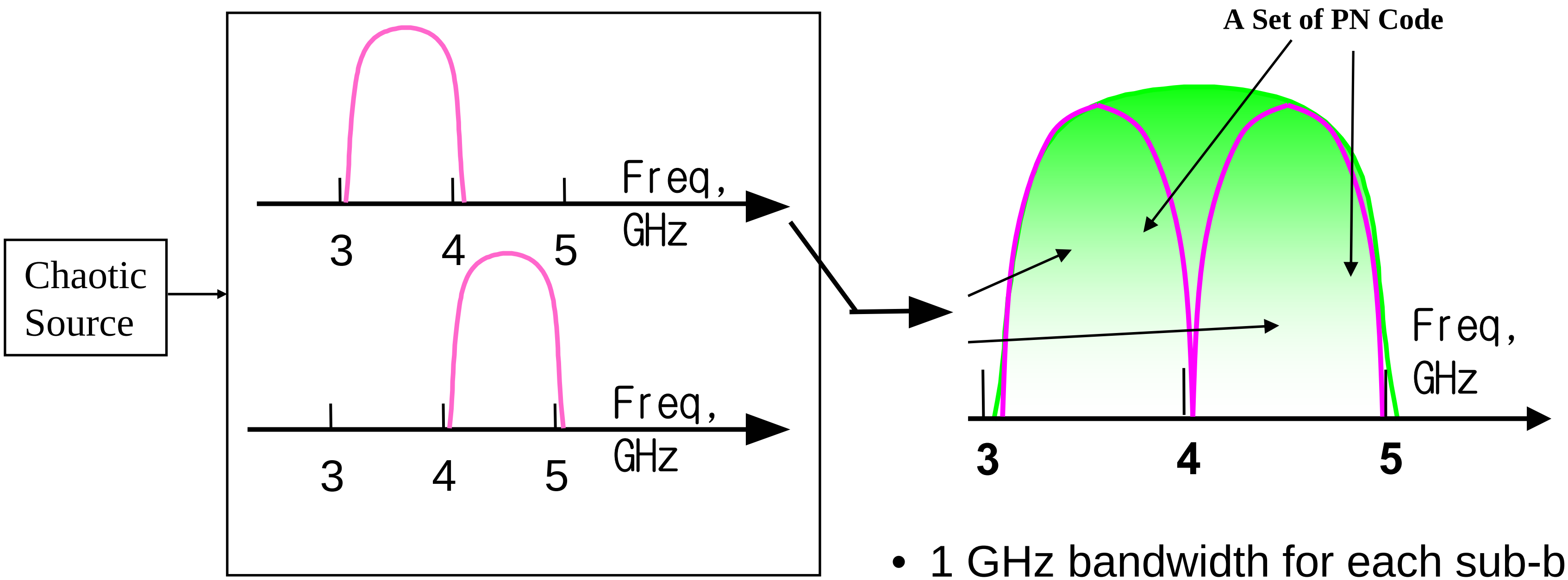
Three Methods to Achieve SOP

- **Frequency division multiplexing (FDM)**
  - Four independent frequency channels on 500 MHz guaranties simultaneously operating four piconets.
- **Code division multiplexing (CDM)**
  - Deployed a class of unipolar codes (0,1) having ZCD/LCD property maintain orthogonality among piconets.
  - Four set of codes can support four simultaneously operating piconets.
- **Frequency-code division multiplexing (FCDM)**
  - Two independent frequency channels with 1 GHz bandwidth and within each frequency channel, a set of codes is used
  - Only two set of codes require to support four SOPs

5.4. Simultaneously Operating Piconets

Combination of FDM and CDM (FCDM)

- **2 sub-bands and a set of PN code for each sub-bands => 4 SOPs**



- 1 GHz bandwidth for each sub-band.

Subband	fc, GHz	fL, GHz	fR, GHz
1	3.6	3.1	4.1
2	4.6	4.1	5.1

5.4. Simultaneously Operating Piconets

CDM Methods to Achieve SOP

- **Chaotic OOK based CDM schemes using ZCD/LCD codes**

- **Simultaneous operating can be obtained by Unipolar codes having ZCD or LCD property**

  where,

  ZCD(Zero Correlation Duration)

  =Local time duration with Zero ACF sidelobe & Zero CCF, and

  LCD(Low Correlation Duration)

  =Local time duration with Low ACF sidelobe & Low CCF

- **Local time duration function as an Interference rejection interval for SOP**

5.4. Simultaneously Operating Piconets

Chaotic-OOK based ZCD/LCD-CDM

- **Combination of Unipolar ZCD/LCD Code & Chaotic-OOK**

- **Characteritics of combined schemes**
  - Simple UWB spectrum Spreading (High Security)
  - Simple circuit with noncoherent envelope detector
  - Based on a class of (0,1) codes having ZCD/LCD property
  - Correlator based receiver
  - Simple Mod/Demod Schemes
  - Novel Inter/Intra Piconet Interference immunity for an efficient SOP

5.4. Simultaneously Operating Piconets

Unipolar ZCD/LCD codes for CDM

- **A class of (0,1) codes having ZCD/LCD property**
- **Flexible code design according to the system requirements is possible**
  - Variable code period
  - Variable ZCD/LCD length & Family size
- **Circular & Non-Circular types are exist**
- **Depicted by (N,w,A,C)**
  - N=sequence period,
  - w=number of nonzero elements,
  - A=ACF sidelobe in ZCD/LCD,
  - C=CCF value in ZCD/LCD
  - M= family size, Truncation of $N/M=w$

5.4. Simultaneously Operating Piconets

Type example of Unipolar ZCD Codes

- **Type1 : Circular type sequence**
  - A code set is constructed by chip shift of a seed code
  - An example of (8,4,0,0) with M=2

    code a=[1 0 1 0 1 0 1 0]

    code b=[0 1 0 1 0 1 0 1]
- **Type2 : Non-Circular type sequence**
  - An example of (5,2,0,0) with M=3

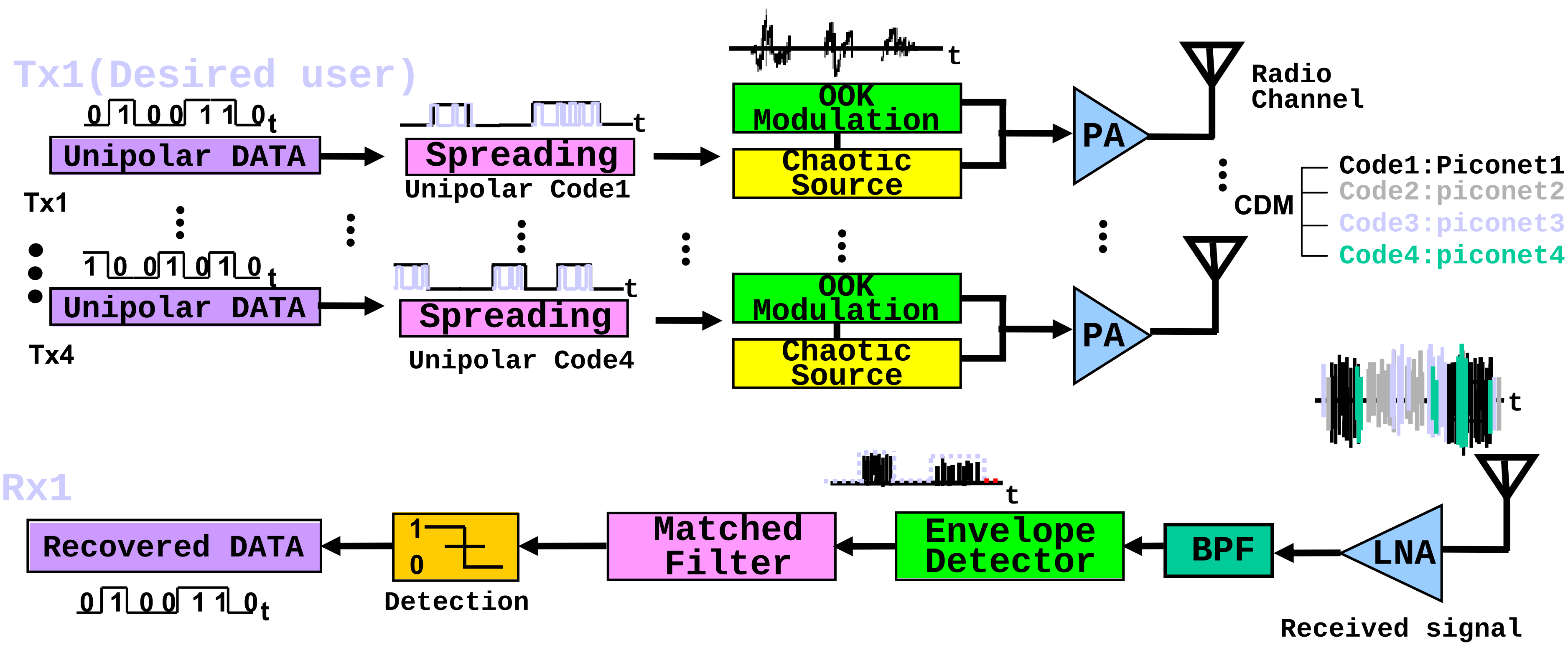
    code a=[1 0 0 1 0 0]

    code b=[0 1 0 0 0 1]

    code c=[0 0 1 0 1 0]

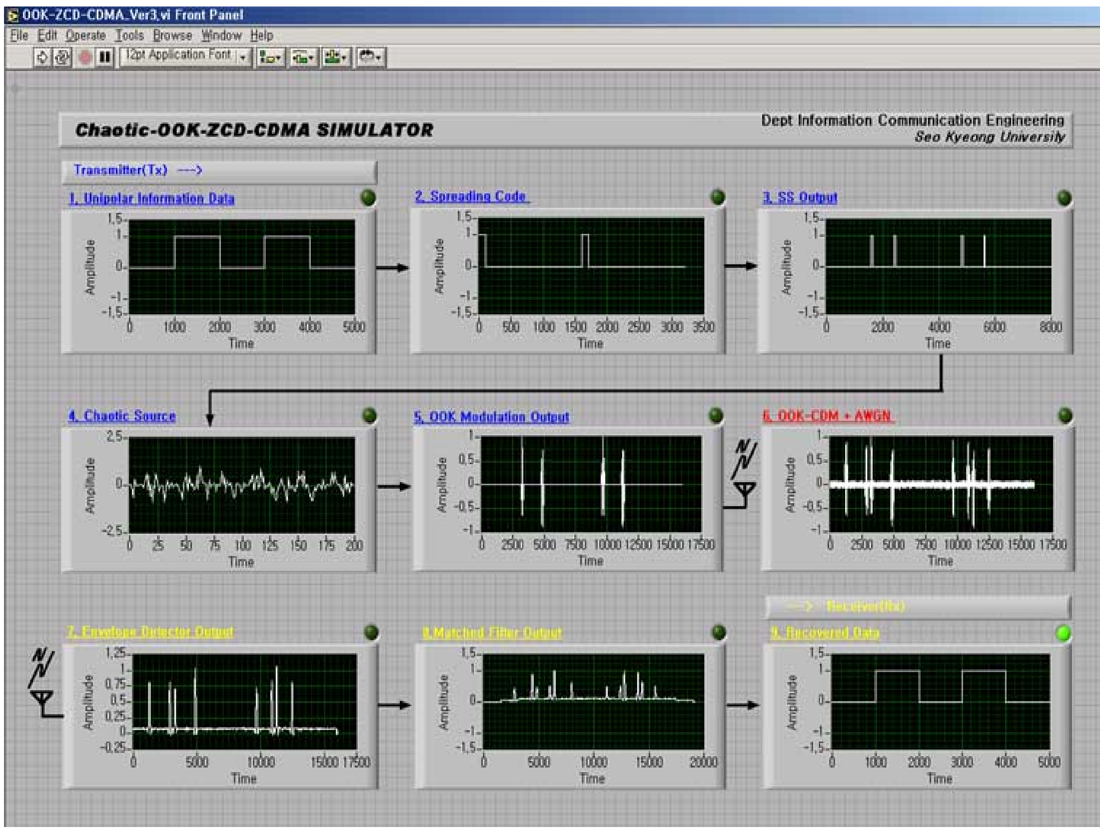
5.4. Simultaneously Operating Piconets

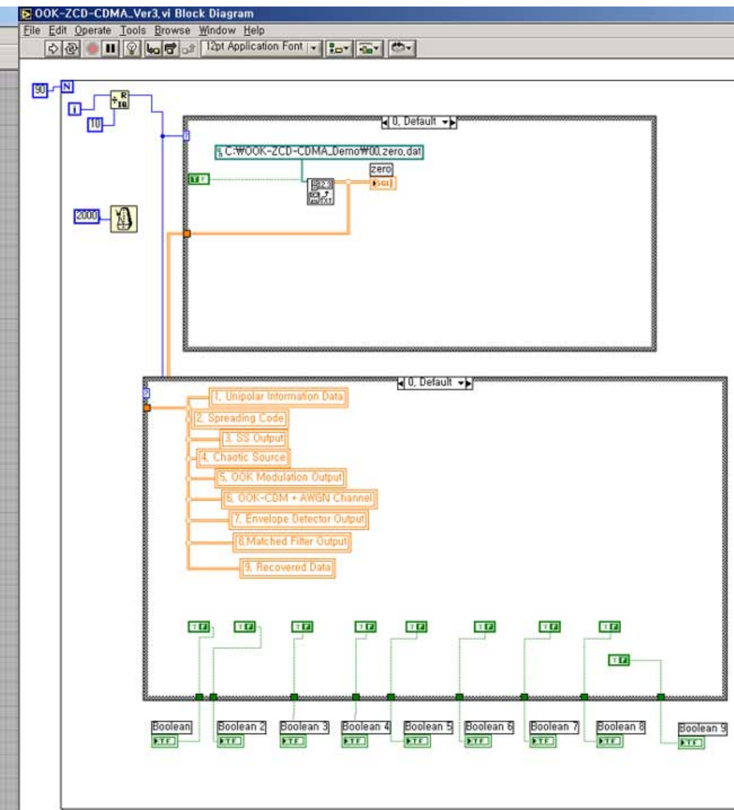
Transceiver Architecture of Chaotic-OOK Based ZCD/LCD-CDM



5.4. Simultaneously Operating Piconets

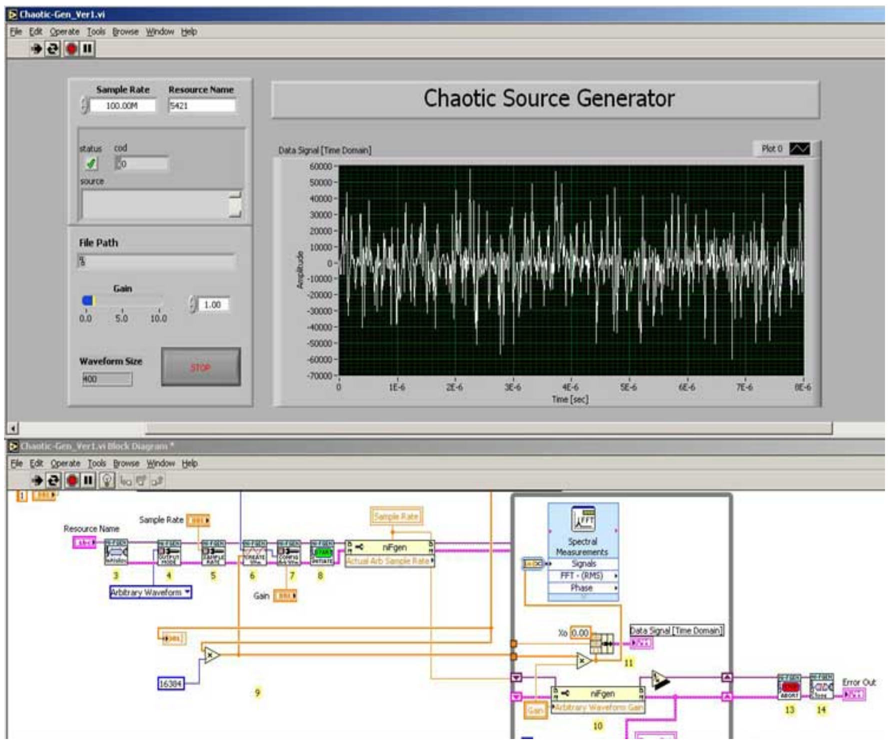
Baseband Chaotic-OOK- ZCD-CDM

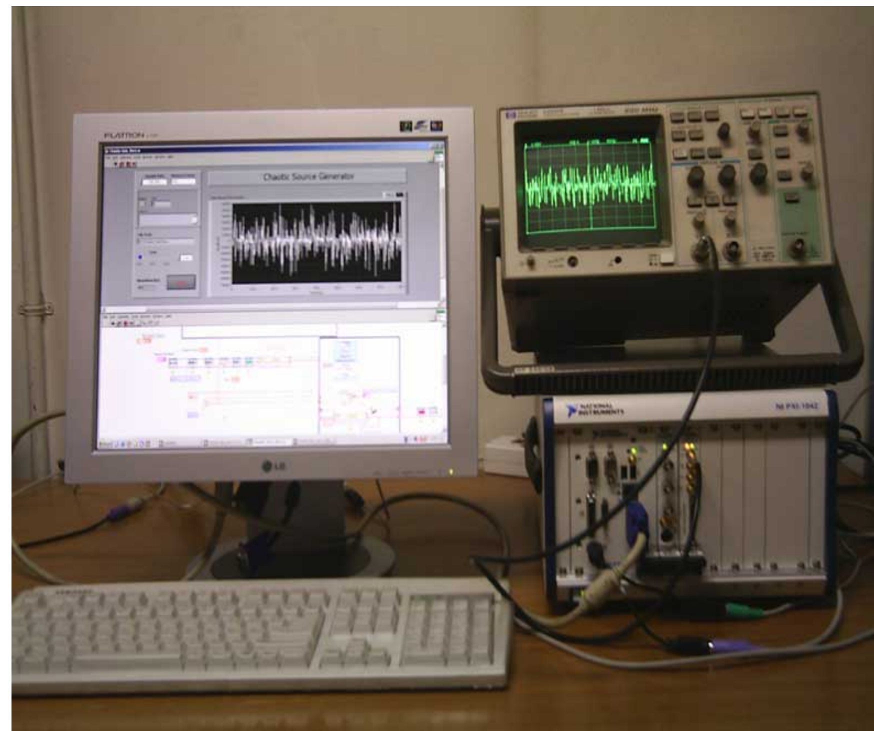




5.4. Simultaneously Operating Piconets

Source: Chaotic-OOK-ZCD-CDM





5.4. Simultaneously Operating Piconets

BER Evaluation of Chaotic-OOK-ZCD-CDM

- **Simulation target**
  - BER comparison
    - Walsh code based Chaotic-OOK-CDM vs.
      Unipolar ZCD code based Chaotic-OOK-CDM
      in the AWGN &IPI (Inter Piconet Interference) environment

- **Simulation conditions**
  - Case1 : No delay times(Chip sync.), & 4 piconets
  - Case2 : Delay times with equal gain, & 4 piconets
  - Case3 : Delay times with path loss, & 4 piconets

5.4. Simultaneously Operating Piconets

BER Evaluation of Chaotic-OOK-ZCD-CDM

- **Simulation Parameters**

Classification	Contents
CDM code for SOP	Unipolar orthogonal codes with ZCD/LCD
Code period	8chip, 32chip
Modulation scheme	Chaotic-OOK-CDM
Detection method	Envelope detector & Matched Filter
Piconet number	Max. 4
Interference piconet number	Max. 3
Delay time	Max. 100ns
E_b/N_0 Range	0 ~ 30dB
Etc.	Applied a pathloss from an interference-piconet

5.6. System Performance

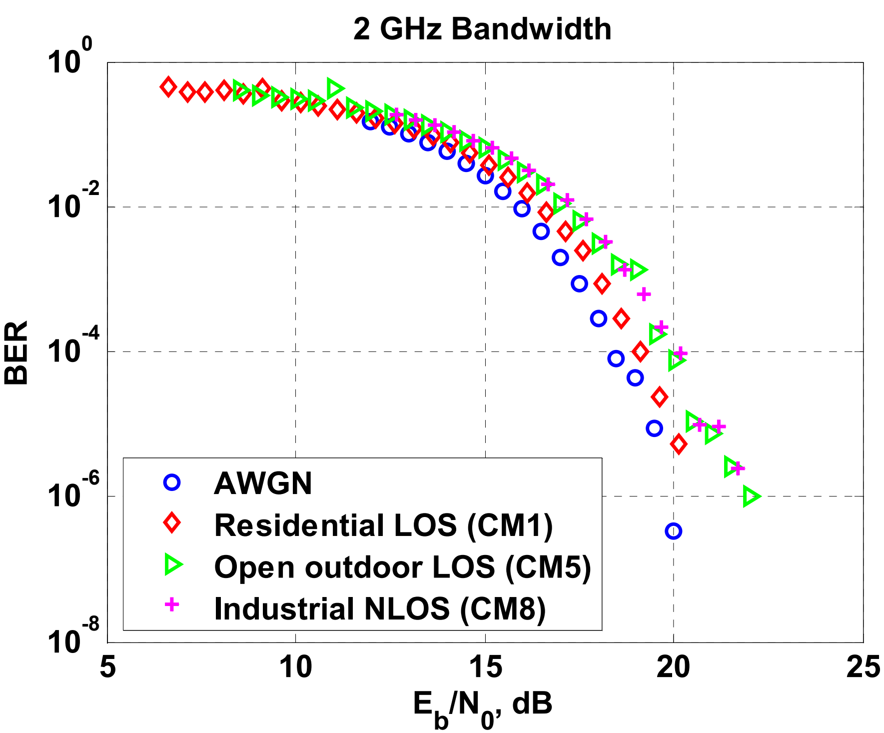
System Simulation Parameters

- Modulation: OOK
- Bandwidth: 2GHz
- Pulse bin width, Tm: 400ns
- Pulse emission time, Ts: 100ns
- PSDU length: 32 bytes

5.6. System Performance

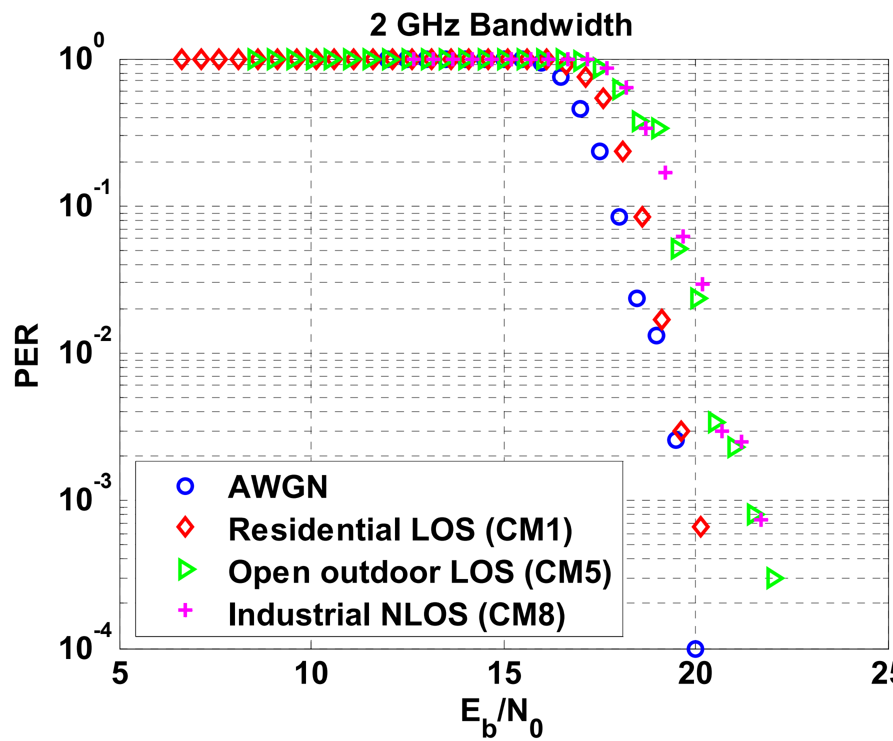
AWGN & Multipath

- BER Vs. Eb/No



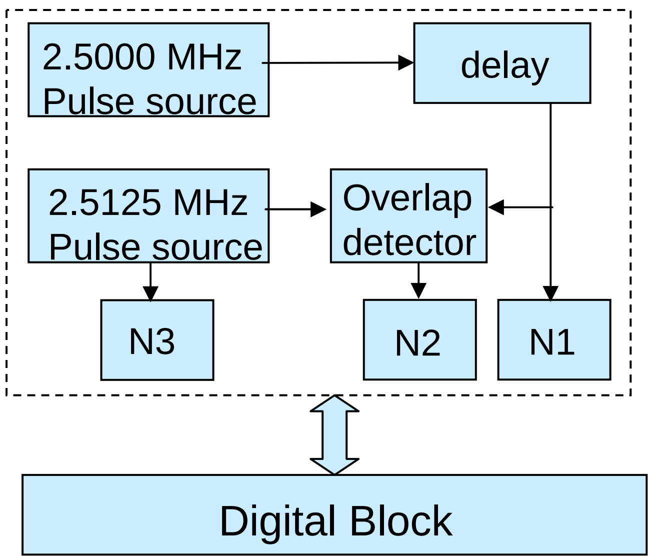
AWGN & Multipath

- PER Vs. Eb/No

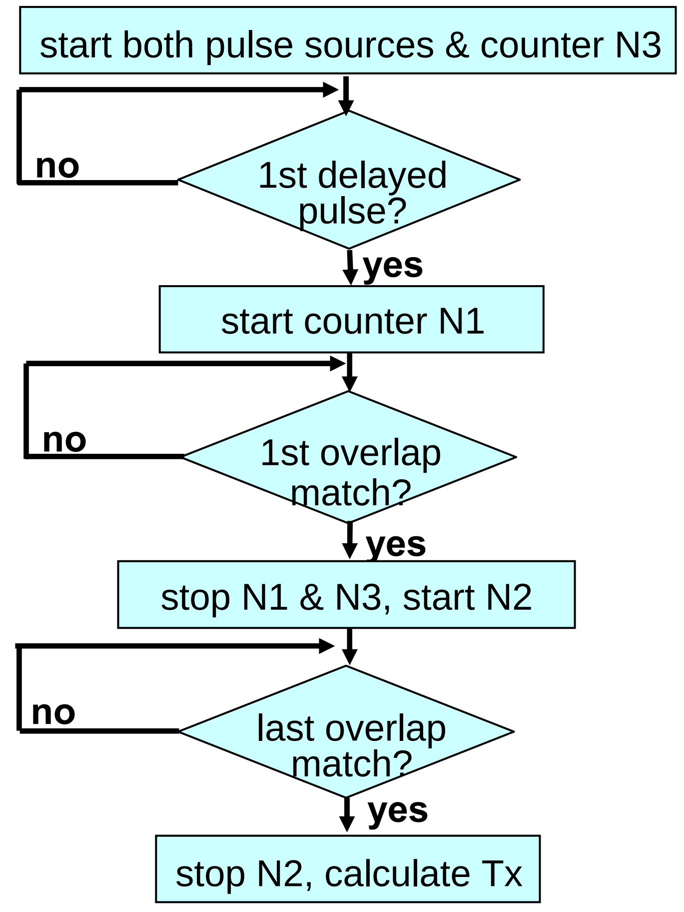


5.7. Ranging

Algorithm

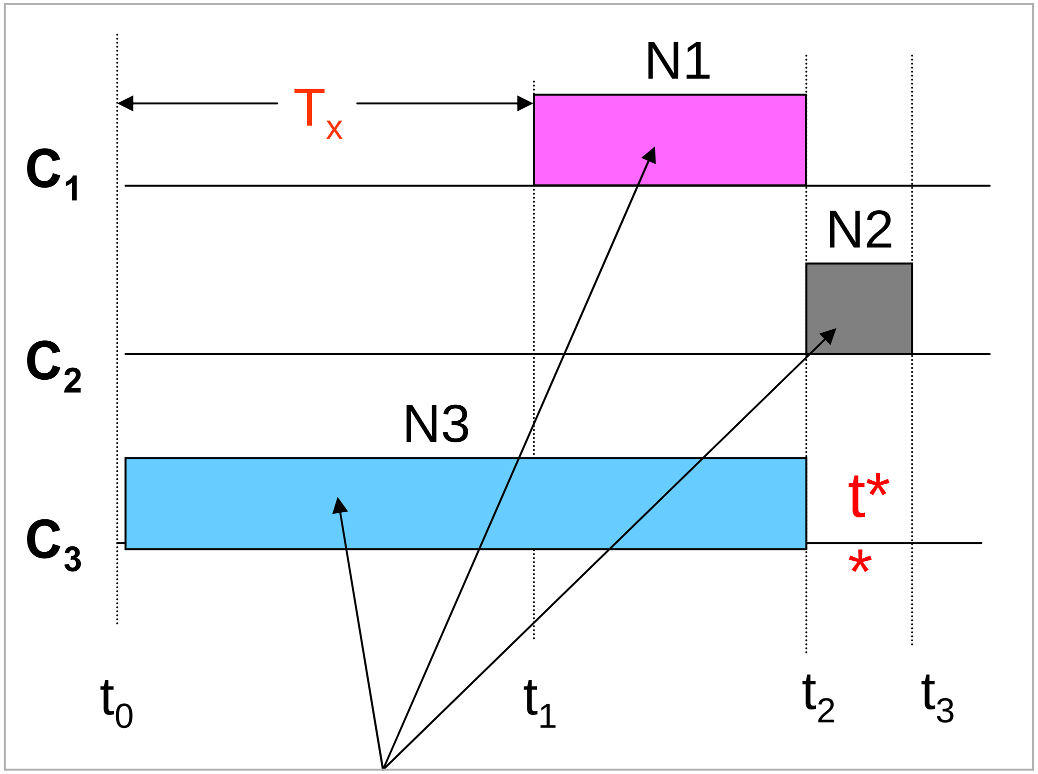


- Counter **N1** counts delayed pulses
- Counter **N2** counts overlaps between delayed pulses(2.5000 MHz) and reference pulses(2.5125 MHz)
- Counter **N3** counts reference pulses



5.7. Ranging

Algorithm



N1, N2, N3 – pulse numbers

$T_x = (N3+0.5*N2)/f_1 - (N1+0.5*N2)/f_0$

distance

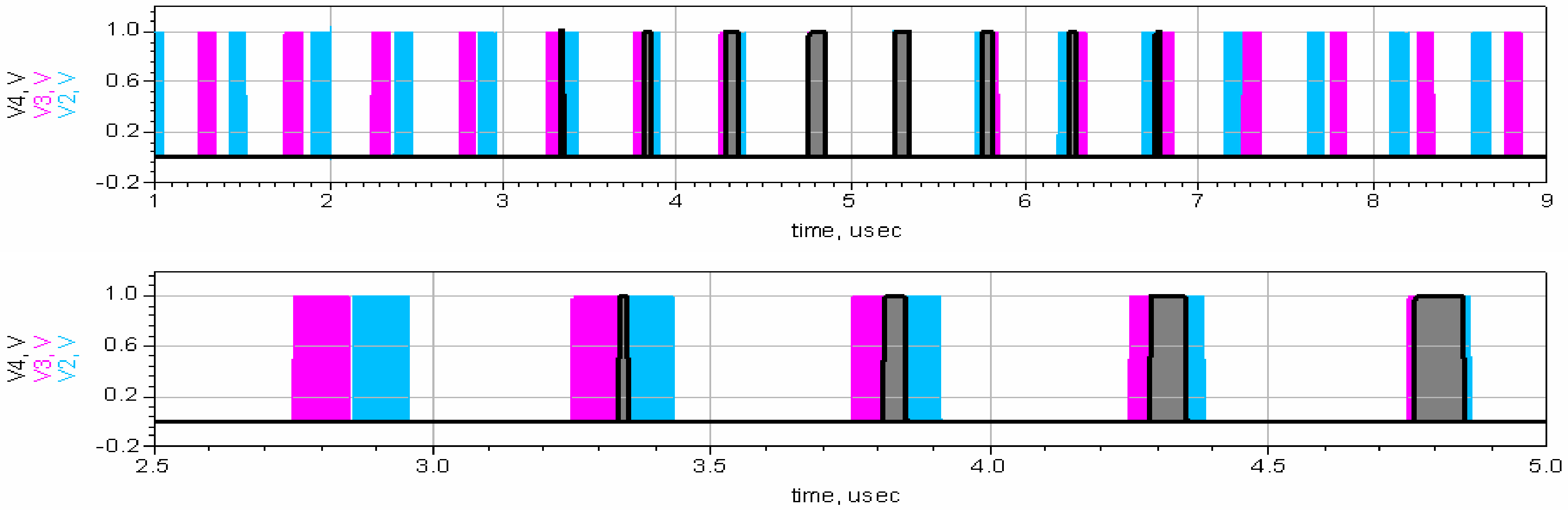
$S = 0.5*c*(T_x-\tau_0)$

τ_0 – retranslation time

Operation time of counters $\mathbf{C_1, C_2, C_3}$.

5.7. Ranging

Overlapping of Delayed & Reference Pulses



Delayed pulse

Reference pulse

Pulse overlap

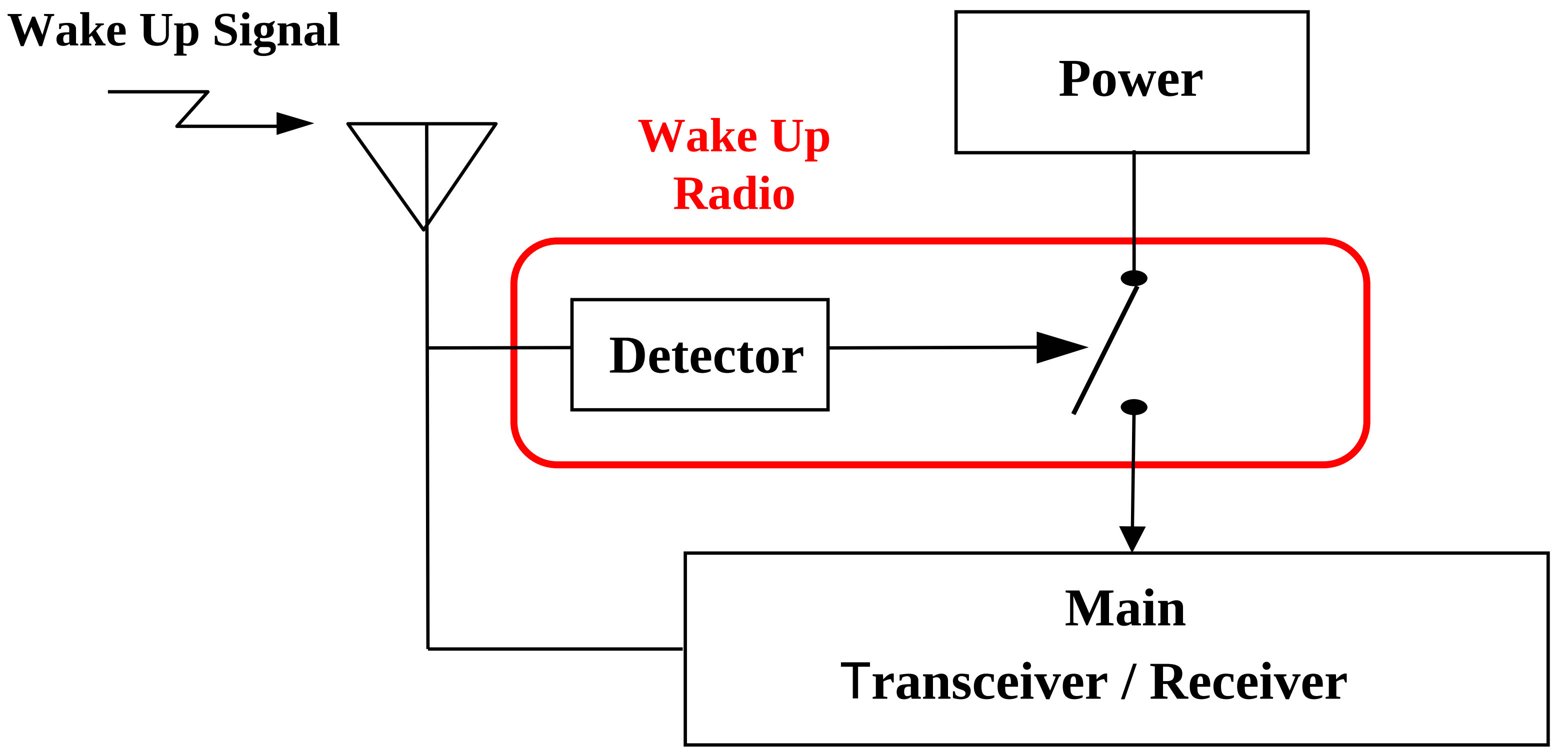
5.8. Link Budget

Parameter	**(mandatory) Value**	**(optional) Value**
Peak payload bit rate (R_b)	X_0=2440 kbps	X_i=1630 kbps
Average Tx power (P_T)	-8.3 dBm	-8.3 dBm
Tx antenna gain (G_T)	0 dBi	0 dBi
$f_c' = \sqrt{f_{\min} f_{\max}}$: geometric center frequency of waveform ($f_{\min}$ and $f_{\max}$ are the -10 dB edges of the waveform spectrum)	3.976 GHz	3.976 GHz
Path loss at 1 meter ($L_1 = 20\log_{10}(4\pi f_c' / c)$) $c = 3\times 10^8$ m/s	44.43 dB	44.43 dB
Path loss at d=30 m ($L_2 = 20\log_{10}(d)$)	29.54 dB	29.54 dB
Rx antenna gain (G_R)	0 dBi	0 dBi
Rx power ($P_R = P_T + G_T + G_R - L_1 - L_2$ (dB))	-82.3 dBm	-82.3 dBm
Average noise power per bit ($N = -174 + 10 * \log_{10}(R_b)$)	-110.1 dBm	-111.9 dBm
Rx Noise Figure (N_F) note [1]	7 dB	7 dB
Average noise power per bit ($P_N = N + N_F$)	-103.1 dBm	-104.9 dBm
Minimum E_b/N_0 (S)	15.5 dB	15.5 dB
Implementation Loss[1] (I)	3 dB	3 dB
Link Margin ($M = P_R - P_N - S - I$)	2.3 dB	4.1 dB
Proposed Min. Rx Sensitivity Level[2]	-86.1 dBm	-87.9 dBm

5.10. Power Management Modes

Sleep and Wake-up Scheme

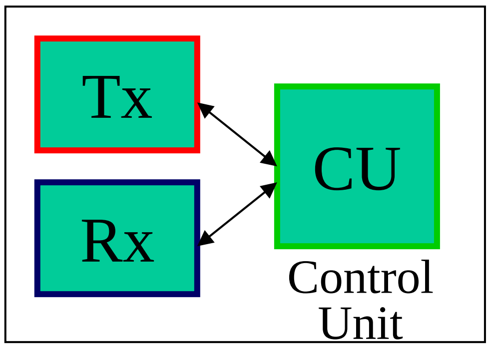
Wake Up Structure



5.11. Power Consumption

Power Calculation

Transceiver



Operation time T_{oper}

$$T_{oper} = C_b \cdot U_b / P_{av}$$

Average power consumption P_{av}

$$P_{av} = P_{Tx} + P_{Rx} + P_{CU}$$

$$P_{Tx} = P_e / \eta \qquad P_{Rx} = P_e / \eta_{best}$$

$$P_e = P_{in} \cdot T_e = 1/2 \cdot D \cdot P_{in} \cdot T_{bit} \cdot R$$

P_e is emitted power,

η is efficiency,

η_{best} is the best of all possible efficiencies,

P_{in} is instantaneous emission power,

T_e is time of emission for given transmission rate,

T_{bit} is duration of one bit,

R is transmission rate,

C_b is battery capacity,

U_b is battery voltage,

D is duty cycle.

5.11. Power Consumption

Duty Cycle and Power Consumption

Transmission Rate *R*, kbps	Average Emitted Power P_e, mW	Average Power Consumption P_{av} (η = 5%)	Lifetime of the AAA battery, years
1	**$2 \cdot 10^{-4}$**	**15.5 μW**	**8.3** **100% duty cycle**
10	**$2 \cdot 10^{-3}$**	**87.5 μW**	**15** **10% duty cycle**
1000	**$2 \cdot 10^{-1}$**	**8 mW**	**16.4** **0.1% duty cycle**

P_{CU} = 7.5 μW ; P_{in} = 4 mW ; η_{best} = 5%; U_b = 1.5 V ; C_b = 750 mAh; D = 1/4

Example: R = 1 kbps; T_{bit} = 400 *ns*; η = 5%

$$P_e = 1/2 \cdot D \cdot P_{in} \cdot T_{bit} \cdot R = 0.2\ \mu W$$

$$P_{av} = P_{Tx} + P_{Rx} + P_{CU} = P_e/\eta + P_e/\eta_{best} + P_{CU} = 15.5\ \mu W$$

Conclusion

- Chaotic communications meet the low power, low cost & low complexity requirements → best suited for 15.4a applications.
- Proposed DCC-OOK compliant with FCC UWB PSD regulation.
- Feasibility and scalability are guaranteed with precision ranging and SOP capabilities.
- The implemented test bed demonstrated that the feasibility of DCC technology.

DCSK: Compatible Modulation Scheme for Direct Chaotic Communication

DCSK Modulation

DCSK

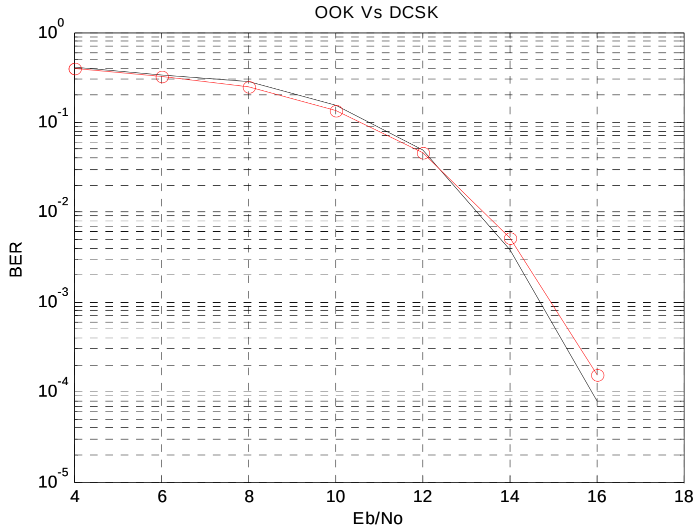
- **Differential Chaos Shift Keying (DCSK)**
  - Can be a modulation scheme as an alternative to OOK DCC
  - The Chaotic properties are maintained as in the case of the OOK
  - Same data rate as in the proposed OOK
  - Constant decision threshold in the receiver
  - SOP can be achieved by transmitting different Chaotic pulse length
  - DCSK transmits a reference chaotic pulse and an information data pulse depending on whether information bit 1 (same ref. chaotic pulse) or 0 (inverted of the chaotic pulse) is being transmitted
  - The information signal can be recovered by a correlator.

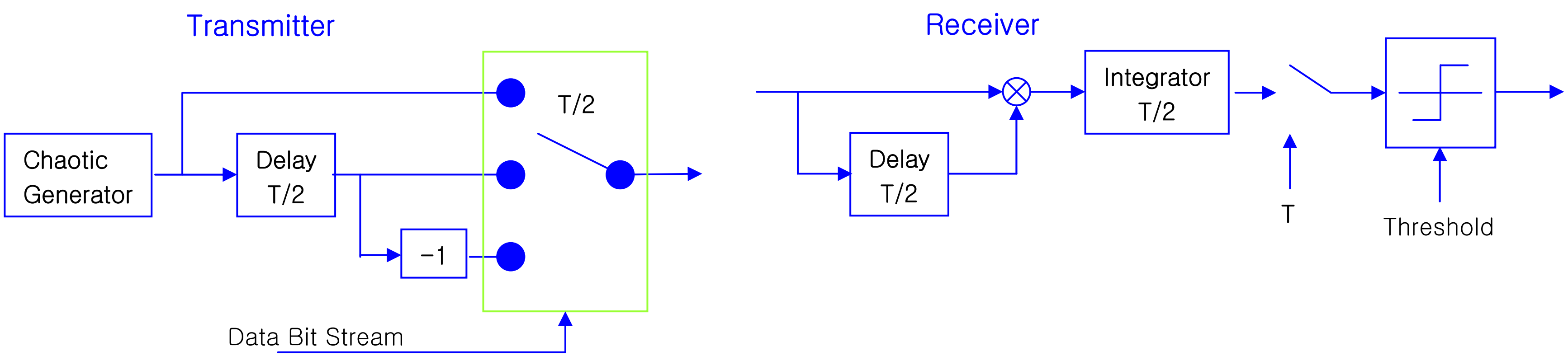
DCSK Modulation

Principle

$$s(t)=\begin{cases} x(t), & t_i \le t < t_i + T/2 \\ +x(t-T/2), & t_i + T/2 \le t < t_i + T \end{cases}$$

$$s(t)=\begin{cases} x(t), & t_i \le t < t_i + T/2 \\ -x(t-T/2), & t_i + T/2 \le t < t_i + T \end{cases}$$

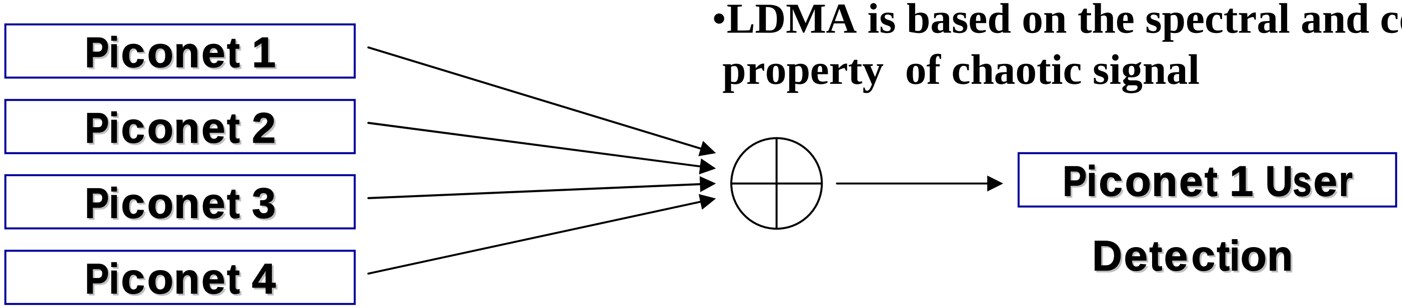


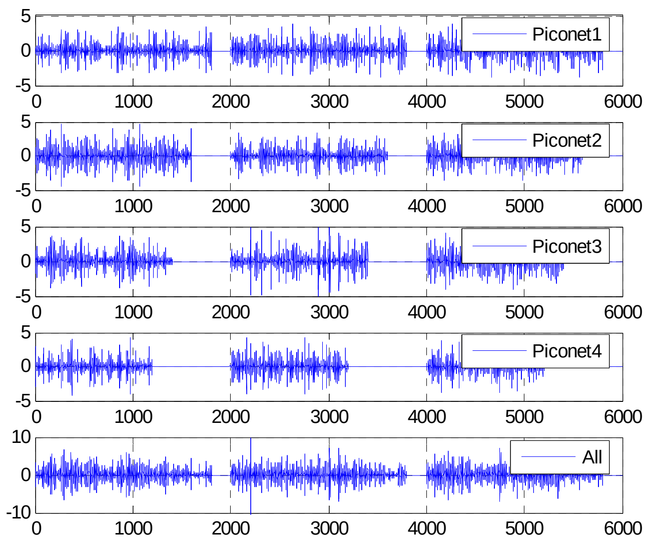


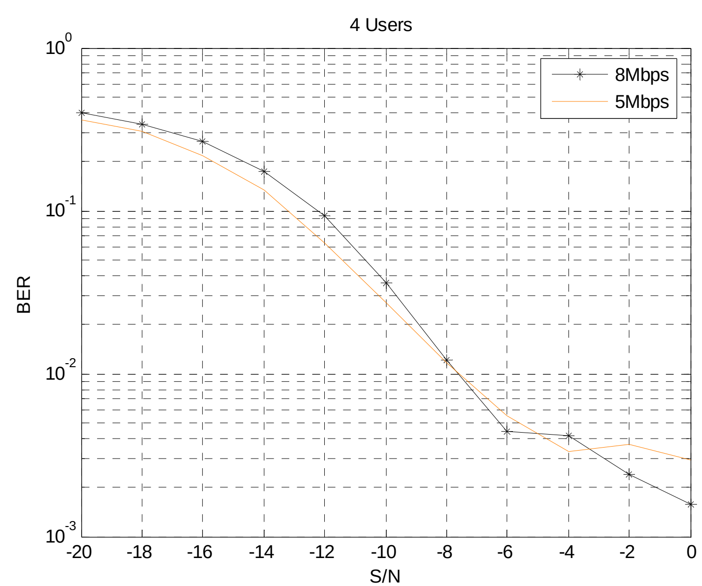
DCSK Modulation

SOP: LDMA

- In DCSK SOP can be done using Chaotic Length Division Multiple Access (LDMA)
- LDMA works based on the exploitation of different chaotic length assigned to each piconets.
- LDMA is based on the spectral and correlation property of chaotic signal



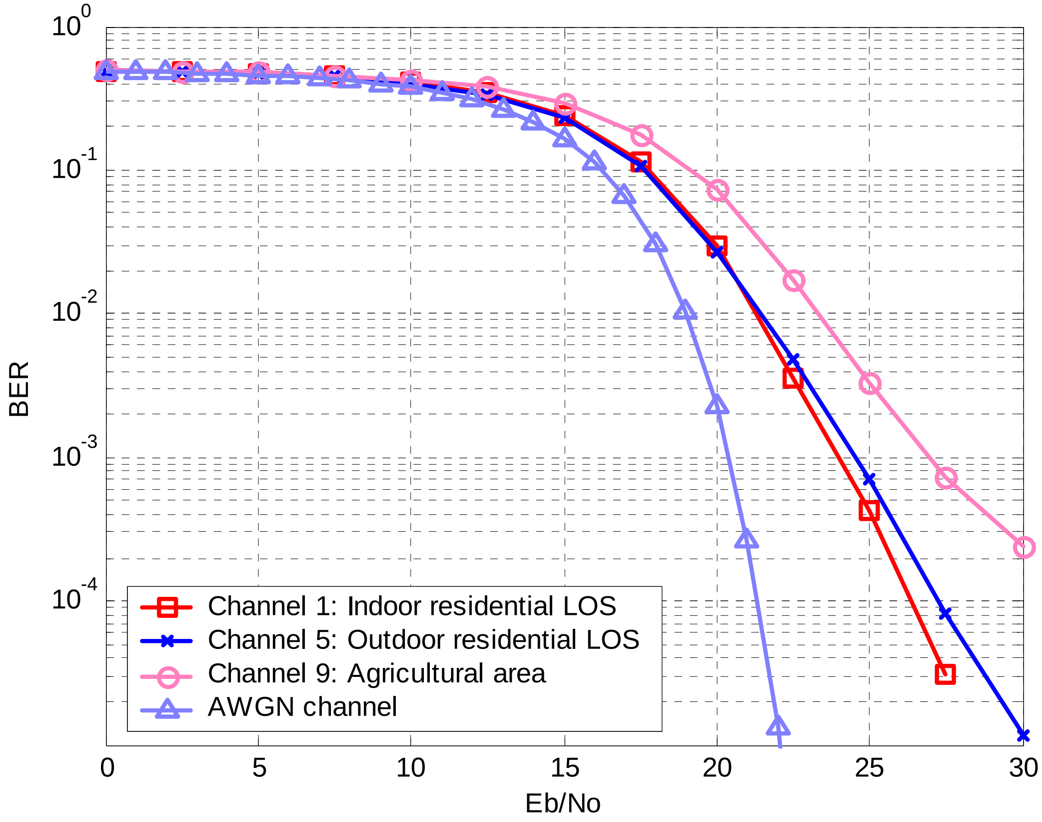




DCSK Modulation

Simulation Results

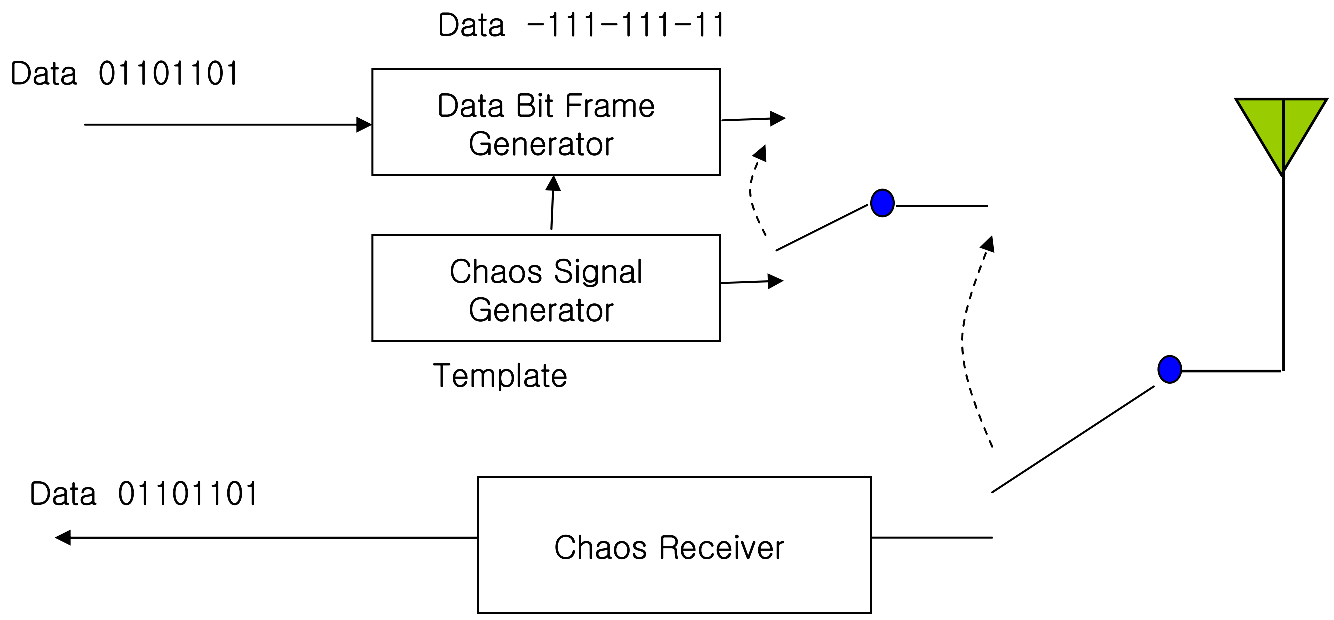
- **AWGN & Multipath**



DCSK Modulation

SOP

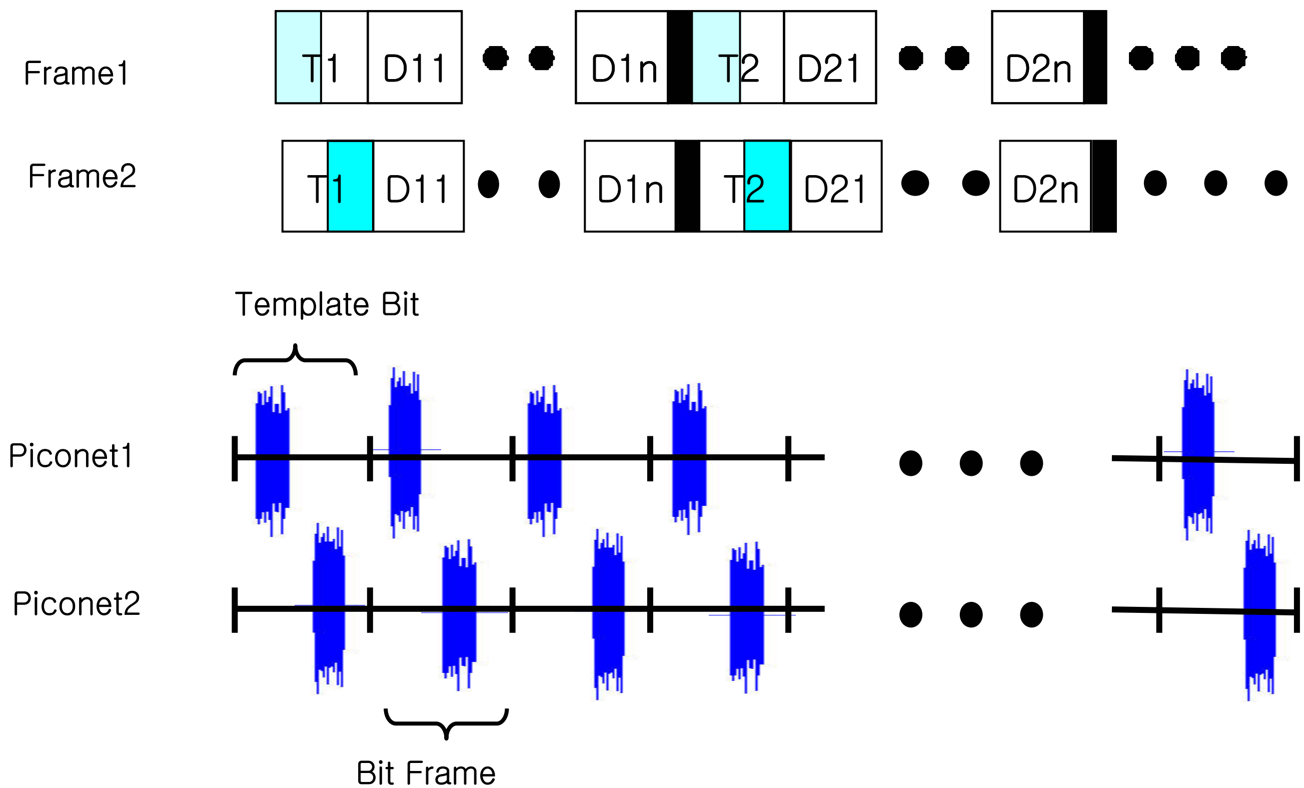
- **System Block**



DCSK Modulation

SOP

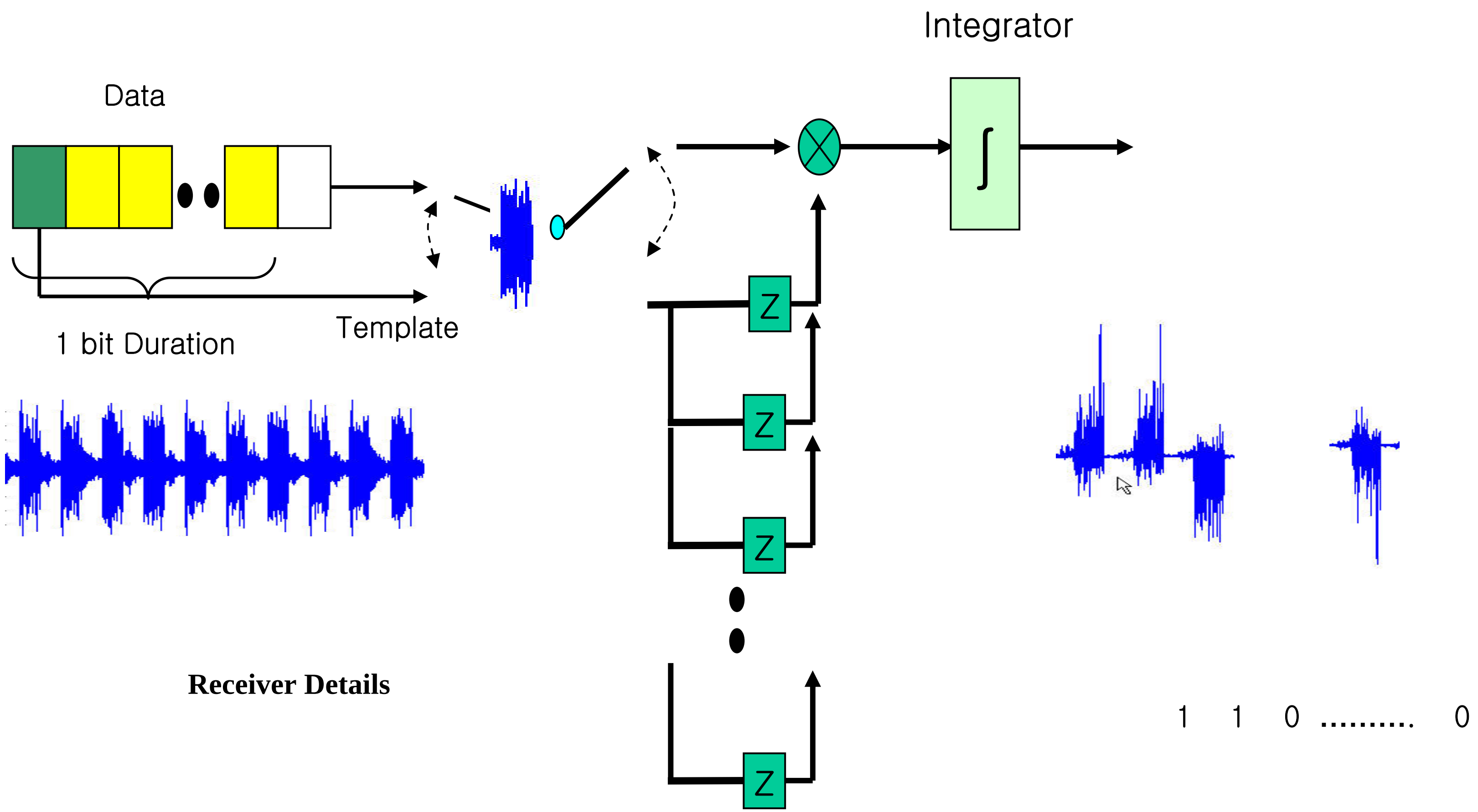
- **Transmission**



DCSK Modulation

SOP

- **Detail**

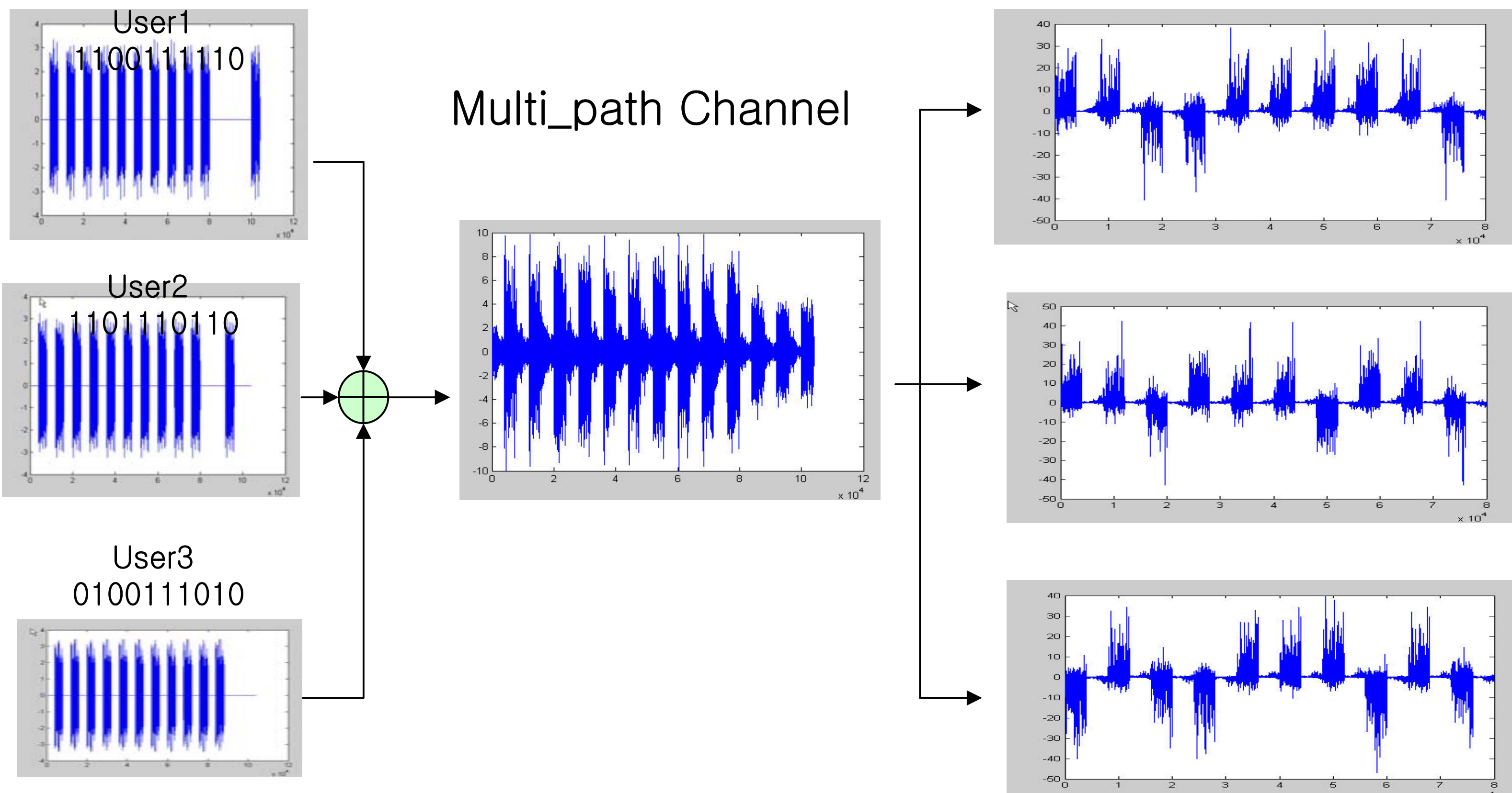


Receiver Details

DCSK Modulation

SOP

- **Signal Processing**

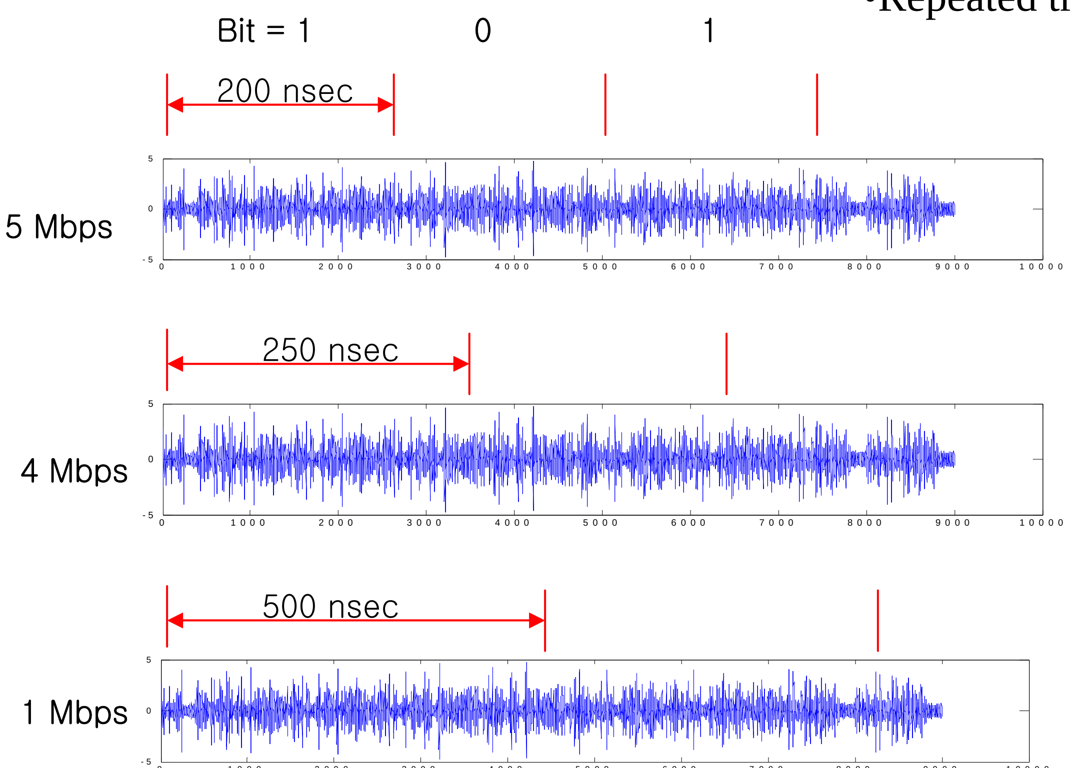


DCSK Modulation

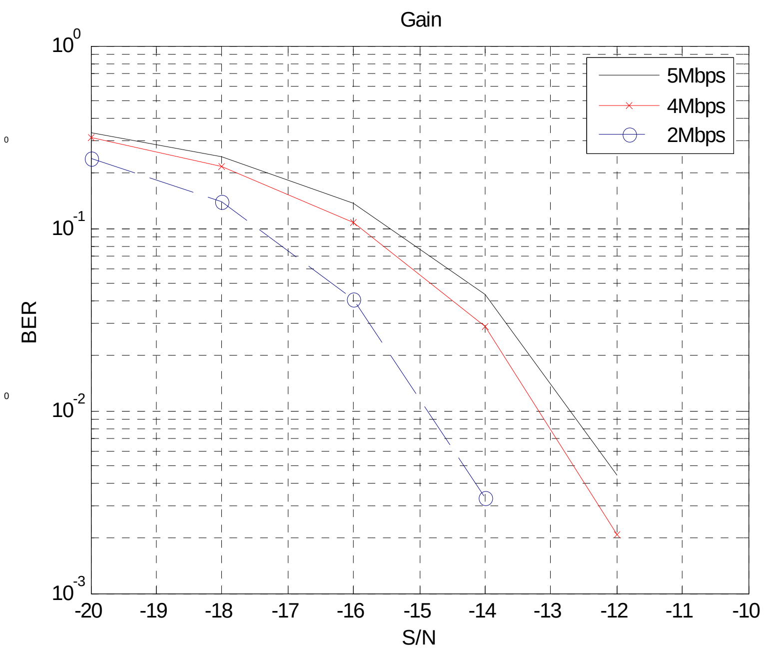
Scalability

Scalability can be achieved using

- Chaotic gain
- Varying bit duration
- Duty cycle
- Repeated transmission of information bearing chip.



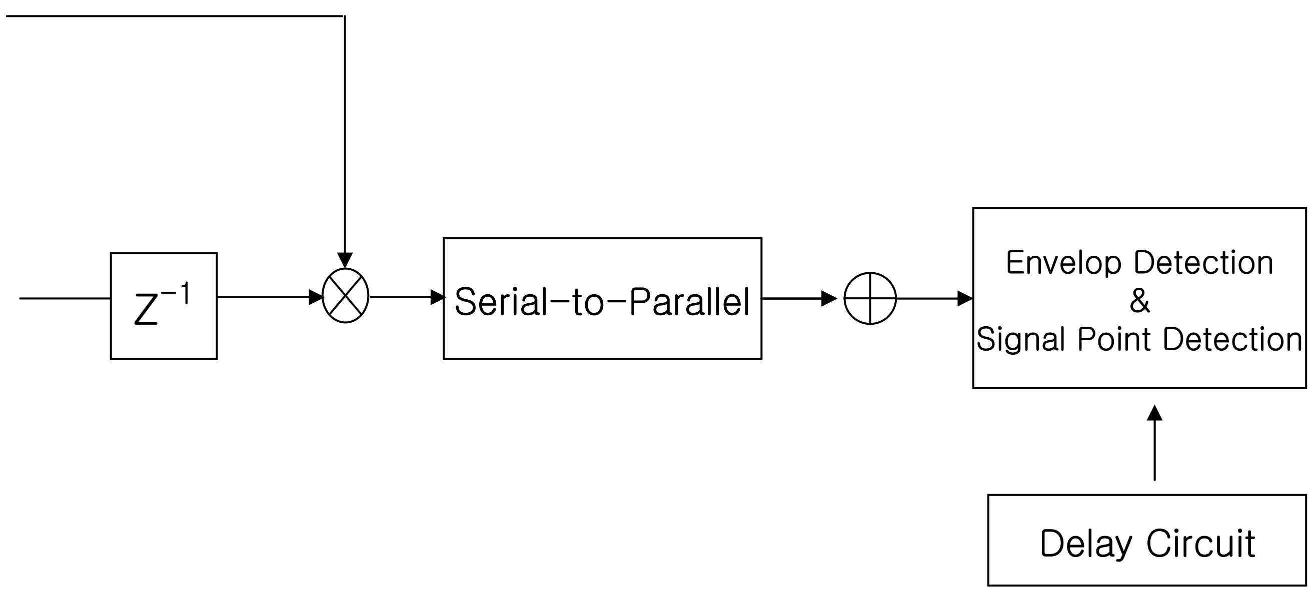
Chaotic Gain in DCSK



DCSK Modulation

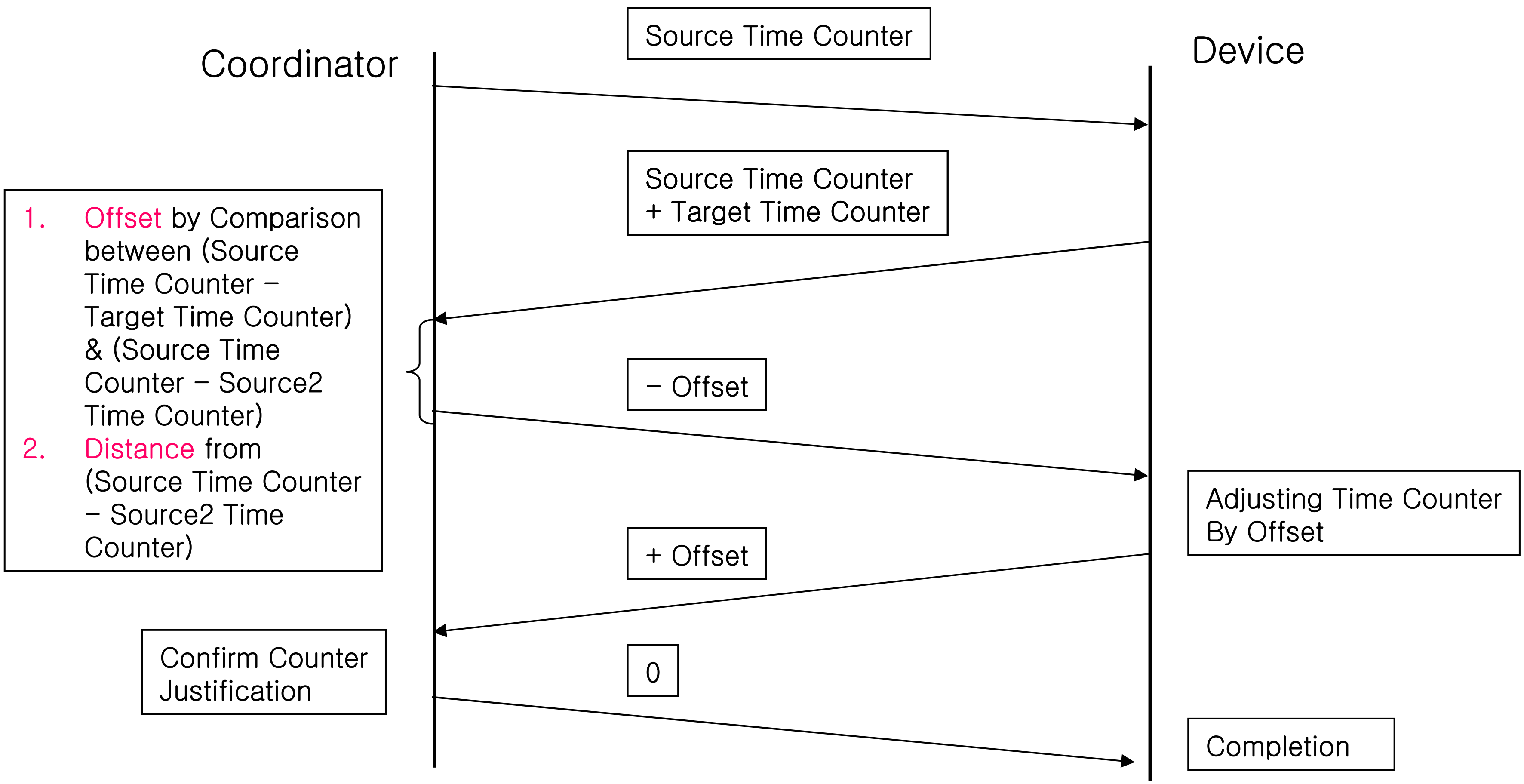
Ranging

- **Block Diagram**



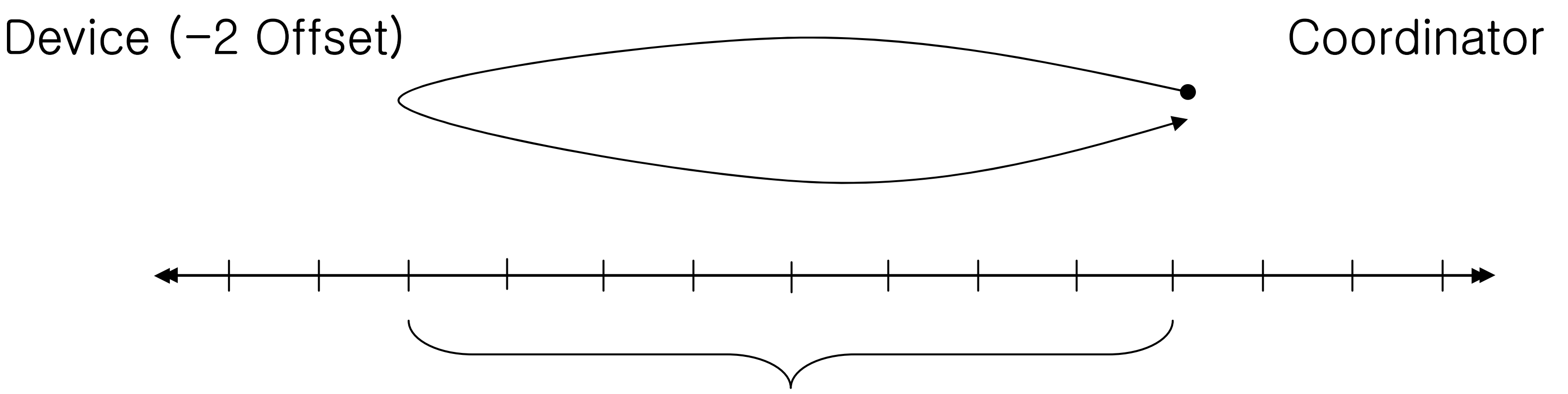
DCSK Modulation

Ranging



DCSK Modulation

Ranging



Initial : 356 358

1st Pass : 364 ← 356+8 374 ← 358+16

1. PNC recalculates Device Arrival time : 366 ← 358 + (16/2)
2. Compare value from 1 and Device : −2 ← 364 – 366
3. +2 Transferred as –Offset
4. 8 Kept for Distance between PNC and Device

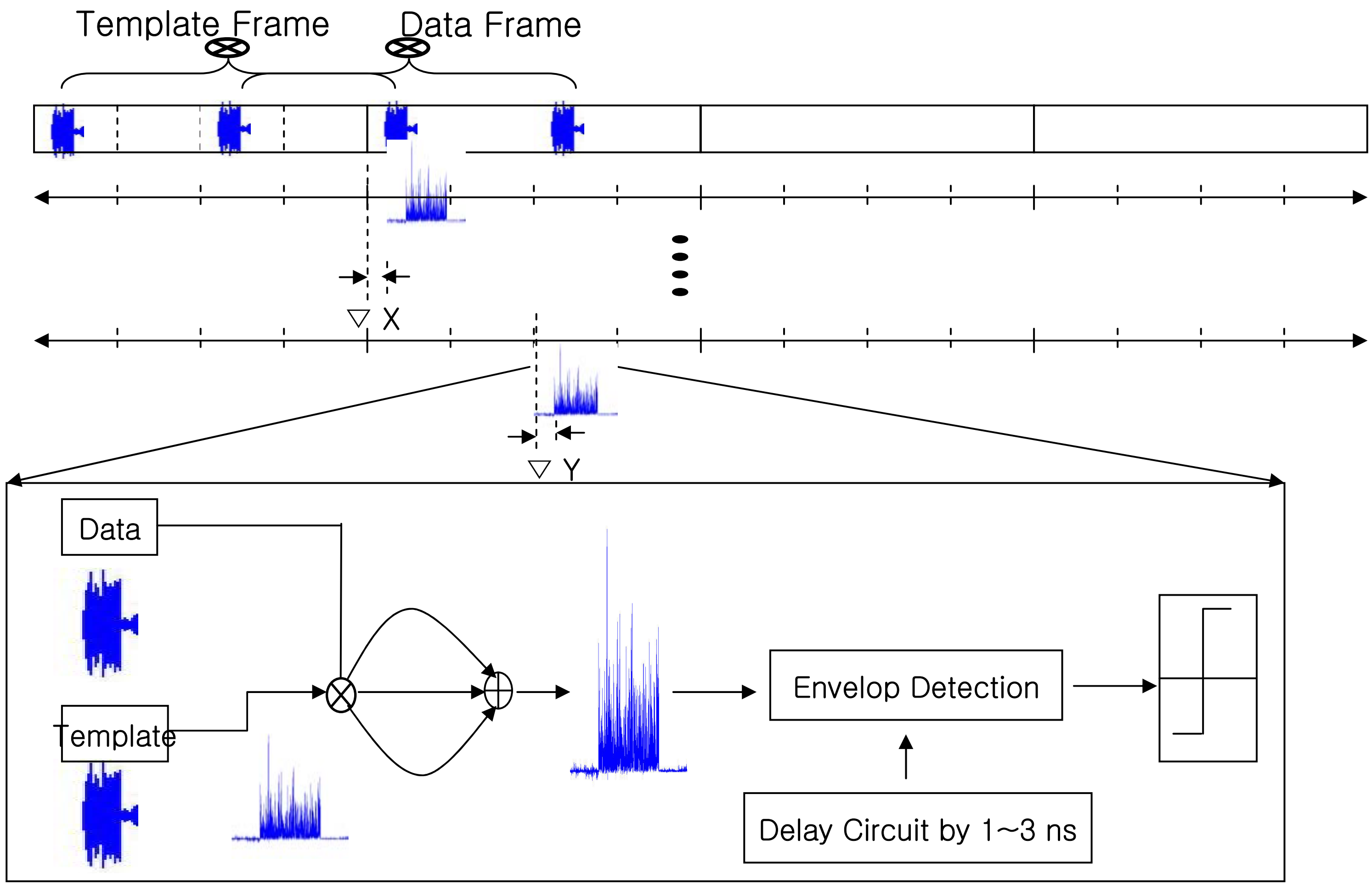
DCSK Modulation

Location Awareness Special Mode

- **Timing Counter Fine Synchronization**
  - PNC disseminates special frame to inform Device of Location special mode
  - Device acknowledges with its own timing count
  - PNC compares its own count with Device’s count, and extract an offset between them
  - PNC sends negative offset in order for Device to compensate its timer
  - Device informs PNC of all being set

DCSK Modulation

Location Awareness Special Mode



DCSK Modulation

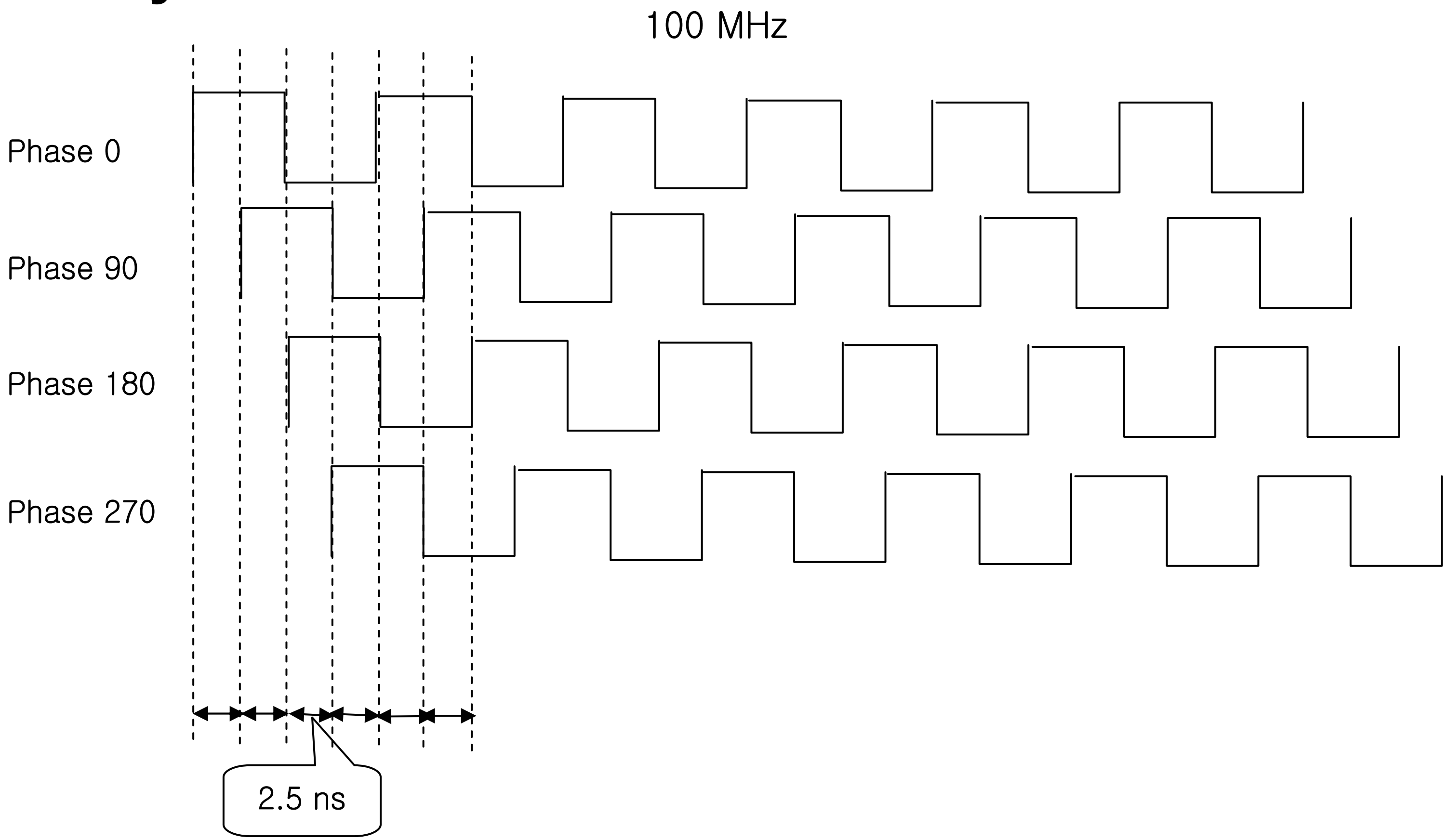
Ranging

- **Fine Precision TOA Estimation**
  - Suggest Special mode different from Normal mode, which needs faster clock
  - In special mode, Estimate how far Signal detached from fixed time slot with finer clock
  - This obtained value returned with Response command to Request command from MAC

DCSK Modulation

Ranging

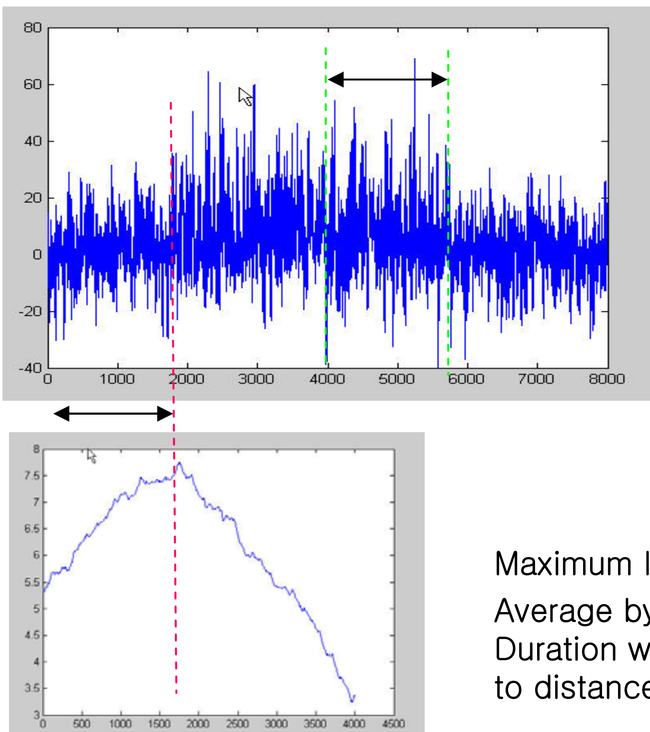
- Delay Circuit



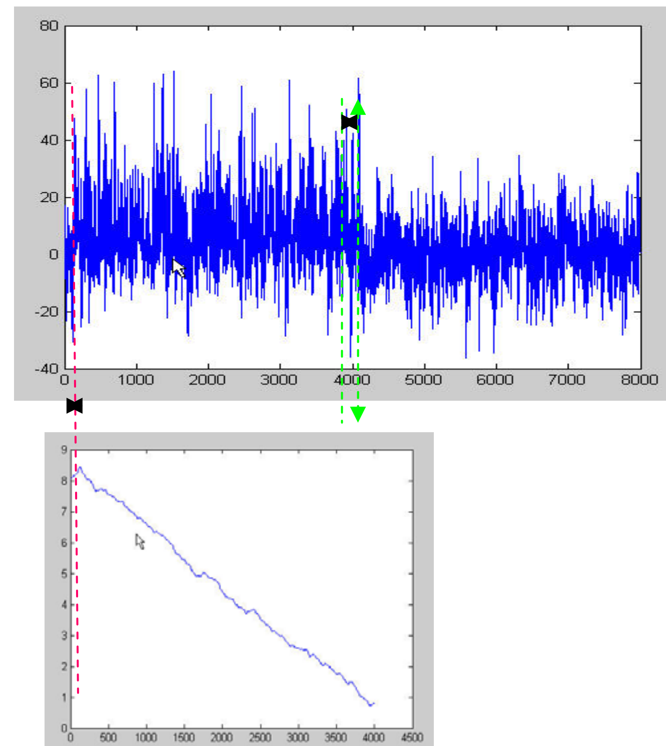
DCSK Modulation

Ranging

- **Simulation (BNR 16dB)**



Maximum Index of Moving Average by duty cycle
Duration will be converted to distance.



real distance : 13.118 meter
2.5 ns precision distance : 12.750 meter
Error : −0.367 meter

real distance : 0.968 meter
2.5 ns precision distance : 0.750 meter
Error : −0.218 meter

DCSK Modulation

Complexity, Cost & Technical Feasibility

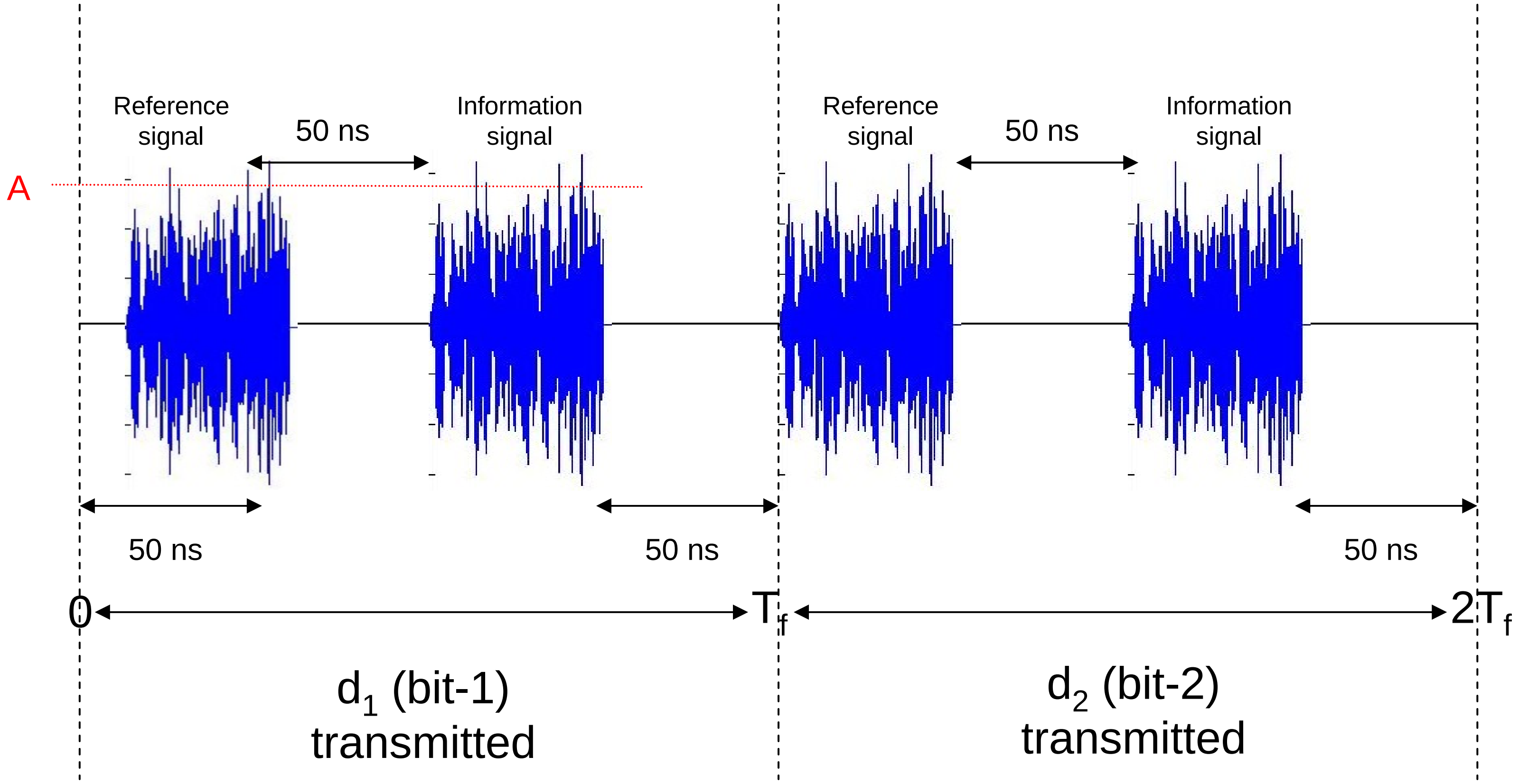
- Complexity and cost will be slightly higher compare to the OOK chaotic system proposed

Conclusion

- Chaotic communication based on DCSK modulation is an alternative solution.
- SOP and ranging can also be solved using DCSK.
- Hardware complexity is slightly higher than OOK since most hardware from OOK is retained.

Combining MCSK TH-IR with Chaotic Signaling

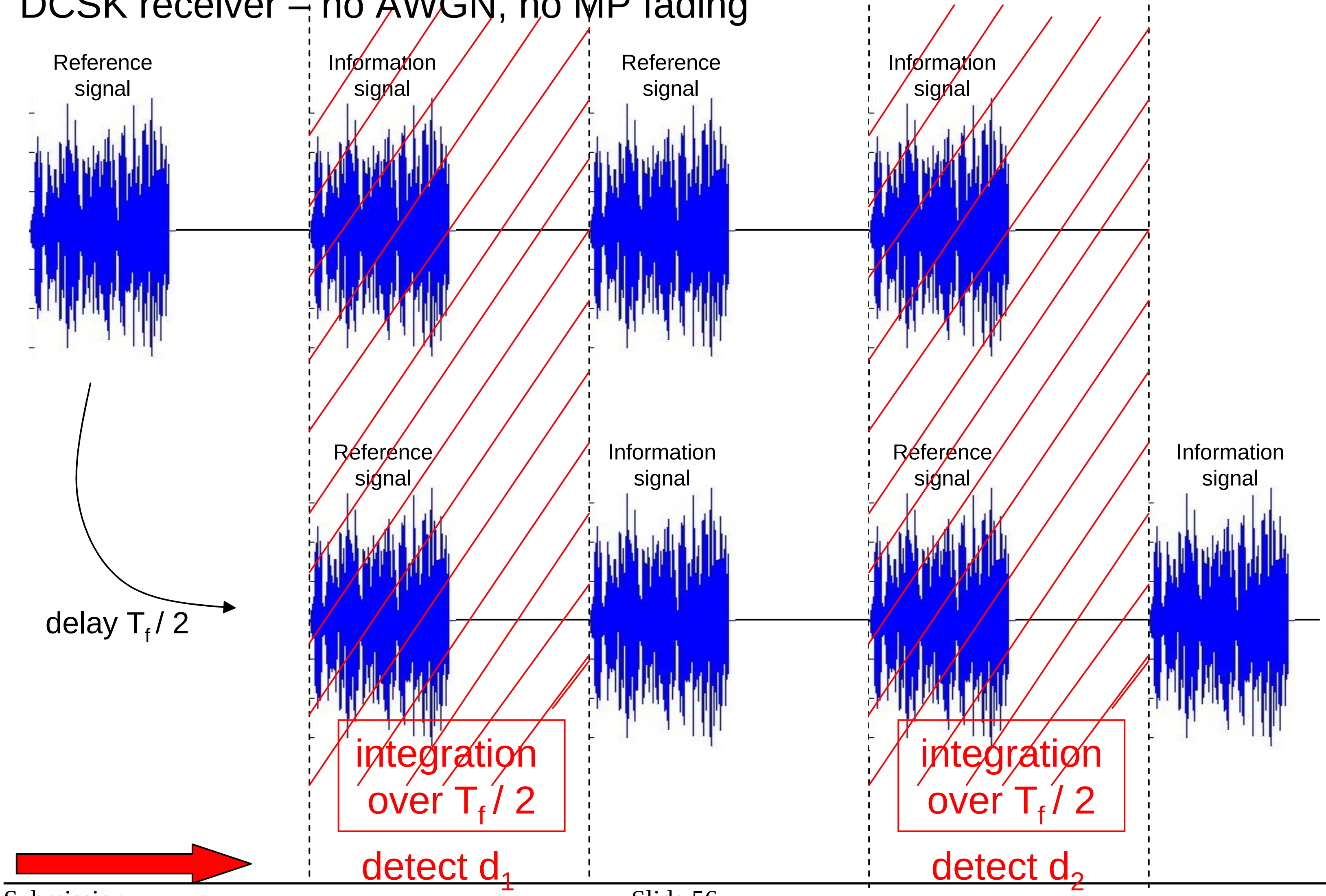
DCSK transmitting d=[d_1 d_2], $d_i \; \varepsilon \; (-1,1)$



where ***info. signal = sign(d_i) x ref. signal***

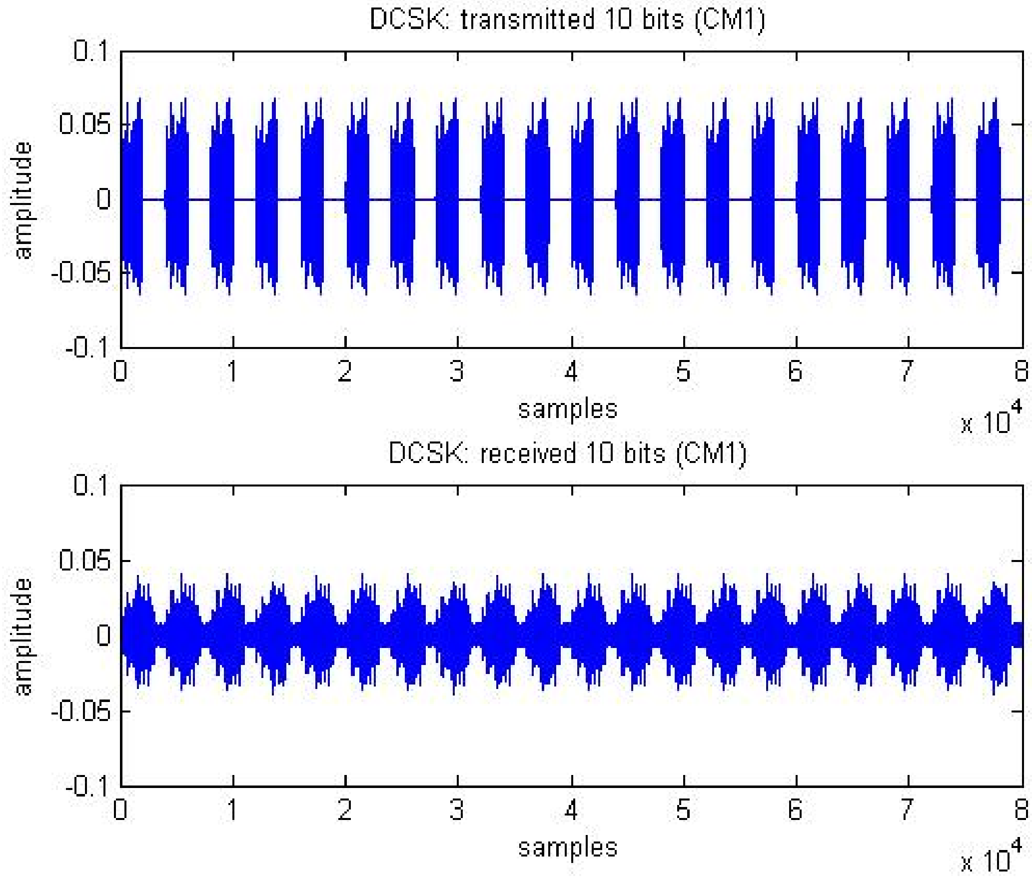
Combining MCSK TH-IR with Chaotic Signaling

DCSK receiver – no AWGN, no MP fading



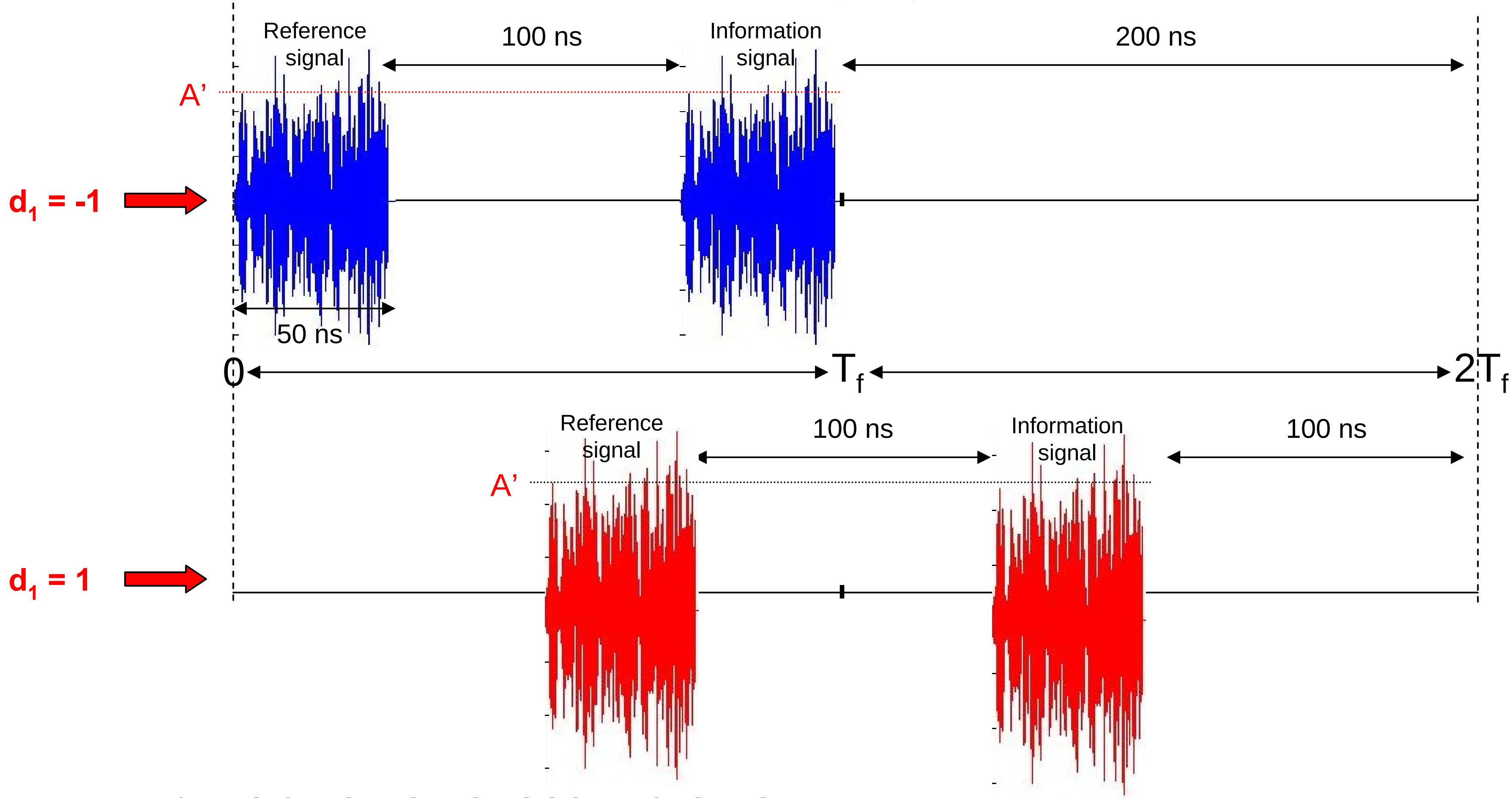
Combining MCSK TH-IR with Chaotic Signaling

DCSK: Transmitted and received signals (CM1, no AWGN)



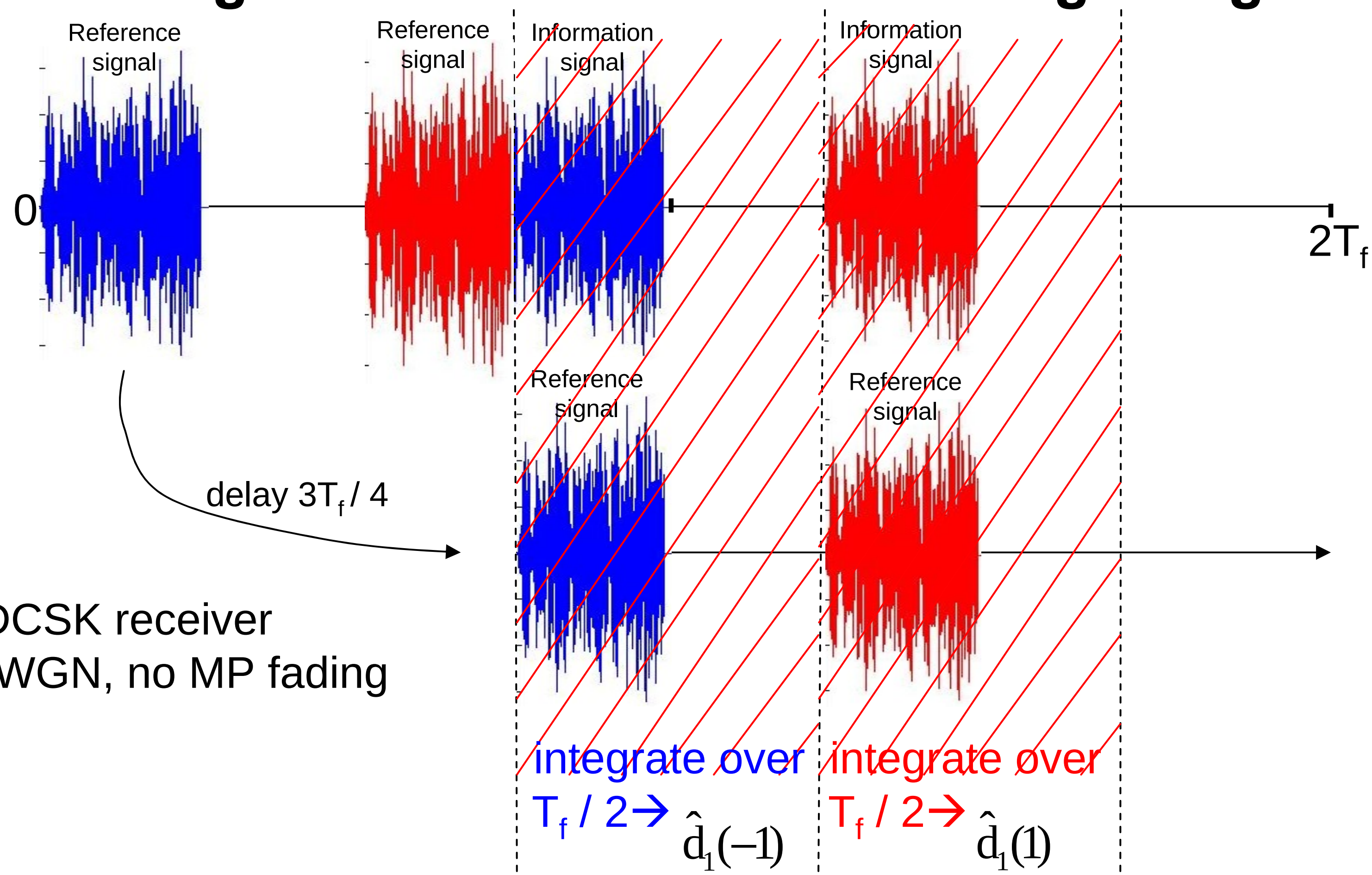
Combining MCSK TH-IR with Chaotic Signaling

MCS-DCSK transmitting d=[d1 d2], di ε $(-1,1)$



where ***info. signal = sign(d_2) x ref. signal***

Combining MCSK TH-IR with Chaotic Signaling



MCS-DCSK receiver
– no AWGN, no MP fading

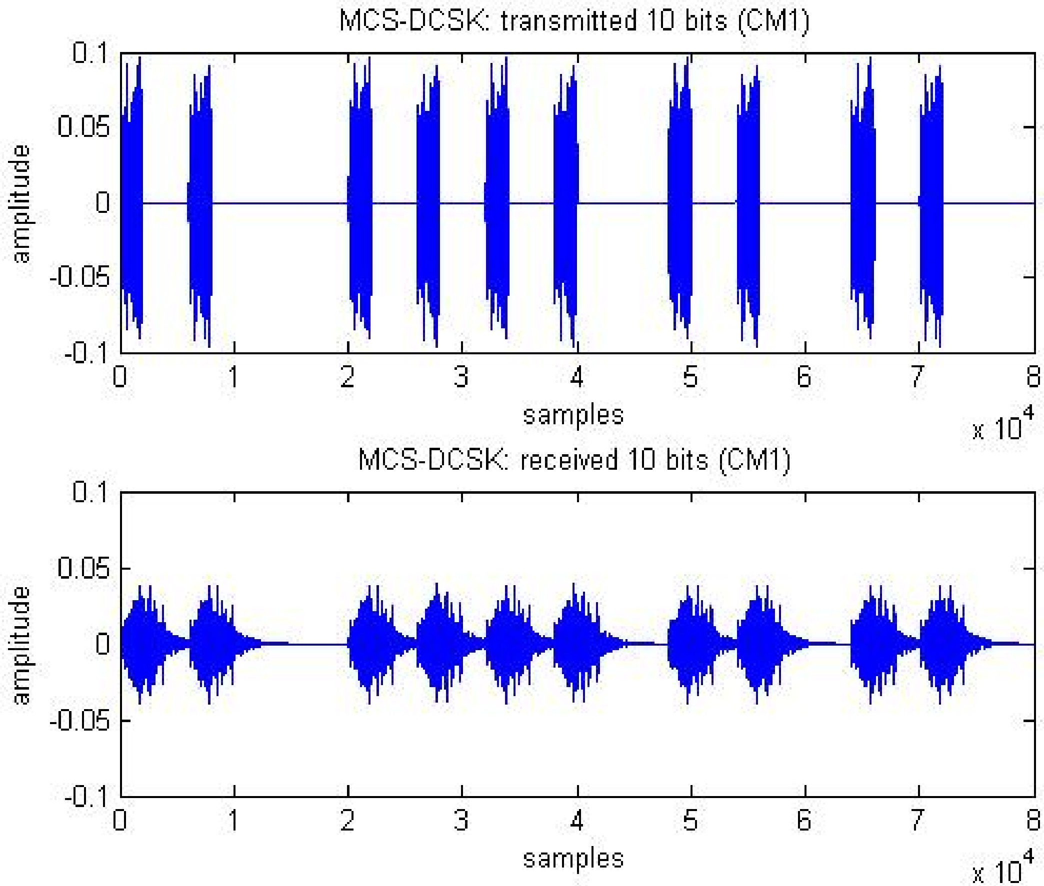
Decision

Step 1: $\left|\hat{d}_1(-1)\right| > \left|\hat{d}_1(1)\right| \longrightarrow d_1 = -1; \quad \left|\hat{d}_1(-1)\right| < \left|\hat{d}_1(1)\right| \longrightarrow d_1 = 1$

Step 2: $\text{if } \; d_1 = -1 \longrightarrow d_2 = \text{sign}\left(\hat{d}_1(-1)\right); \quad \text{if } \; d_1 = 1 \longrightarrow d_2 = \text{sign}\left(\hat{d}_1(1)\right)$

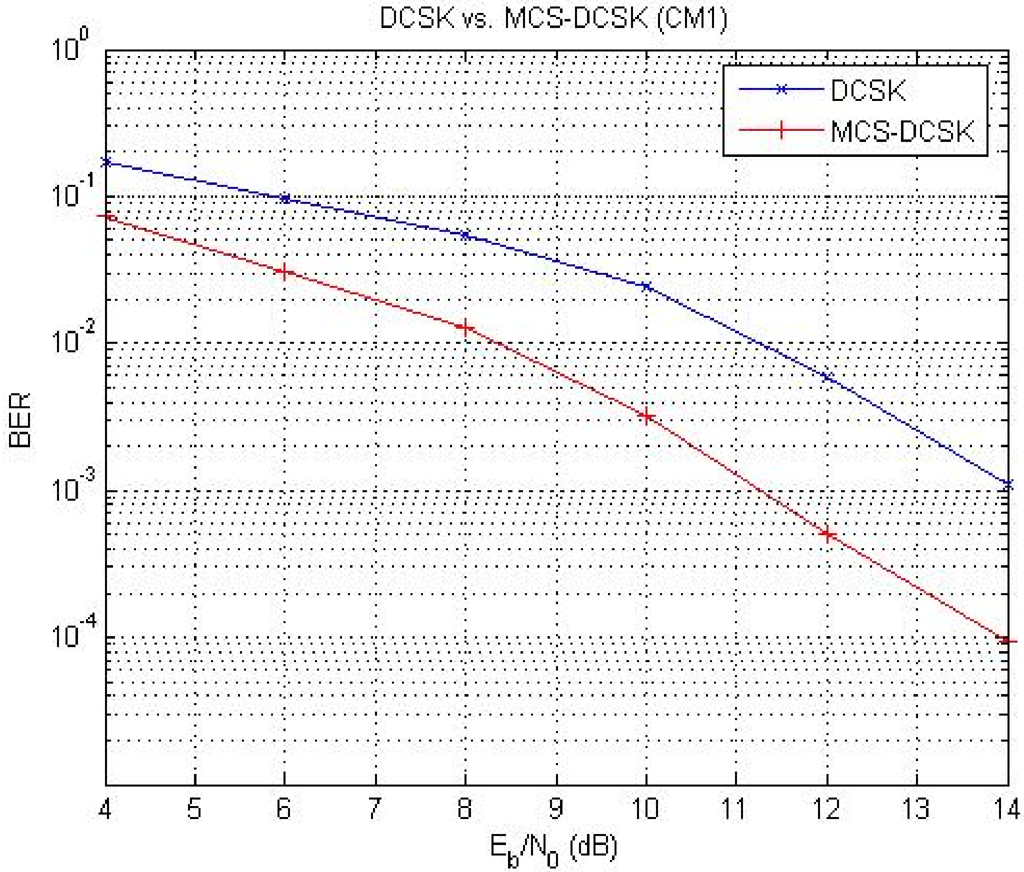
Combining MCSK TH-IR with Chaotic Signaling

MCS-DCSK: Transmitted and received signals (CM1, no AWGN)

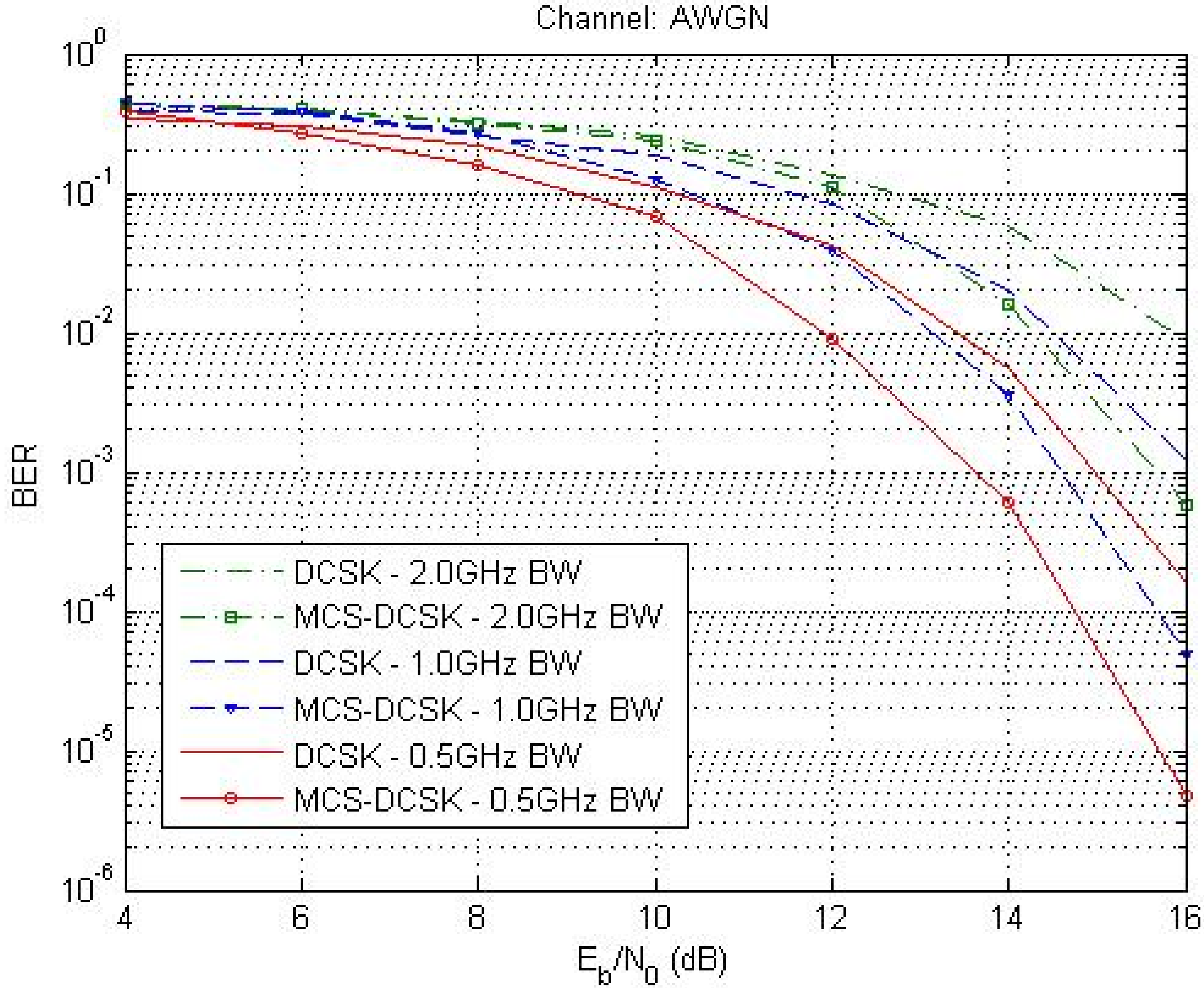


Combining MCSK TH-IR with Chaotic Signaling

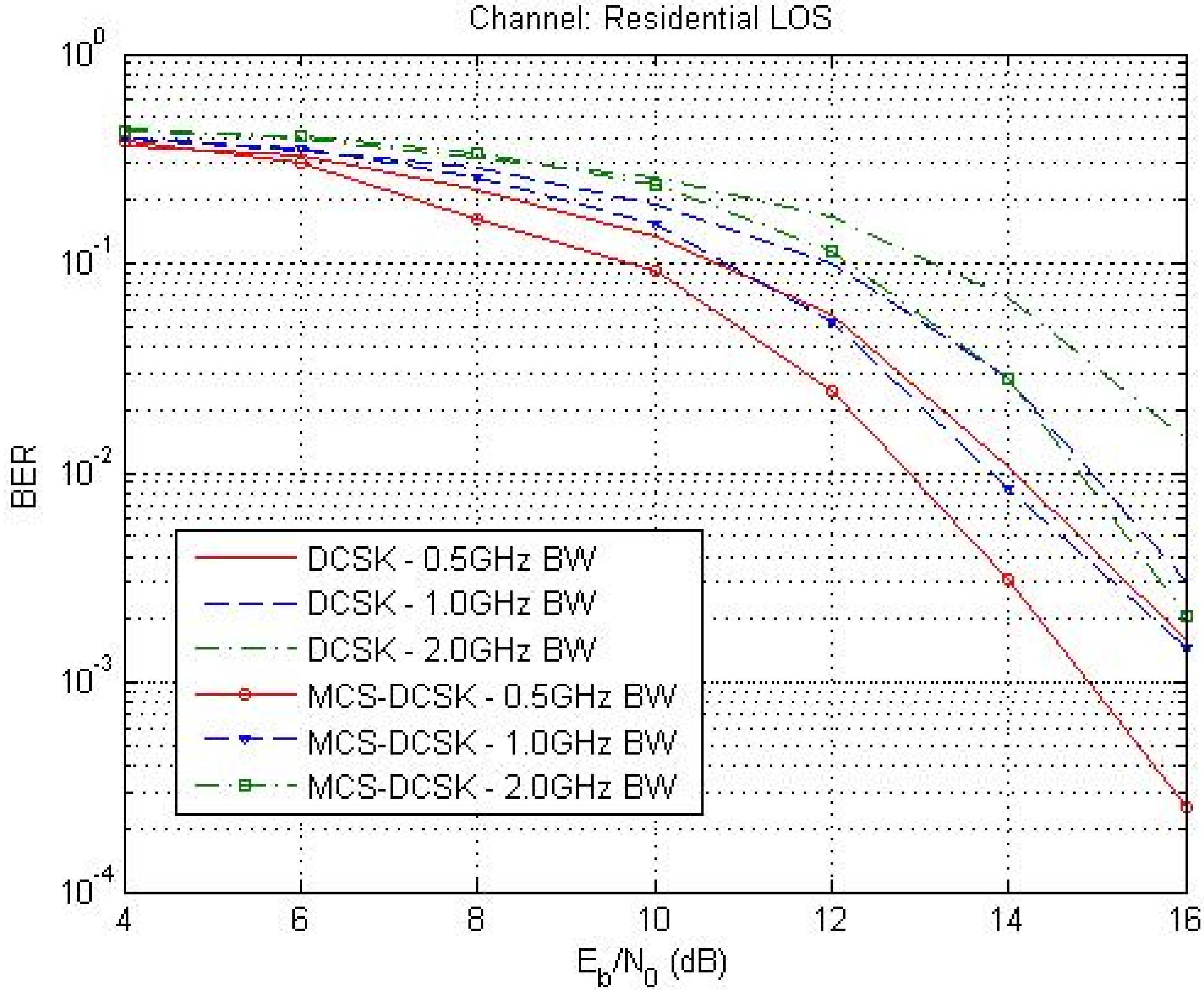
Performance Comparison: DCSK vs. MCS-DCSK



Combining MCSK TH-IR with Chaotic Signaling



Combining MCSK TH-IR with Chaotic Signaling



MC-PPM: Compatible Modulation Scheme for Direct Chaotic Communication

MC-PPM Modulation

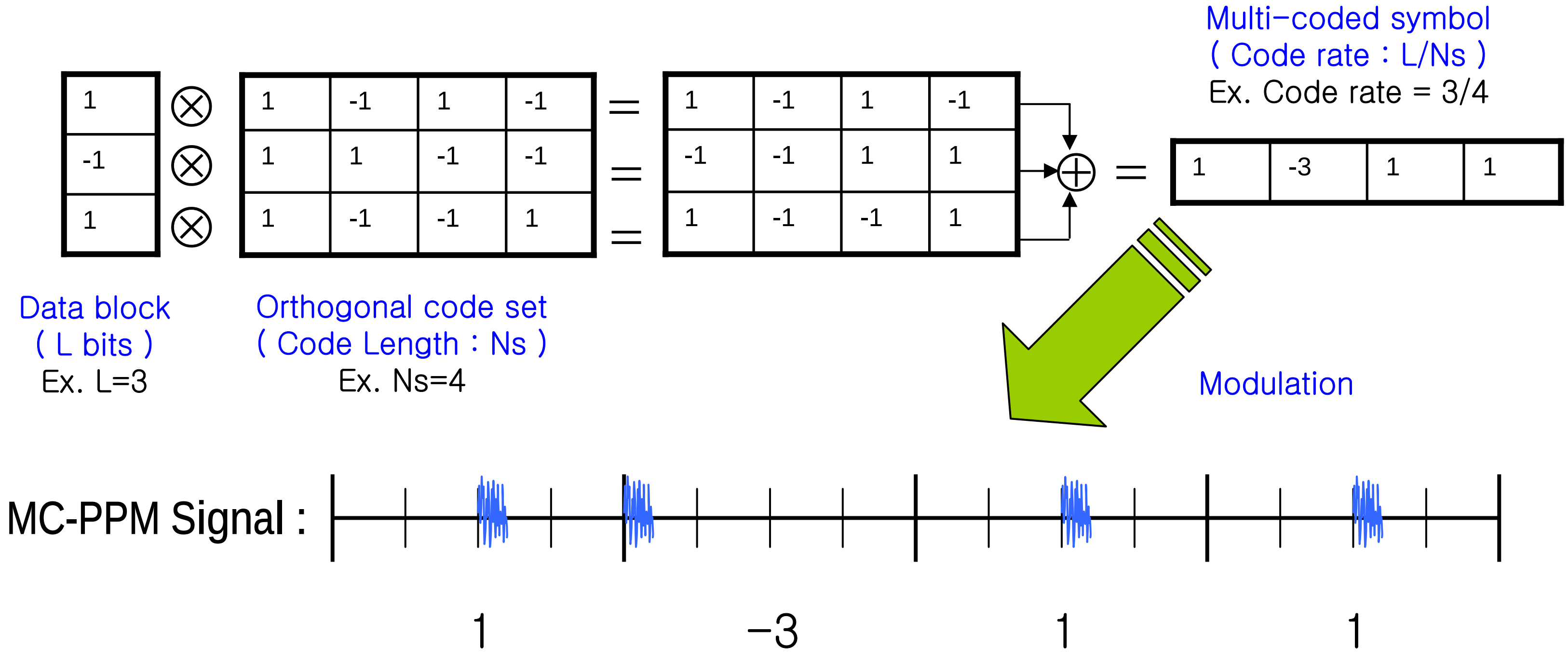
MC-PPM

- **Multi-coded Pulse Position Modulation (MC-PPM)**
  - Power efficient scheme
  - Inherent coding gain due to orthogonal multi-codes
  - Support wide pulse shaping in same data rate condition
  - Constant decision threshold in the receiver
  - OOK is one special mode of MC-PPM

MC-PPM Modulation

Principle

- **Principle operation (L=3, Ns=4)**

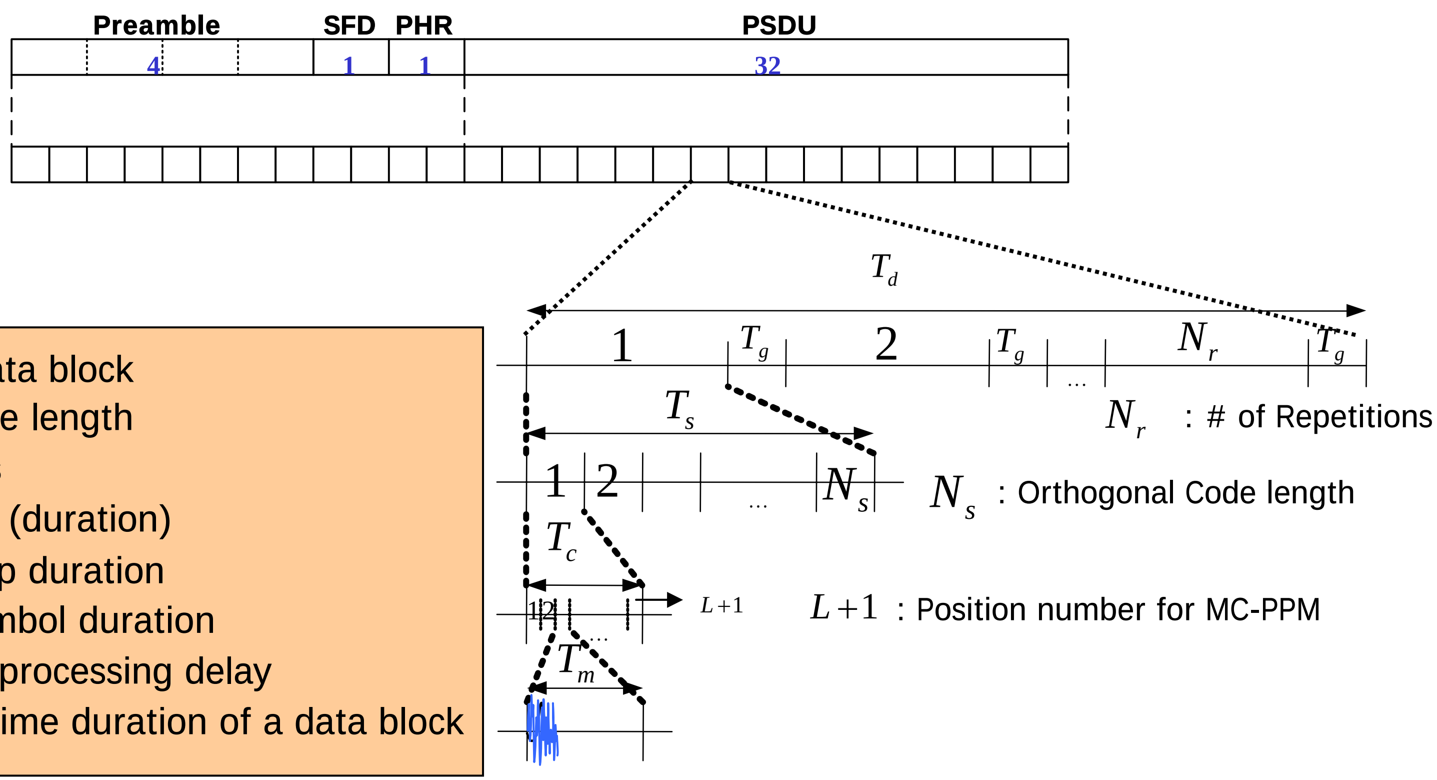


MC-PPM Modulation

Data Frame Structure

- **1 data block (L data) interval of PSDU :**

$$T_d = N_r(T_s + T_g),\ T_s = N_s T_c,\ T_c = (L+1)T_m$$

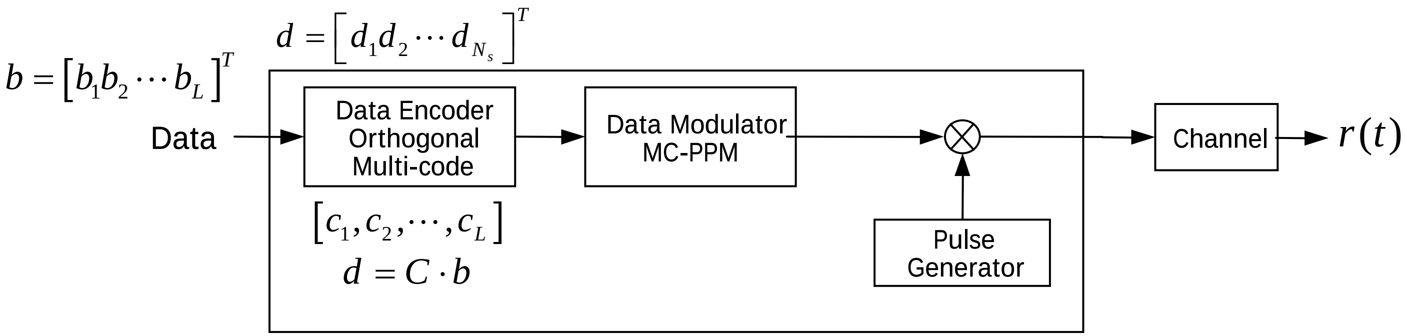


L	: # of bits per data block
N_s	: Orthogonal code length
N_r	: # of repetitions
T_m	: Pulse bin width (duration)
T_c	: Multi-coded chip duration
T_s	: Multi-coded symbol duration
T_g	: Guard time for processing delay
T_d	: Total transmit time duration of a data block

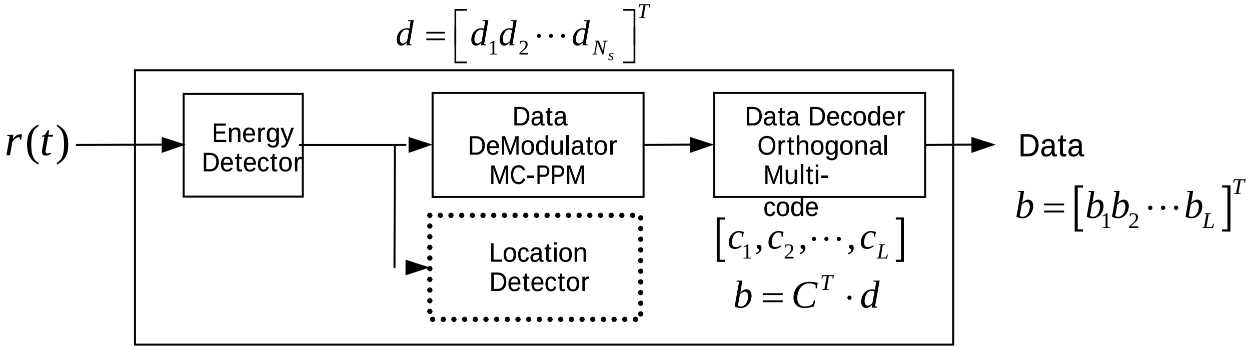
MC-PPM Modulation

Transceiver Architecture

- Transmitter



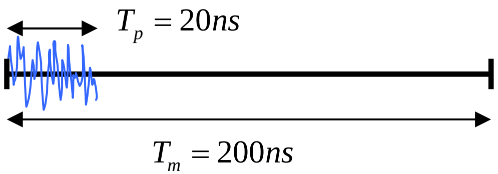
- Receiver



MC-PPM Modulation

PHY-SAP Data Rates

- Flexible data rates can be supported according to several design parameter (Tm, L, Ns, Nr, Tg)

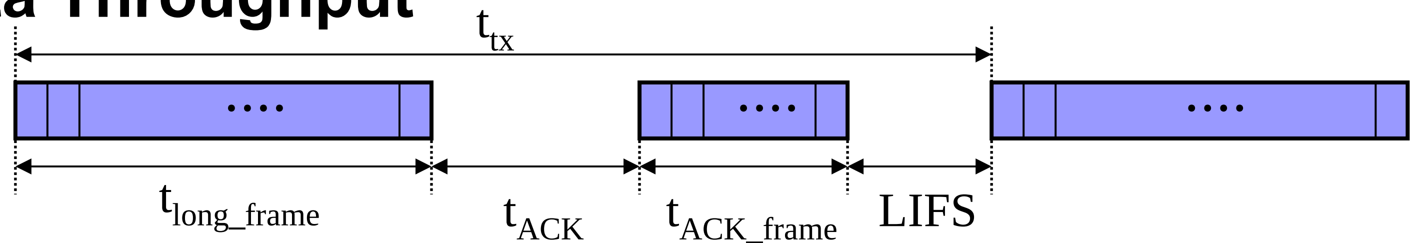


Tp	Tm	L	Ns	Nr	Tg	Data Rate
20ns	200ns	1	16	128	0ns	1.190 kbps
20ns	200ns	3	16	1	0ns	228 kbps
20ns	200ns	3	8	1	0ns	457 kbps
20ns	200ns	1	1	1	0ns	2.44 Mbps

MC-PPM Modulation

Data Throughput

- Data Throughput



- Transmission time (ttx) & Data throughput (Rth)
  - For L=3, Ns=8, Nr=1,Tg=0ns (457kbps)
    - ttx = tlong_frame + tACK + tACK_frame + LIFS
      = 614.4 u + 25.6 u + 187.7 u + 85.3 u = 913 u
    - Rth = 32×8 / 913u ≈ 280.3 kbps
      (Nominal throughput based on 32 bytes payload)
  - For L=3, Ns=16, Nr=1,Tg=0ns (228kbps)
    - ttx = tlong_frame + tACK + tACK_frame + LIFS
      = 1228.8 u + 51.2 u + 375.5 u + 170.7 u = 1826.2 u
    - Rth = 32×8 / 1826.2 u ≈ 140.2 kbps
      (Nominal throughput based on 32 bytes payload)

MC-PPM Modulation

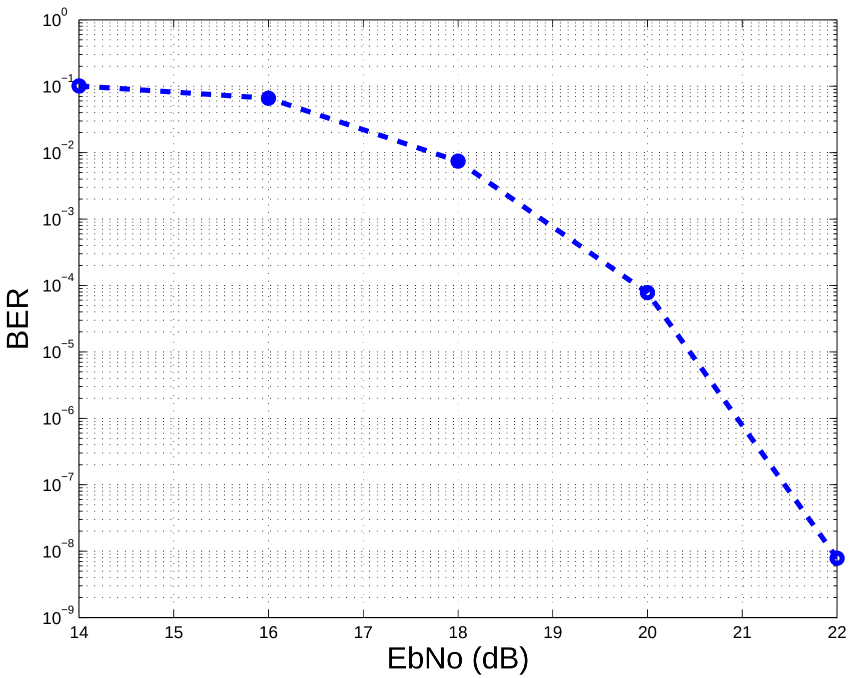
Signal Acquisition

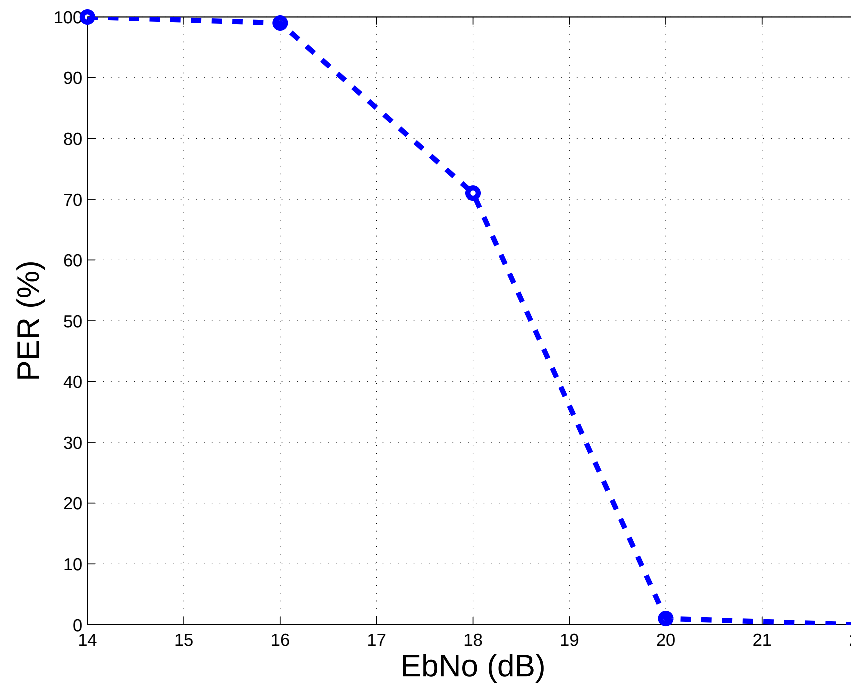
- Energy detection based acquisition
- Acquisition should be performed in order to make synchronization and demodulate data
- Synchronization : Non-coherent

MC-PPM Modulation

Performance

- **MC-PPM Performance : AWGN**
  - BER & PER
    - L=3, Ns=8, Nr=1 (457 kbps PHY-SAP data rate)

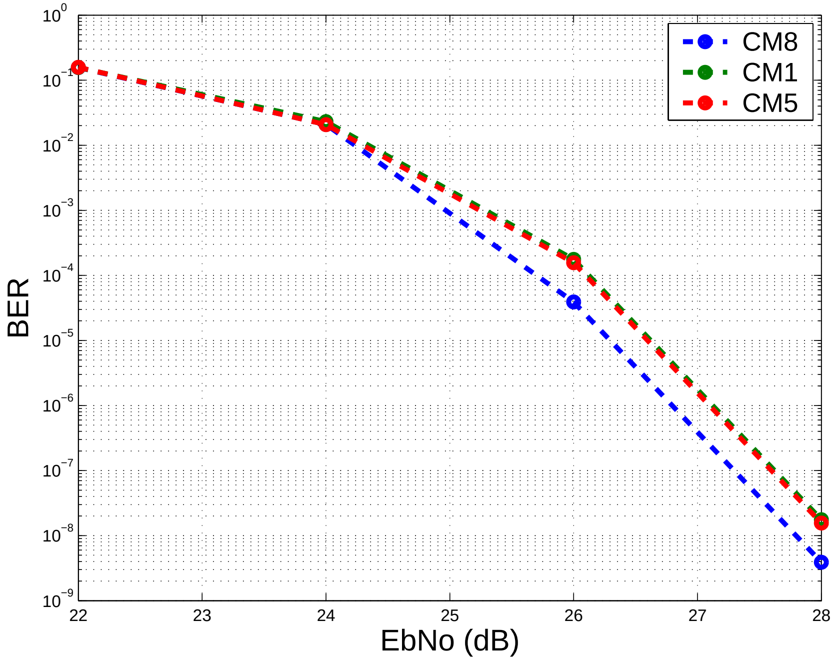


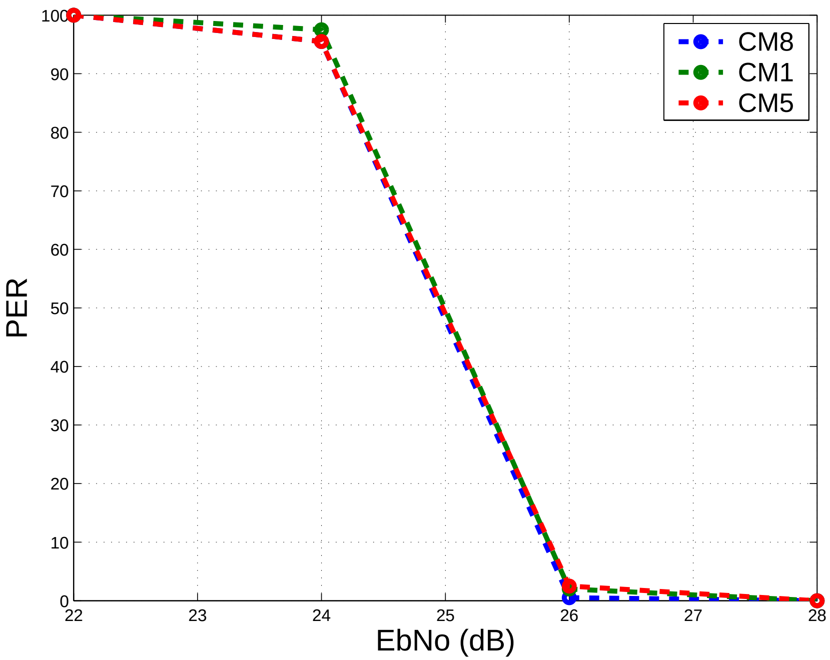


MC-PPM Modulation

Performance

- **MC-PPM Performance : 4a Channel Models**
  - BER & PER
    - – L=3, Ns=8, Nr=1

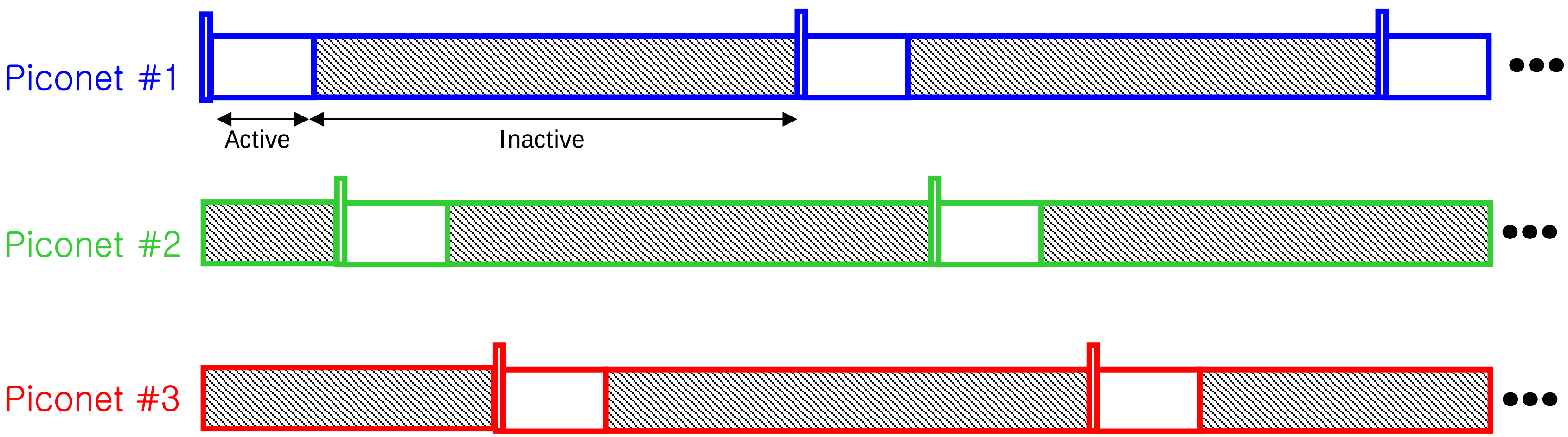




MC-PPM Modulation

SOPs

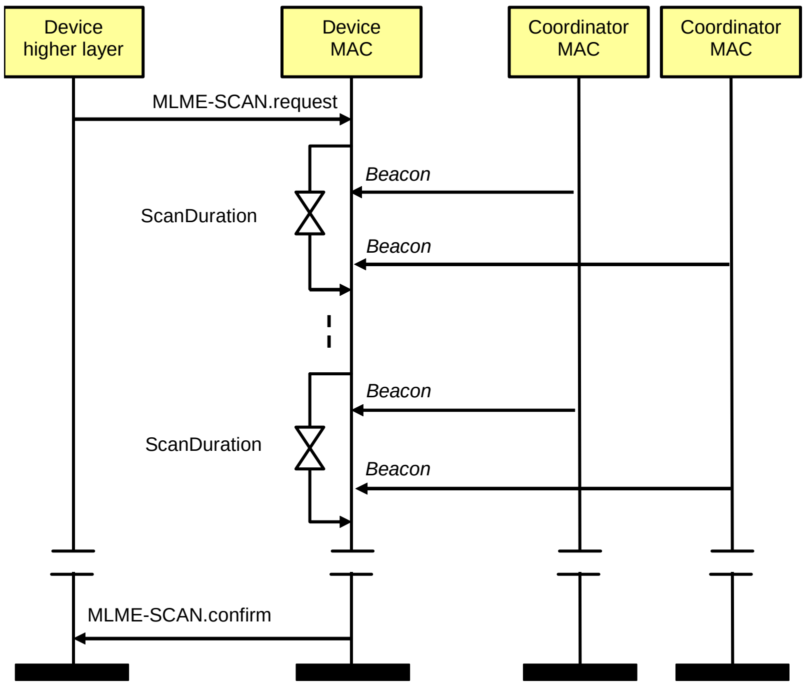
- **Time Division**
  - Configuration of SOPs
    - – Self configuration of SOPs is possible



MC-PPM Modulation

SOPs

- **Self Configuration of SOP**
  - Passive Scan
    - – Repeat scanning one channel
    - – Usage
      - – Starting a new piconet (FFD)
      - – Association (FFD or RFD)



MC-PPM Modulation

Link Budget & Sensitivity

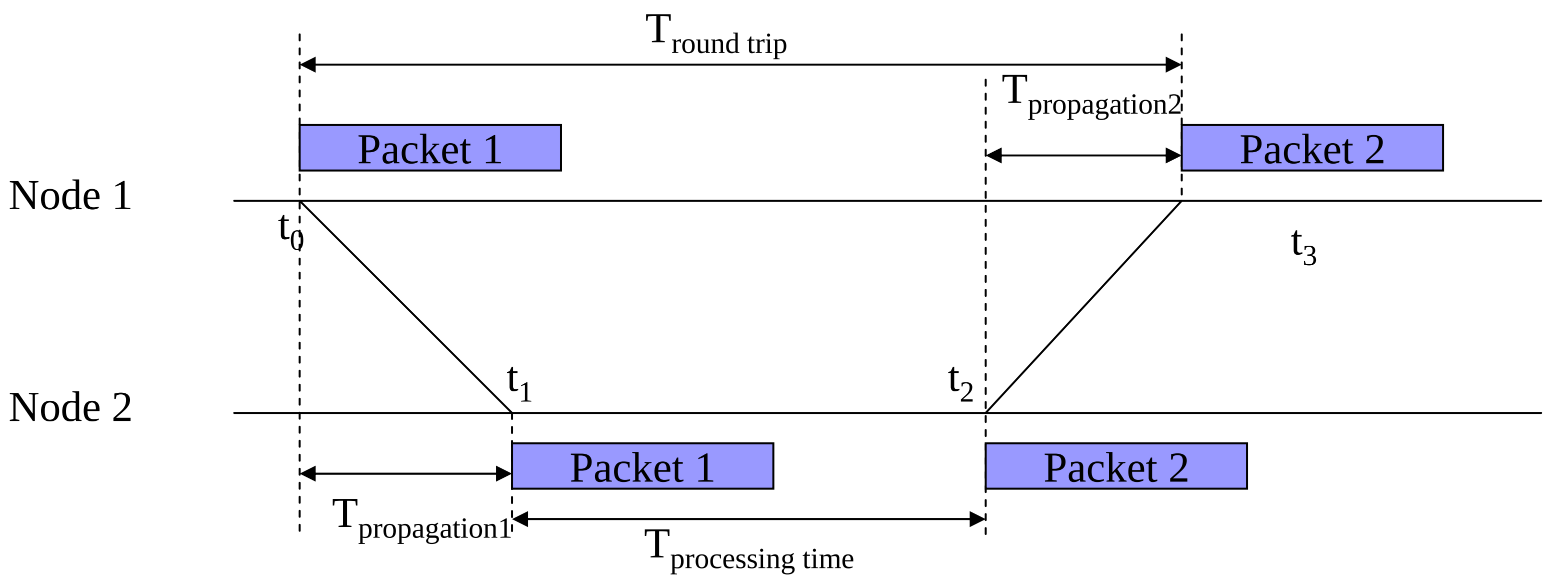
- **Link Budget & Sensitivity based on MC-PPM**

Parameter	(mandatory) Value at d=30m	(mandatory) Value at d=10m
peak payload bit rate	**(457kb/s) [L=3,Ns=8,Nr=1]**	**(457kb/s) [L=3,Ns=8,Nr=1]**
Average Tx power	**-8.75 (dBm)**	**-8.75 (dBm)**
Tx antenna gain	**0 (dBi)**	**0 (dBi)**
geometric center frequency of waveform	**3.90 (GHz)**	**3.90 (GHz)**
Path loss at 1 meter	**44.5dB**	**44.5dB**
Path loss at *d* m	**29.54 dB at *d* =30m**	**20 dB at *d* =10m**
Rx antenna gain	**0 (dBi)**	**0 (dBi)**
Rx power	**-82.55 (dBm)**	**-73.01 (dBm)**
Average noise power per bit	**-117.4 (dBm)**	**-117.4 (dBm)**
Rx Noise Figure	**7 (dB)**	**7 (dB)**
Average noise power per bit	**-110.4(dBm)**	**-110.4(dBm)**
Minimum Eb/N0 (*S*) [Ep/N0]	**20 (dB)**	**20 (dB)**
Implementation Loss (I)	**5 (dB)**	**5 (dB)**
Link Margin	**2.85(dB)**	**12.39(dB)**
Proposed Min. Rx Sensitivity Level	**-85.4(dBm)**	**-85.4(dBm)**

MC-PPM Modulation

Ranging

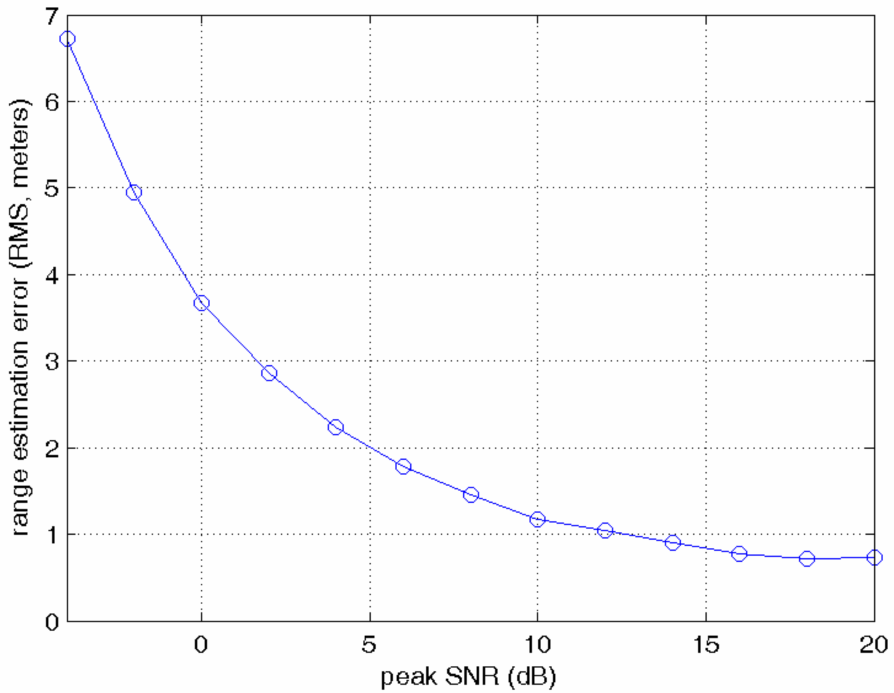
- **Scheme**
  - TOA/TWR -> Measurement of Roundtrip time



MC-PPM Modulation

Ranging

- **Performance**



802.15.4a channel (cm4)

Single user

No narrowband interference

Pulse width = 20ns

Integration time = 2ns

Pulse repetition period = 200ns

Length of search region = 40ns

Threshold level was determined relative to noise floor

A separate envelope detector for range estimation was employed