

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

**Submission Title:** [Merged Proposal of Chaotic UWB System for 802.15.4a]

**Date Submitted:** [March 7, 2005]

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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.]

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## Chaotic UWB System

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**Compatible Modulation Scheme: DCSK**

**Compatible Modulation Scheme: MC-PPM**

# 1. INTRODUCTION

## Features of Proposed System

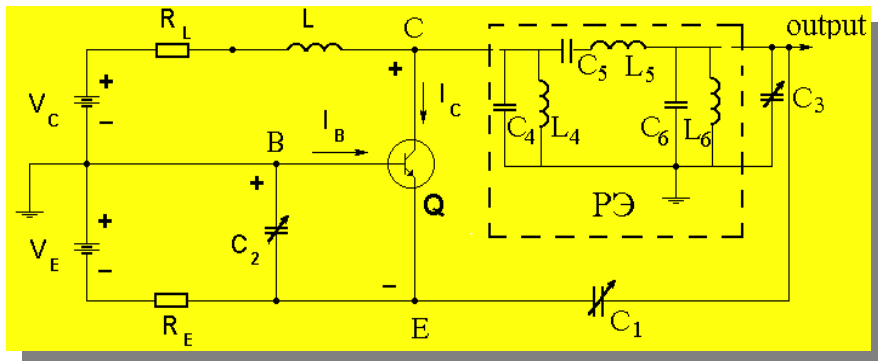
- **Low Hardware Complexity / Low Cost**
  - Chaotic signal can be generated directly into the desired microwave band (Simple RF circuit)
- **Efficient Power Management**
  - Sleep / Wake-up capability can save the battery life time
- **Robust in Multipath**
  - In case of OOK Modulation, BER performance against multipath is close to the AWGN (only few dB difference)
- **Flexible Pulse Length**
  - Chaotic radio pulse can be transmitted with different pulse time duration regardless of the spectral bandwidth

## 2. CHAOTIC COMMUNICATION SYSTEM

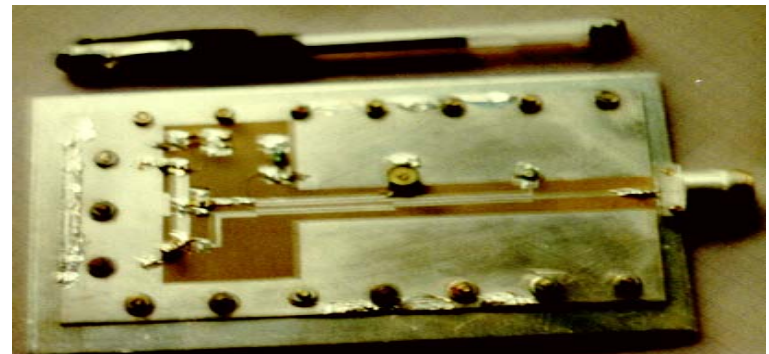
### Chaotic Source

- Chaotic source generates oscillations directly in a specified microwave band.
- Information component is put into the chaotic carrier to form a stream of chaotic radio pulses.
- Information can be retrieved from the chaotic radio pulses without intermediate heterodyning.

Chaotic Source Generator Circuit



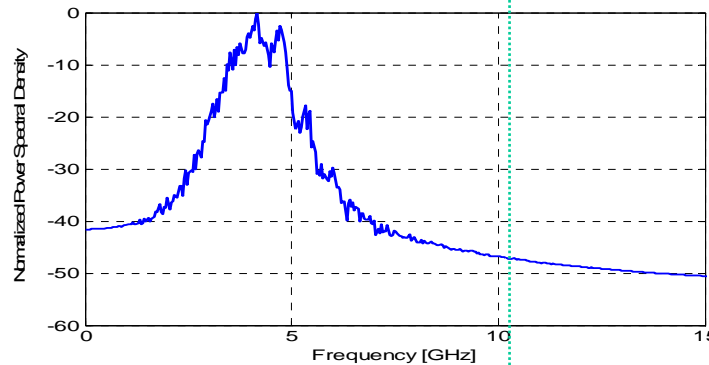
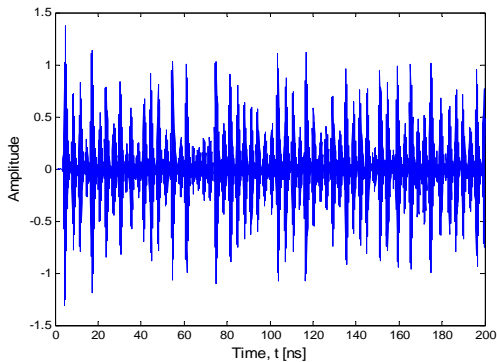
Experiment device



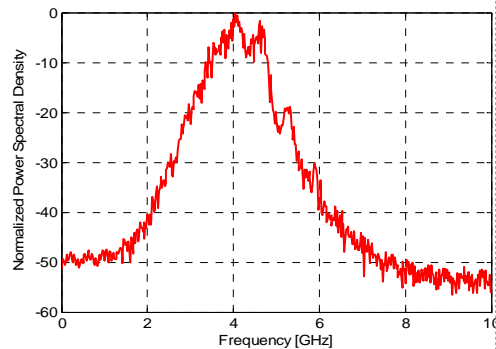
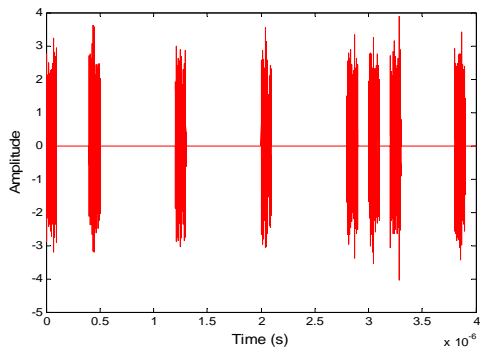
# 2. CHAOTIC COMMUNICATION SYSTEM

## 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 (main modulation type)

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

#### ■ DCSK (compatible modulation type)

#### ■ PPM (compatible modulation type)

# 3.1. Unit Manufacturing Cost/Complexity

## Complexity (OOK)

- **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 2.002 MHz (for ranging)
  - **Digital part with ~ 10K gates**



## 3.4. Technical Feasibility

### Prototype 1

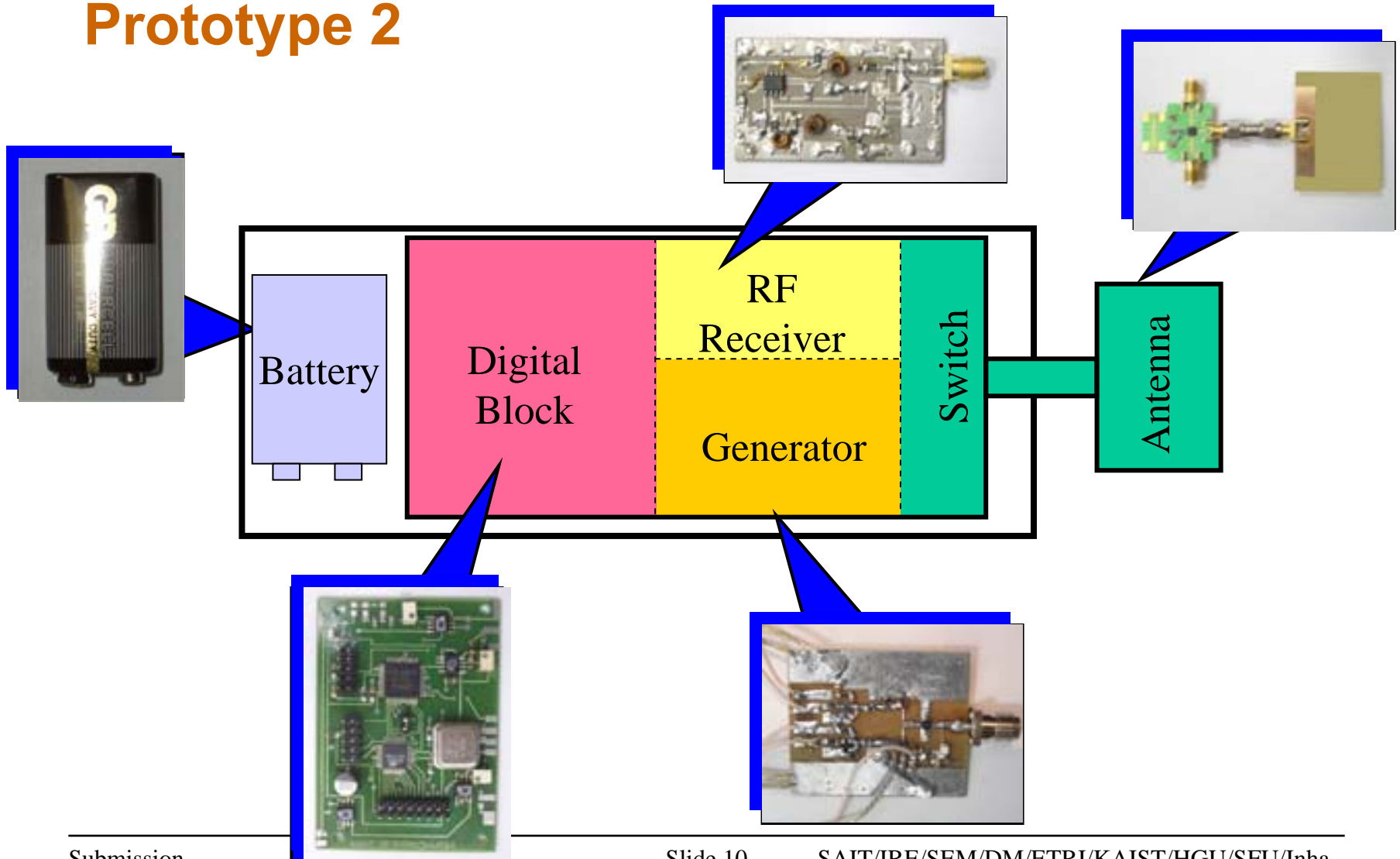
- The communication test has successfully done using Chaotic pulses

#### UWB DCC-OOK Test-bed



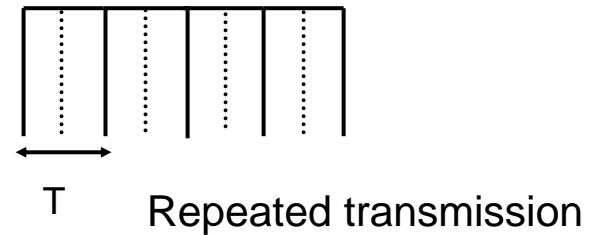
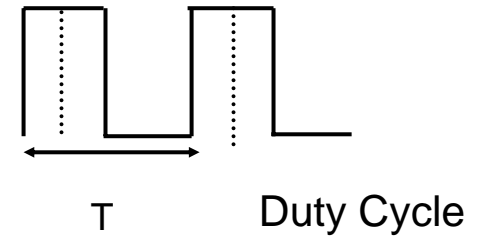
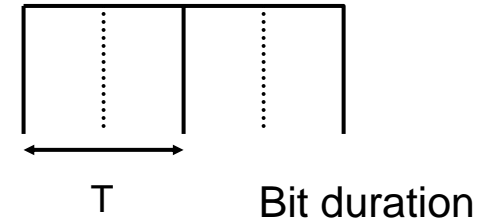
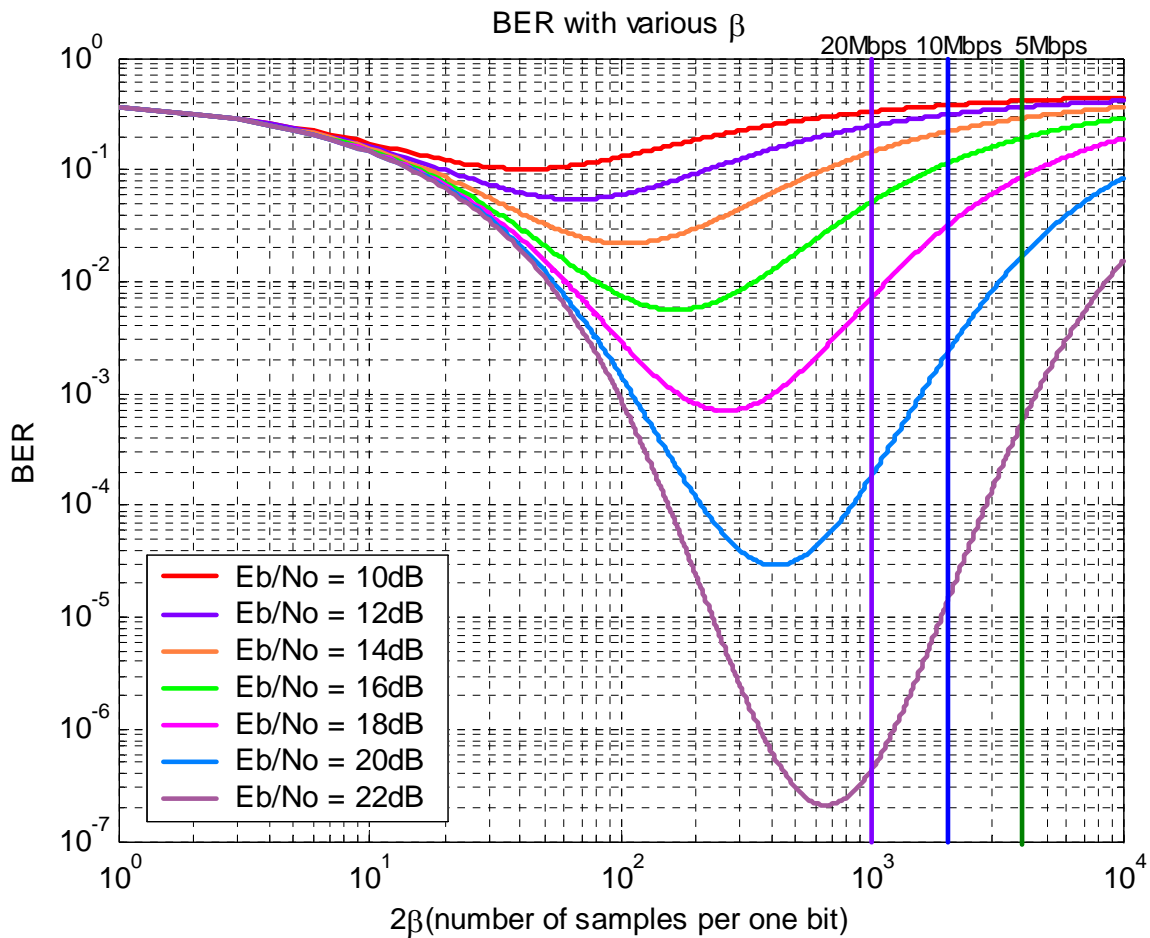
# 3.4. Technical Feasibility

## Prototype 2



# 3.5. Scalability

## Chaotic Pulse Duration



## 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

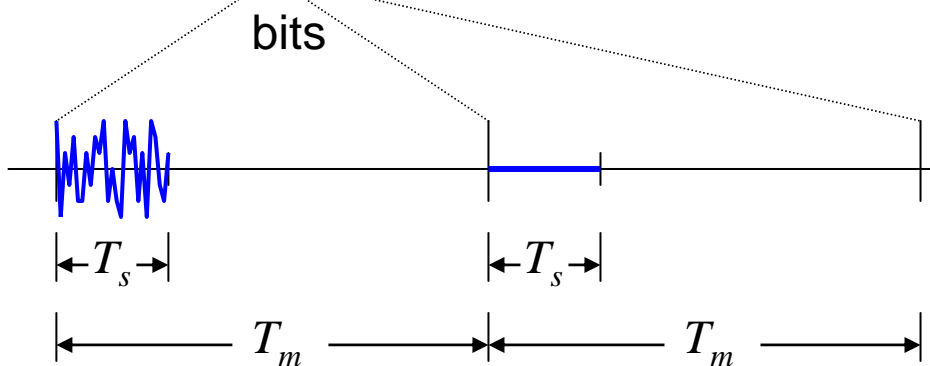
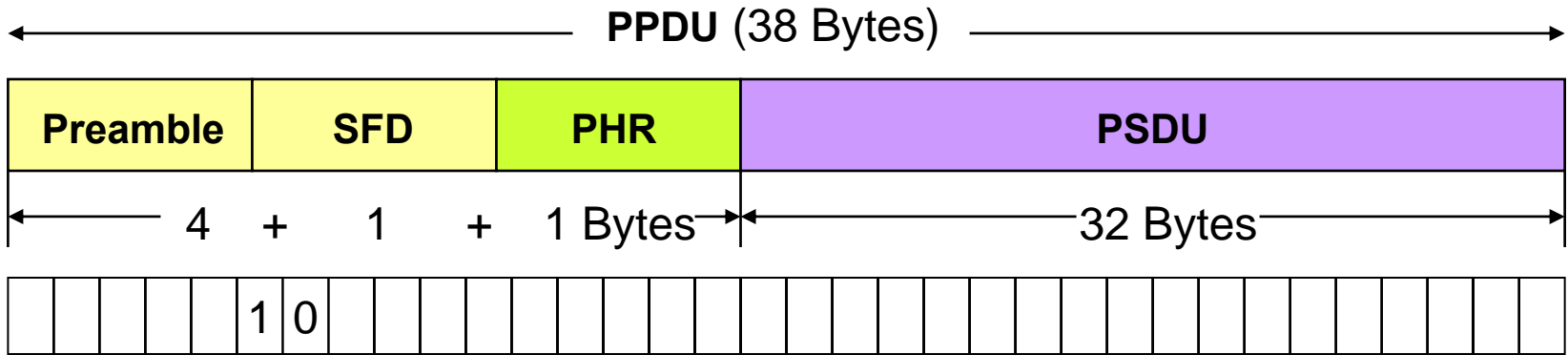
### Values

#### ■ PHY-level (130 nm technology)

- RF part of transceiver => 0.3 mm<sup>2</sup>
- Analog part of transceiver PHY-level baseband => 0.2 mm<sup>2</sup>
- Digital part of transceiver PHY-level baseband => 0.3 mm<sup>2</sup>
- Common layout square for PHY-level => 1.0 mm<sup>2</sup>
- Antenna: 2.0 x 2.0 cm<sup>2</sup>

# 5.3. PHY-SAP Payload Bit Rate / Throughput

## Payload Bit Rate



$T_s = 100 \text{ ns}$  : Pulse emission time  
 $T_m = 400 \text{ ns}$  : Pulse bin width or Bit period  
 $\therefore$  Duty cycle,  $D = 1/4$

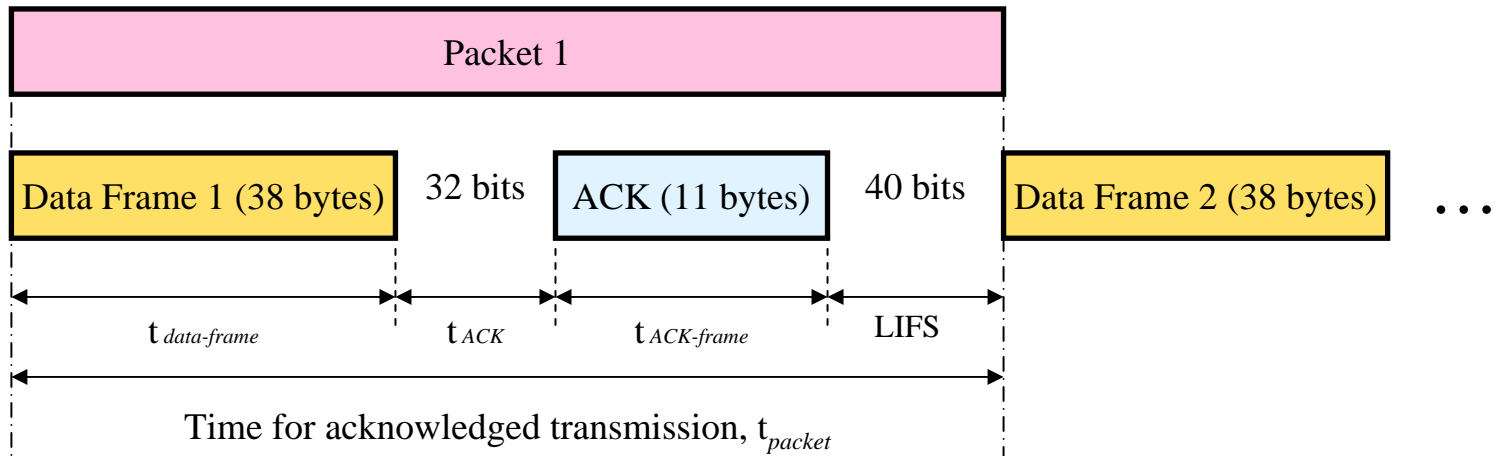
$T_s = 100 \text{ ns}$  : Pulse emission time  
 $T_m = 600 \text{ ns}$  : Pulse bin width or Bit period  
 $\therefore$  Duty cycle,  $D = 1/6$

**Nominal PHY-SAP payload bit rate,  $X_0 = (1/400\text{ns}) \times (1000/1024) = 2.44\text{Mbps}$**

**Optional PHY-SAP payload bit rate,  $X_i = (1/600\text{ns}) \times (1000/1024) = 1.63\text{Mbps}$**

# 5.3. PHY-SAP Payload Bit Rate / Throughput

## Throughput



$$\begin{aligned}
 t_{packet} &= t_{data-frame} + t_{ACK} + t_{ACK-frame} + LIFS \\
 &= (38 \times 8 \times 400ns) + (32 \times 400ns) + (11 \times 8 \times 400ns) + (40 \times 400ns) \\
 &= 121.6\mu s + 12.8\mu s + 35.2\mu s + 16\mu s = 185.6\mu s
 \end{aligned}$$

$$\begin{aligned}
 t_{packet} &= t_{data-frame} + t_{ACK} + t_{ACK-frame} + LIFS \\
 &= (38 \times 8 \times 600ns) + (32 \times 600ns) + (11 \times 8 \times 600ns) + (40 \times 600ns) \\
 &= 182.4\mu s + 19.2\mu s + 52.8\mu s + 24\mu s = 278.4\mu s
 \end{aligned}$$

**Nominal Data Throughput,  $T_0 = (32 \times 8 / 185.6\mu s) \times (1000 / 1024) = 1.35Mbps$**

**Optional Data Throughput,  $T_i = (32 \times 8 / 278.4\mu s) \times (1000 / 1024) = 898kbps$**

## 5.4. Simultaneously Operating Piconets

### Three Methods to Achieve SOP

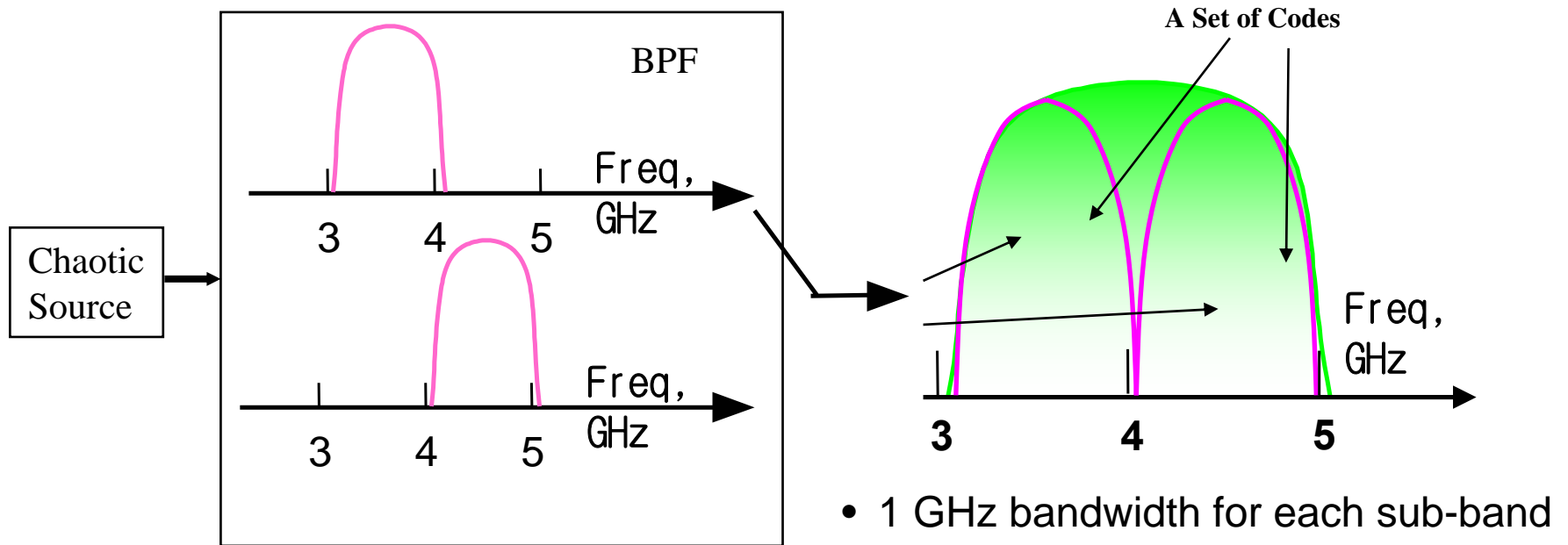
- **Frequency division multiplexing (FDM)**
  - Four independent frequency channels on 500 MHz guaranties simultaneously operating four piconets.
- **Code division multiplexing (CDM)**
  - Deployed a class of unipolar codes (0,1) having ZCD/LCD property maintain orthogonality among piconets.
  - Four 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
  - Ex: Only two codes are required to support four SOPs



# 5.4. Simultaneously Operating Piconets

## Combination of FDM and CDM (FCDM)

- 2 sub-bands and a set of codes for each sub-bands => at least 4 SOPs



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

#### ■ CDM for SOP can be achieved using Unipolar ZCD/LCD Code in chaotic-OOK modulation

- ZCD(Zero Correlation Duration): Local time duration with zero autocorrelation function sidelobe & zero cross-correlation function
- LCD(Low Correlation Duration): Local time duration with low zero autocorrelation function sidelobe & low cross-correlation function

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

#### ■ Characteristics of combined schemes

- Simple circuit with noncoherent envelope detector
- Novel Inter/Intra Piconet Interference immunity for an efficient SOP

## 5.4. Simultaneously Operating Piconets

### Example of Unipolar ZCD Codes Type

#### ■ 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]

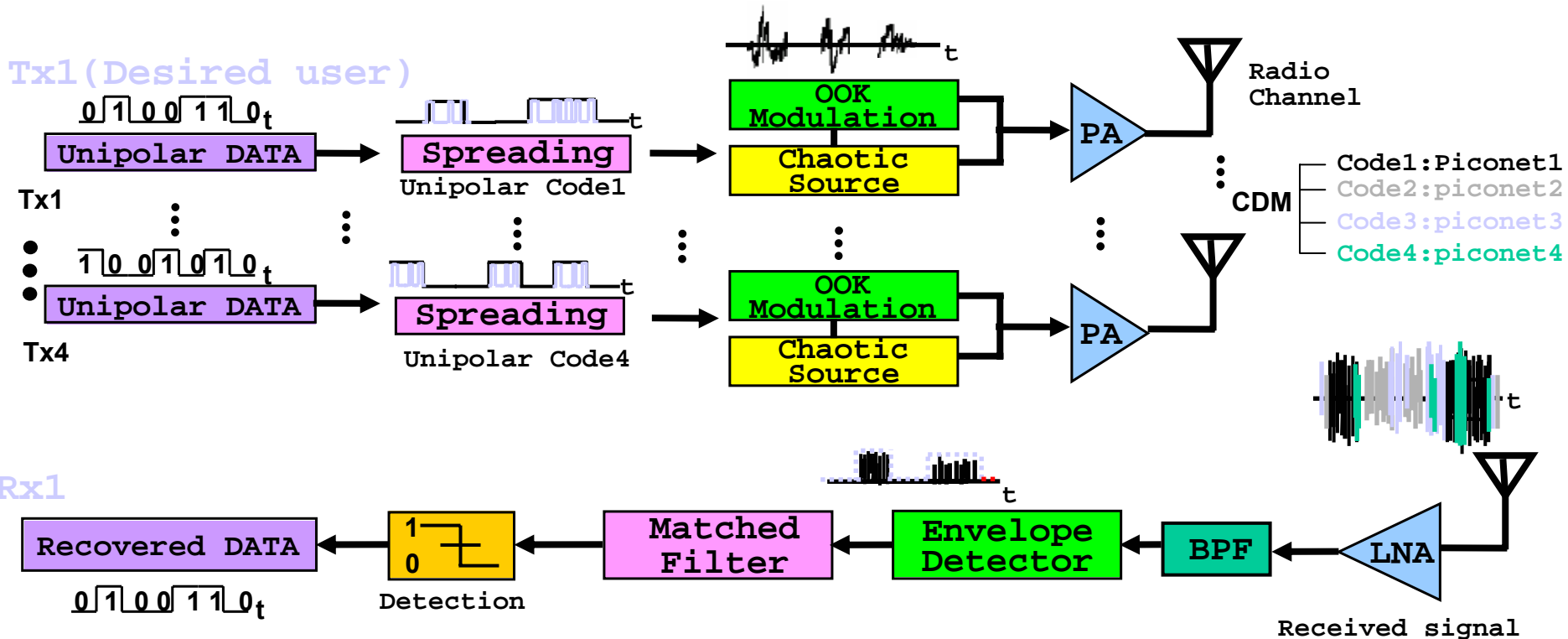
code c=[0 0 1 0 1 0]

#### ■ Where $(N, W, A, C)$ is

- $N$  = sequence period,
- $W$  = number of nonzero elements,
- $A$  = ACF sidelobe in ZCD/LCD,
- $C$  = CCF value in ZCD/LCD
- $M$  = family size, Truncation of  $N/M = W$

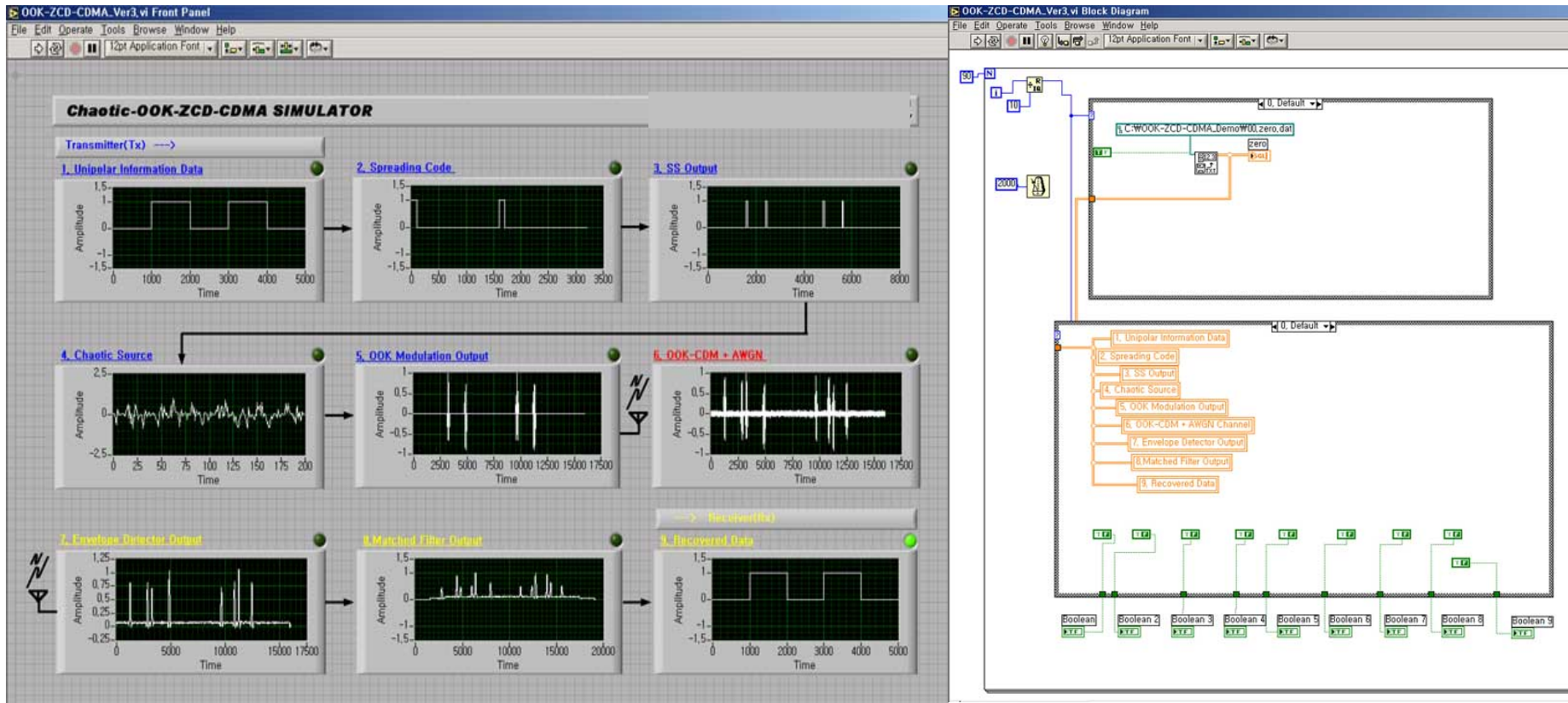
# 5.4. Simultaneously Operating Piconets

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



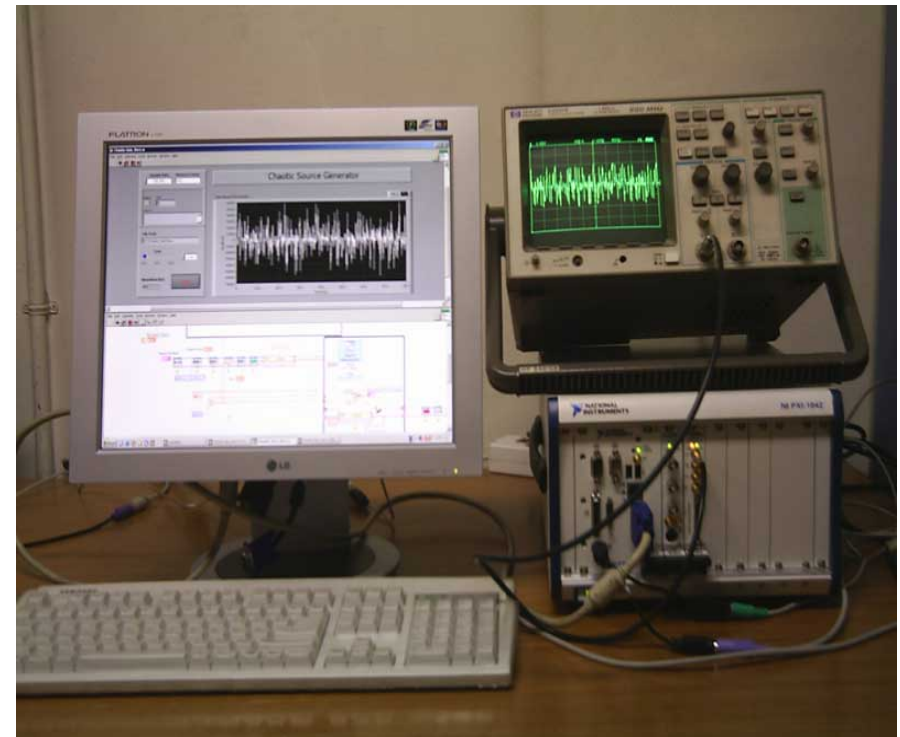
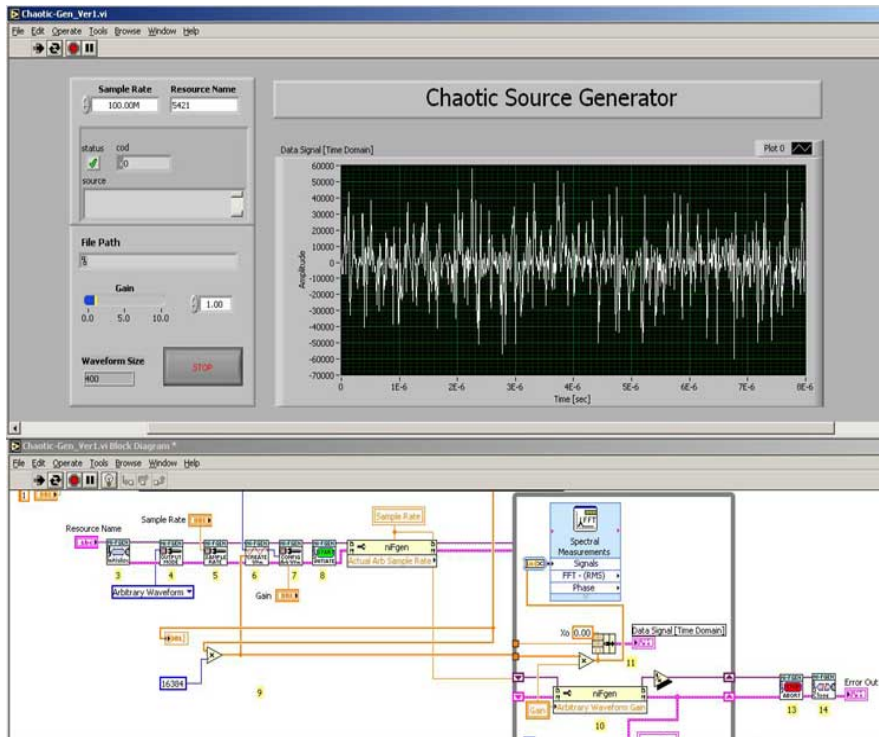
# 5.4. Simultaneously Operating Piconets

## Baseband Chaotic-OOK- ZCD-CDM



# 5.4. Simultaneously Operating Piconets

## Chaotic-OOK-ZCD-CDM



# 5.6. System Performance

## AWGN & Multipath

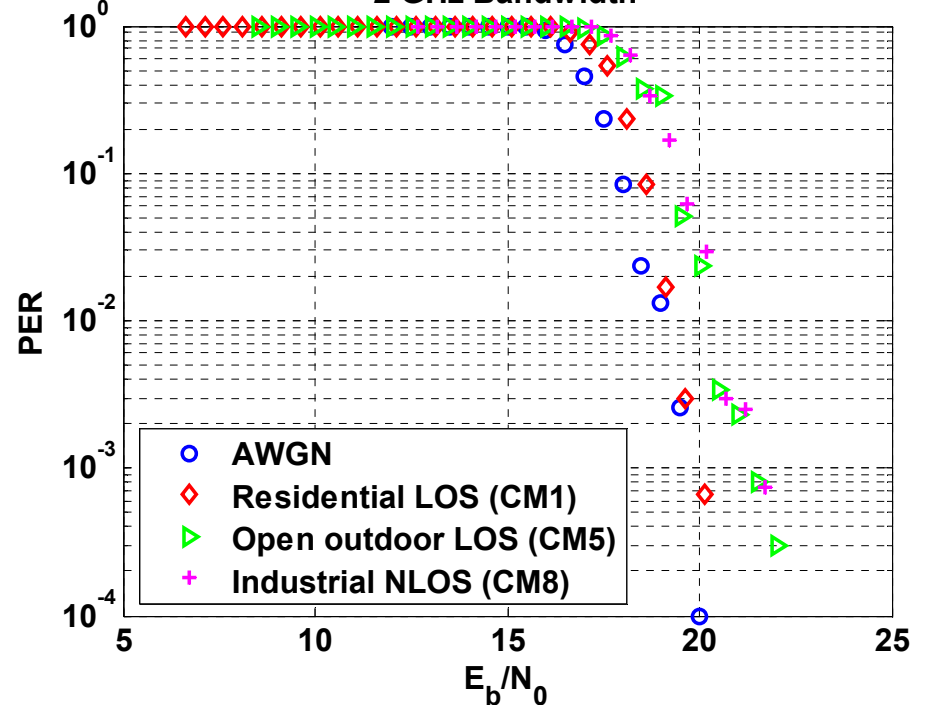
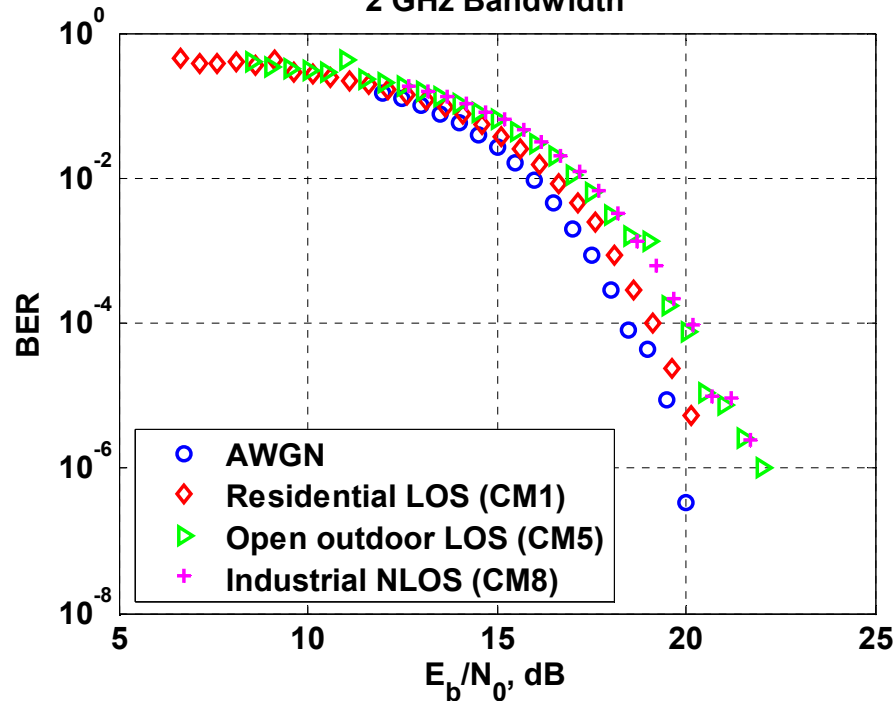
### ■ BER Vs. Eb/No

## AWGN & Multipath

### ■ PER Vs. Eb/No

2 GHz Bandwidth

2 GHz Bandwidth



**Modulation:** OOK, **Bandwidth:** 2GHz, **Pulse width:**  $T_m=400\text{ns}$ ,  
**Pulse emission time:**  $T_s = 100\text{ns}$ , **PSDU length:** 32 bytes

## 5.6. System Performance

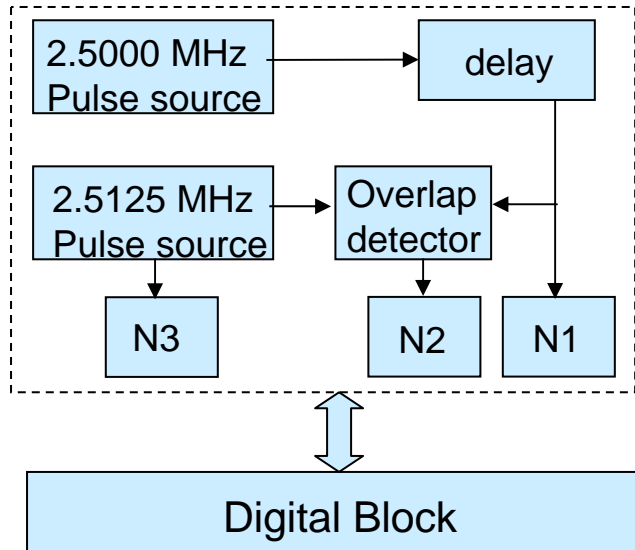
### Values: Bit Rate and Distance

<b>X<sub>o</sub></b> <b>(Mbps)</b>	<b>Channel</b>	<b>M+L1+L2 (free space), dB</b>	<b>PL, dB</b>	<b>PL<sub>0</sub>, dB</b>	<b>n</b>	<b>Distance, m</b>
<b>2.44</b>	<b>AWGN</b>	<b>76.27</b>	<b>76.27</b>	<b>44.43</b>	<b>2</b>	<b>39</b>
<b>1.63</b>	<b>AWGN</b>	<b>78.07</b>	<b>78.07</b>	<b>44.43</b>	<b>2</b>	<b>48</b>
<b>0.4075</b>	<b>AWGN</b>	<b>84.07</b>	<b>84.07</b>	<b>44.43</b>	<b>2</b>	<b>96</b>

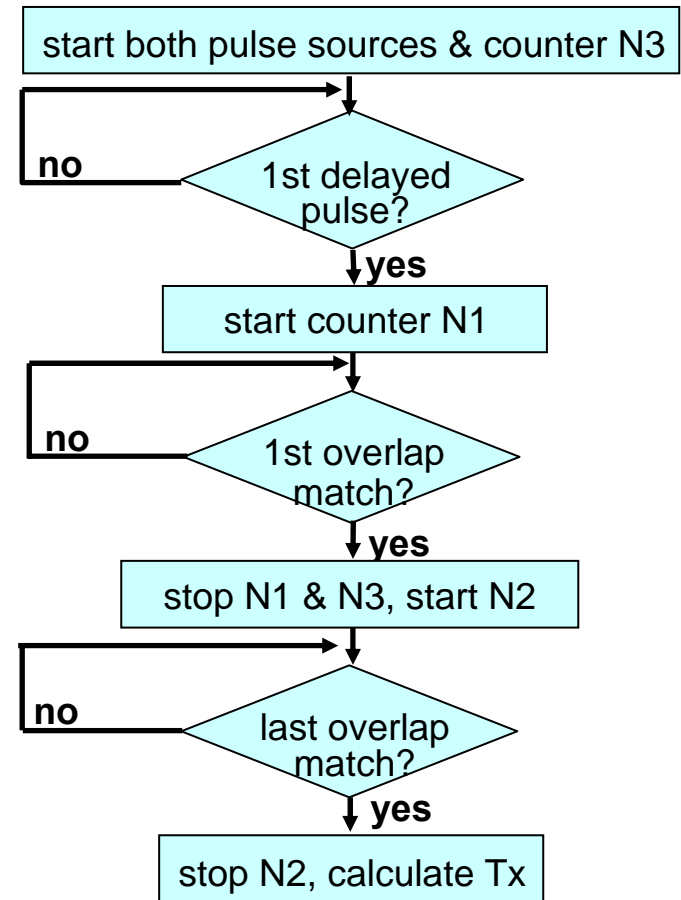


# 5.7. Ranging

## Ranging Algorithm

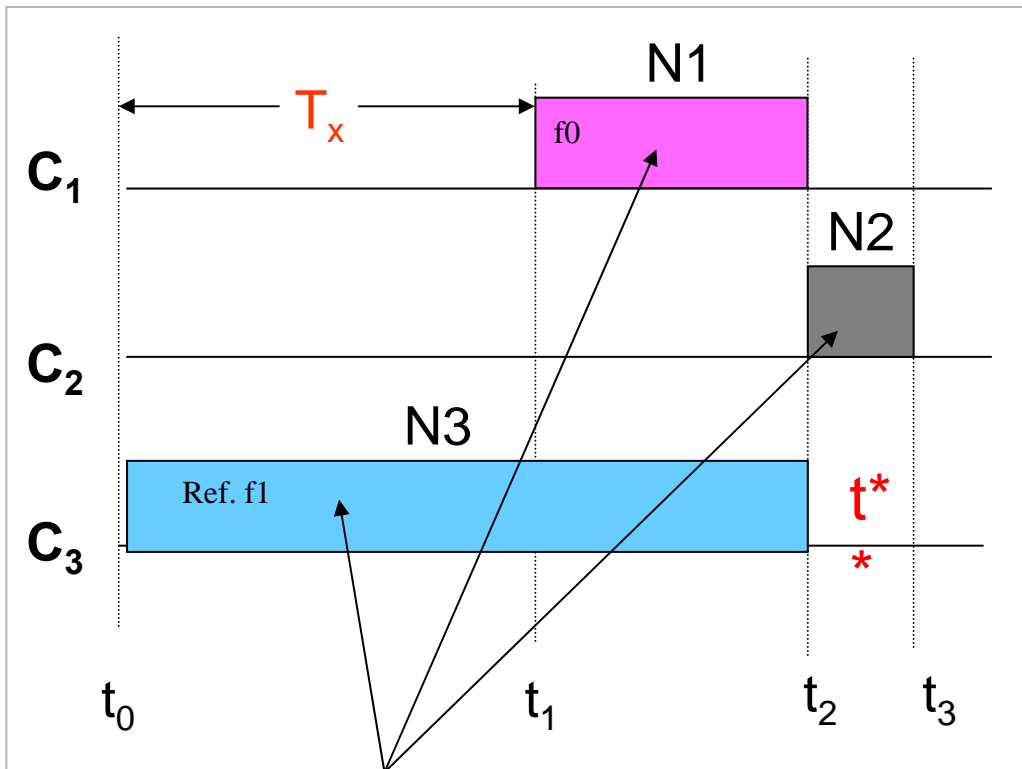


- Counter **N1** counts delayed pulses
- Counter **N2** counts overlaps between delayed pulses(2.5000 MHz) and reference pulses(2.5125 MHz)
- Counter **N3** counts reference pulses



# 5.7. Ranging

## Operation of Counters



**N1, N2, N3** – pulse numbers

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

**distance**

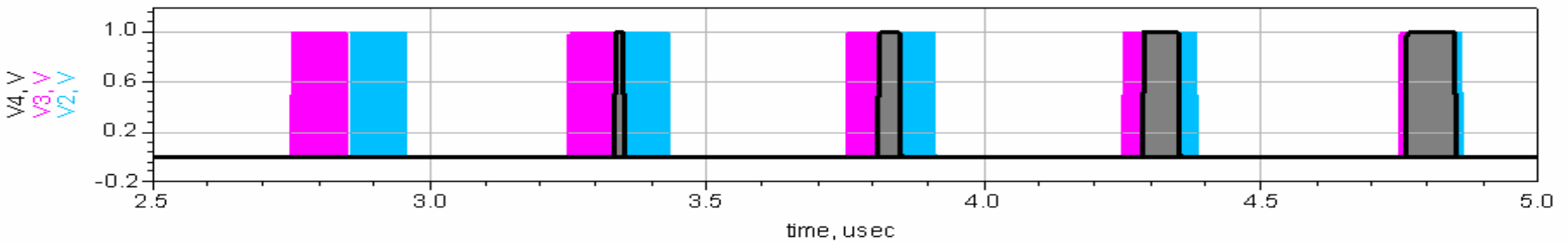
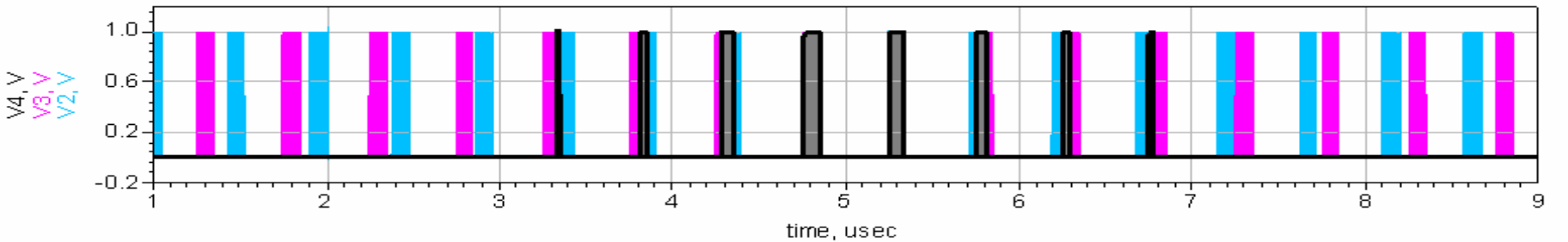
$$S = 0.5 * c * (T_x - \tau_0)$$

$\tau_0$  – retranslation time

Operation time of counters **C<sub>1</sub>, C<sub>2</sub>, C<sub>3</sub>**.

# 5.7. Ranging

## Overlapping of Delayed & Reference Pulses



- Delayed pulse
- Reference pulse
- Pulse overlap

## 5.7. Ranging

### Values: Range

System supports ranges:

- Range from 0 to 30 m (typical)
- Range up to 100 m (max 10 kbps data rate)

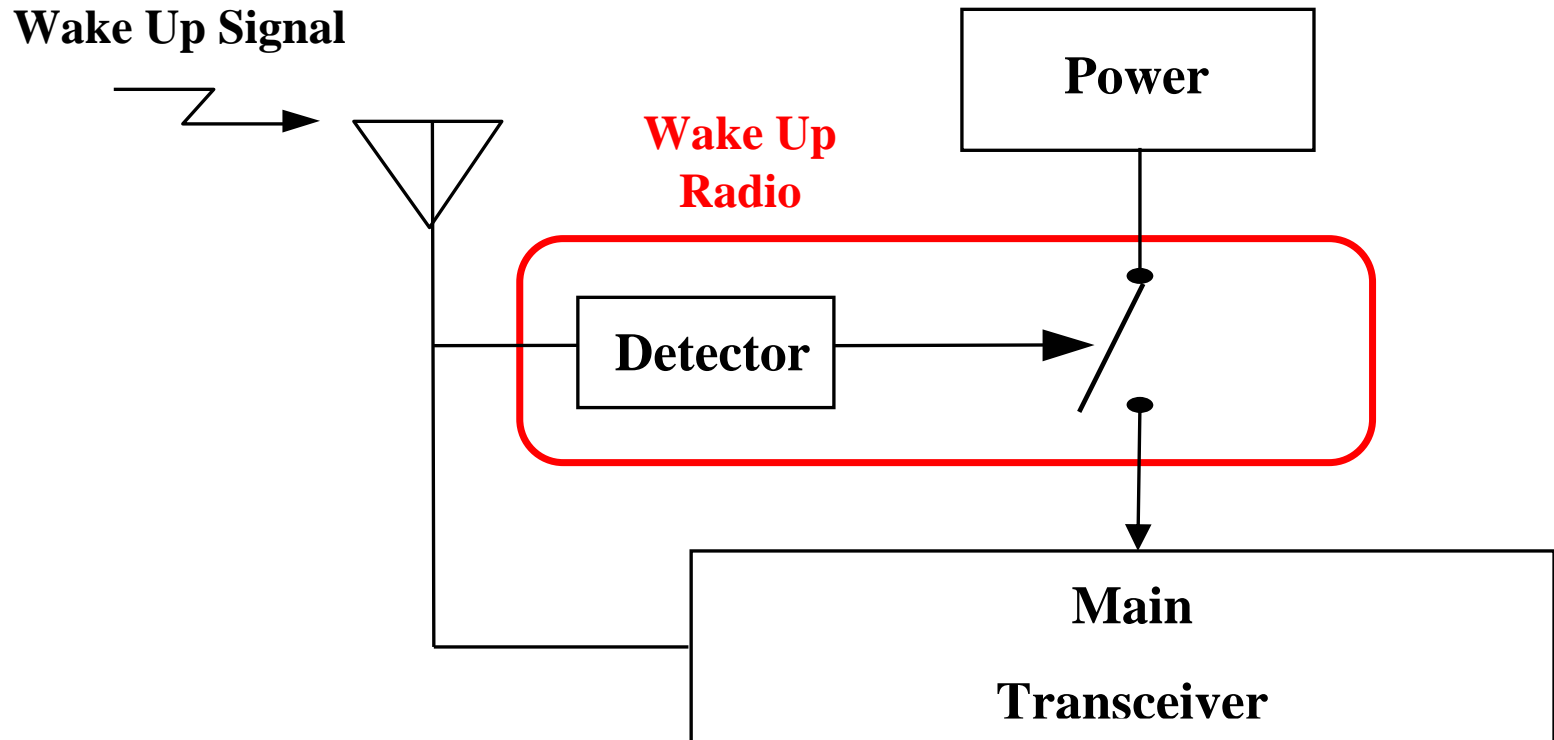
# 5.8. Link Budget

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 <sup>1</sup>	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 <sup>1</sup> ( $I$ )	3 dB	3 dB
Link Margin ( $M = P_R - P_N - S - I$ )	2.3 dB	4.1 dB
Proposed Min. Rx Sensitivity Level <sup>2</sup>	-86.1 dBm	-87.9 dBm

# 5.10. Power Management Modes

## Sleep and Wake-up Scheme

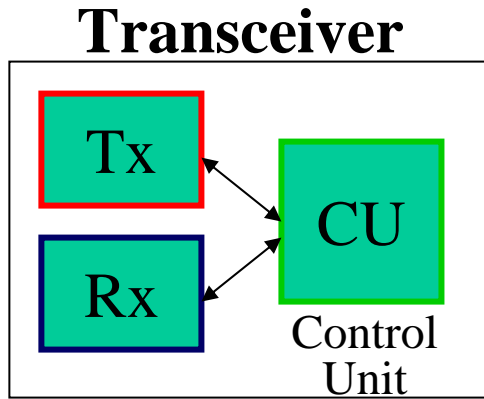
### Wake Up Structure



# 5.11. Power Consumption

## Power Calculation

Average power consumption  $P_{av}$



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

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

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

Operation time  $T_{oper}$

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

$P_e$  is emitted power,

$\eta$  is efficiency,

$\eta_{best}$  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 $P_{av}$ ( $\eta = 5\%$ )	Lifetime of the AAA battery, years
1	$2 \cdot 10^{-4}$	15.5 $\mu$ W	8.3 100% duty cycle
10	$2 \cdot 10^{-3}$	87.5 $\mu$ W	15 10% duty cycle
1000	$2 \cdot 10^{-1}$	8 mW	16.4 0.1% duty cycle

$$P_{CU} = 7.5 \mu\text{W}; \quad P_{in} = 4 \text{ mW}; \quad \eta_{best} = 5\%; \quad U_b = 1.5 \text{ V}; \quad C_b = 750 \text{ mAh}; \quad D = 1/4$$

**Example:**  $R = 1 \text{ kbps}; T_{bit} = 400 \text{ ns}; \eta = 5\%$

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

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



# 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 the feasibility of DCC technology.

# **DCSK: Compatible Modulation Scheme for Direct Chaotic Communication**

# DCSK Modulation

## DCSK

### ■ Differential Chaos Shift Keying (DCSK)

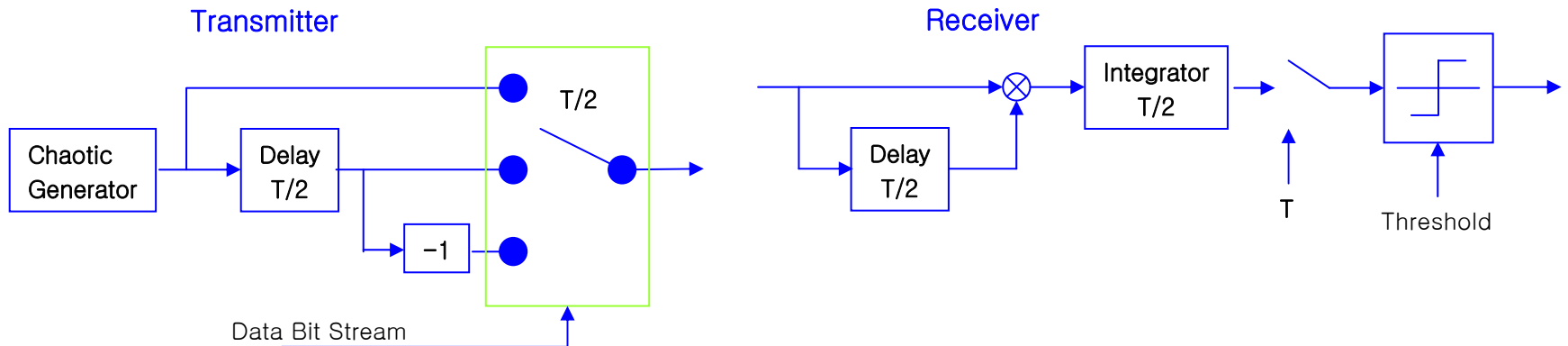
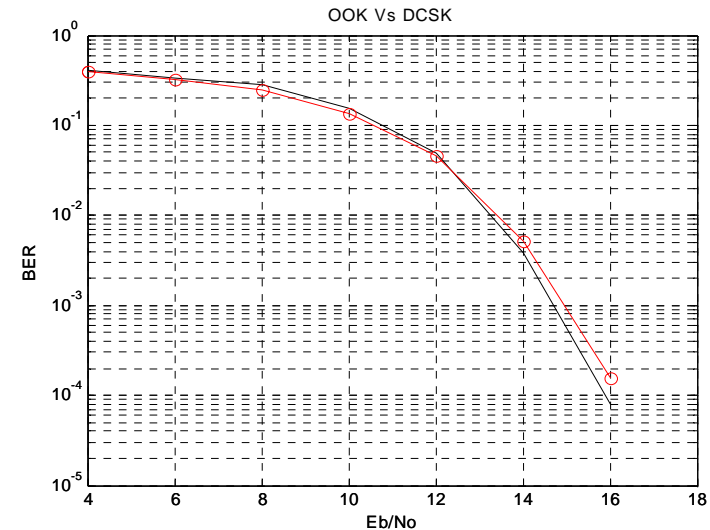
- One of the modulation scheme as an alternative to OOK
- DCSK transmits a reference chaotic pulse and an information data pulse depending on whether information bit 1 (same ref. chaotic pulse) or 0 (inverted of the chaotic pulse) is being transmitted
- The information signal can be recovered in the receiver by a correlator with a constant decision threshold
- The Chaotic properties are maintained as same as OOK
- Data rate is as same as OOK
- SOP can be achieved by transmitting Chaotic pulses with different length

# DCSK Modulation

## Principle

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

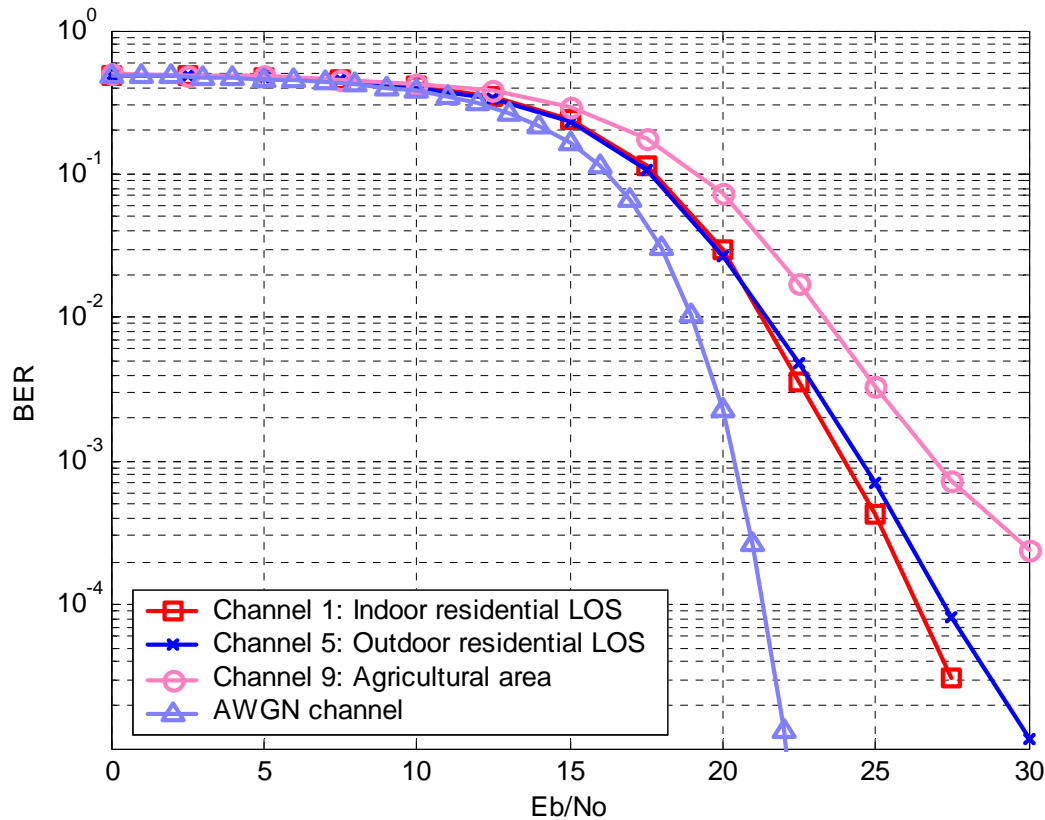
$$s(t) = \begin{cases} x(t), & t_i \leq t < t_i + T/2 \\ -x(t - T/2), & t_i + T/2 \leq t < t_i + T \end{cases}$$



# DCSK Modulation

## System Simulation Results

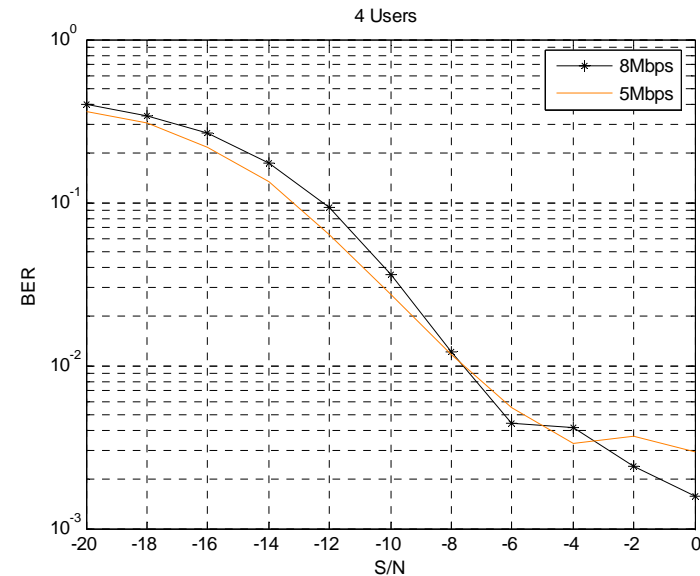
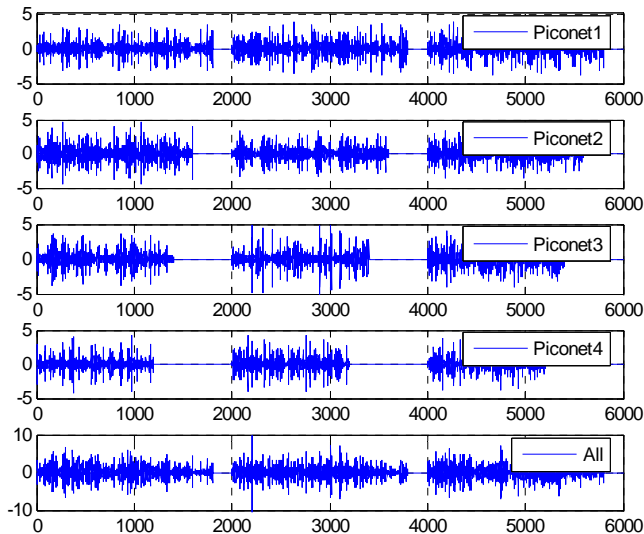
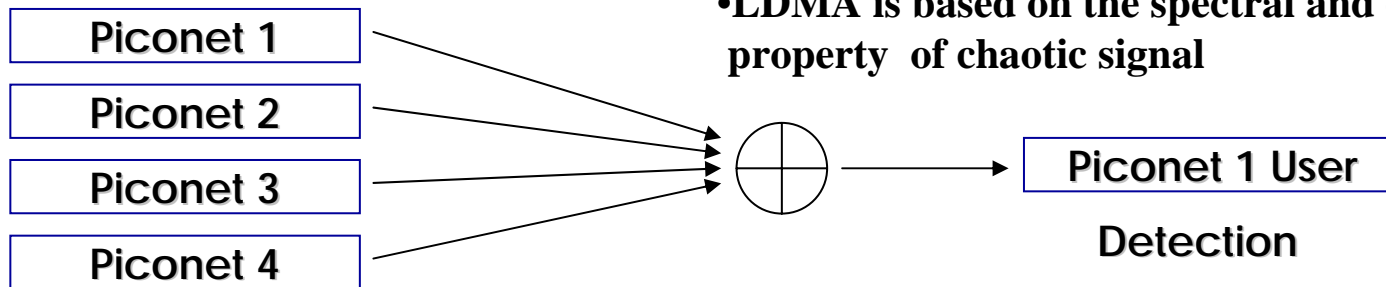
### ■ AWGN & Multipath



# 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

## Scalability

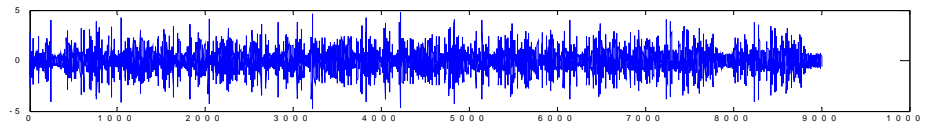
Scalability can be achieved using

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

Bit = 1                      0                      1

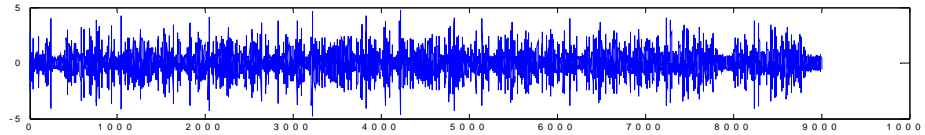
200 nsec

5 Mbps



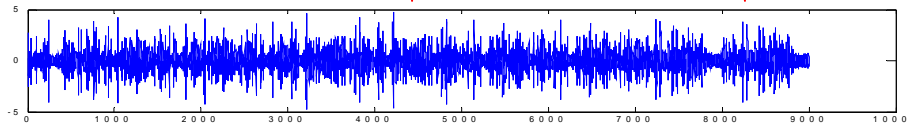
250 nsec

4 Mbps

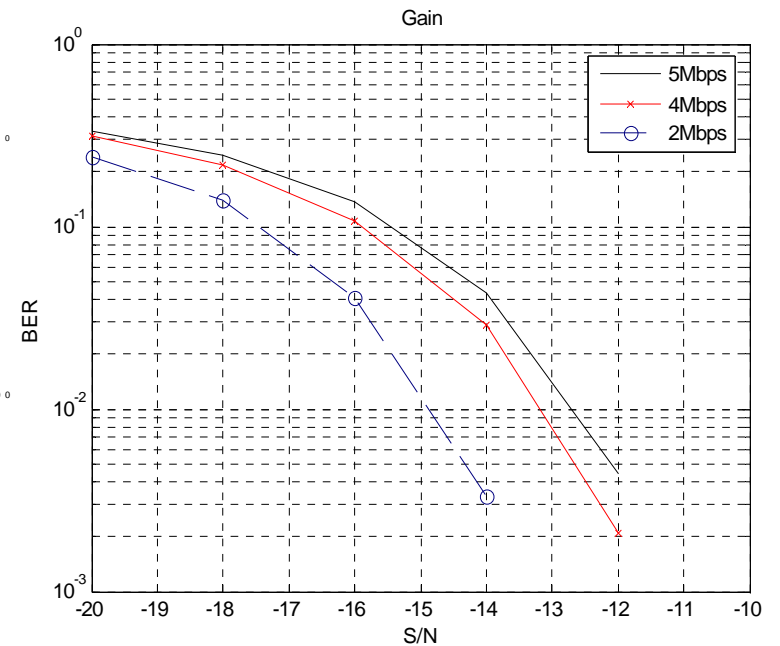


500 nsec

1 Mbps



## Chaotic Gain in DCSK



# MCS-DCSK Modulation

## Combination of MCSK TH-IR with DCSK

### ■ MCS-DCSK

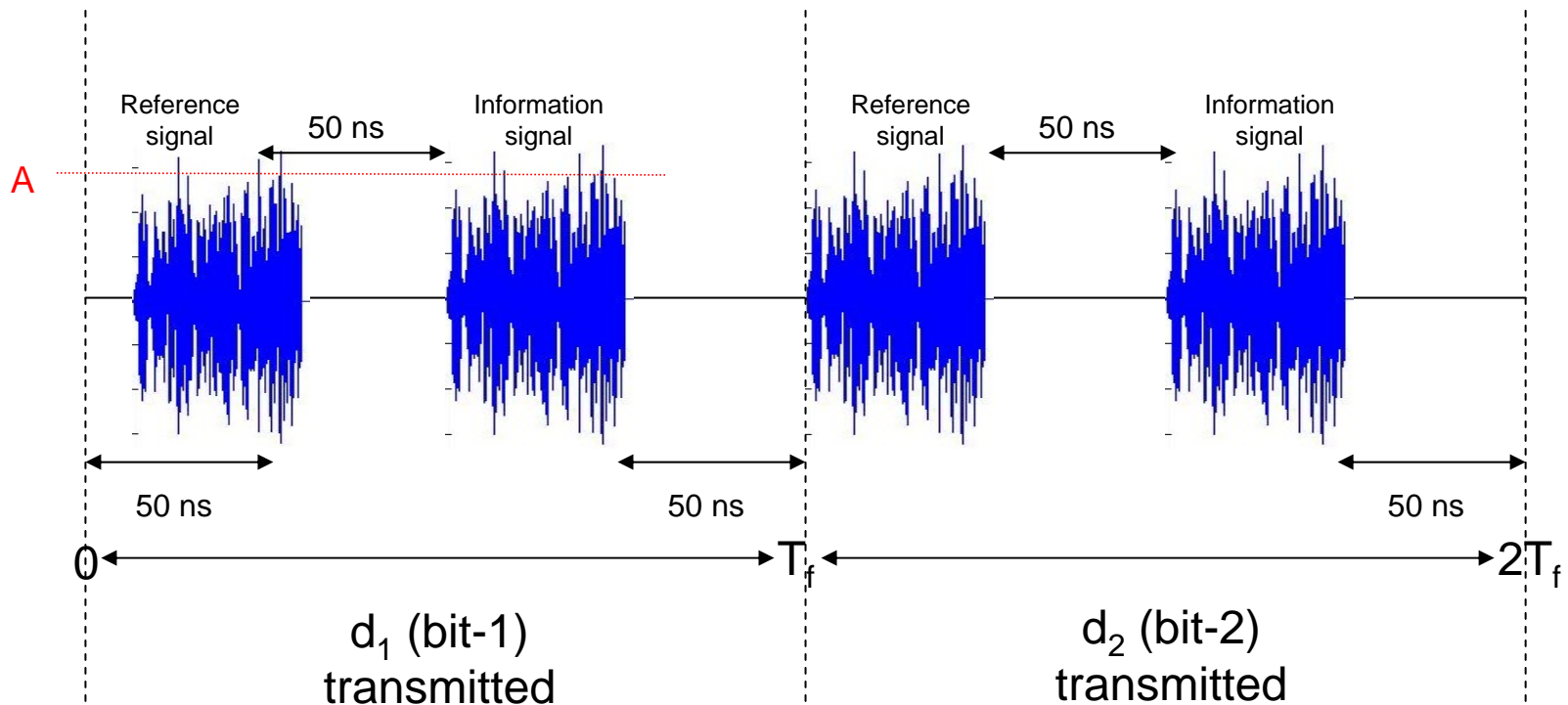
- M-ary code shift keying (MCSK)/binary pulse position modulation (BPPM) for time hopping (TH) impulse radios (IR's) can be used in Chaotic Communications such as DCSK in order to increase the system performance



# MCS-DCSK Modulation

## DCSK TX Signal

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



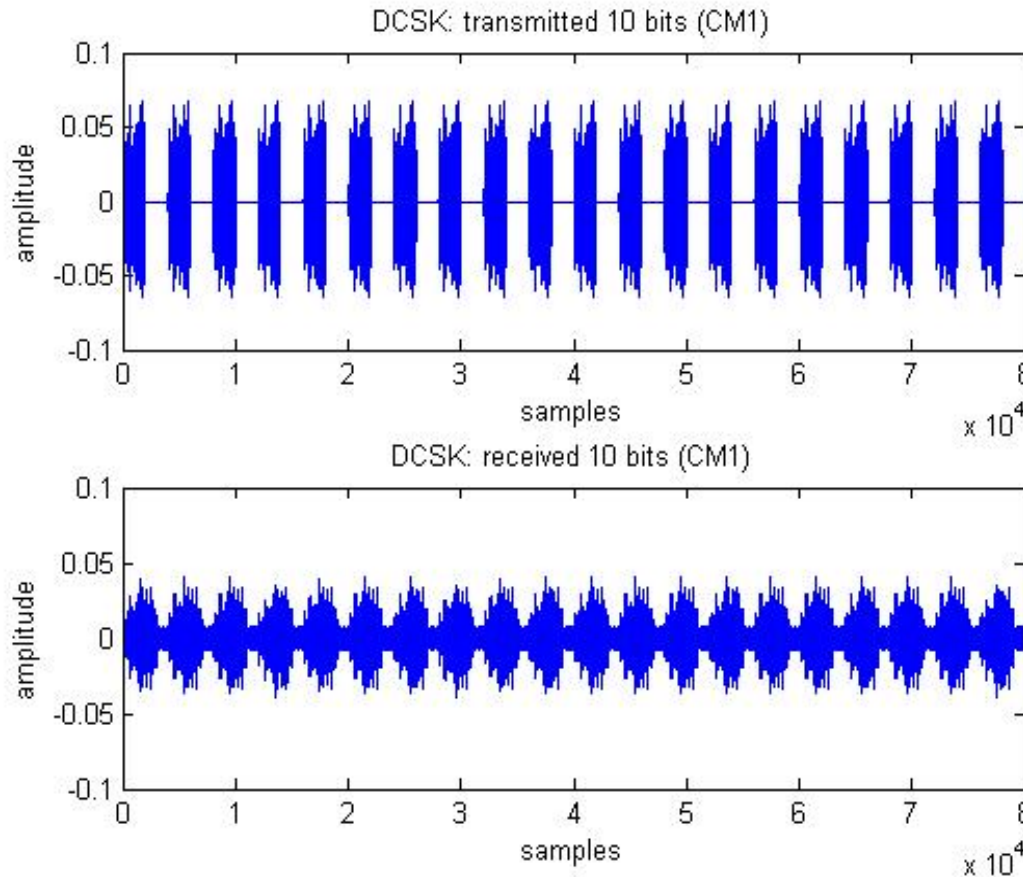
where *info. signal* =  $sign(d_i) \times ref. signal$



# MCS-DCSK Modulation

## DCSK TX and RX Signal

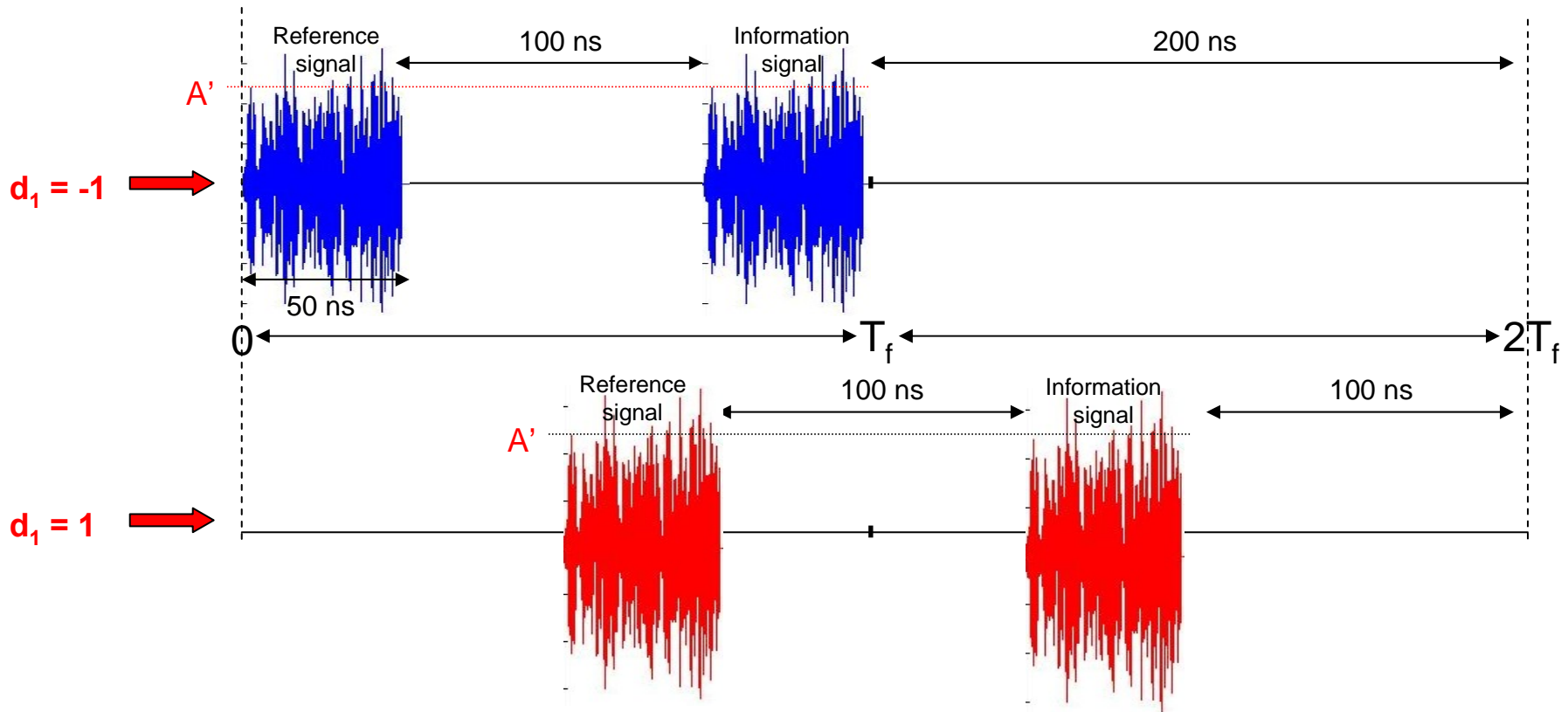
DCSK: Transmitted and received signals (CM1, no AWGN)



# MCS-DCSK Modulation

## MCS-DCSK TX Signal

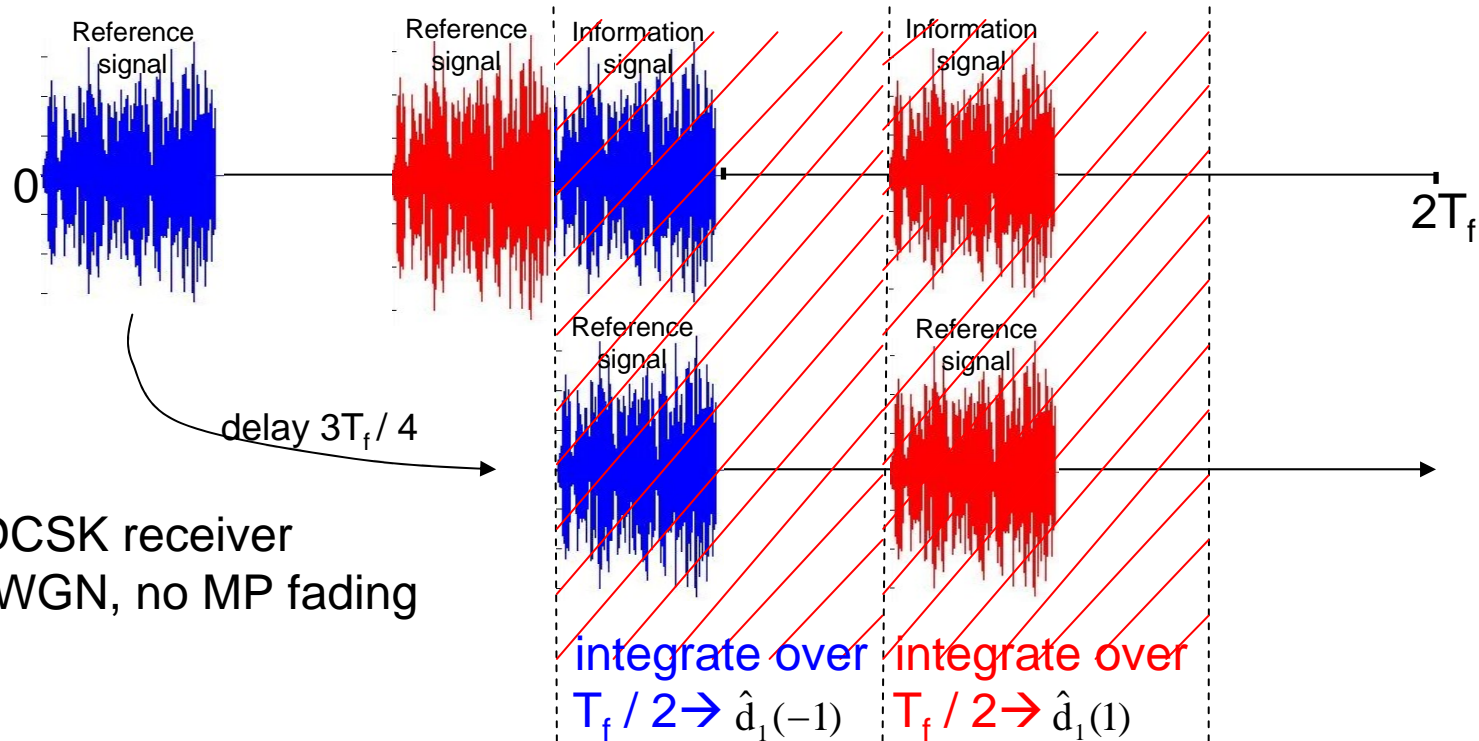
MCS-DCSK transmitting  $d=[d_1 \ d_2]$ ,  $d_i \in (-1,1)$



where *info. signal* =  $\text{sign}(d_2) \times \text{ref. signal}$

# MCS-DCSK Modulation

## MCS-DCSK RX Signal



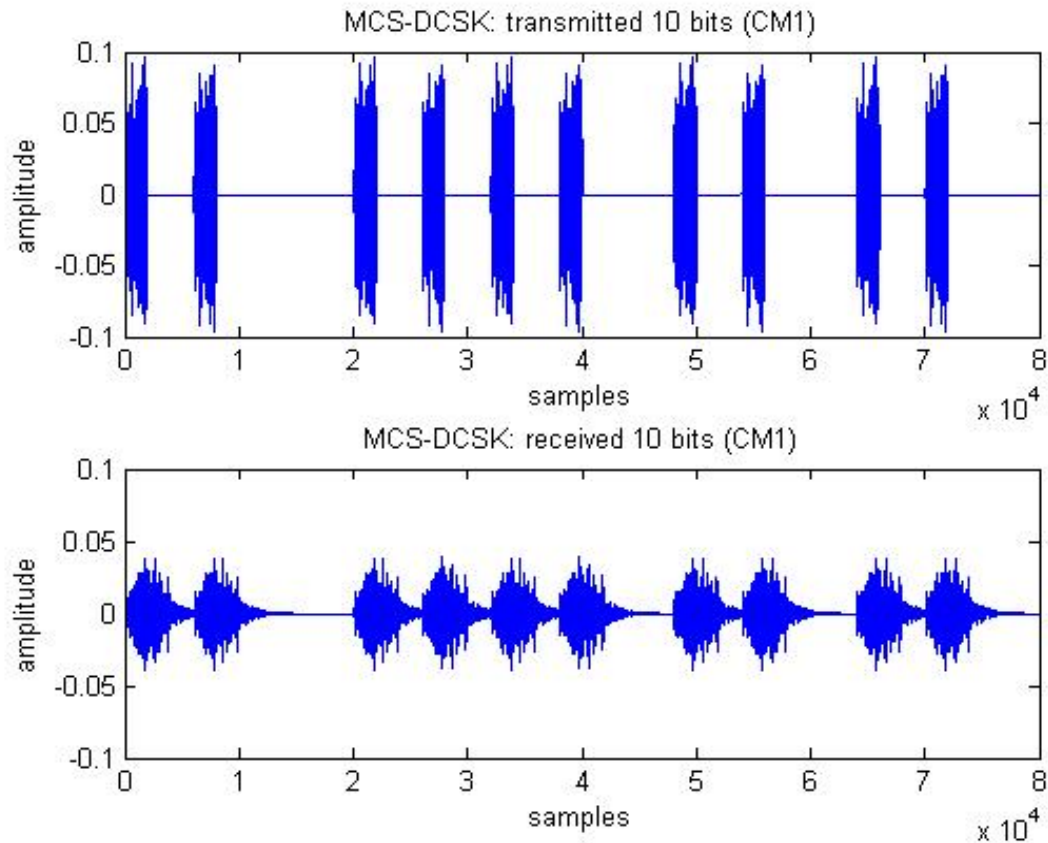
MCS-DCSK receiver  
 – no AWGN, no MP fading

**Decision** {  
 Step 1:  $|\hat{d}_1(-1)| > |\hat{d}_1(1)| \longrightarrow d_1 = -1$ ;  $|\hat{d}_1(-1)| < |\hat{d}_1(1)| \longrightarrow d_1 = 1$   
 Step 2: if  $d_1 = -1 \longrightarrow d_2 = \text{sign}(\hat{d}_1(-1))$ ; if  $d_1 = 1 \longrightarrow d_2 = \text{sign}(\hat{d}_1(1))$

# MCS-DCSK Modulation

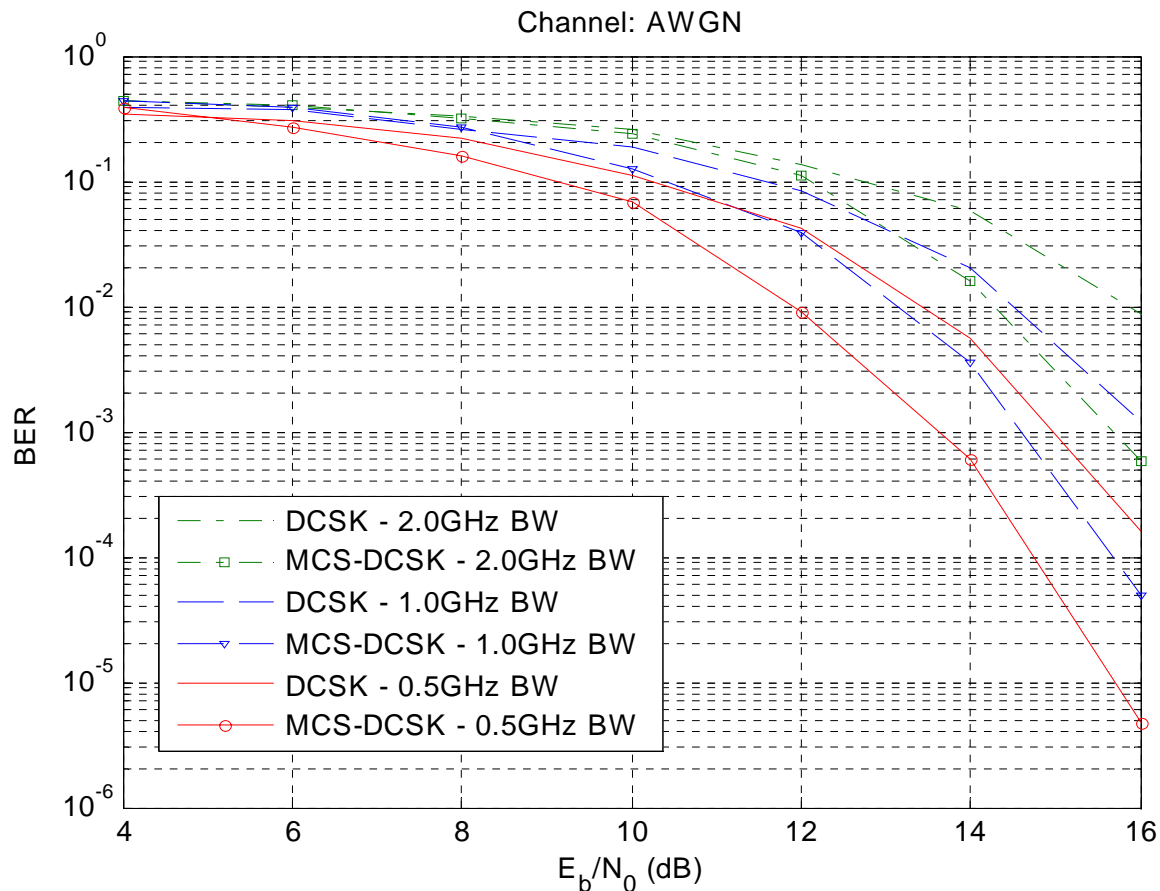
## MCS-DCSK TX and RX Signal

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



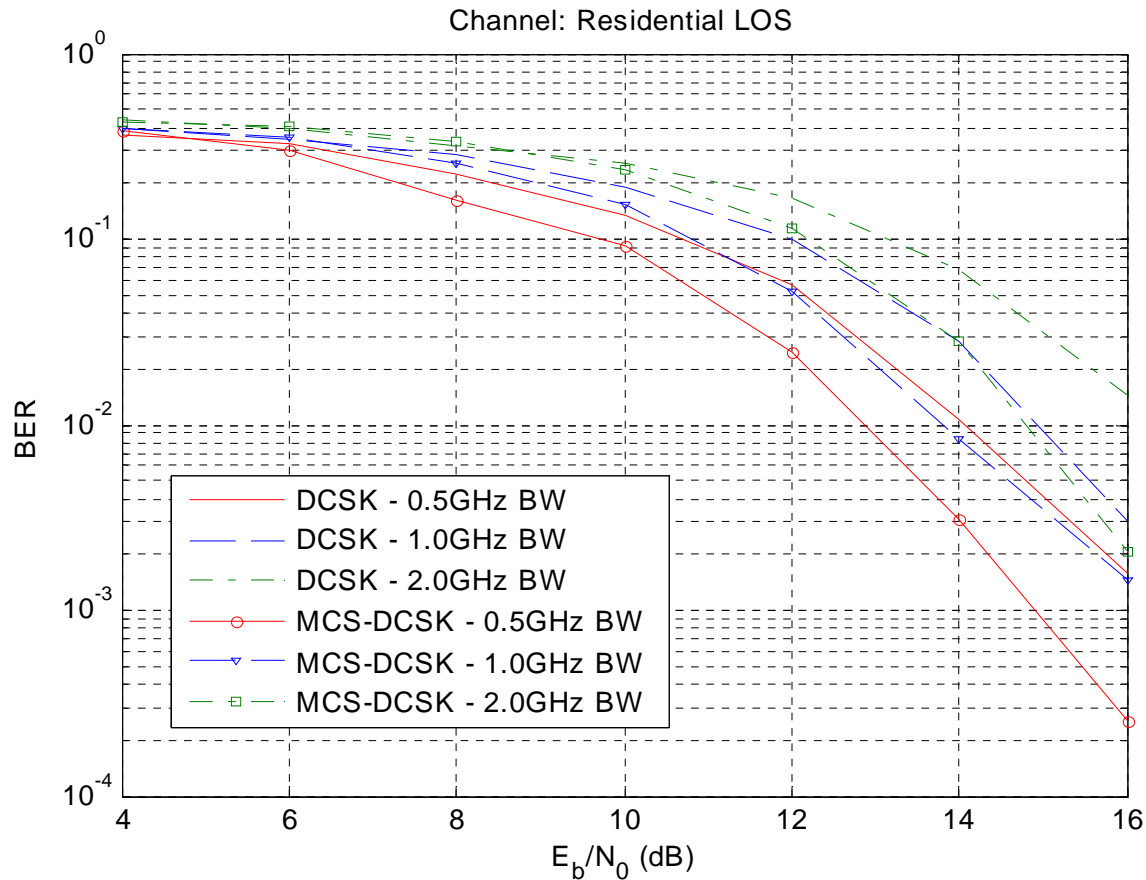
# MCS-DCSK Modulation

## MCS-DCSK Simulation Results



# MCS-DCSK Modulation

## MCS-DCSK Simulation Results





# 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 for TG4a.
- Most hardware from OOK is retained.
- SOP and ranging can be solved effectively using DCSK.

# **MC-PPM : Compatible Modulation Scheme for Direct Chaotic Communication**

# MC-PPM Modulation

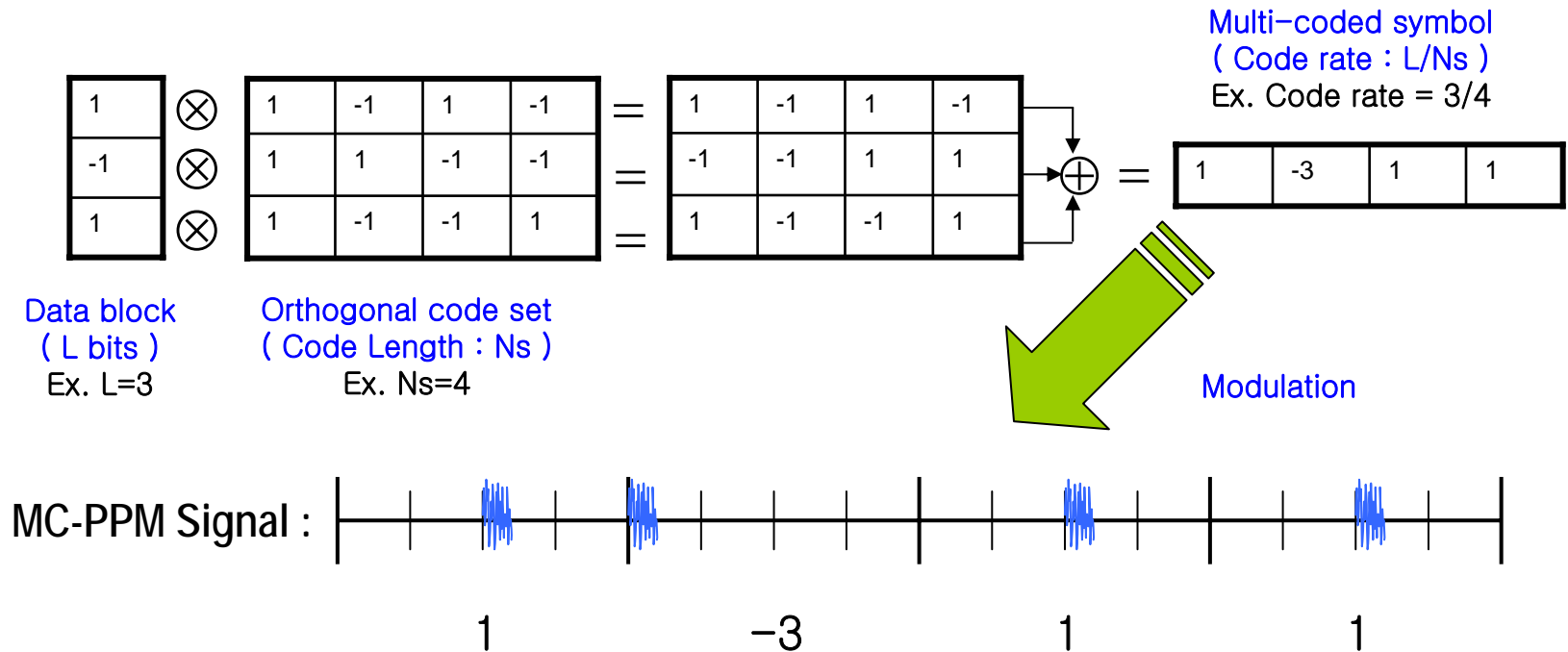
## MC-PPM

- **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)

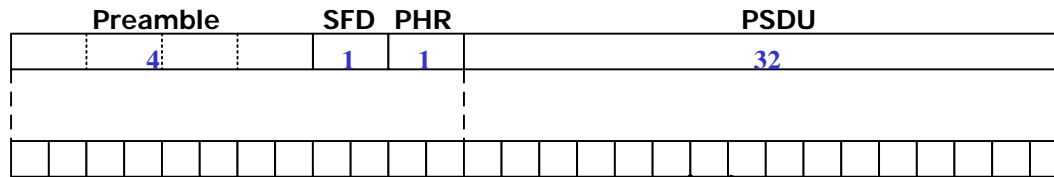


# MC-PPM Modulation

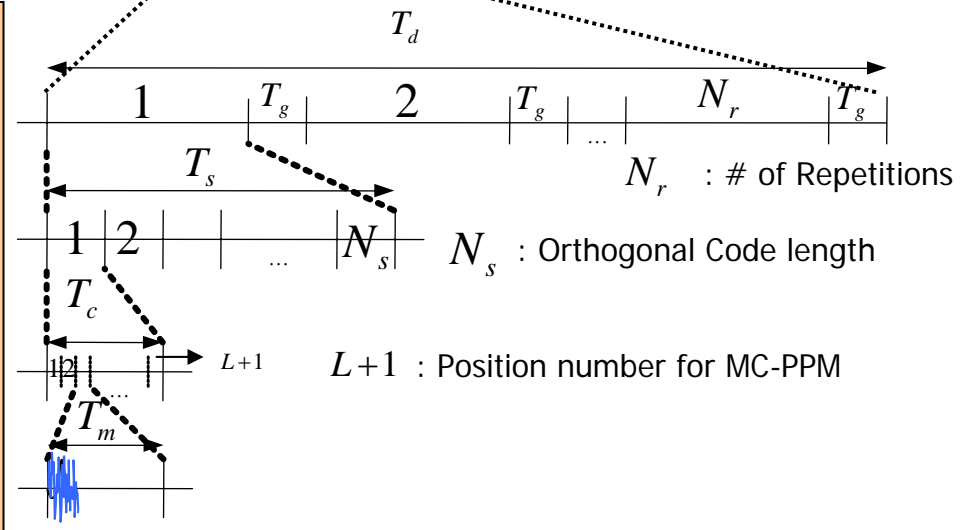
## Data Frame Structure

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

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



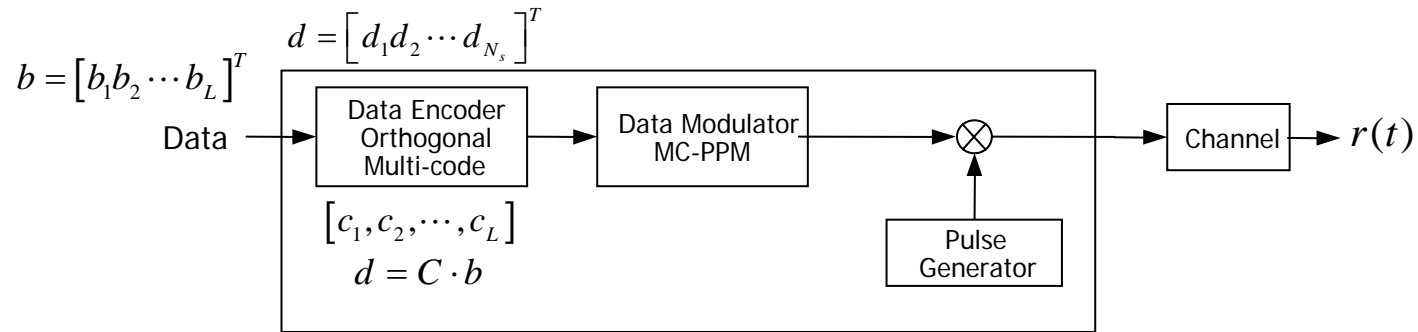
- $L$  : # of bits per data block
- $N_s$  : Orthogonal code length
- $N_r$  : # of repetitions
- $T_m$  : Pulse bin width (duration)
- $T_c$  : Multi-coded chip duration
- $T_s$  : Multi-coded symbol duration
- $T_g$  : Guard time for processing delay
- $T_d$  : Total transmit time duration of a data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



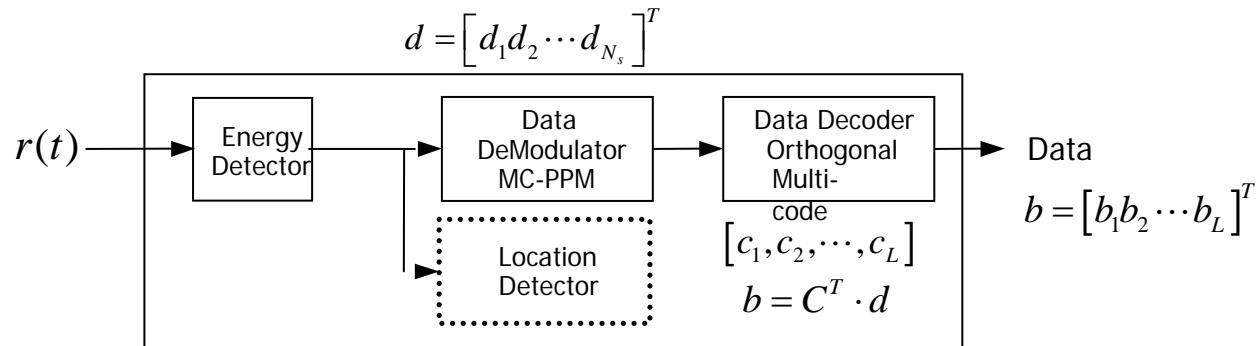
# MC-PPM Modulation

## Transceiver Architecture

- Transmitter



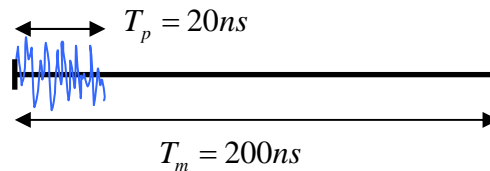
- Receiver



# MC-PPM Modulation

## PHY-SAP Data Rates

- Flexible data rates can be supported according to several design parameter ( $T_m$ ,  $L$ ,  $N_s$ ,  $N_r$ ,  $T_g$ )

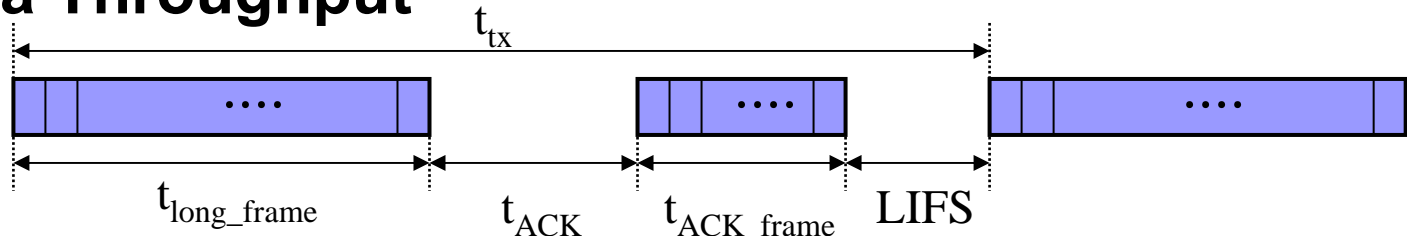


$T_p$	$T_m$	$L$	$N_s$	$N_r$	$T_g$	Data Rate
20ns	200ns	1	16	128	0ns	1.190 kbps
20ns	200ns	3	16	1	0ns	228 kbps
20ns	200ns	3	8	1	0ns	457 kbps
20ns	200ns	1	<b>1</b>	1	0ns	<b>2.44 Mbps</b>

# 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

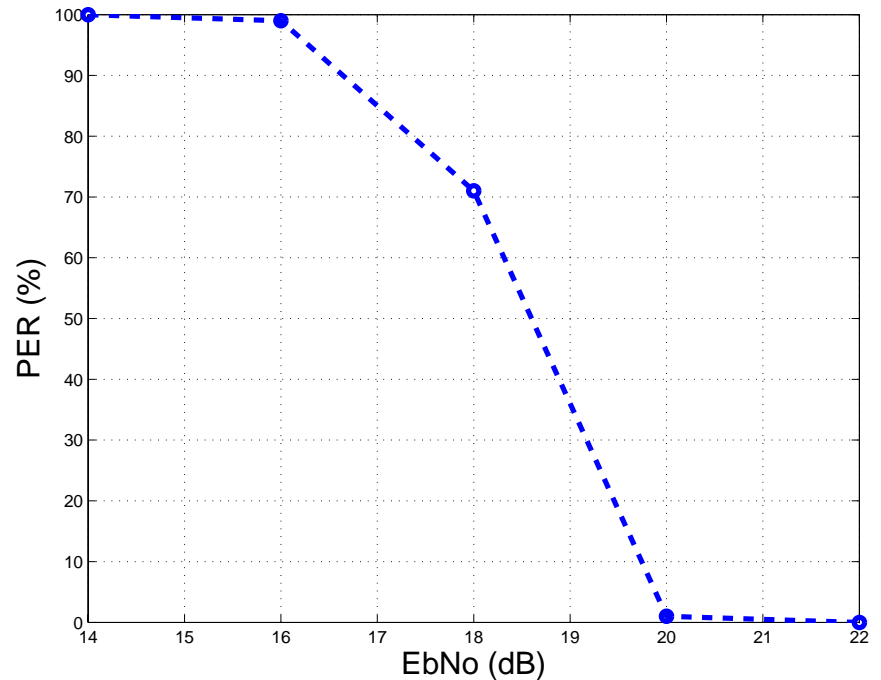
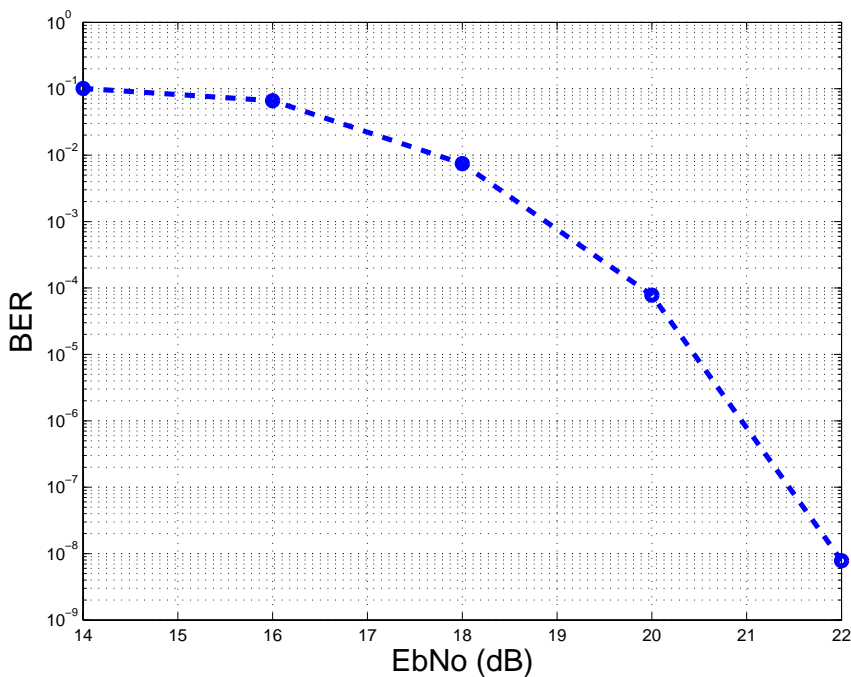
# MC-PPM Modulation

## Performance

### ■ MC-PPM Performance : AWGN

- BER & PER

– L=3, N<sub>s</sub>=8, N<sub>r</sub>=1 (457 kbps PHY-SAP data rate)

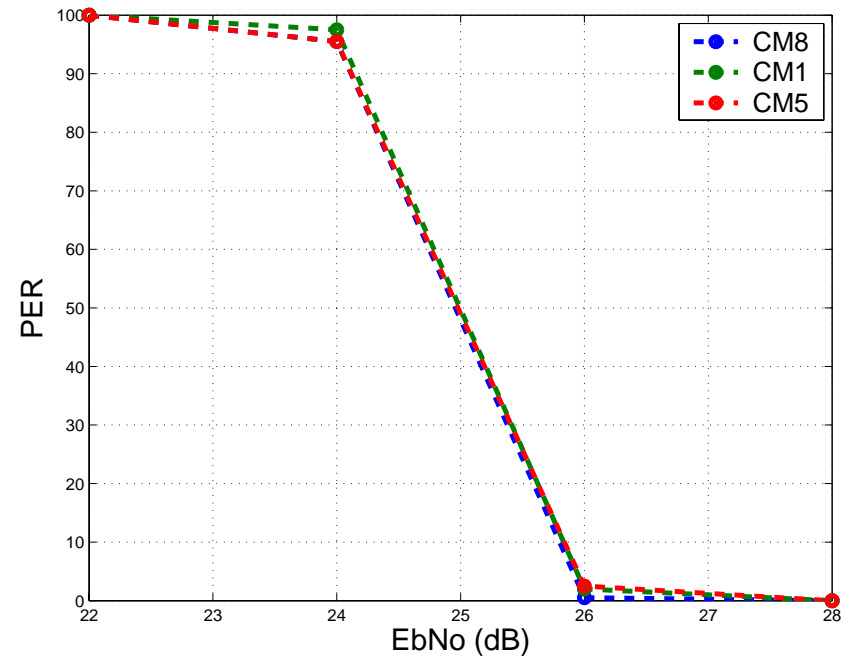
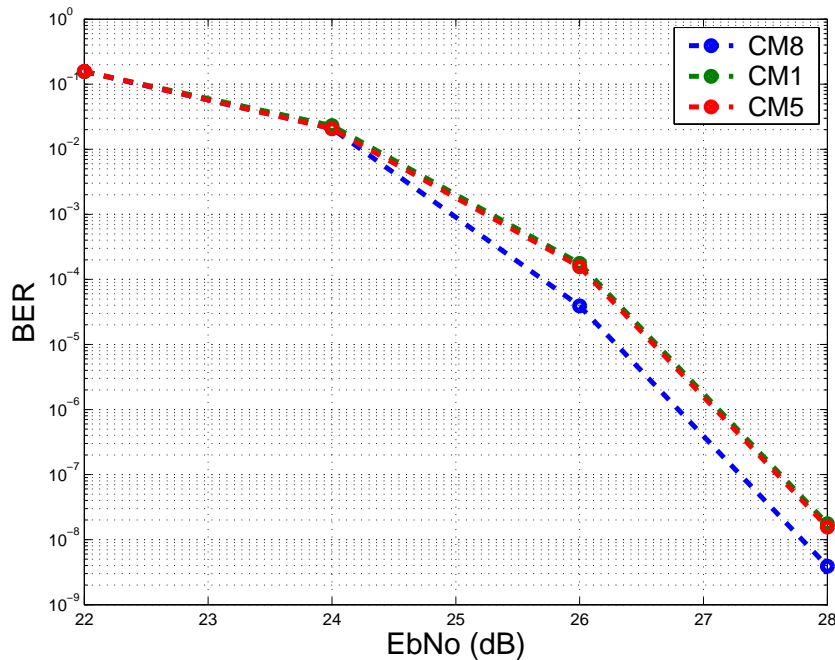


# MC-PPM Modulation

## Performance

### ■ MC-PPM Performance : 4a Channel Models

- BER & PER
  - $L=3, N_s=8, N_r=1$

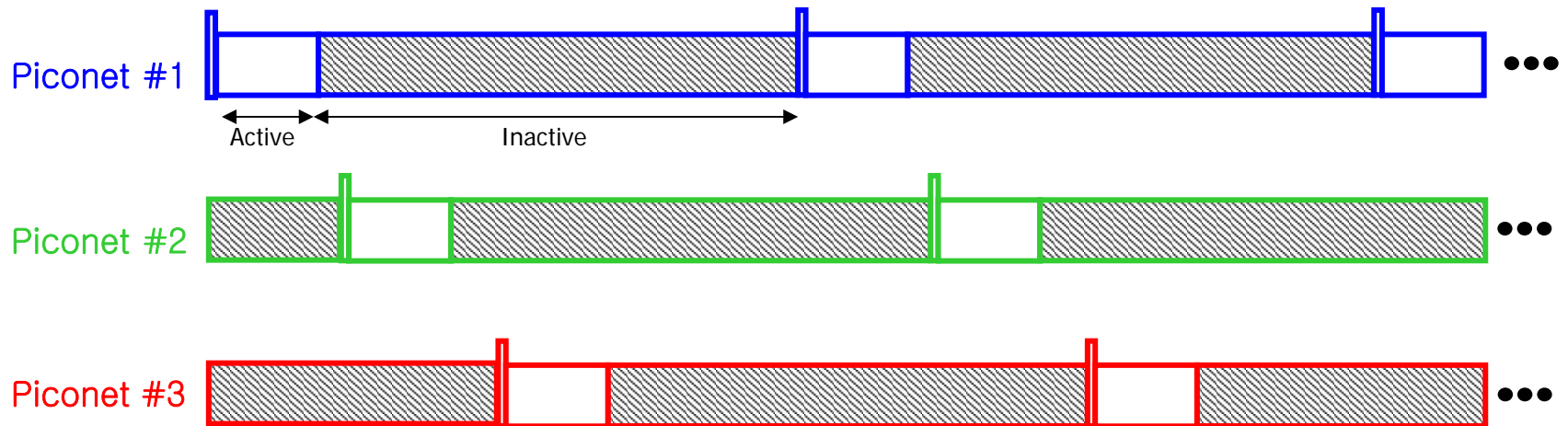


# MC-PPM Modulation

## SOPs

### ■ Time Division

- Configuration of SOPs
  - Self configuration of SOPs is possible

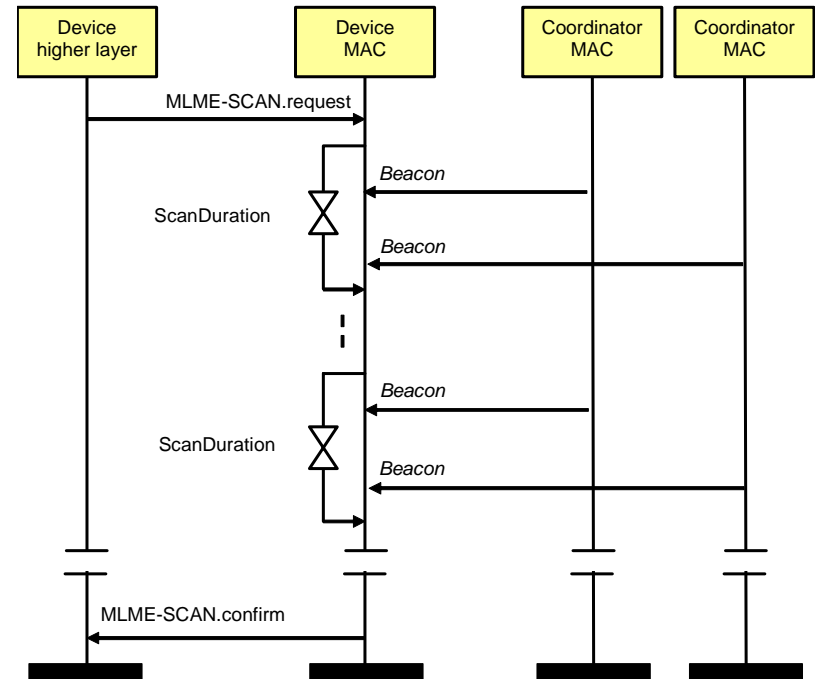


# MC-PPM Modulation

## 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

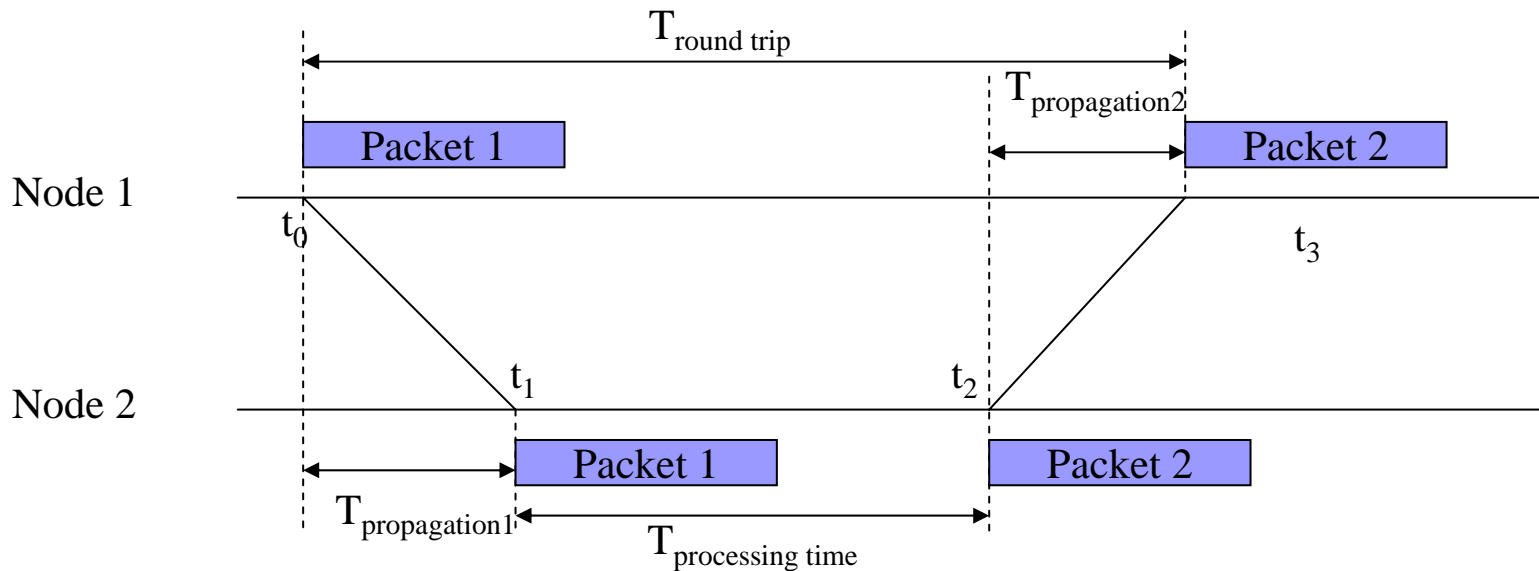
Parameter	(mandatory) Value at d=30m	(mandatory) Value at d=10m
peak payload bit rate	(457kb/s) [ L=3,Ns=8,Nr=1]	(457kb/s) [ L=3,Ns=8,Nr=1]
Average Tx power	-8.75 (dBm)	-8.75 (dBm)
Tx antenna gain	0 (dBi)	0 (dBi)
geometric center frequency of waveform	3.90 (GHz)	3.90 (GHz)
Path loss at 1 meter	44.5dB	44.5dB
Path loss at <i>d</i> m	29.54 dB at <i>d</i> =30m	20 dB at <i>d</i> =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

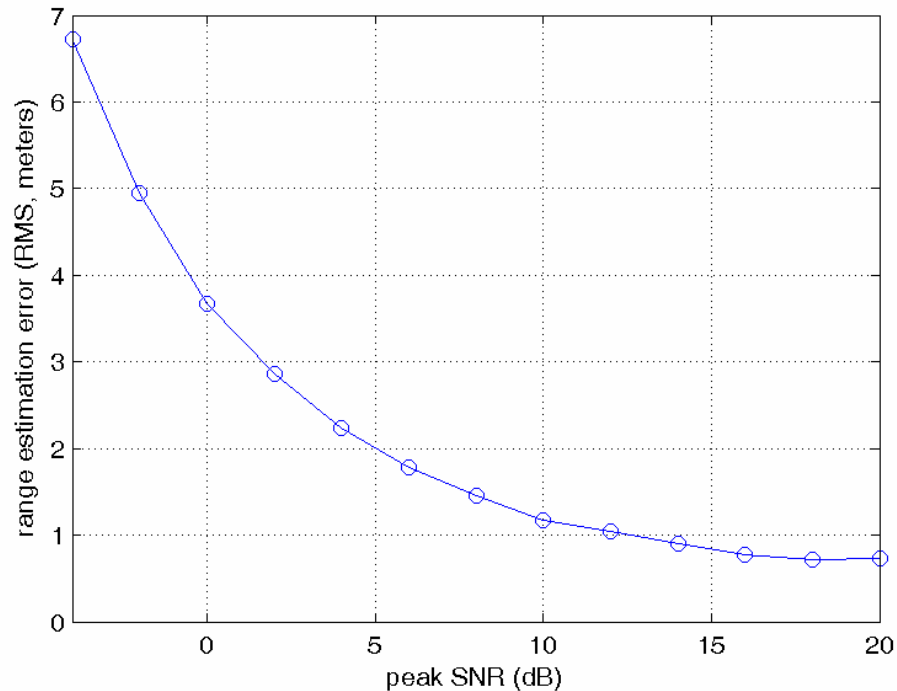
- TOA/TWR -> Measurement of Roundtrip time



# 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**

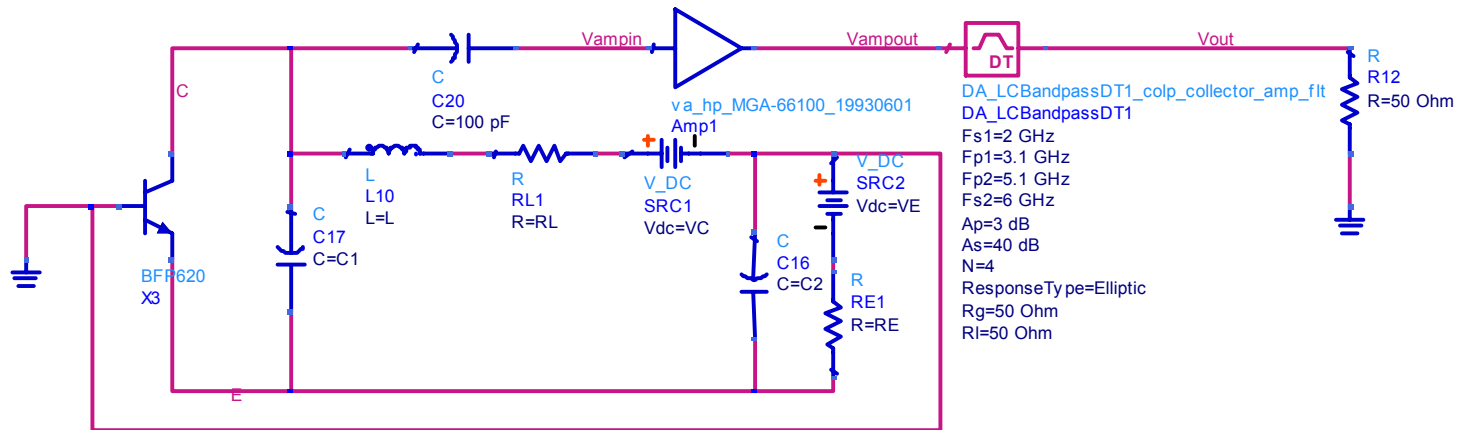
**A separate envelope  
detector for range  
estimation was employed**



# Backup Slides

# Tolerance of Components

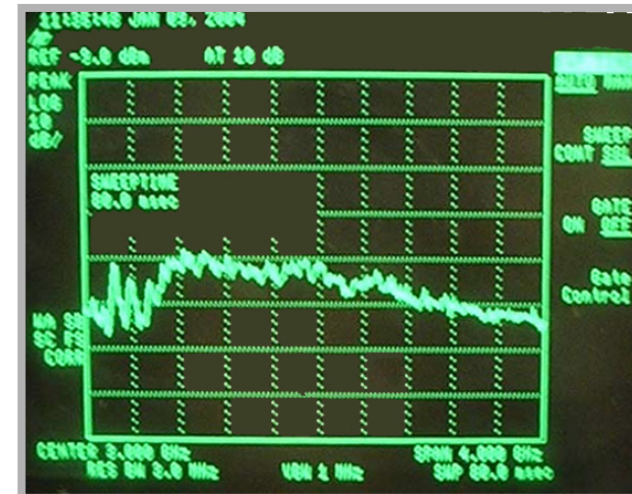
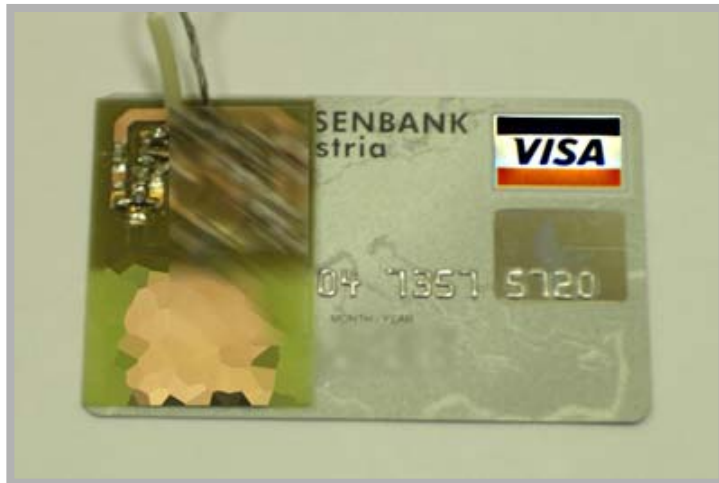
- Capacitor, C1 and inductance, L → 20% tolerance.
- C2 and resistors, RE and R1 → 5% tolerance.



# Summary of Features

<b>Information carrier</b>	<b>Chaotic radio pulses</b>		
<b>Band division</b>	<b>3 bands within FCC Mask (3.1-5.1, 6.1-8.1 and 8.2-10.2 GHz)</b>		
<b>Channel bandwidth</b>	<b>2.0 GHz band or 4 channels with 500 MHz in each in the 2 GHz band</b>		
<b>Pulse duration</b>	<b>400 ns</b>		
<b>Individual bit rate</b>	<b>1 Kbps</b>	<b>10 Kbps</b>	<b>100 Kbps</b>
<b>Transmit power</b>	<b>-30 dBm</b>	<b>-20 dBm</b>	<b>-20 dBm</b>
<b>Battery life</b>	<b>2.5 year 100% duty cycle</b>	<b>2.5 year 10% duty cycle</b>	<b>2.5 year 0.1% duty cycle</b>
<b>Aggregated bit rate</b>	<b>Up to 5 Mbps</b>		

# Tiny Chaotic Transmitter



**Transmitter consists of:**

- chaos generator
- modulator
- antenna

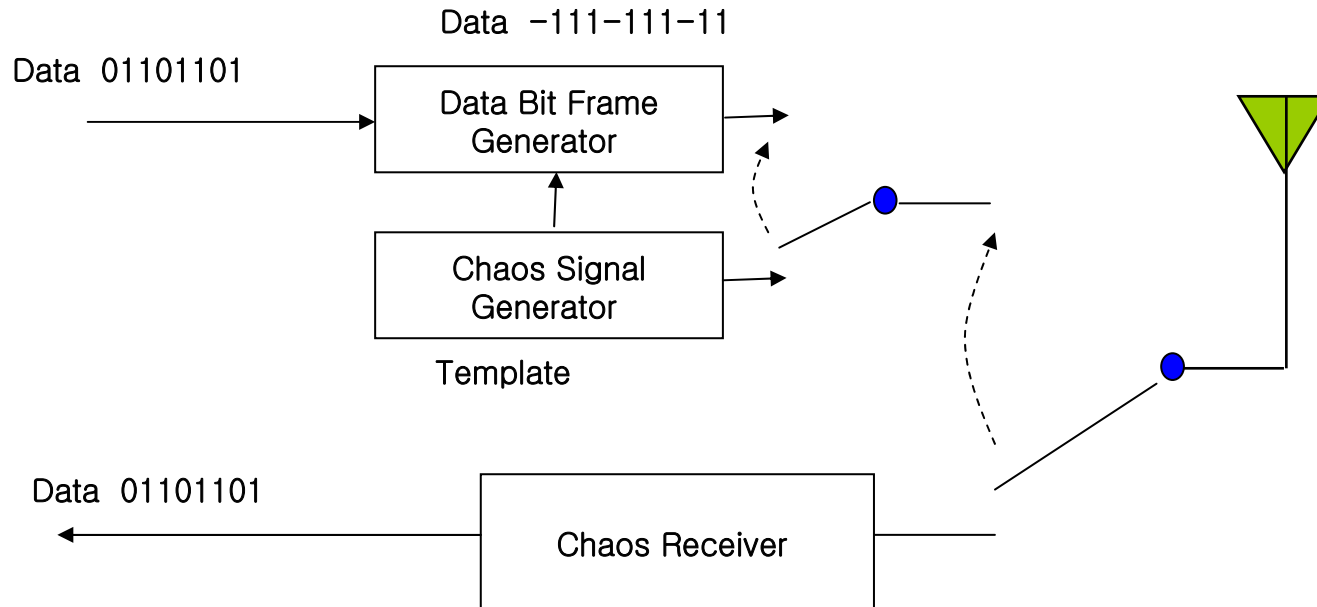
**Frequency band - 2-4 GHz**

**Radiating power - 3-4 mw**

# DCSK Modulation

## SOP

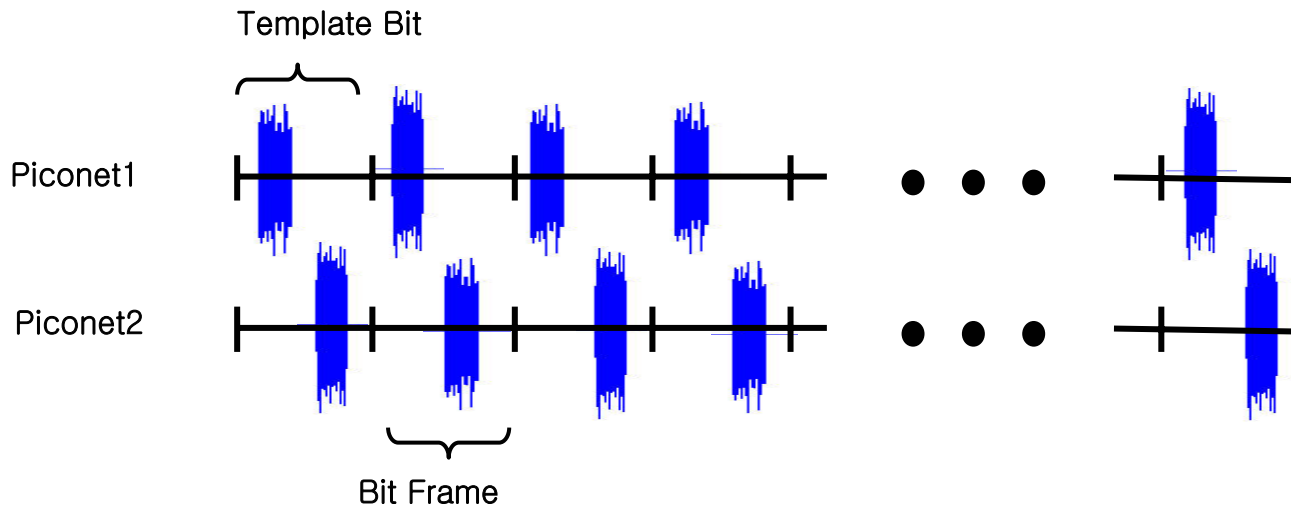
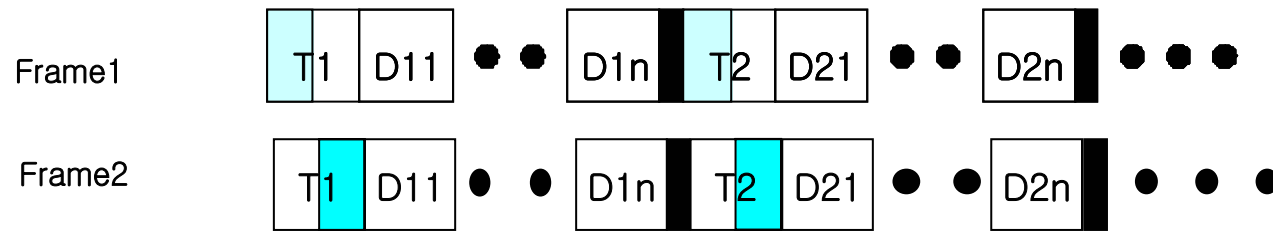
### ■ System Block



# DCSK Modulation

## SOP

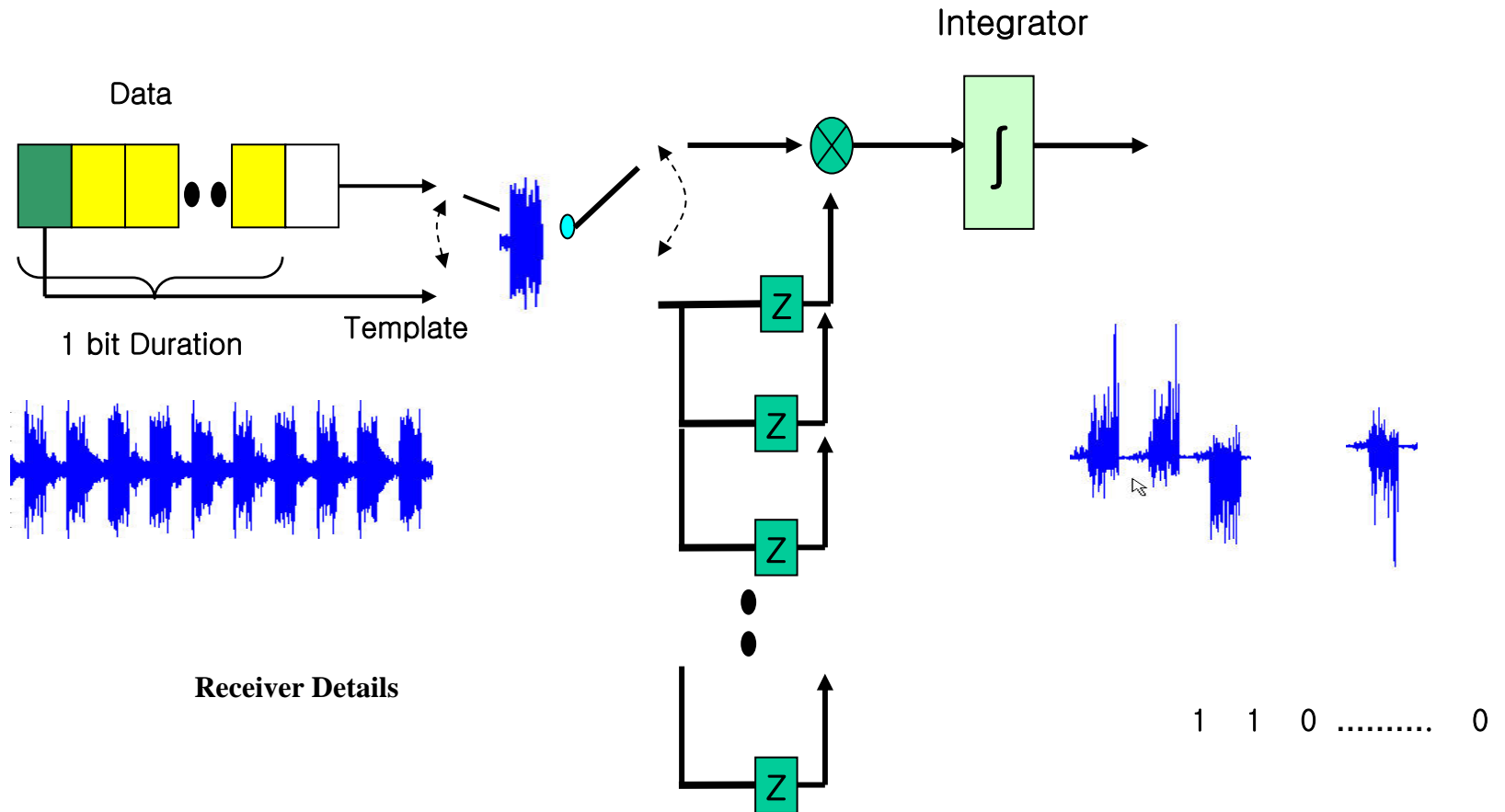
### ■ Transmission



# DCSK Modulation

## SOP

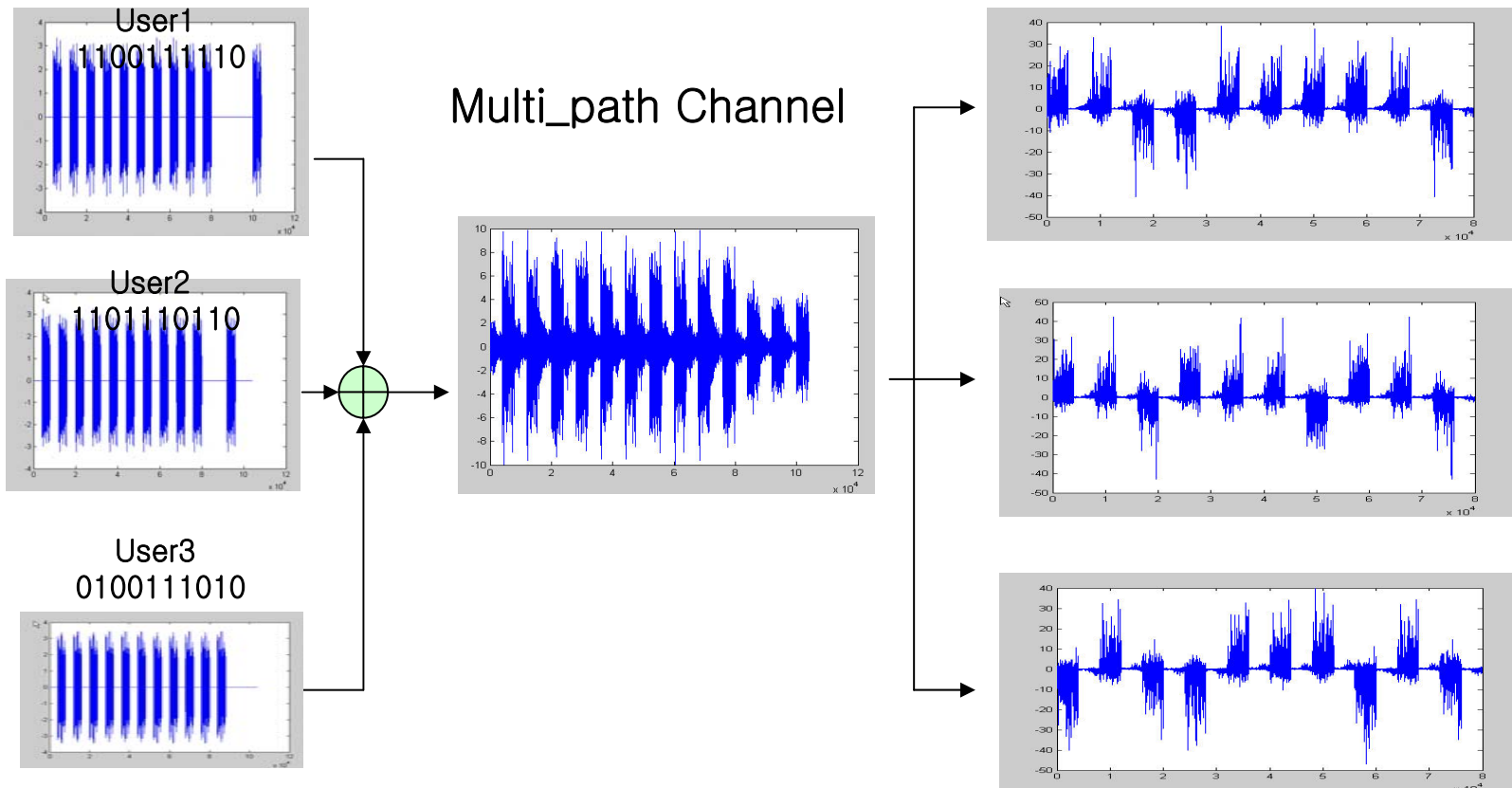
### ■ Detail



# DCSK Modulation

## SOP

### ■ Signal Processing

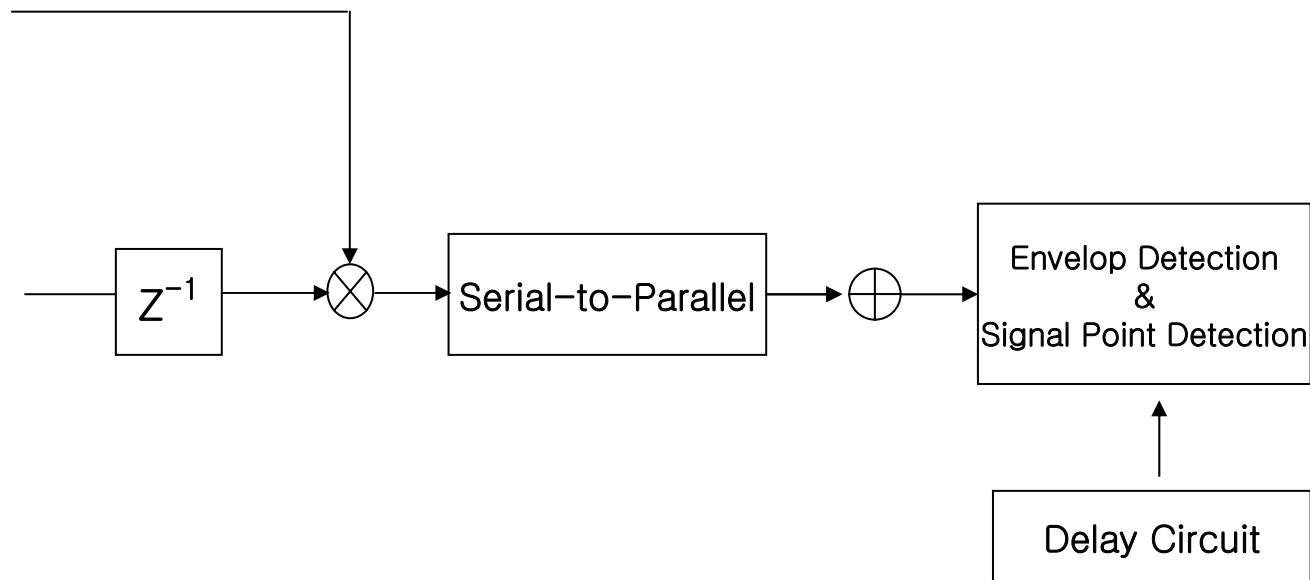




# DCSK Modulation

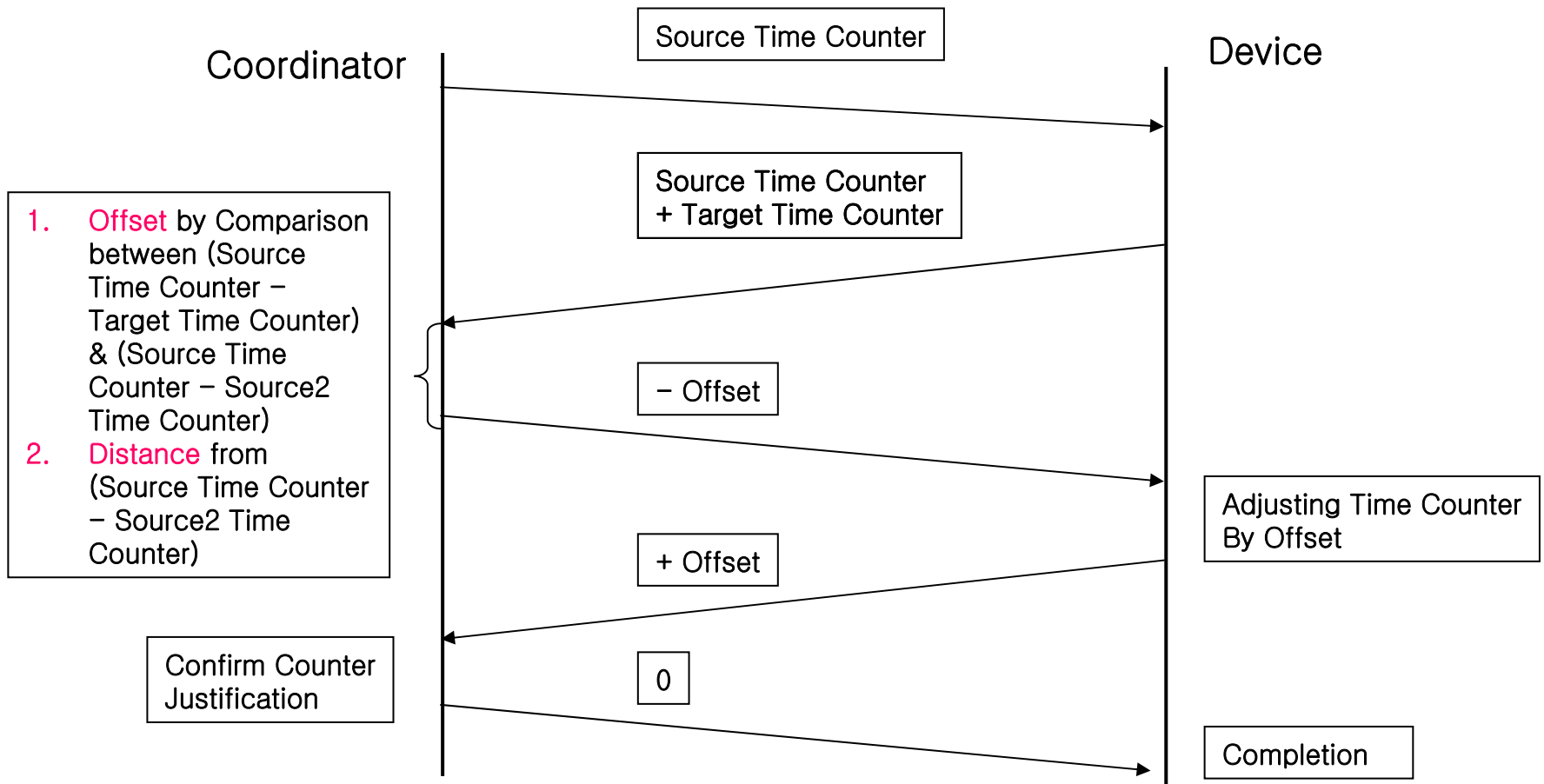
## Ranging

### ■ Block Diagram



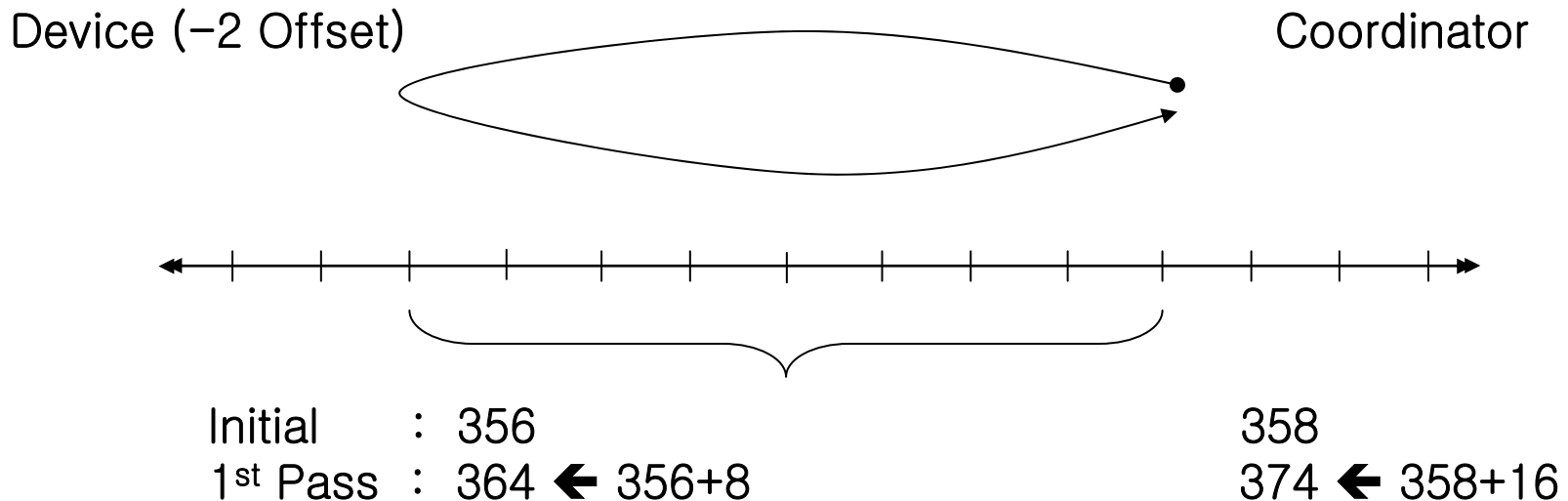
# DCSK Modulation

## Ranging



# DCSK Modulation

## Ranging



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

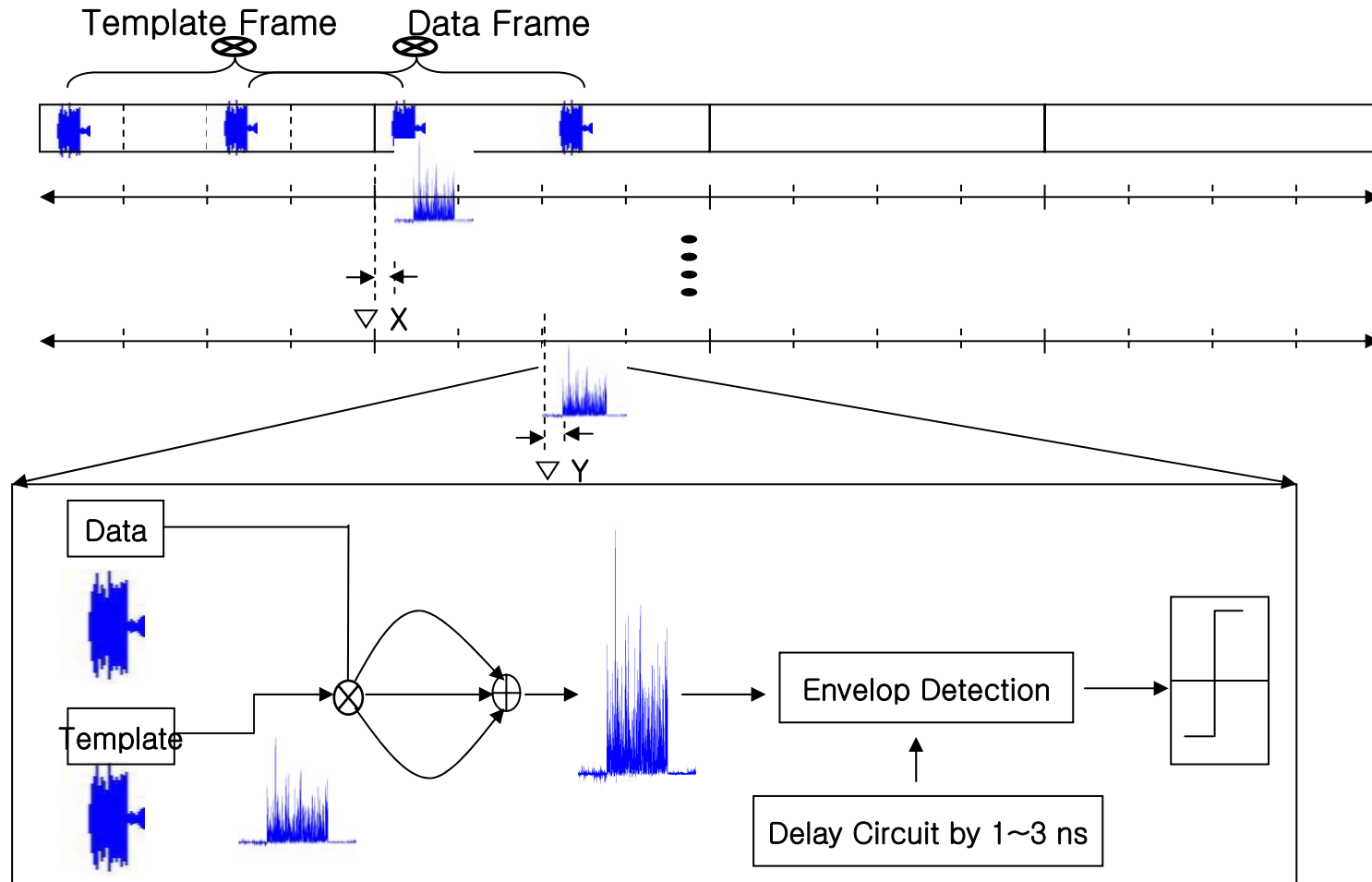
## Location Awareness Special Mode

### ■ 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

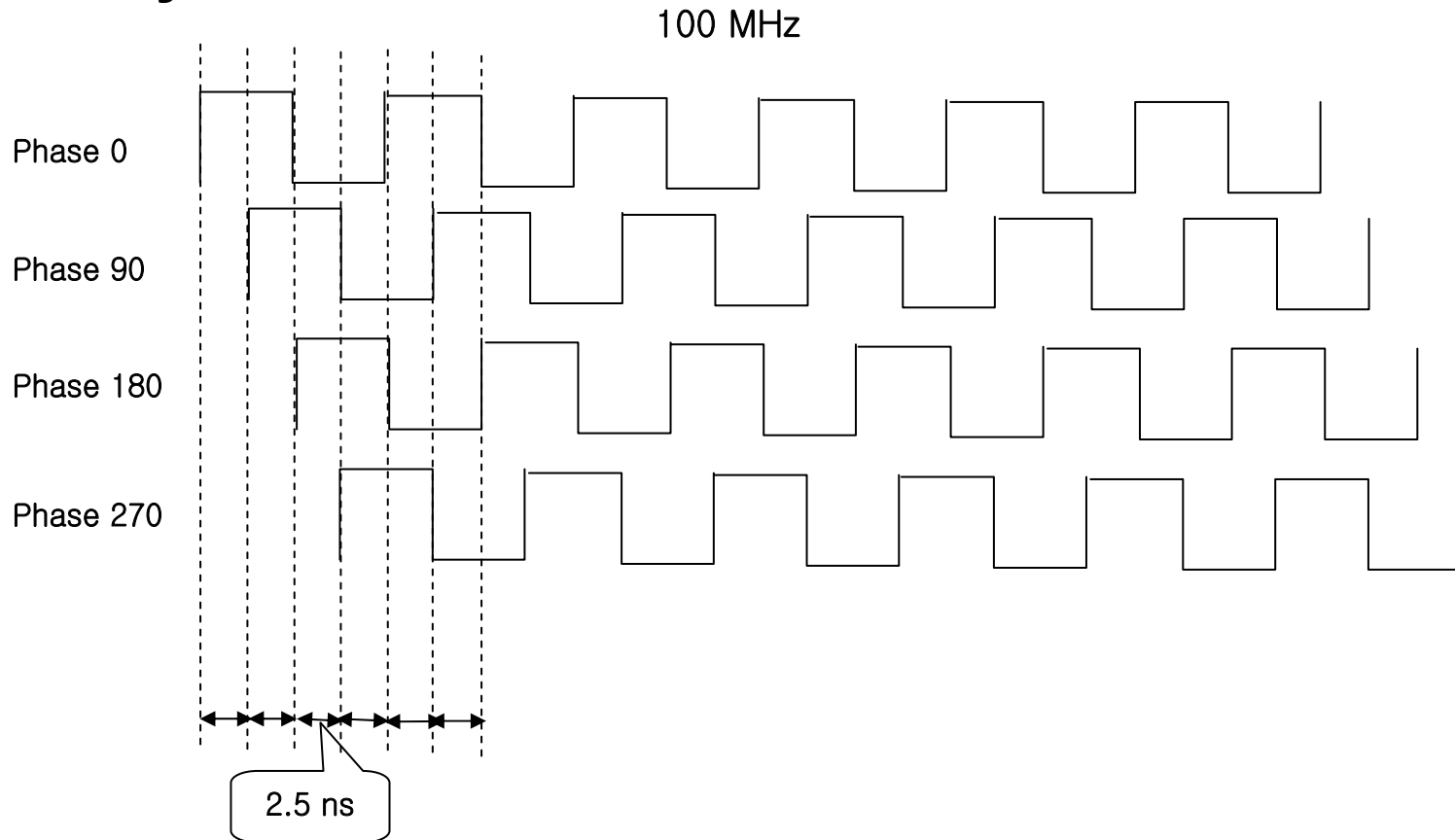
### ■ Fine Precision TOA Estimation

- 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

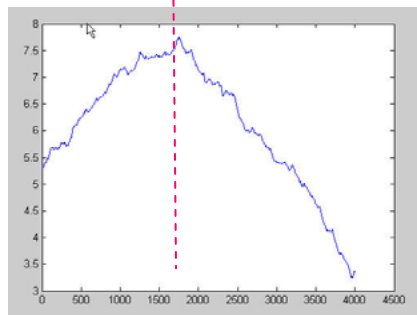
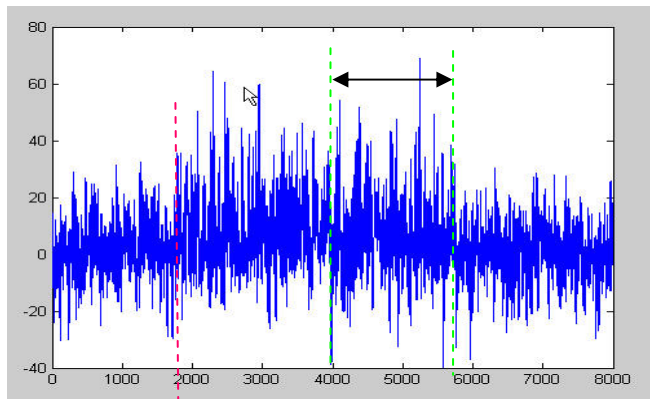
### ■ Delay Circuit



# DCSK Modulation

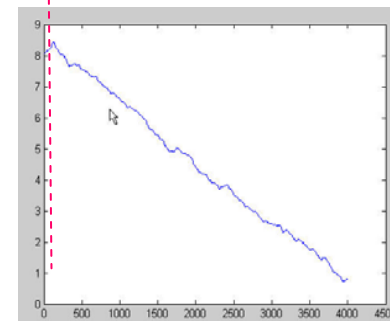
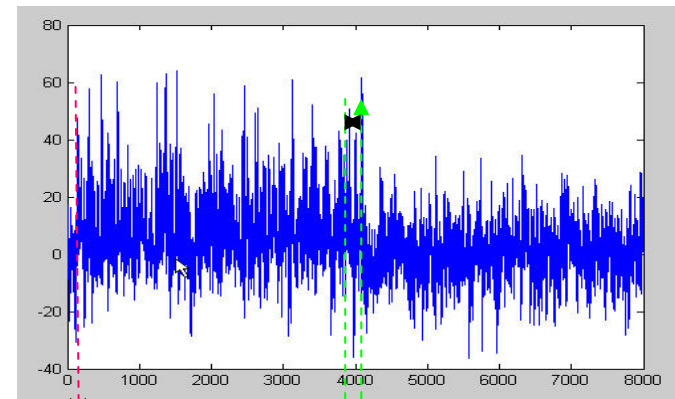
## Ranging

### ■ Simulation (BNR 16dB)



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

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



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