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.]

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Chaotic UWB System

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CONTENTS

1. INTRODUCTION

Features of Proposed System

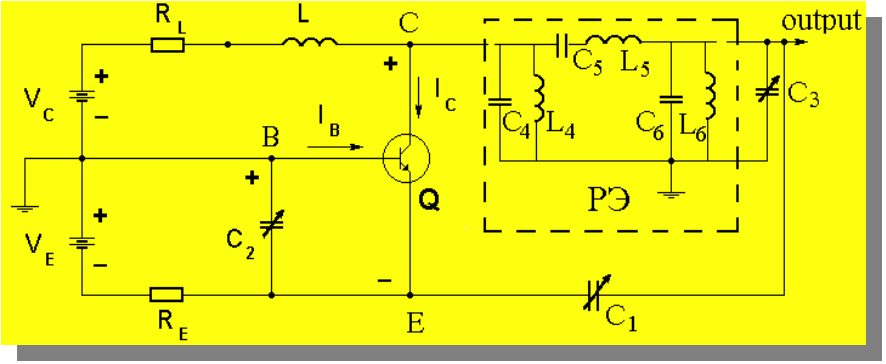
- **Low Hardware Complexity / Low Cost**
  - Chaotic signal can be generated directly into the desired microwave band (Simple RF circuit)
- **Efficient Power Management**
  - Sleep / Wake-up capability can save the battery life time
- **Robust in Multipath**
  - In case of OOK Modulation, BER performance 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

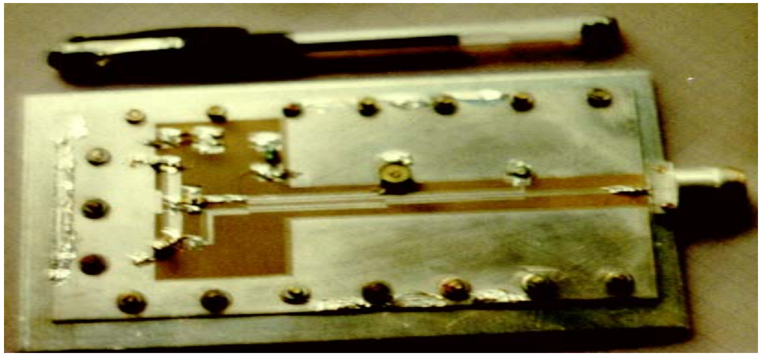
Chaotic Source

- **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



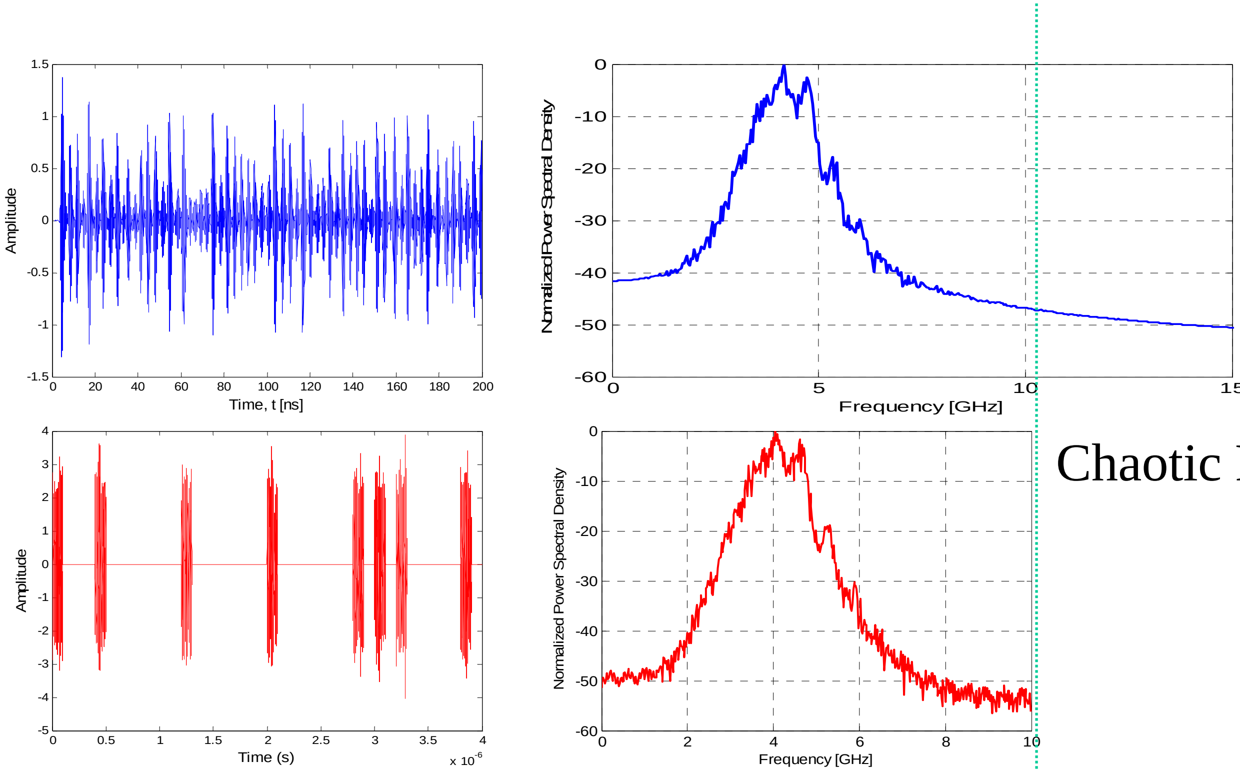
Experiment device



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

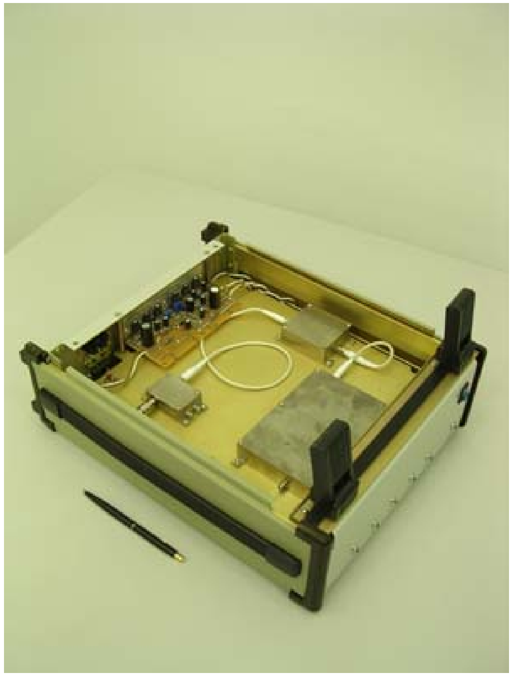
2.5125

3.4. Technical Feasibility

Prototype 1

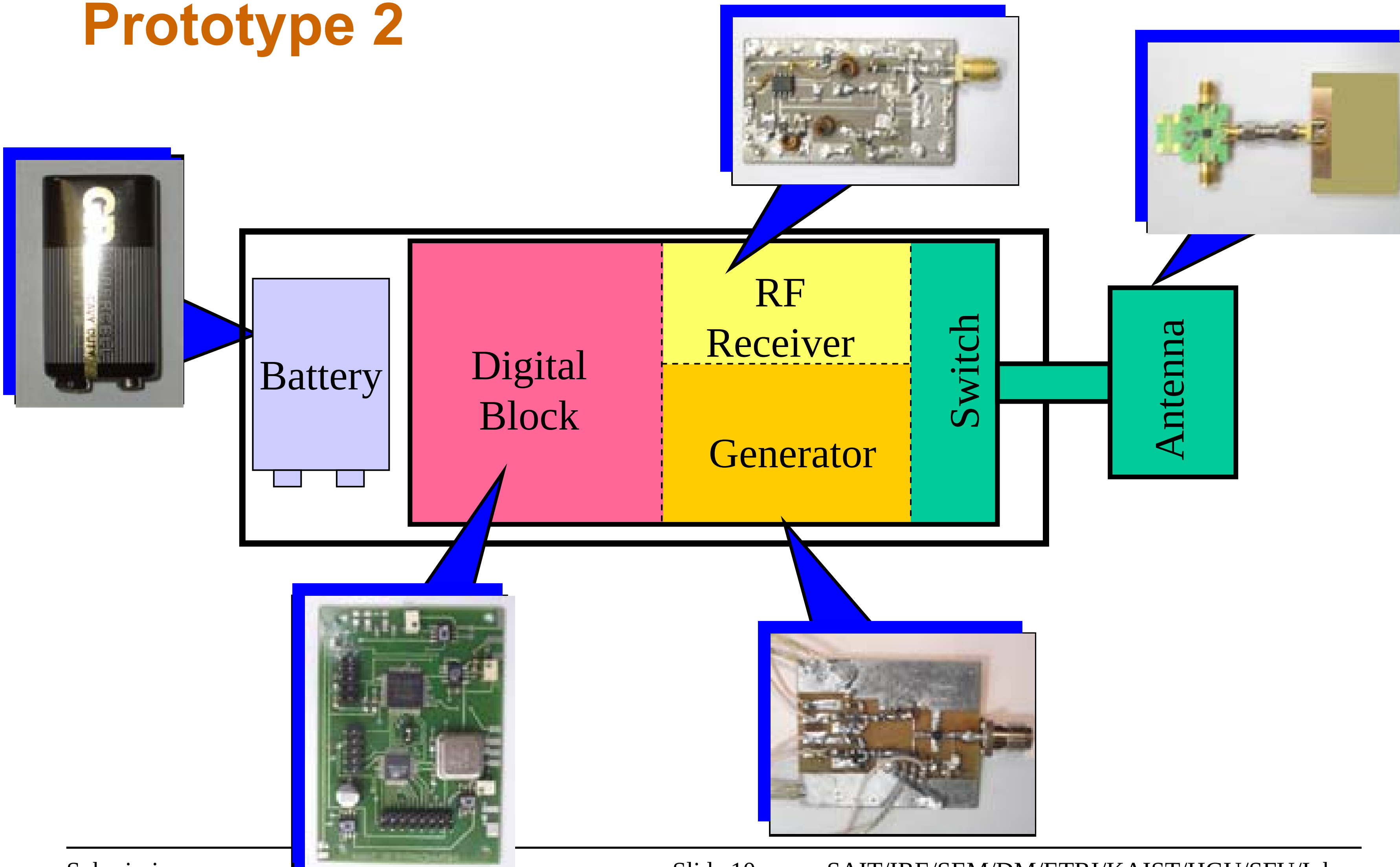
- **The communication test has successfully done using Chaotic pulses**

UWB DCC-OOK Test-bed



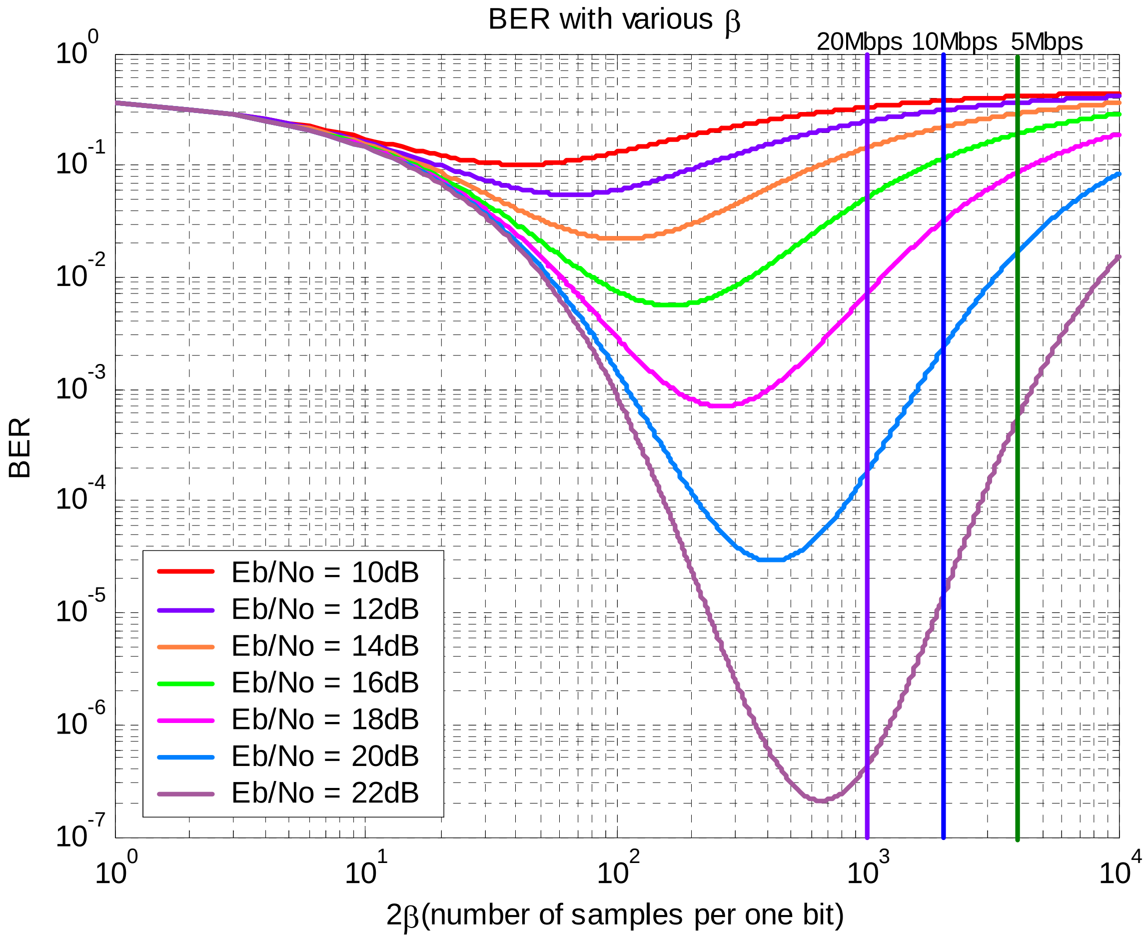
3.4. Technical Feasibility

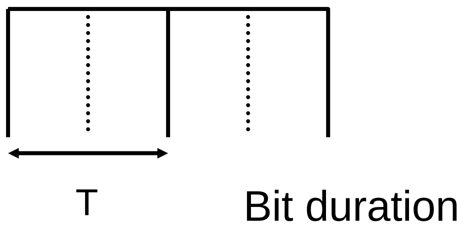
Prototype 2

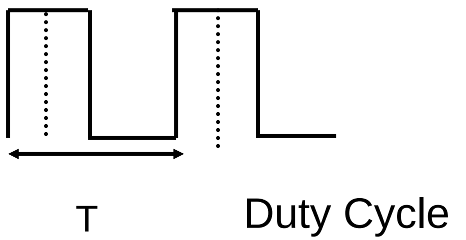


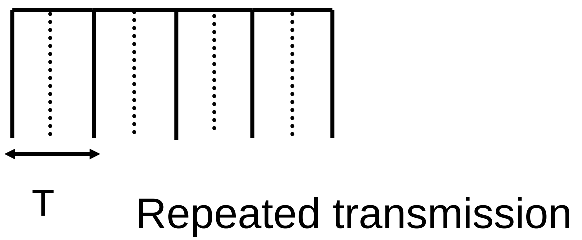
3.5. Scalability

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

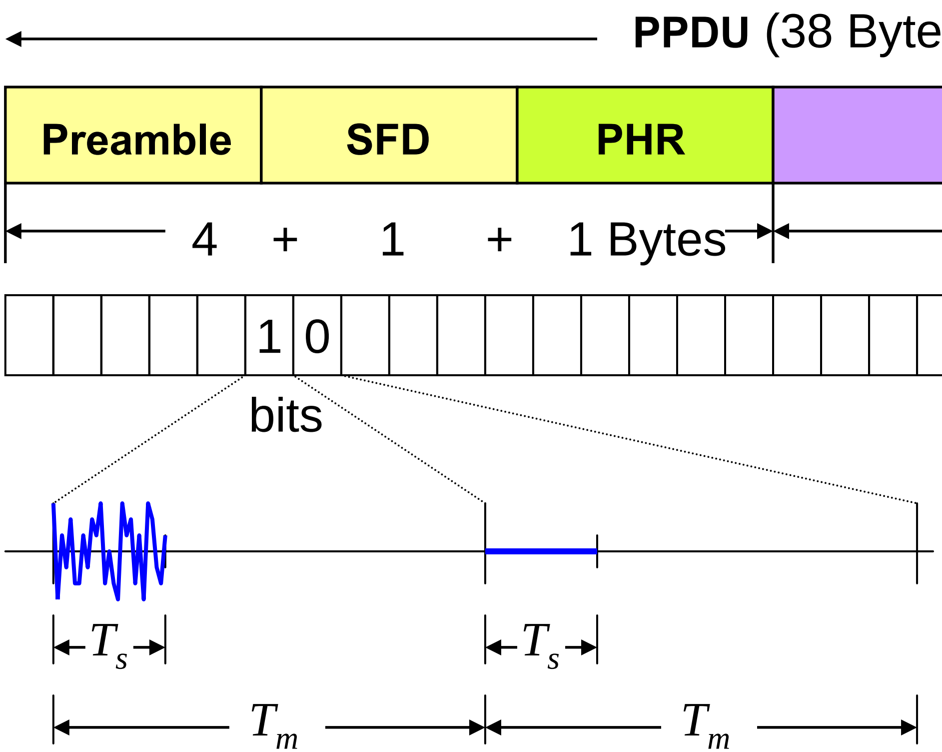
5.2. Size and Form Factor

Values

- **PHY–level (130 nm technology)**
  - RF part of transceiver => 0.3 mm^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

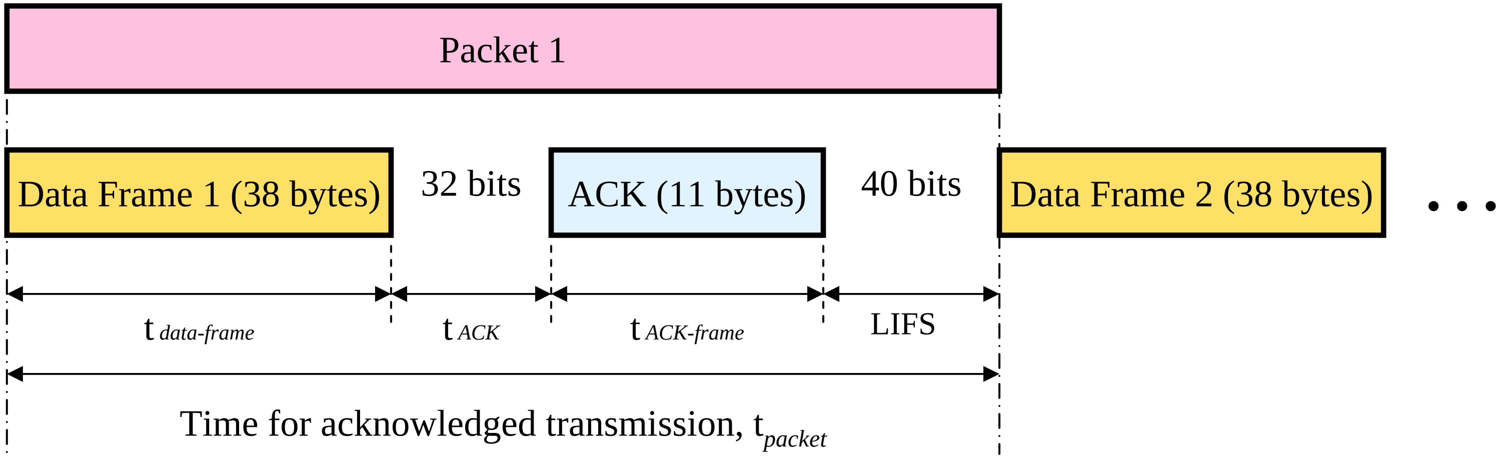
∴ Duty cycle, D = 1/6

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

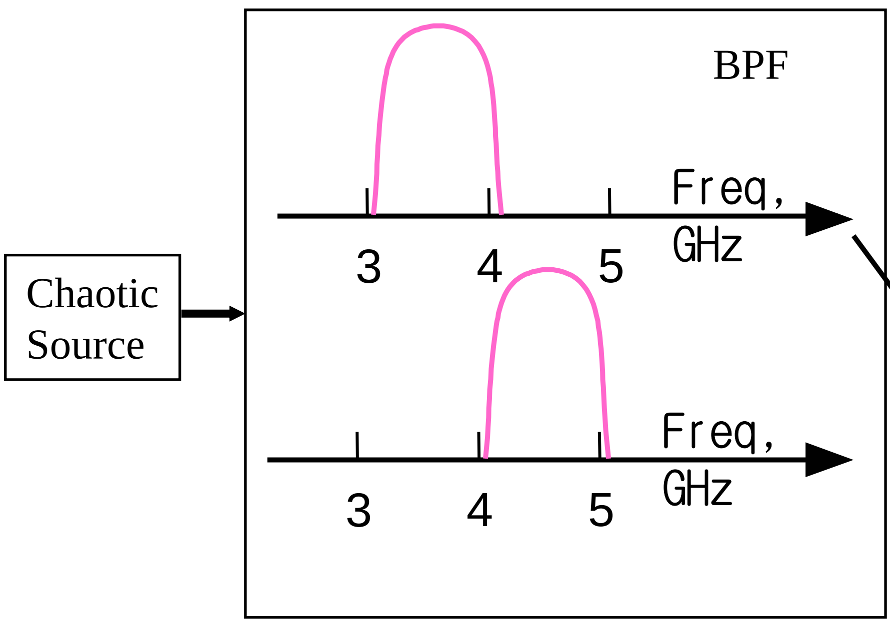
Three Methods to Achieve SOP

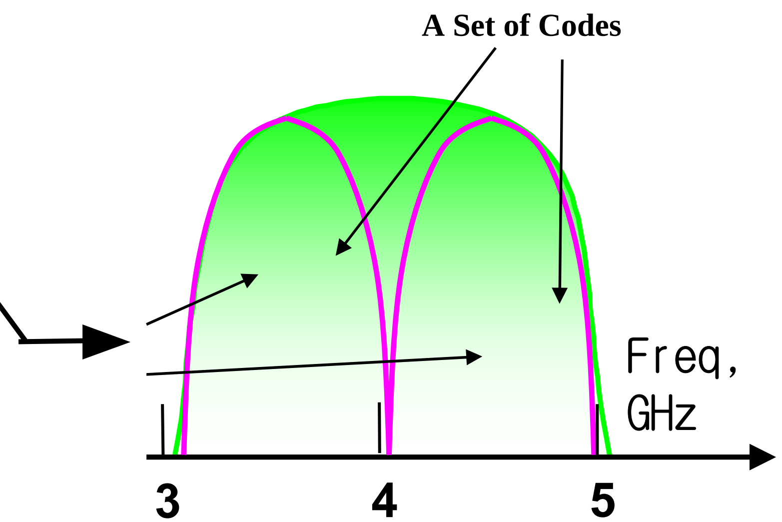
- **Frequency division multiplexing (FDM)**
  - Four independent frequency channels on 500 MHz guaranties simultaneously operating four piconets.
- **Code division multiplexing (CDM)**
  - Deployed a class of unipolar codes (0,1) having ZCD/LCD property maintain orthogonality among piconets.
  - Four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





- 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

- **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
- **Characteritics 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

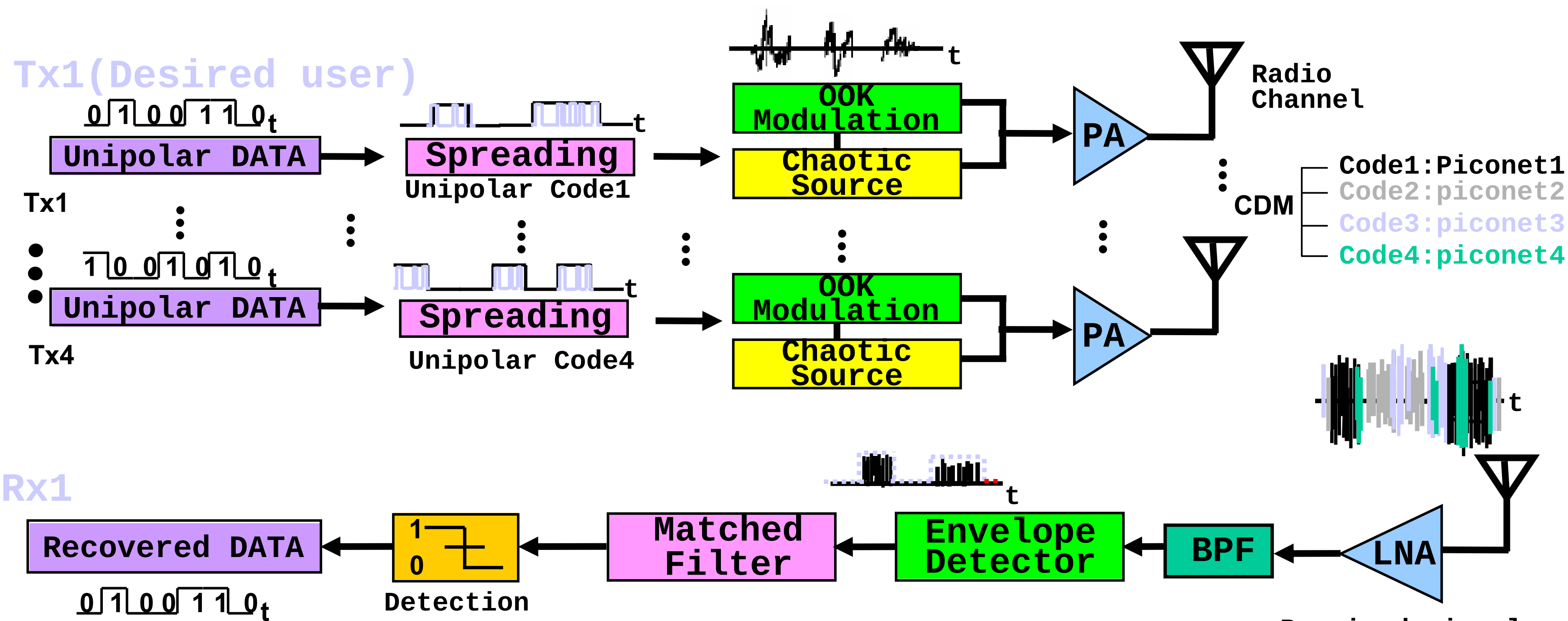
    code a=[1 0 0 1 0 0]

    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 $N/M = W$

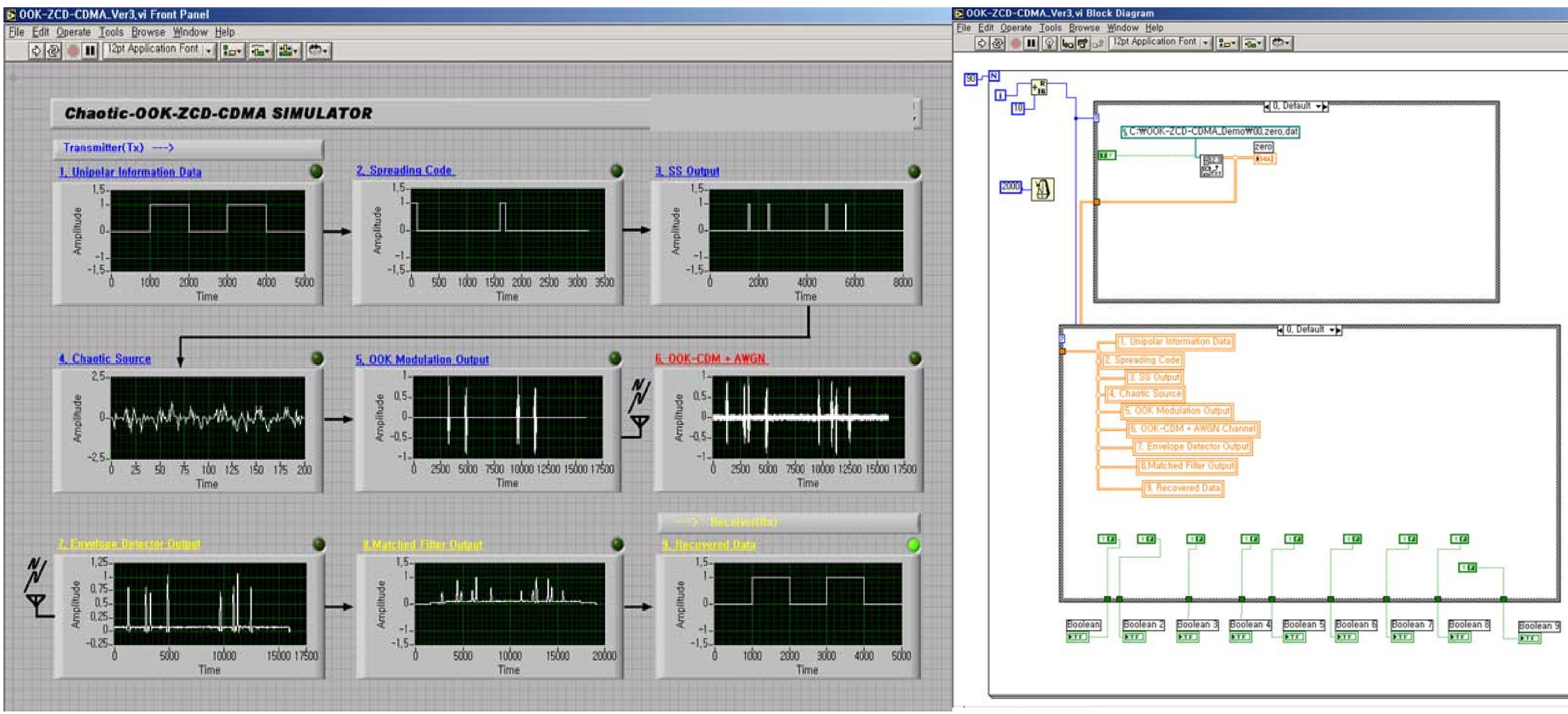
5.4. Simultaneously Operating Piconets

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



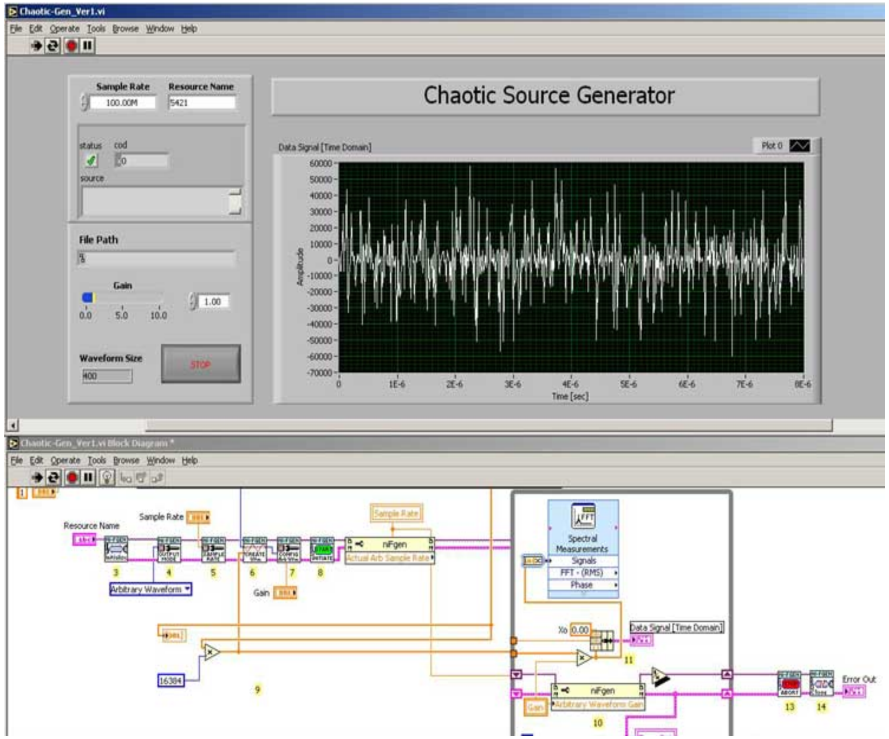
5.4. Simultaneously Operating Piconets

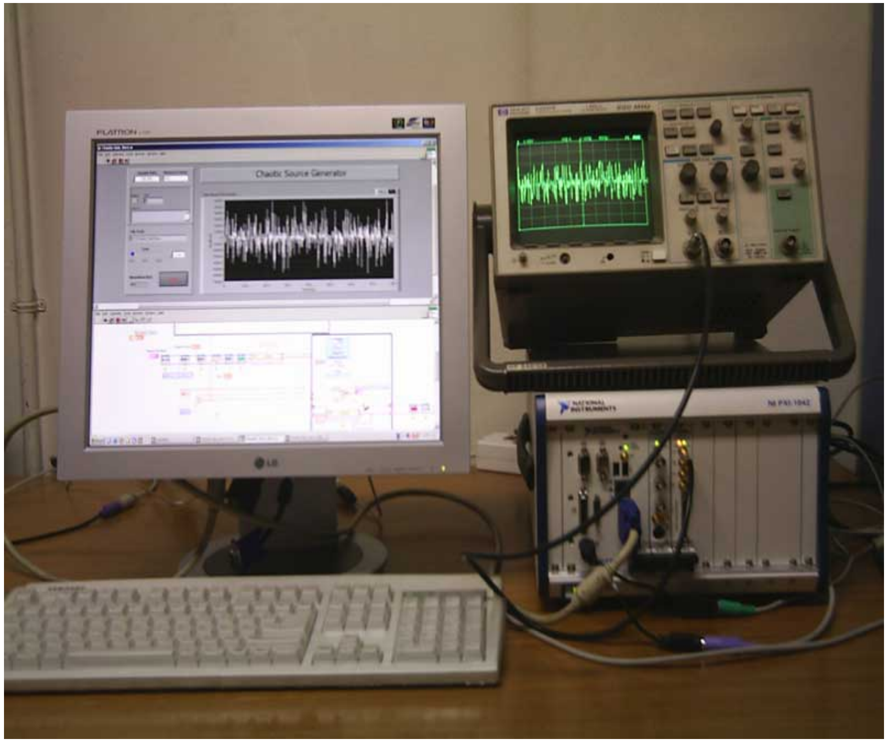
Baseband Chaotic-OOK- ZCD-CDM



5.4. Simultaneously Operating Piconets

Chaotic-OOK-ZCD-CDM

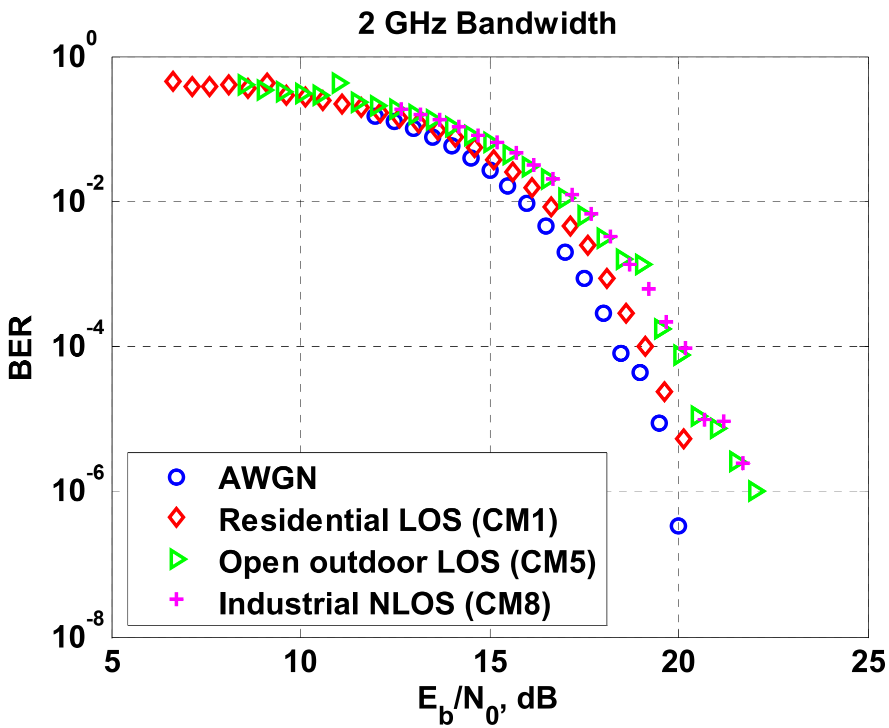




5.6. System Performance

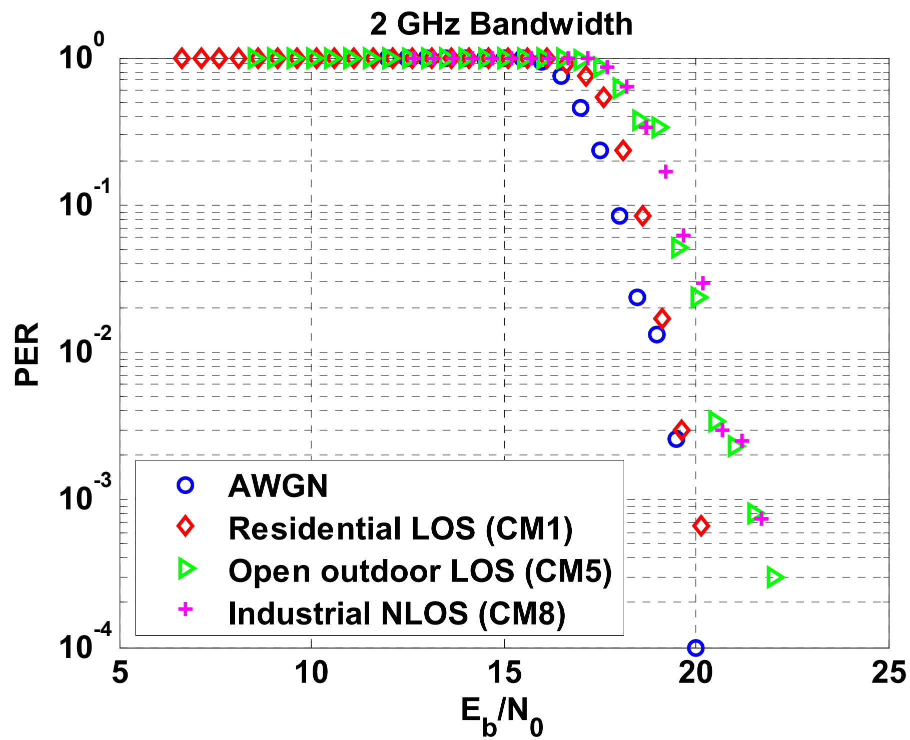
AWGN & Multipath

- BER Vs. Eb/No



AWGN & Multipath

- PER Vs. Eb/No



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

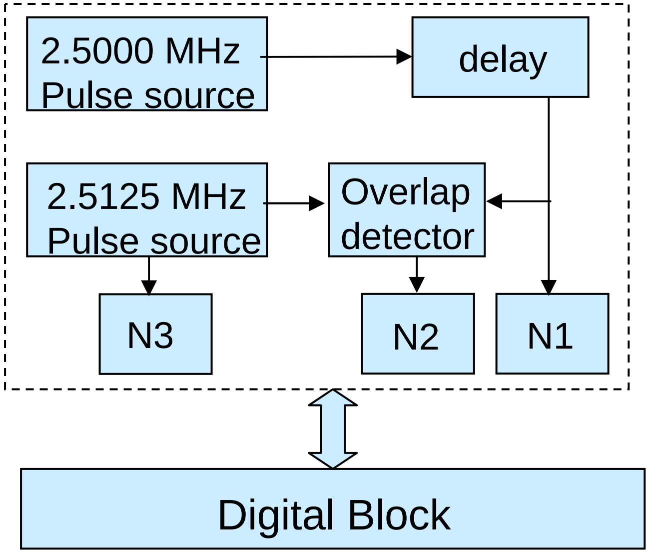
5.6. System Performance

Values: Bit Rate and Distance

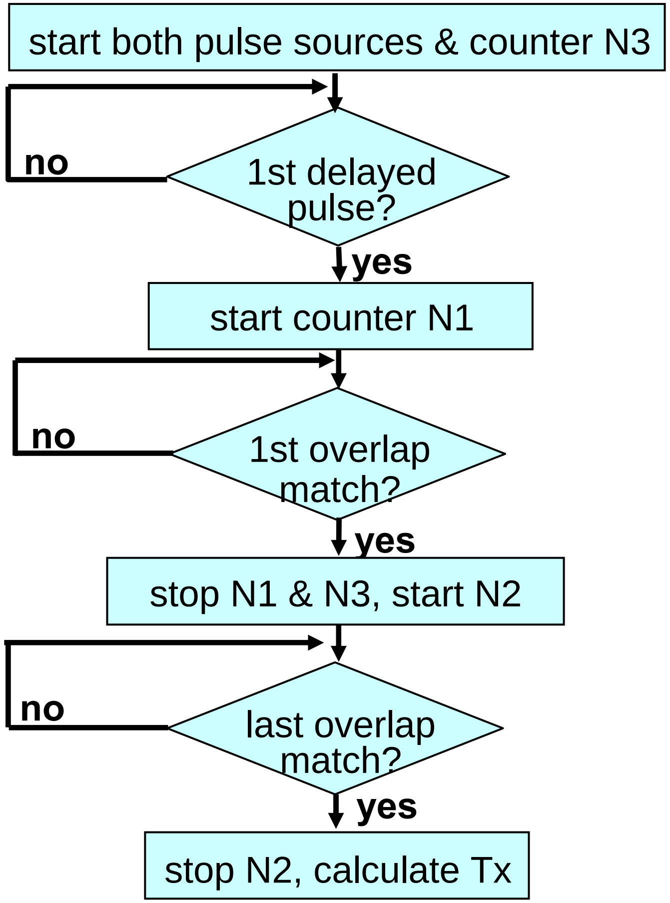
Xo (Mbps)	Channel	M+L1+L2 (free space), dB	PL, dB	PL_0, dB	n	Distance, m
2.44	AWGN	76.27	76.27	44.43	2	39
1.63	AWGN	78.07	78.07	44.43	2	48
0.4075	AWGN	84.07	84.07	44.43	2	96

5.7. Ranging

Ranging Algorithm

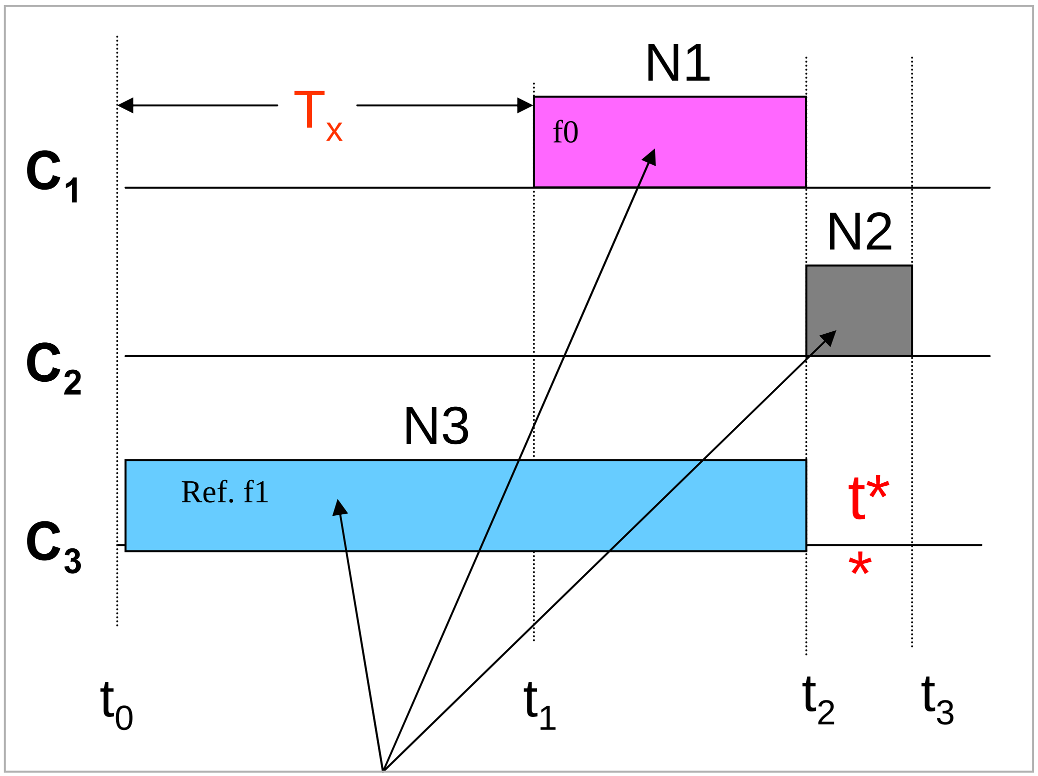


- Counter **N1** counts delayed pulses
- Counter **N2** counts overlaps between delayed pulses(2.5000 MHz) and reference pulses(2.5125 MHz)
- Counter **N3** counts reference pulses



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

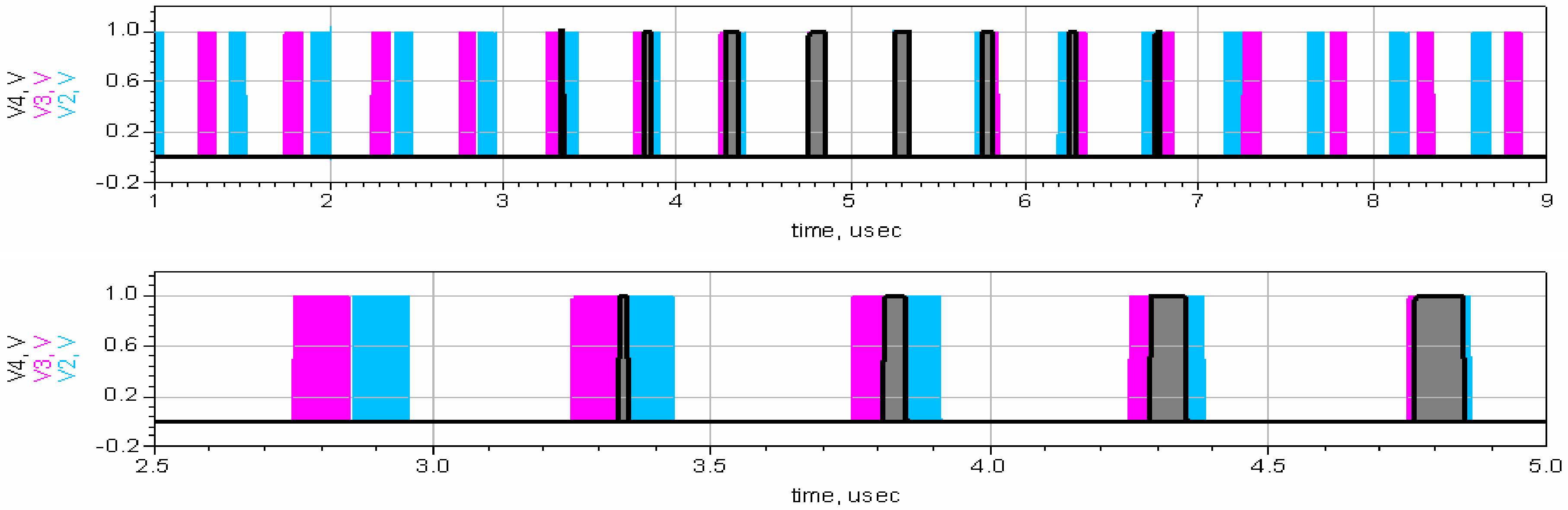
$S = 0.5*c*(T_x-\tau_0)$

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

5.7. Ranging

Values: Range

System supports ranges:

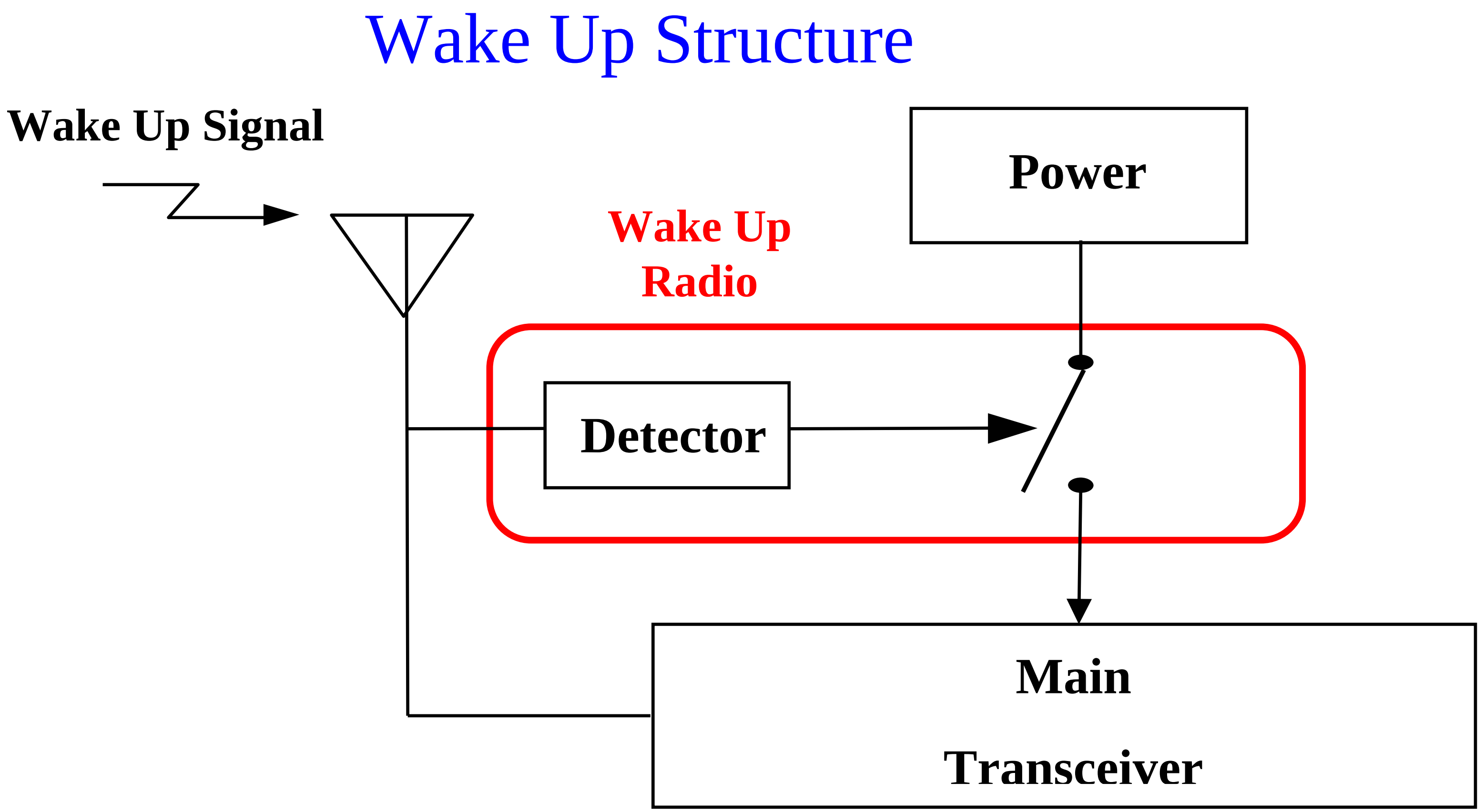
- Range from 0 to 30 m (typical)
- Range up to 100 m (max 10 kbps data rate)

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 [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

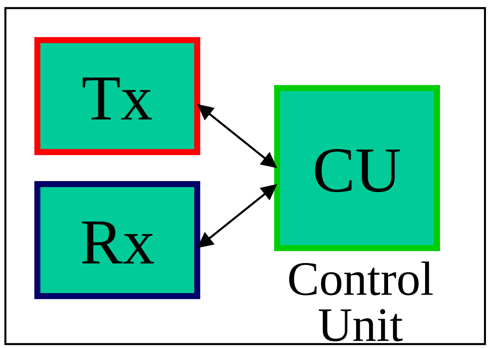
Sleep and Wake-up Scheme



5.11. Power Consumption

Power Calculation

Transceiver



Average power consumption P_{av}

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

$$P_{Tx} = P_e / \eta$$

$$P_{Rx} = P_e / \eta_{best}$$

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

Operation time T_{oper}

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

P_e is emitted power,

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 the feasibility of DCC technology.

DCSK: Compatible Modulation Scheme for Direct Chaotic Communication

DCSK Modulation

DCSK

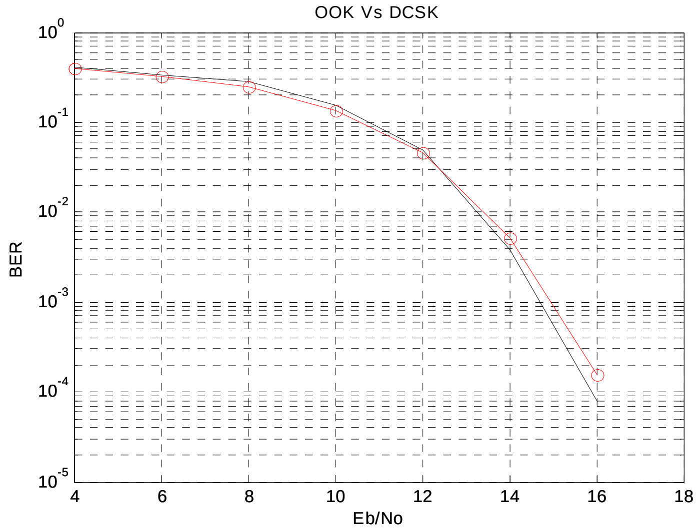
- **Differential Chaos Shift Keying (DCSK)**
  - One of the modulation scheme as an alternative to OOK
  - DCSK transmits a reference chaotic pulse and an information data pulse depending on whether information bit 1 (same ref. chaotic pulse) or 0 (inverted of the chaotic pulse) is being transmitted
  - 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

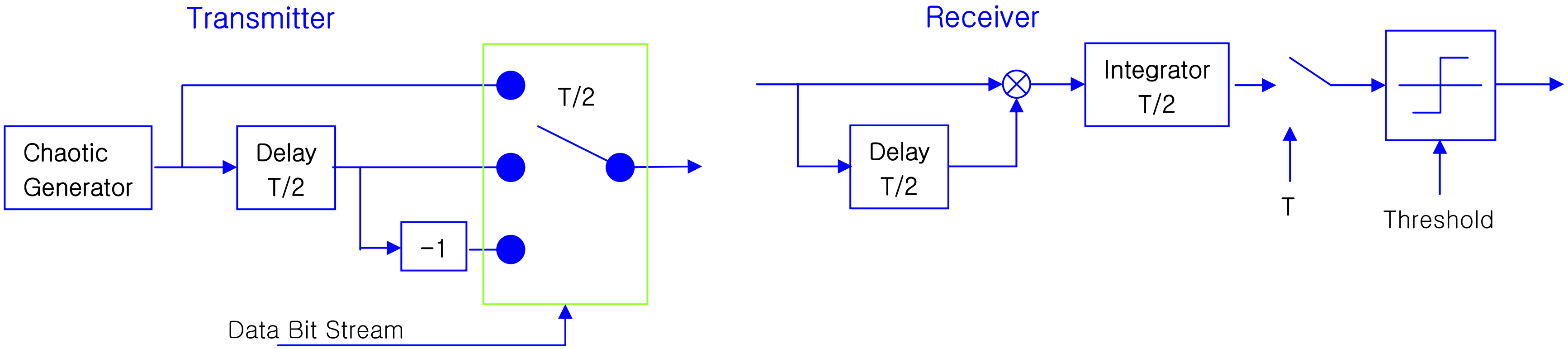
DCSK Modulation

Principle

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

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

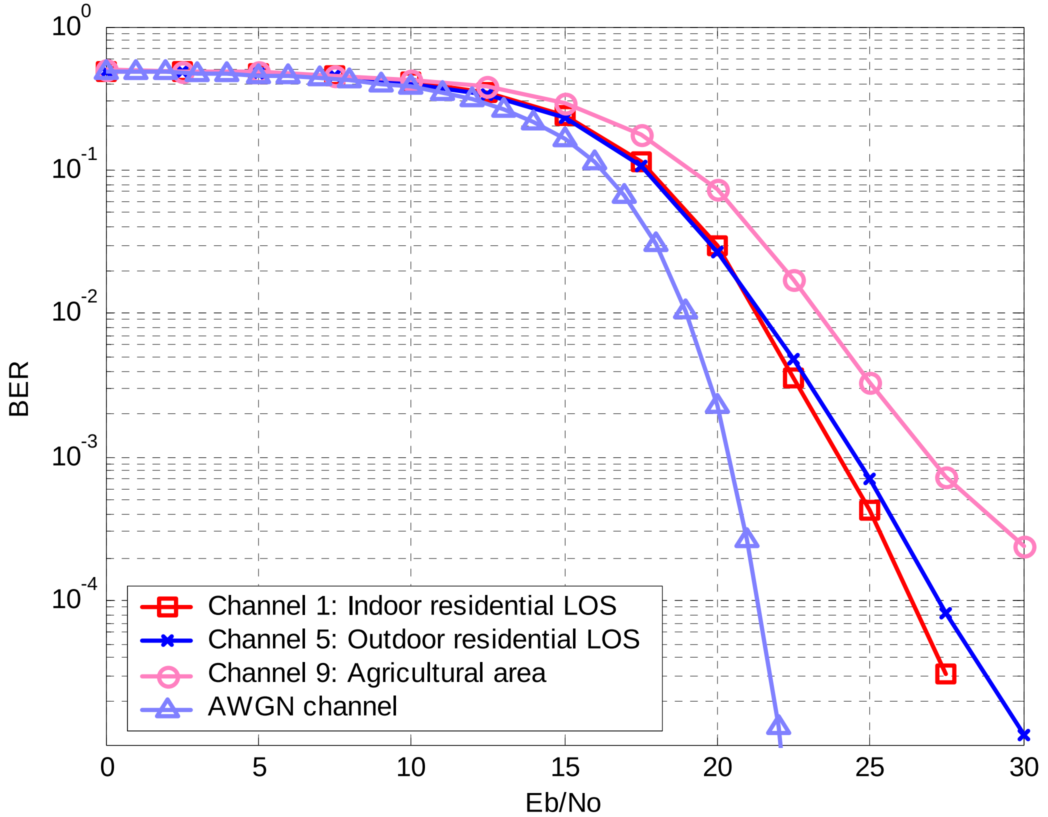




DCSK Modulation

System Simulation Results

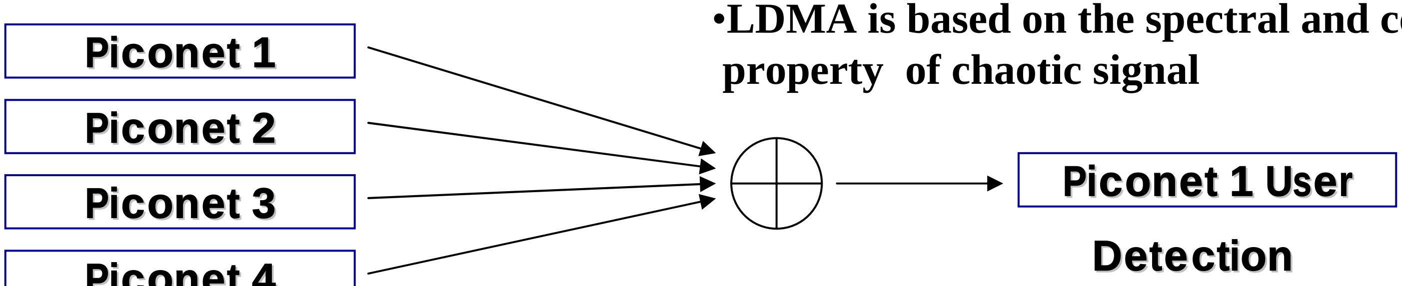
- **AWGN & Multipath**

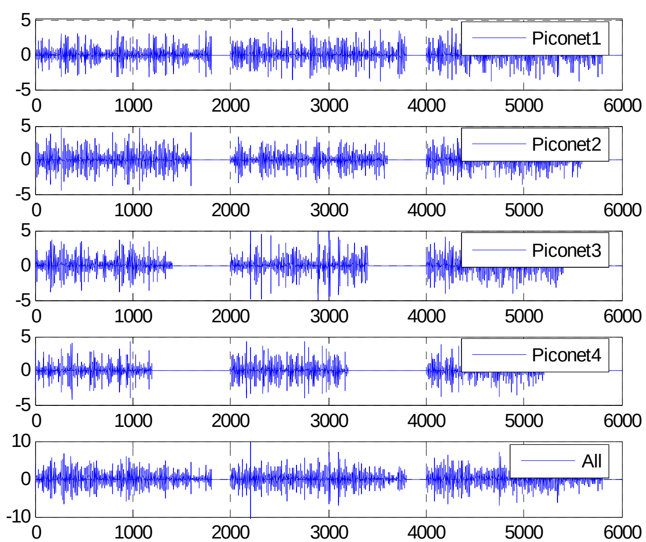


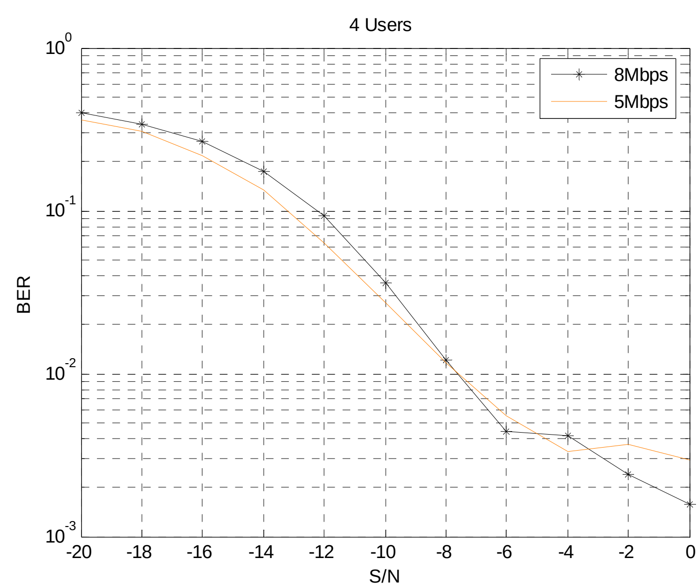
DCSK Modulation

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





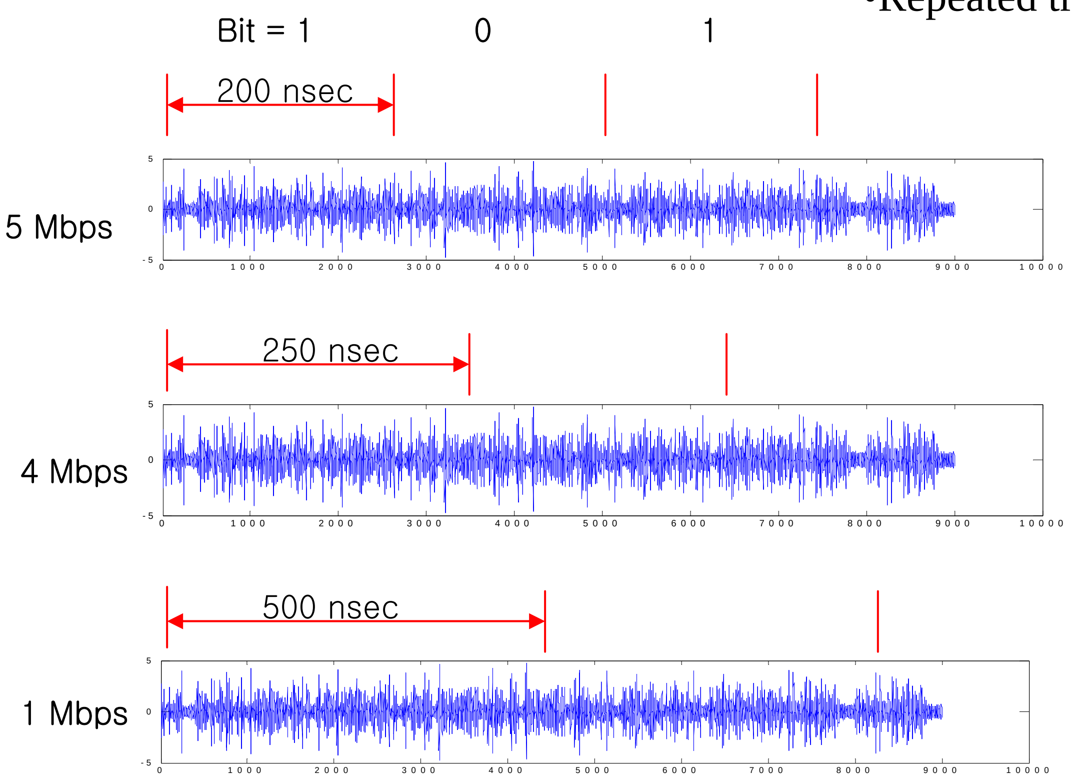


DCSK Modulation

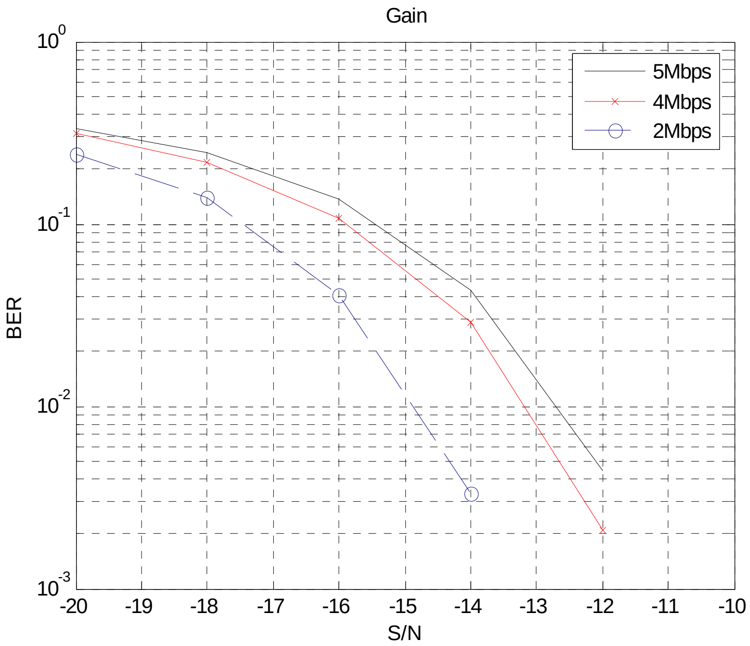
Scalability

Scalability can be achieved using

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



Chaotic Gain in DCSK



MCS-DCSK Modulation

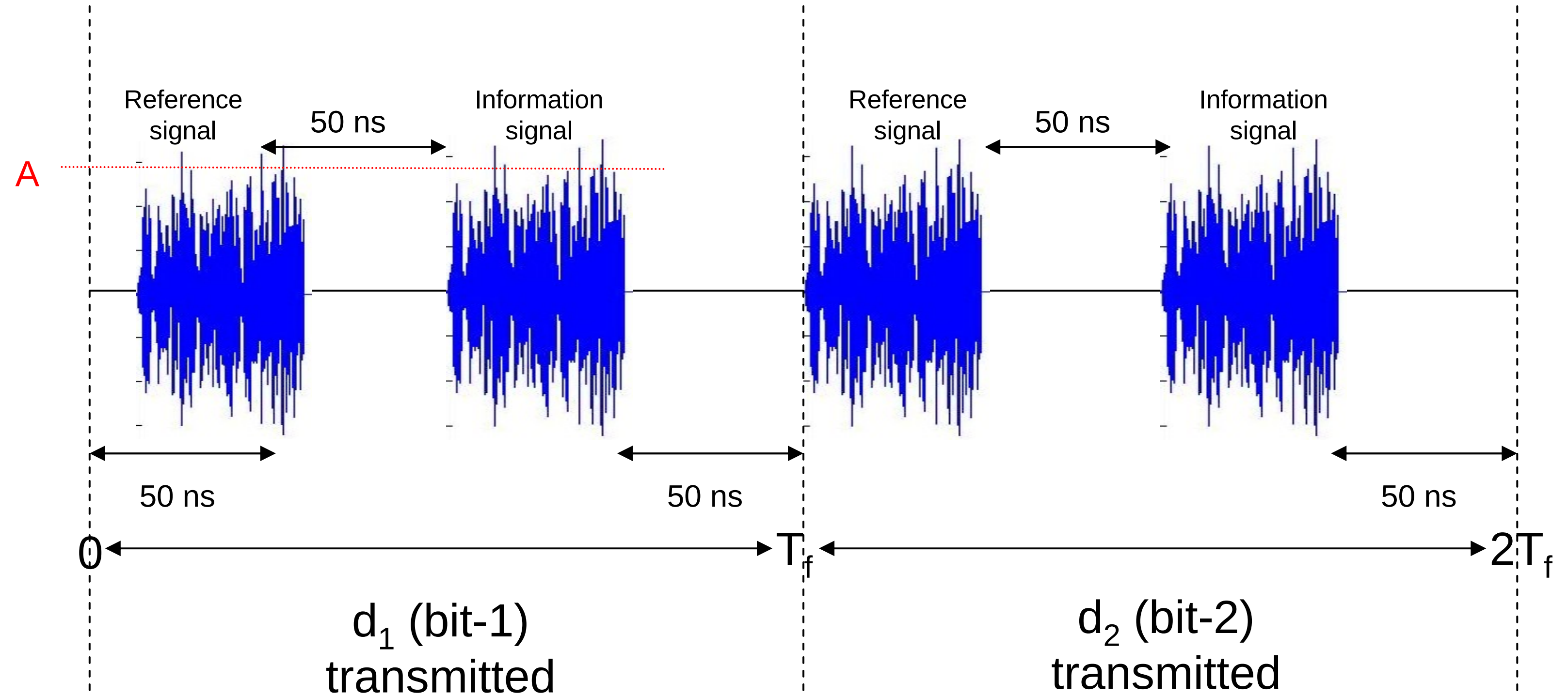
Combination of MCSK TH-IR with DCSK

- **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], $d_i \in (-1,1)$

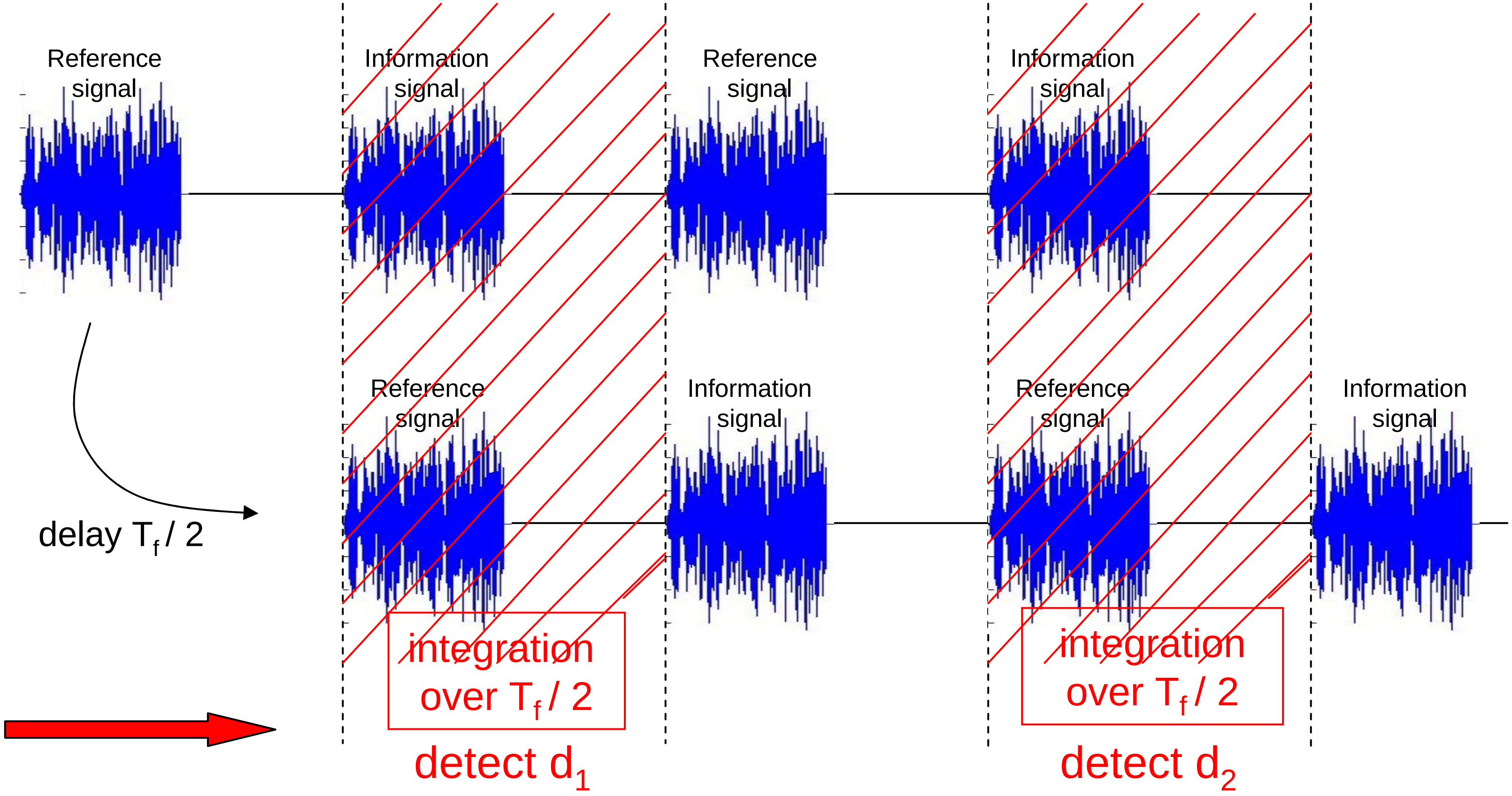


where ***info. signal = sign(d_i) x ref. signal***

MCS-DCSK Modulation

DCSK RX Signal

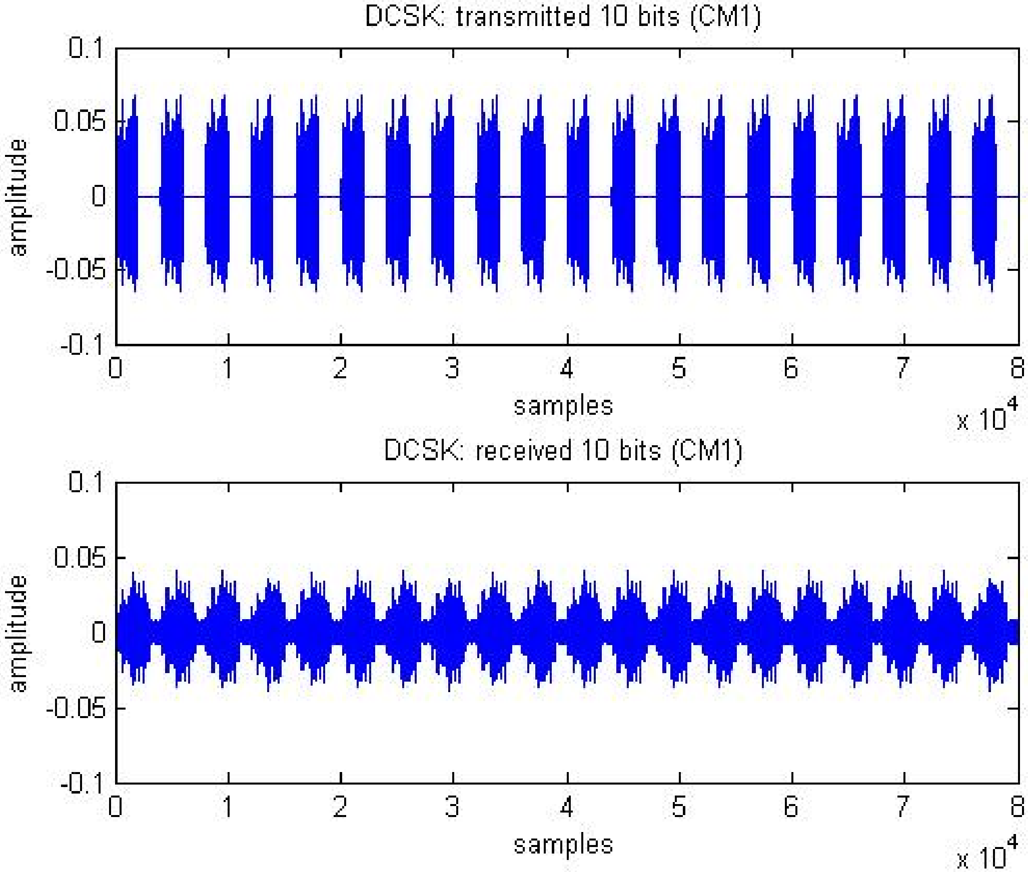
DCSK receiver – no AWGN, no MP fading



MCS-DCSK Modulation

DCSK TX and RX Signal

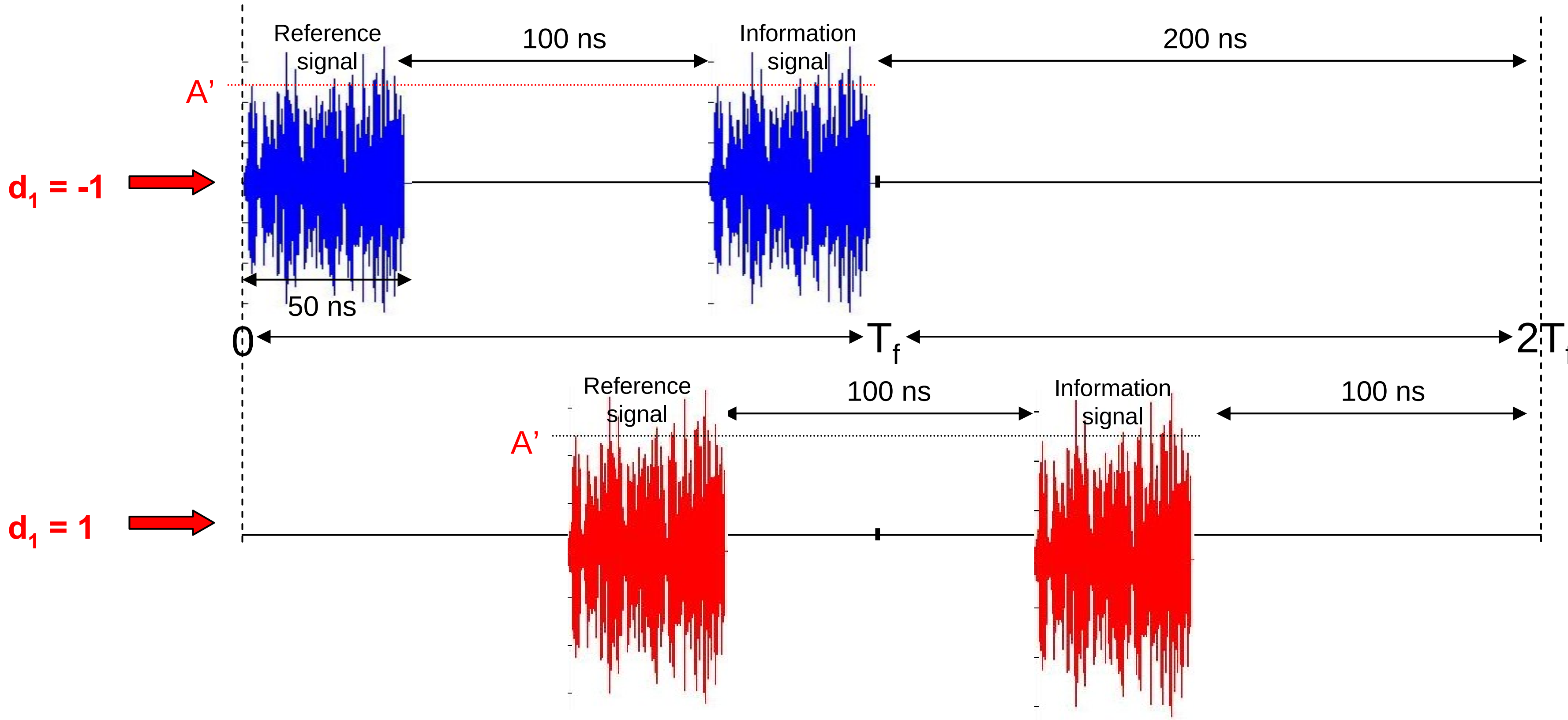
DCSK: Transmitted and received signals (CM1, no AWGN)



MCS-DCSK Modulation

MCS-DCSK TX Signal

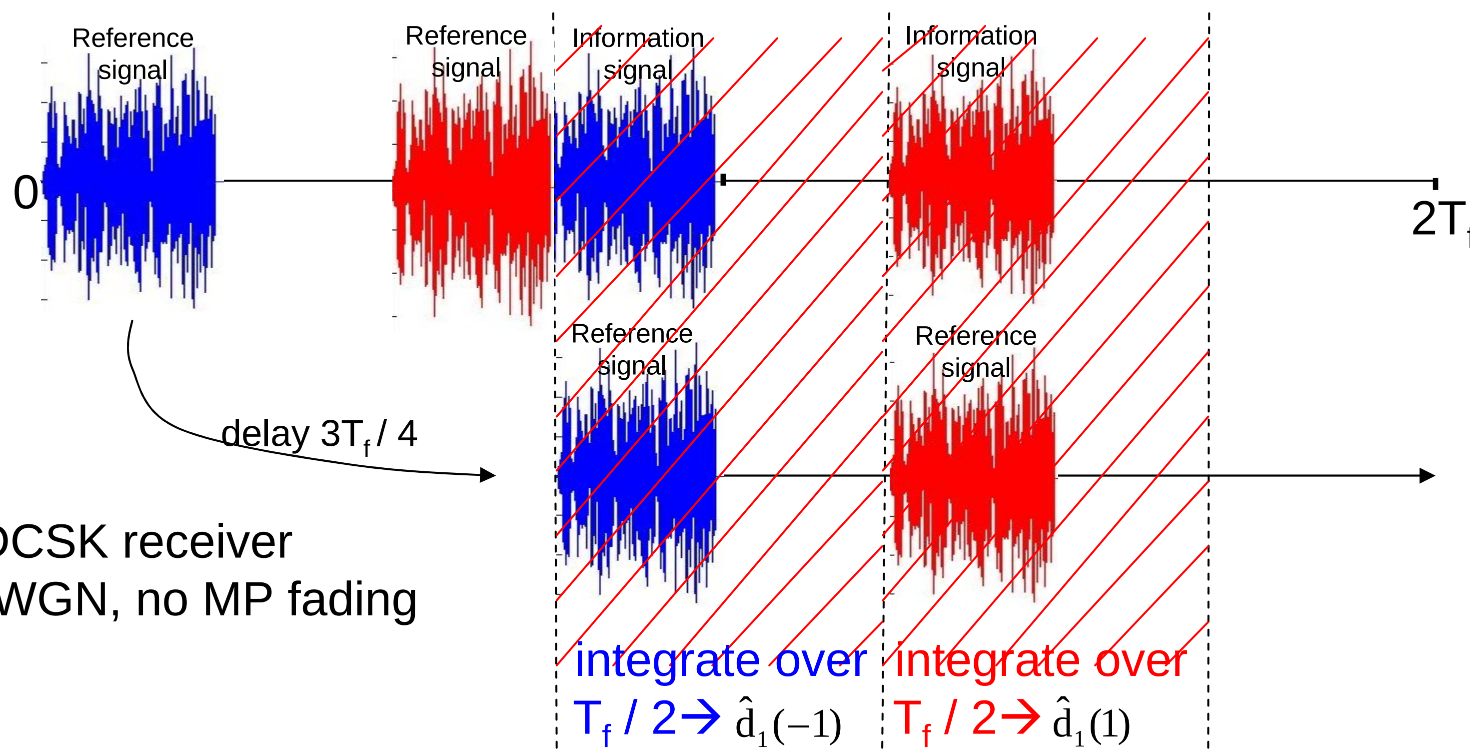
MCS-DCSK transmitting d=[d1 d2], di ε (−1,1)



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

MCS-DCSK Modulation

MCS-DCSK RX Signal



MCS-DCSK receiver
– no AWGN, no MP fading

Decision

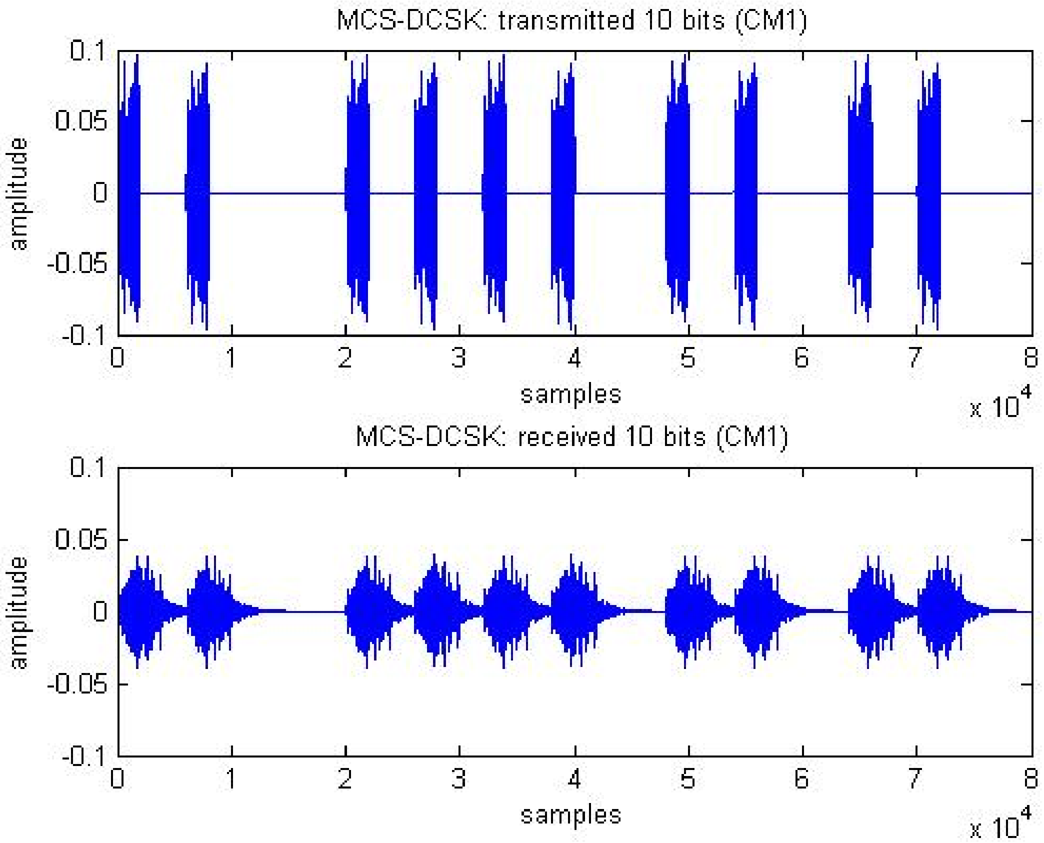
Step 1: $|\hat{d}_1(-1)| > |\hat{d}_1(1)| \longrightarrow d_1 = -1$; $|\hat{d}_1(-1)| < |\hat{d}_1(1)| \longrightarrow d_1 = 1$

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

MCS-DCSK Modulation

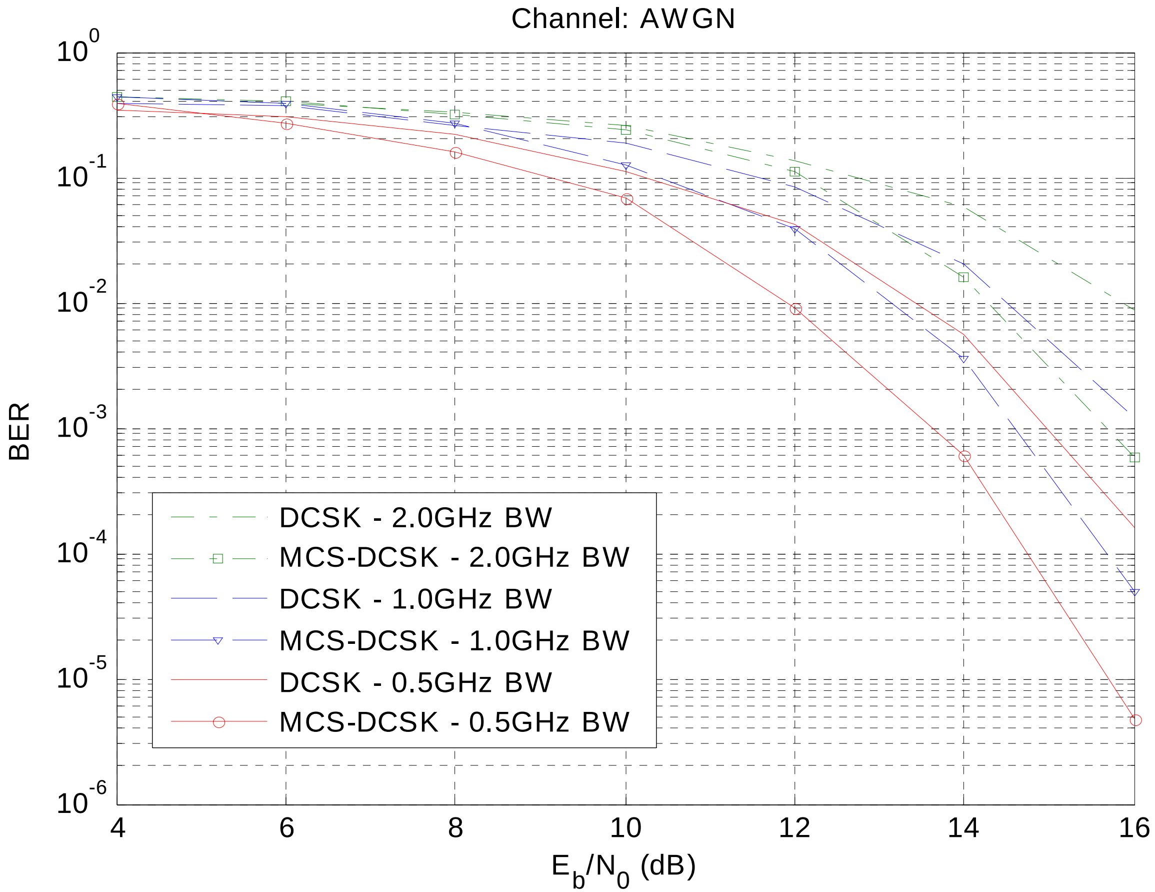
MCS-DCSK TX and RX Signal

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



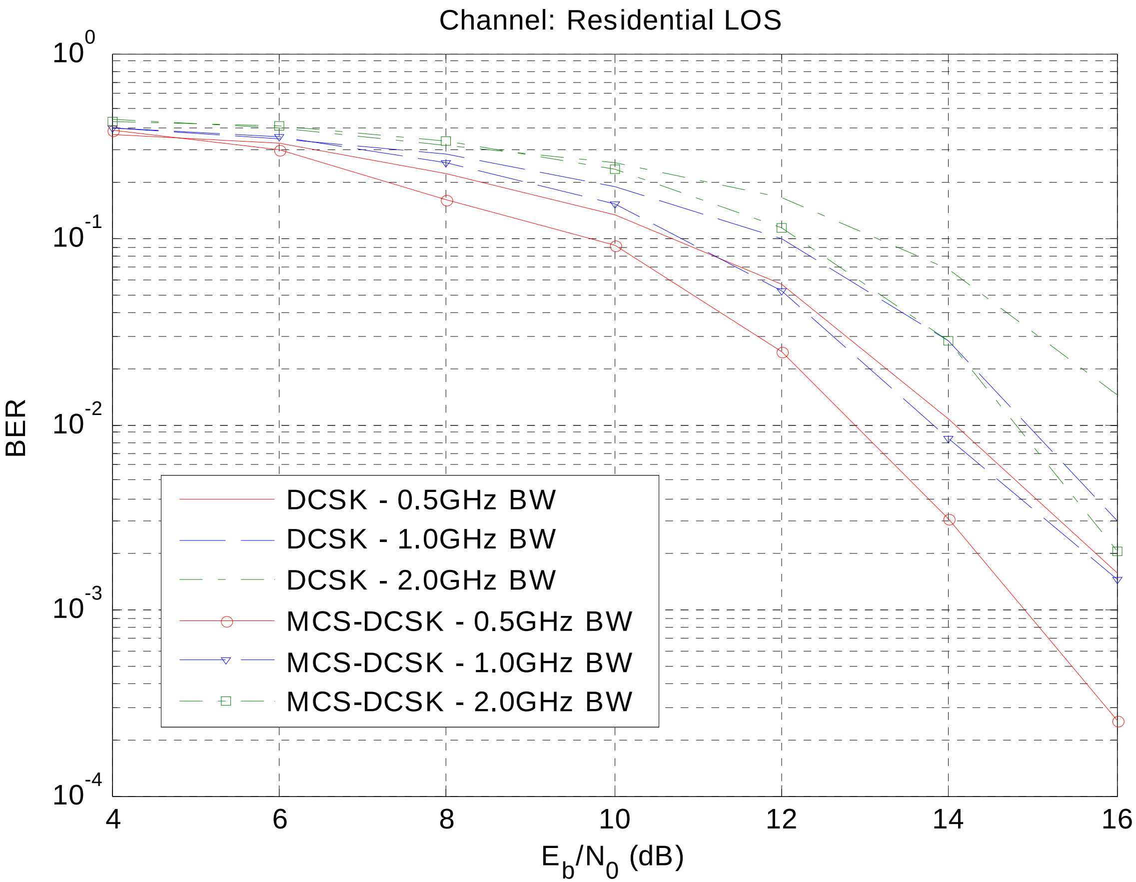
MCS-DCSK Modulation

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

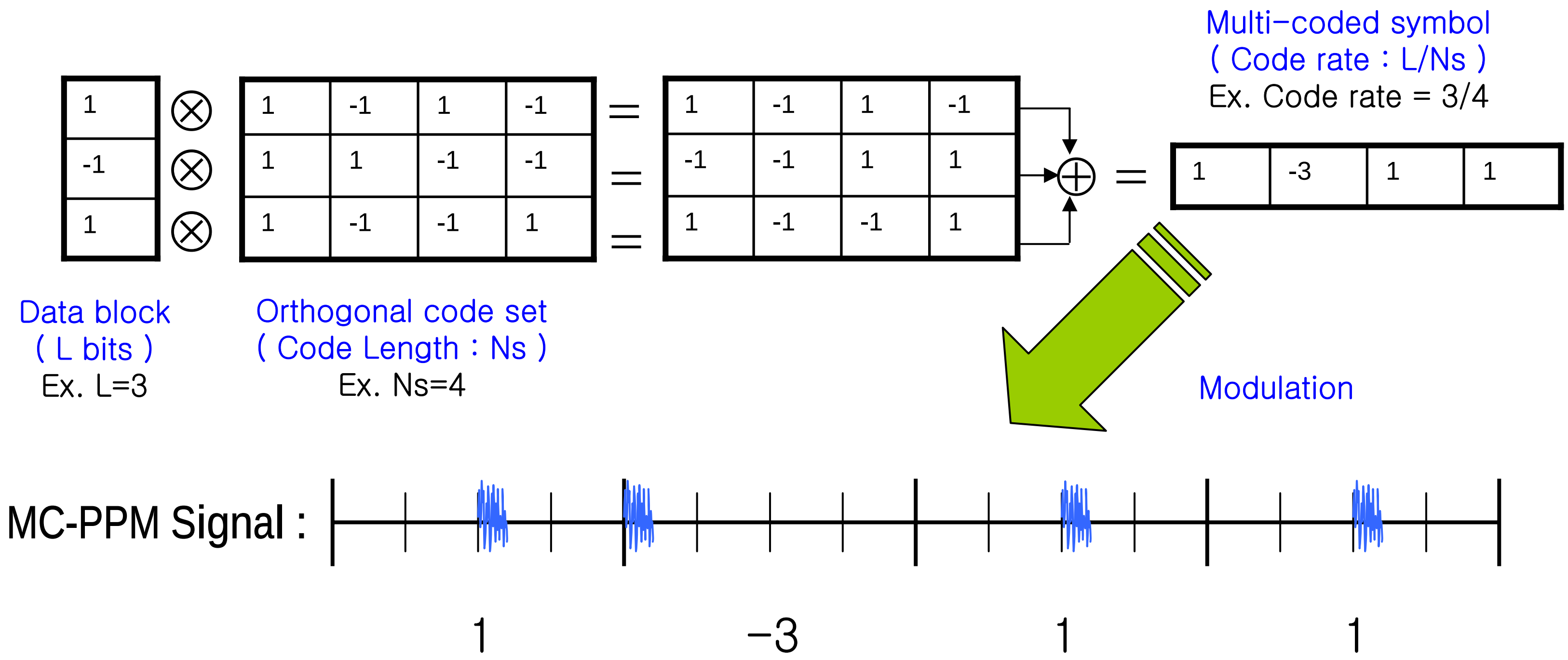
MC-PPM

- **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)**

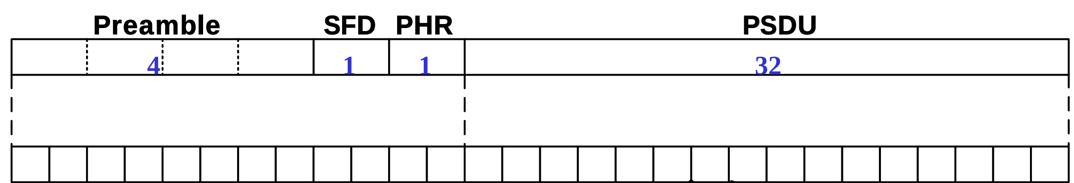


MC-PPM Modulation

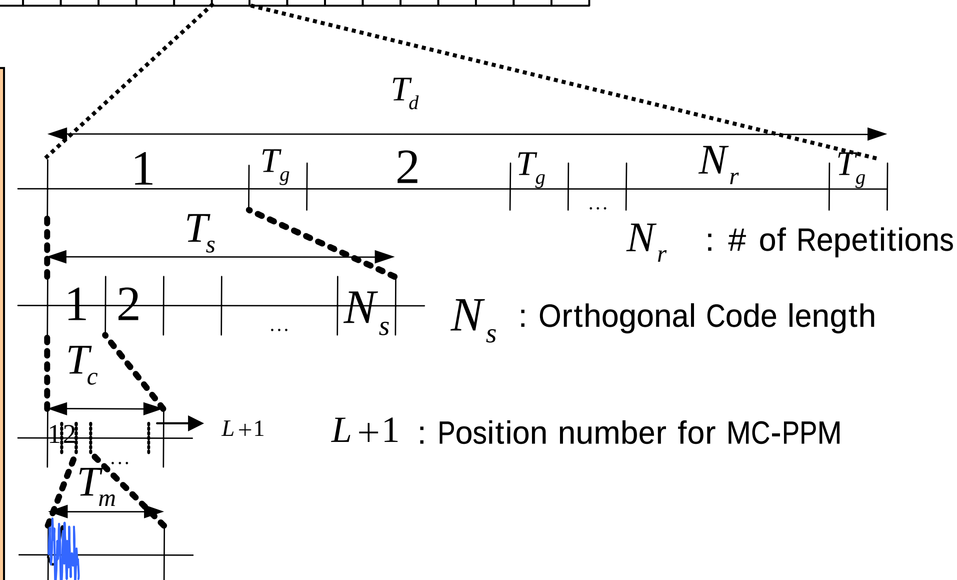
Data Frame Structure

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

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



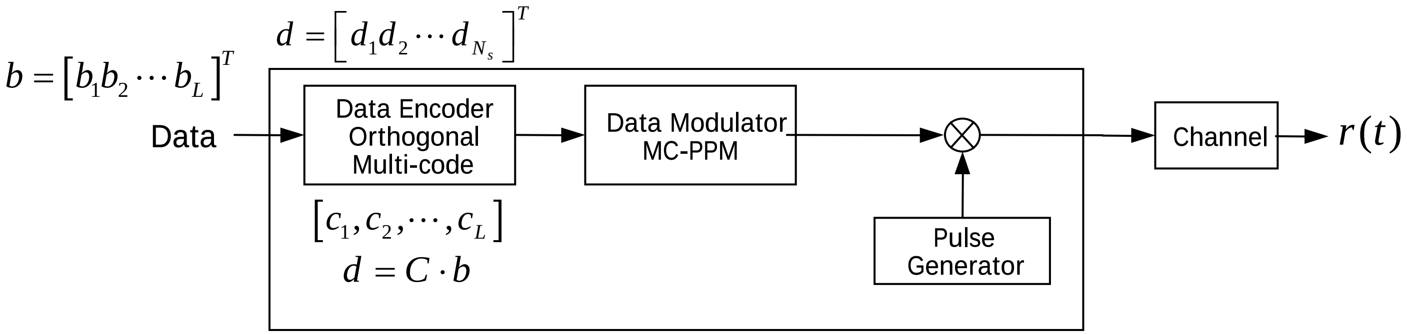
L	:	# of bits per data block
N_s	:	Orthogonal code length
N_r	:	# of repetitions
T_m	:	Pulse bin width (duration)
T_c	:	Multi-coded chip duration
T_s	:	Multi-coded symbol duration
T_g	:	Guard time for processing delay
T_d	:	Total transmit time duration of a data block



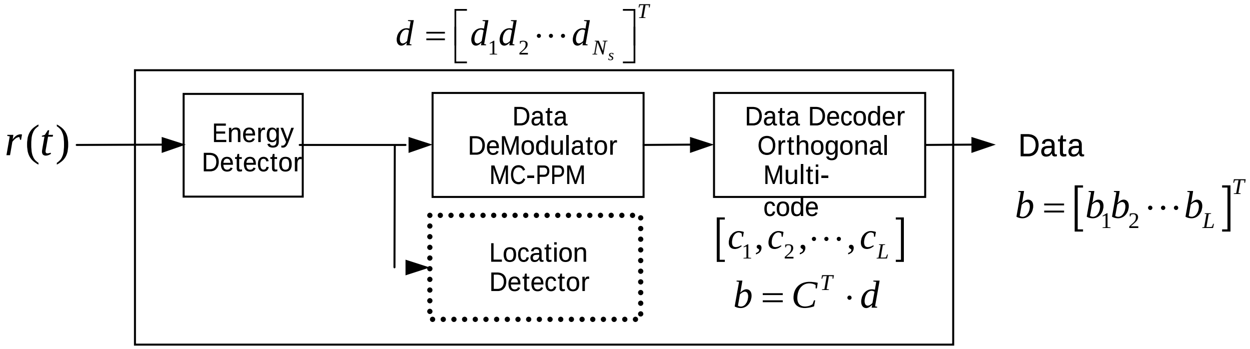
MC-PPM Modulation

Transceiver Architecture

- Transmitter



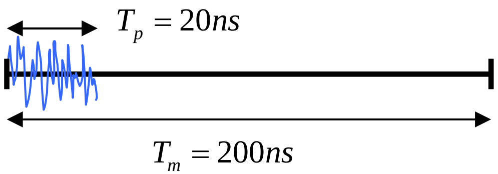
- Receiver



MC-PPM Modulation

PHY-SAP Data Rates

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

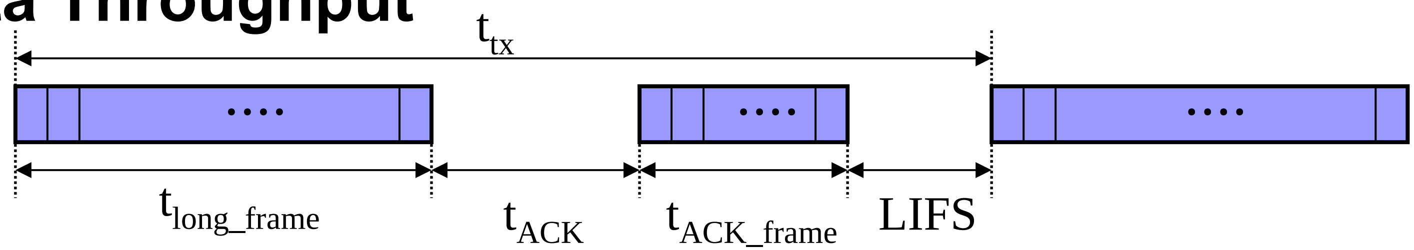


Tp	Tm	L	Ns	Nr	Tg	Data Rate
20ns	200ns	1	16	128	0ns	1.190 kbps
20ns	200ns	3	16	1	0ns	228 kbps
20ns	200ns	3	8	1	0ns	457 kbps
20ns	200ns	1	**1**	1	0ns	**2.44 Mbps**

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

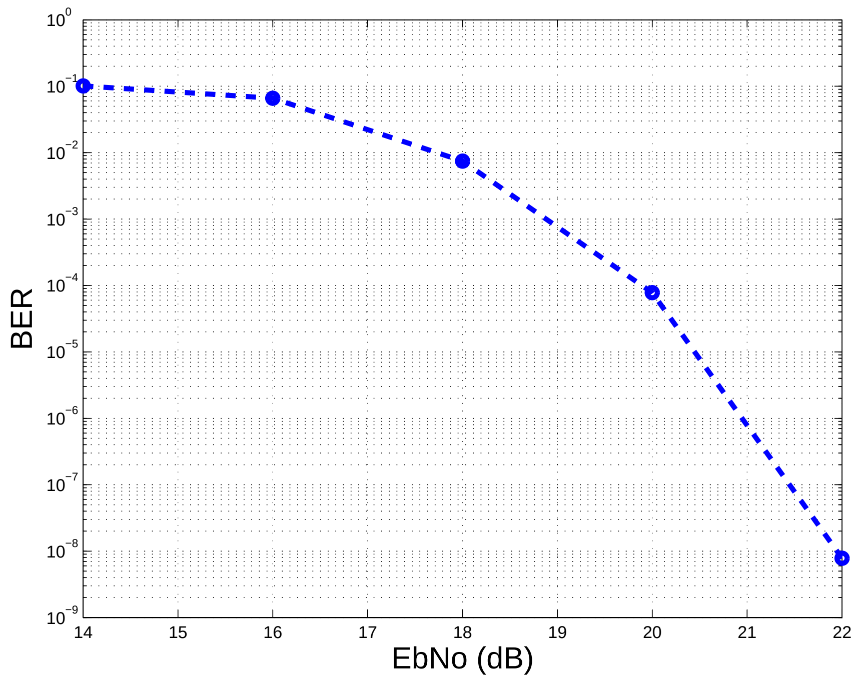
Signal Acquisition

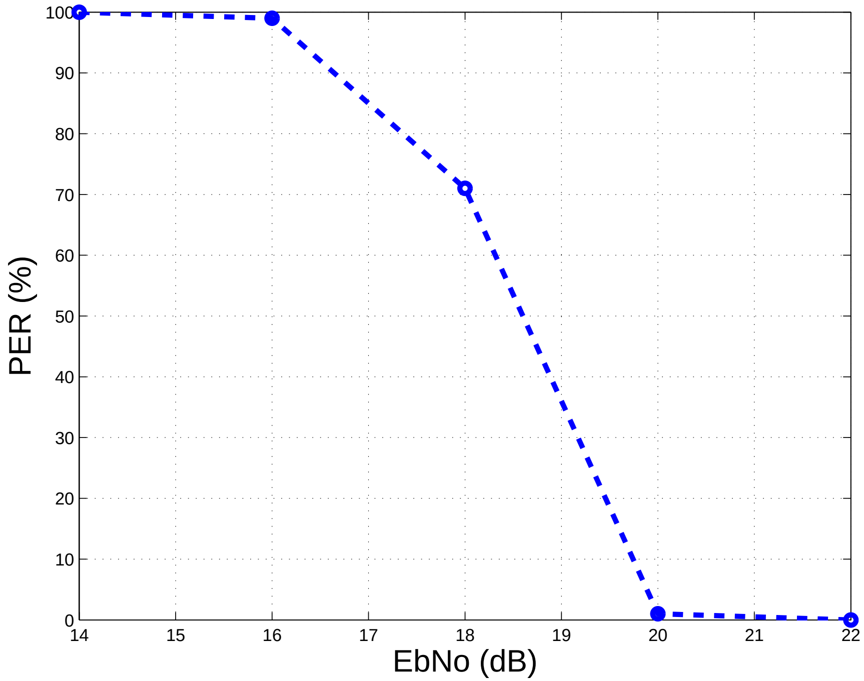
- Energy detection based acquisition
- Acquisition should be performed in order to make synchronization and demodulate data
- Synchronization : Non-coherent

MC-PPM Modulation

Performance

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

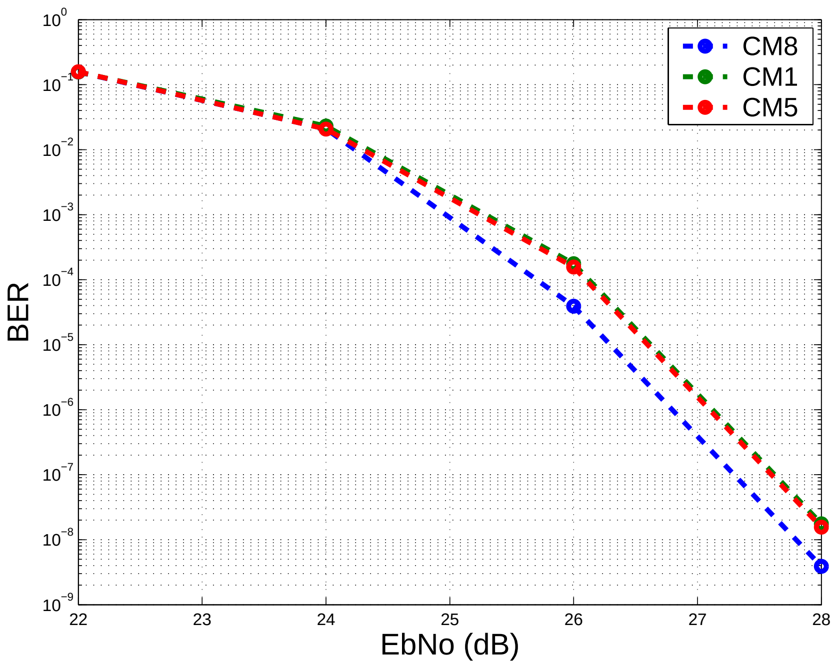


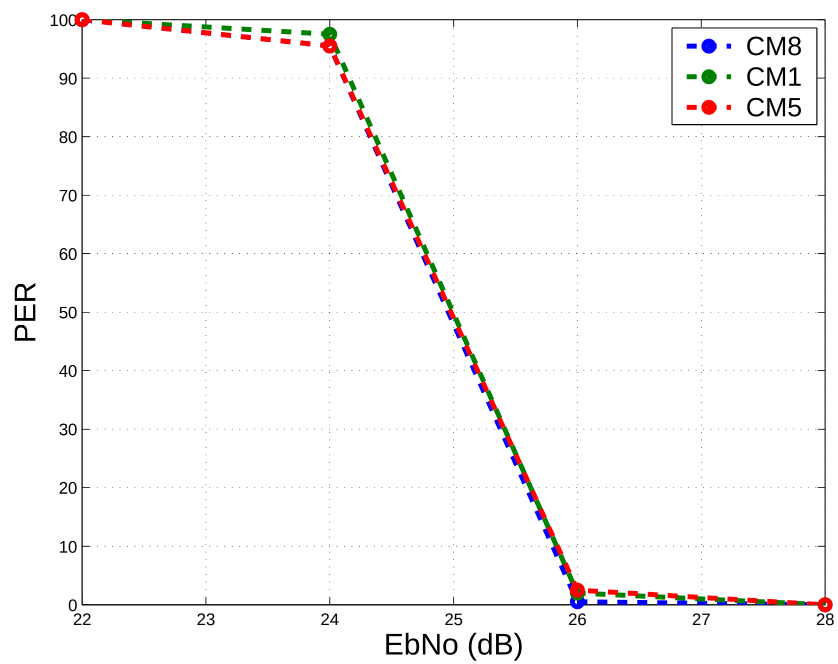


MC-PPM Modulation

Performance

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

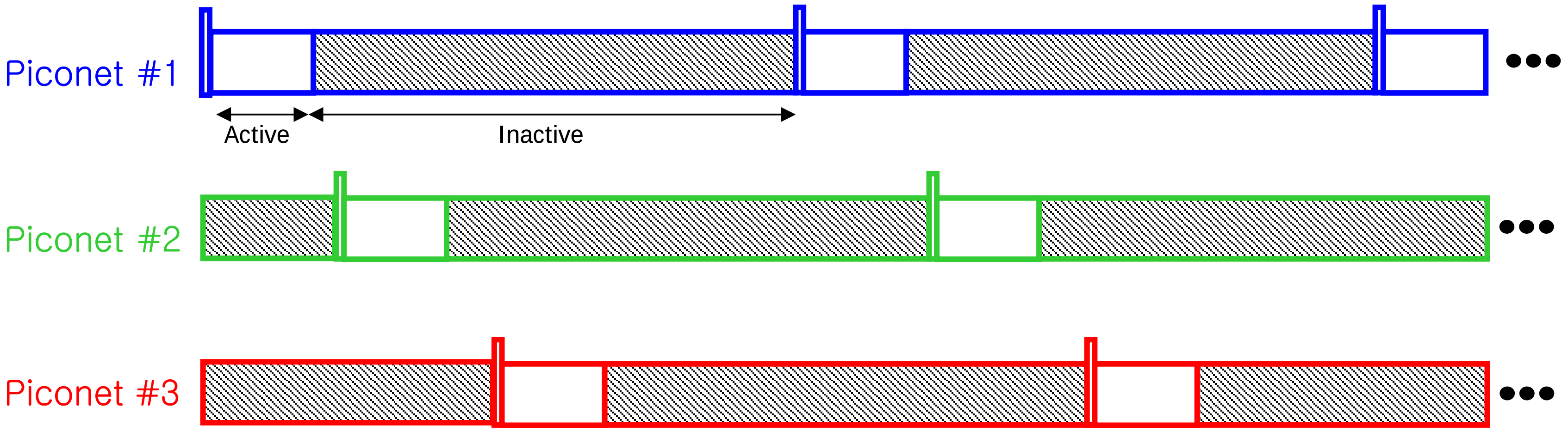




MC-PPM Modulation

SOPs

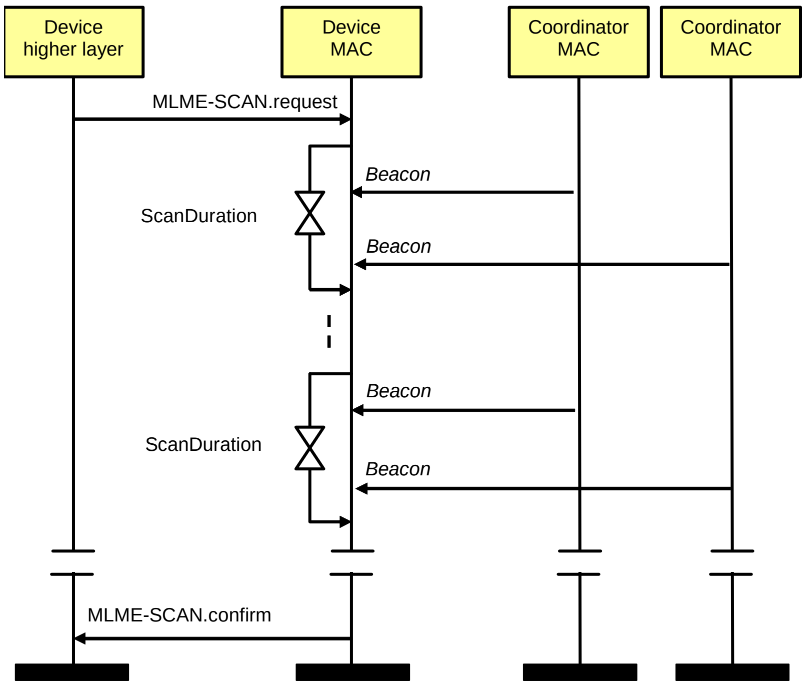
- **Time Division**
  - Configuration of SOPs
    - – Self configuration of SOPs is possible



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

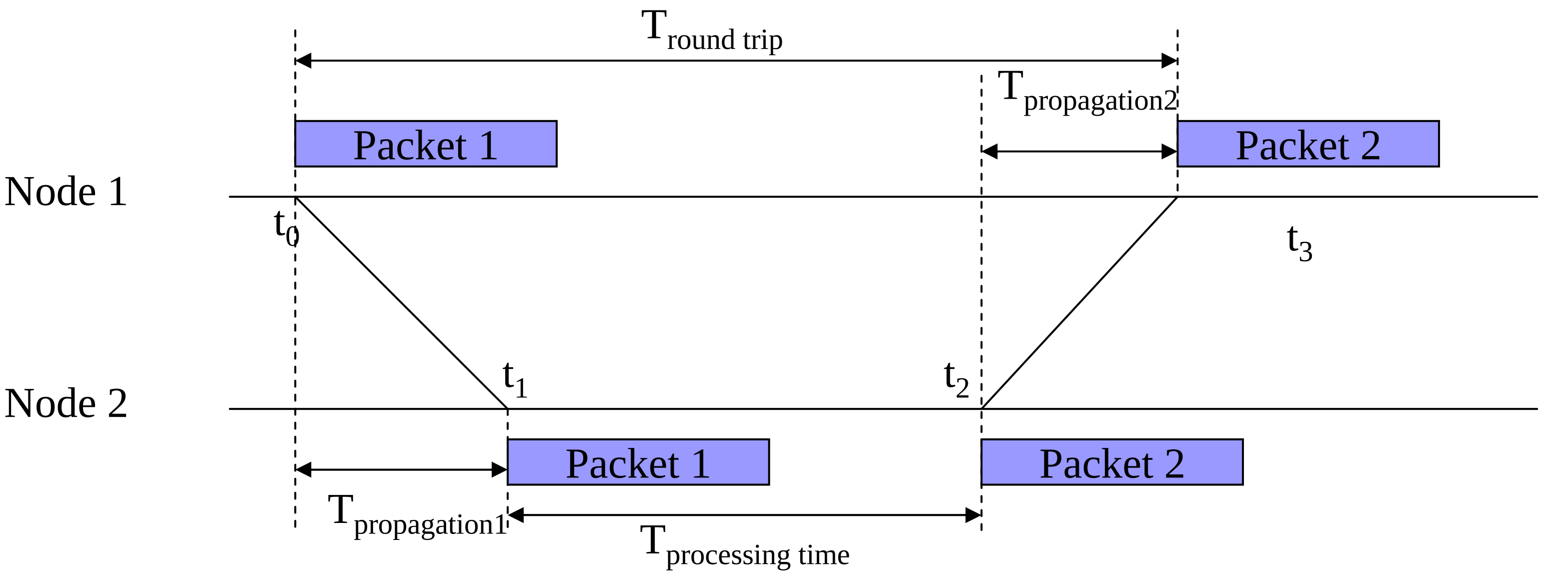
- **Link Budget & Sensitivity based on MC-PPM**

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

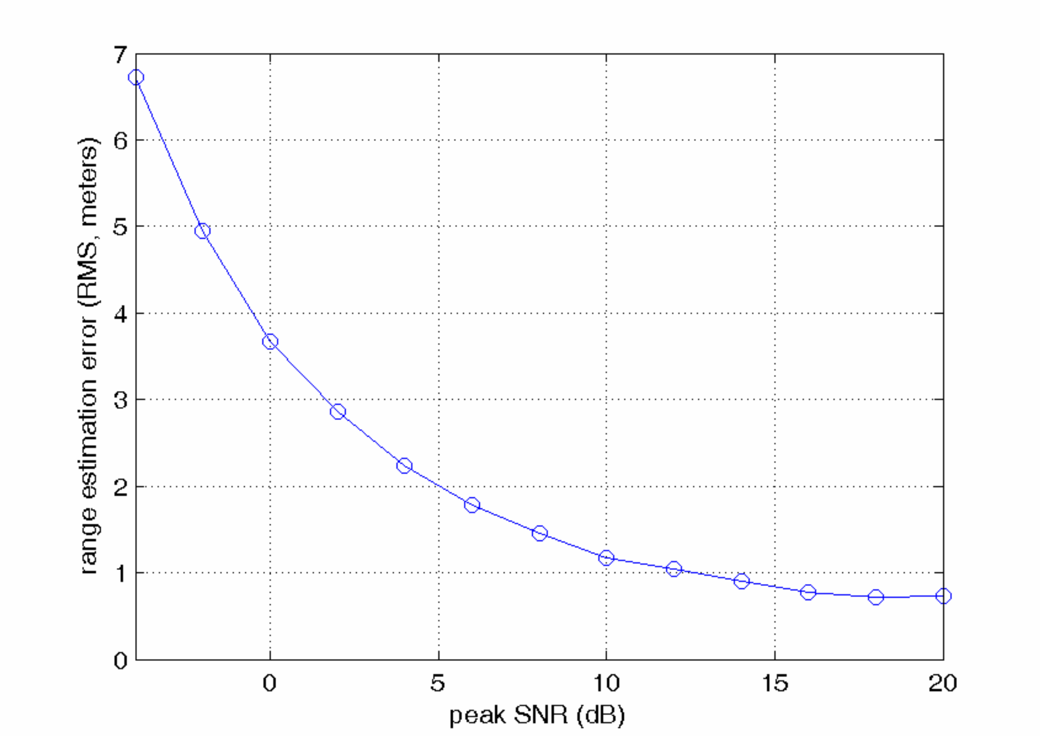
- **Scheme**
  - TOA/TWR -> Measurement of Roundtrip time



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

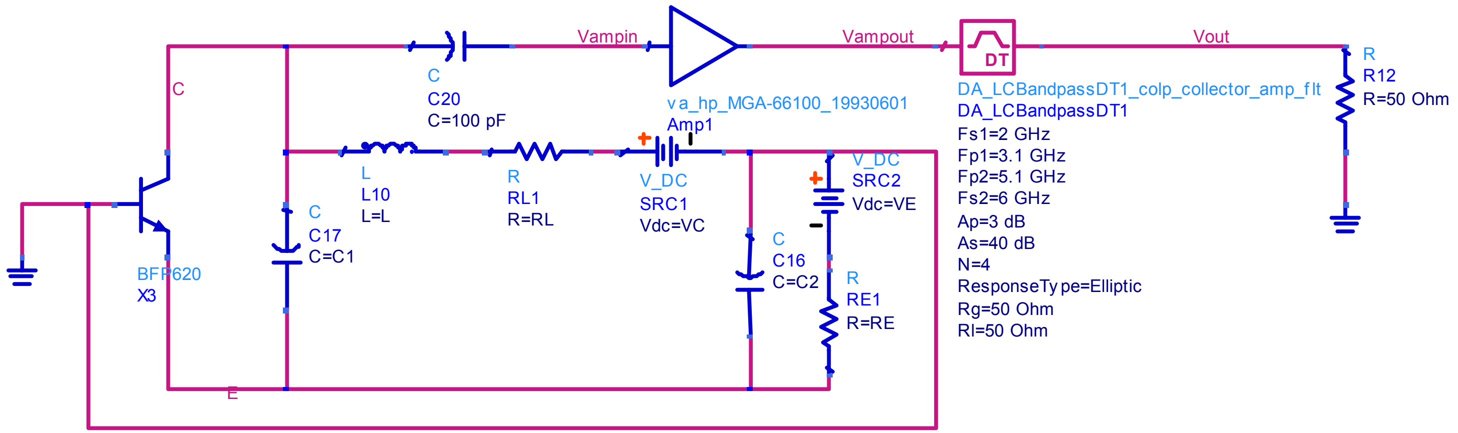
Threshold level was determined relative to noise floor

A separate envelope detector for range estimation was employed

Backup Slides

Tolerance of Components

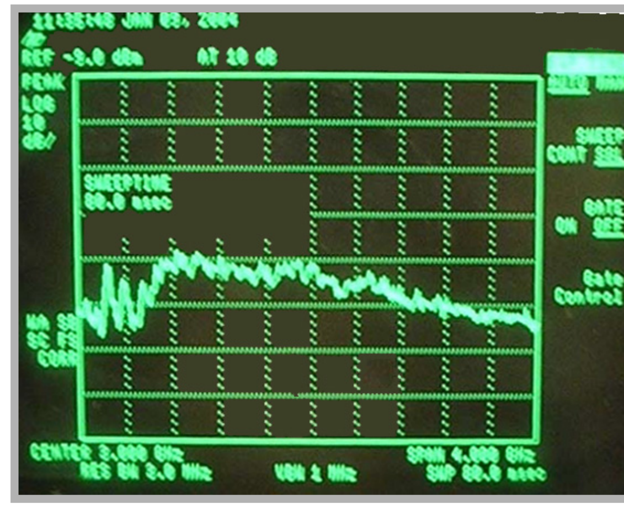
- Capacitor, C1 and inductance, L → 20% tolerance.
- C2 and resistors, RE and R1 → 5% tolerance.



Summary of Features

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

Tiny Chaotic Transmitter



Transmitter consists of:

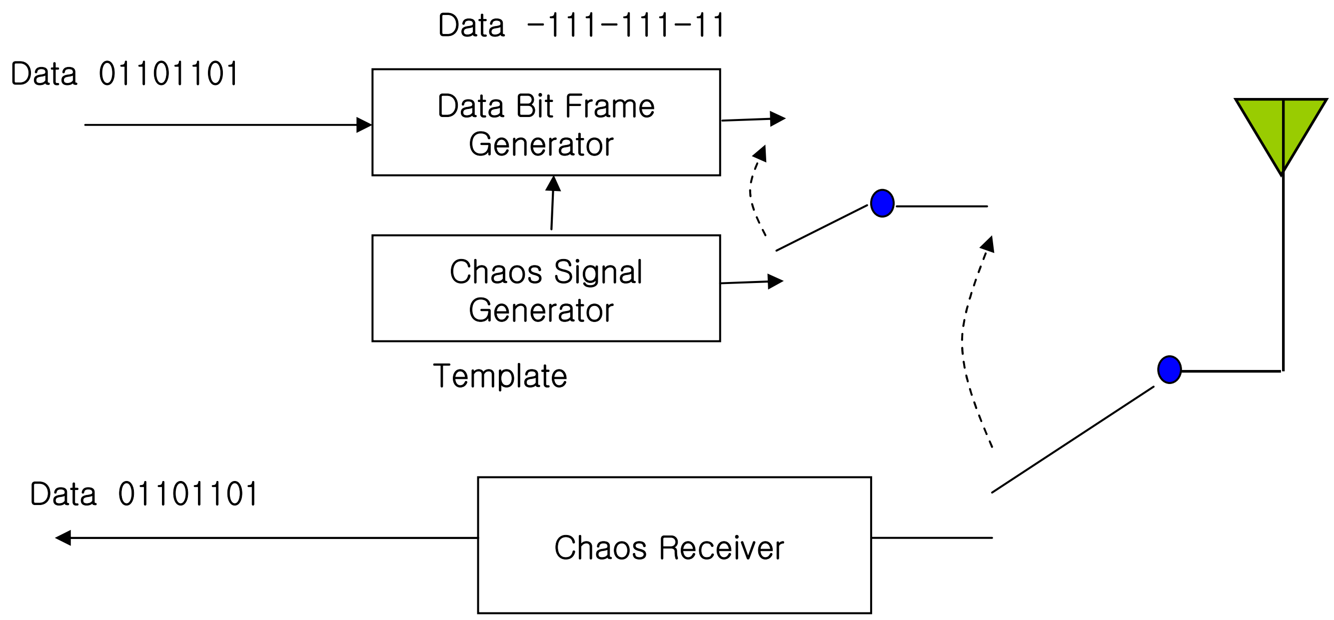
- **chaos generator**
- **modulator**
- **antenna**

Frequency band - 2-4 GHz
Radiating power - 3-4 mw

DCSK Modulation

SOP

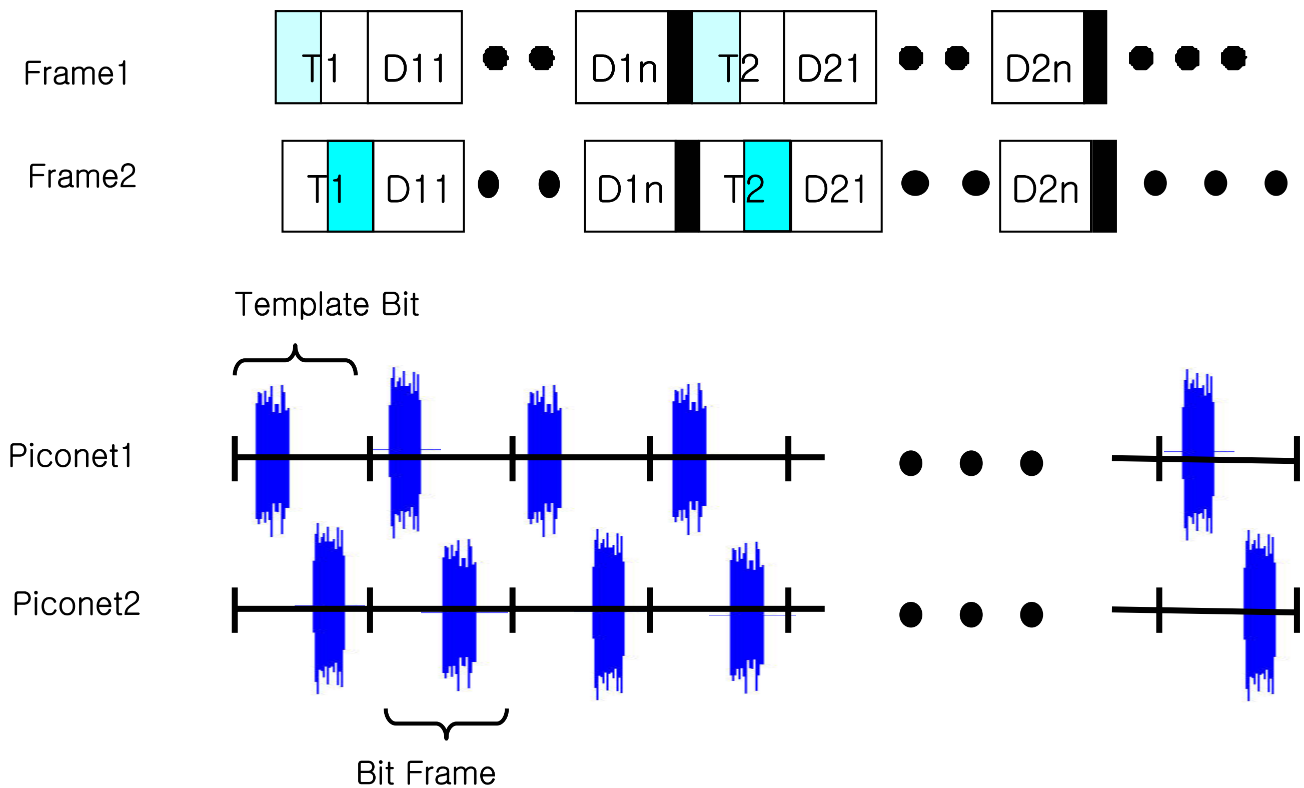
- **System Block**



DCSK Modulation

SOP

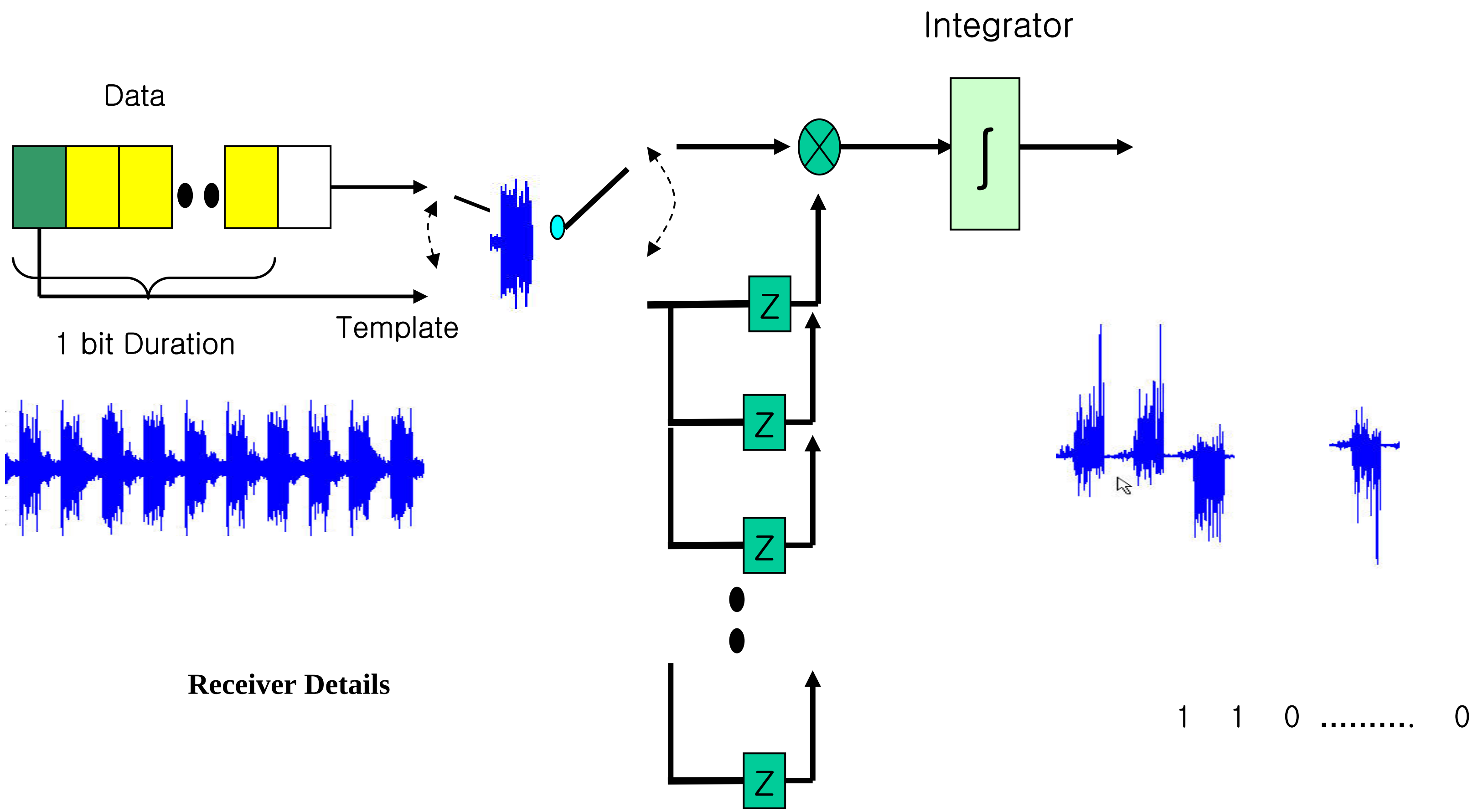
- **Transmission**



DCSK Modulation

SOP

- **Detail**

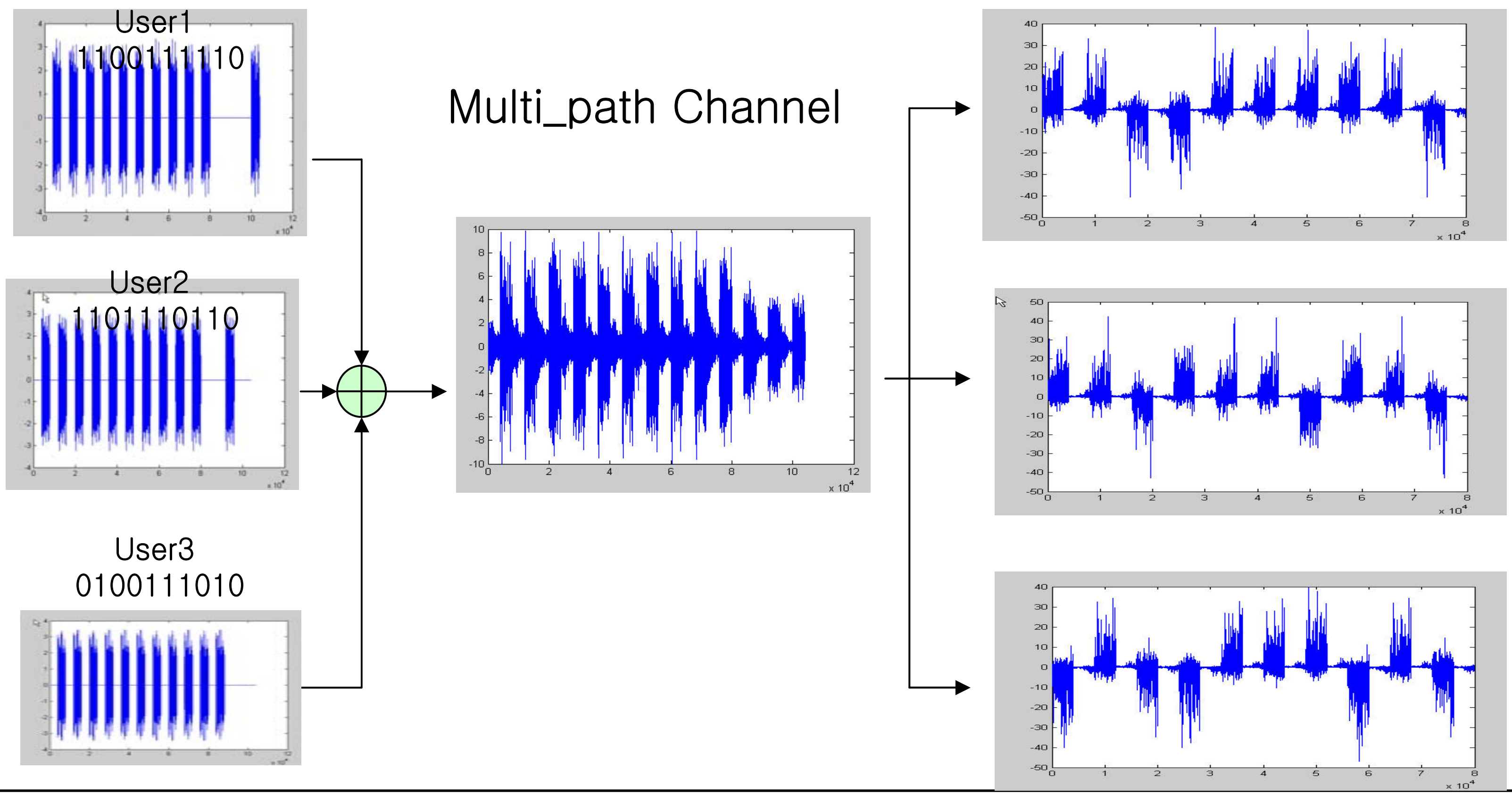


Receiver Details

DCSK Modulation

SOP

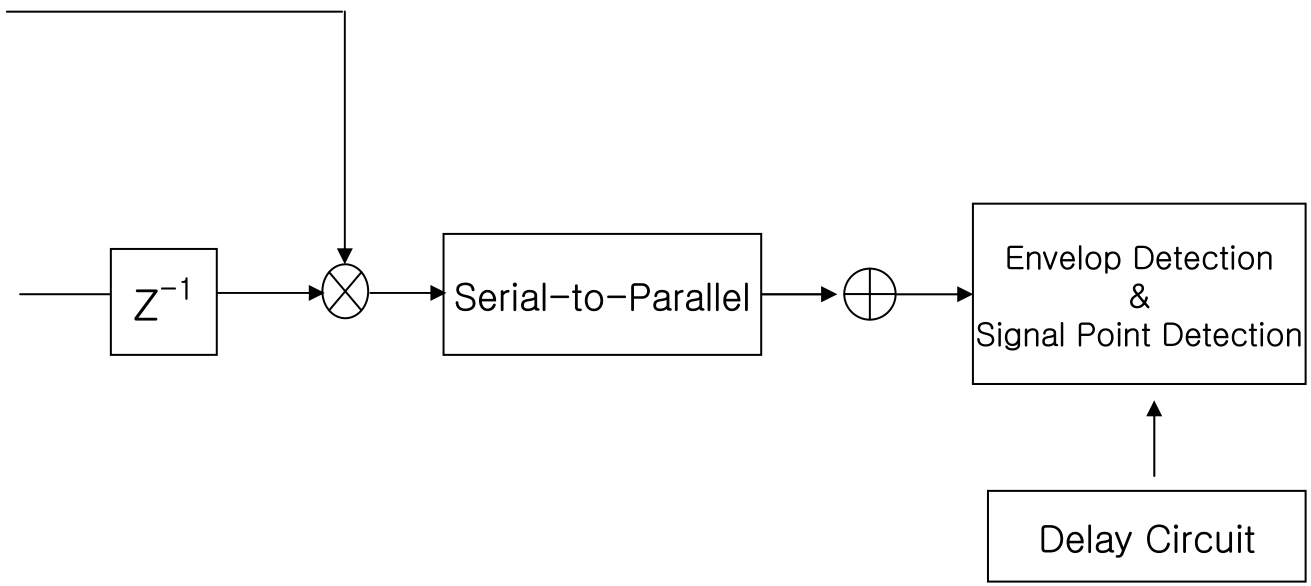
- **Signal Processing**



DCSK Modulation

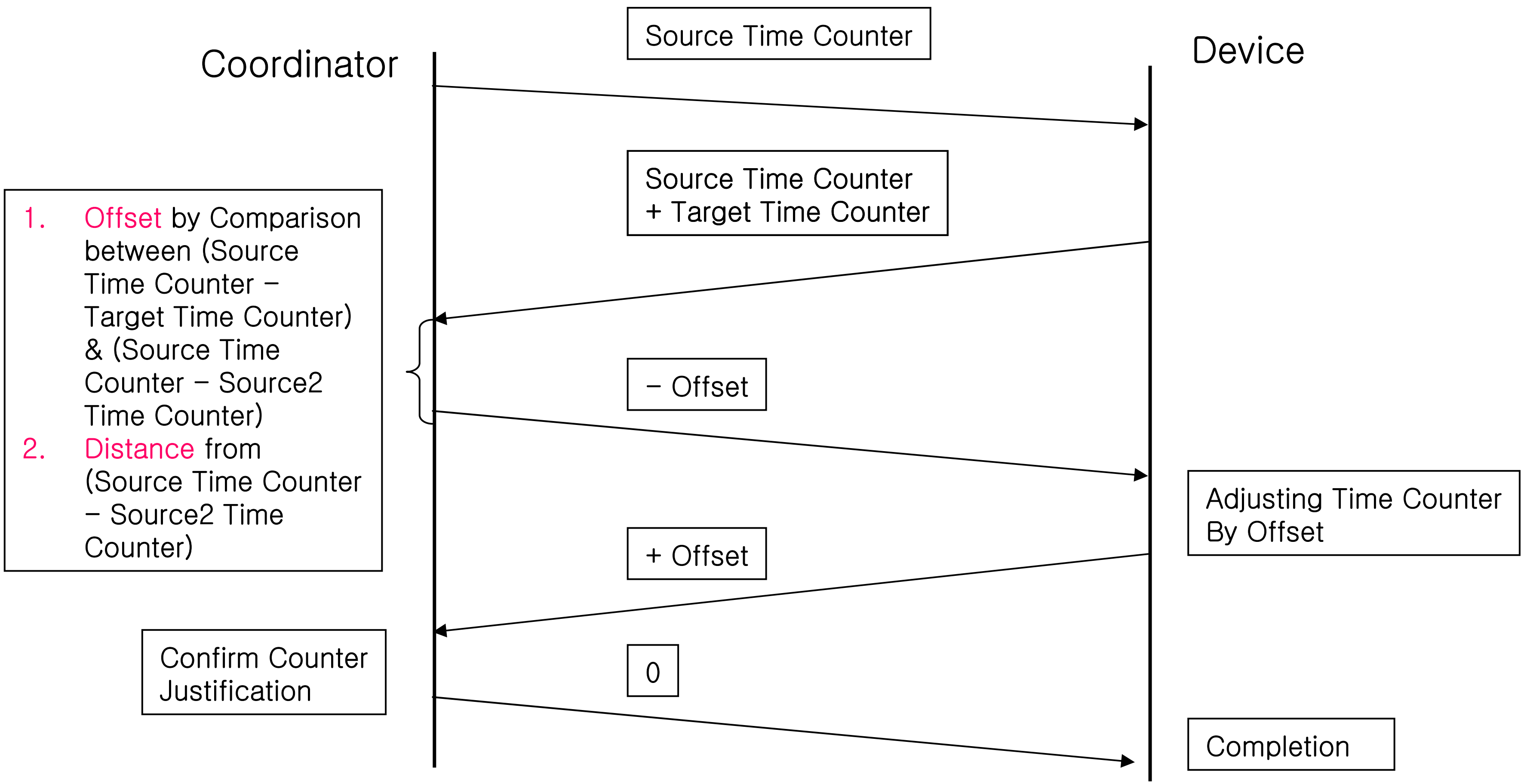
Ranging

- **Block Diagram**



DCSK Modulation

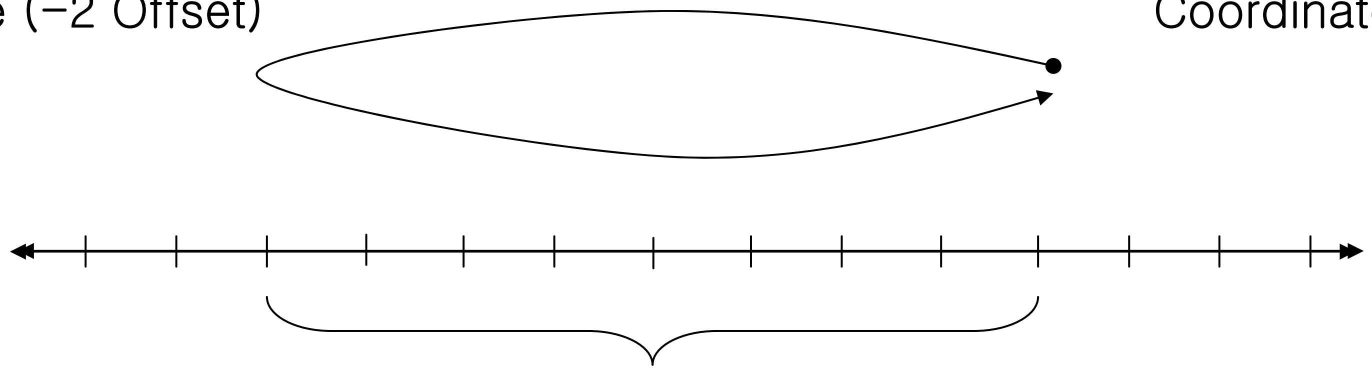
Ranging



DCSK Modulation

Ranging

Device (−2 Offset) Coordinator



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

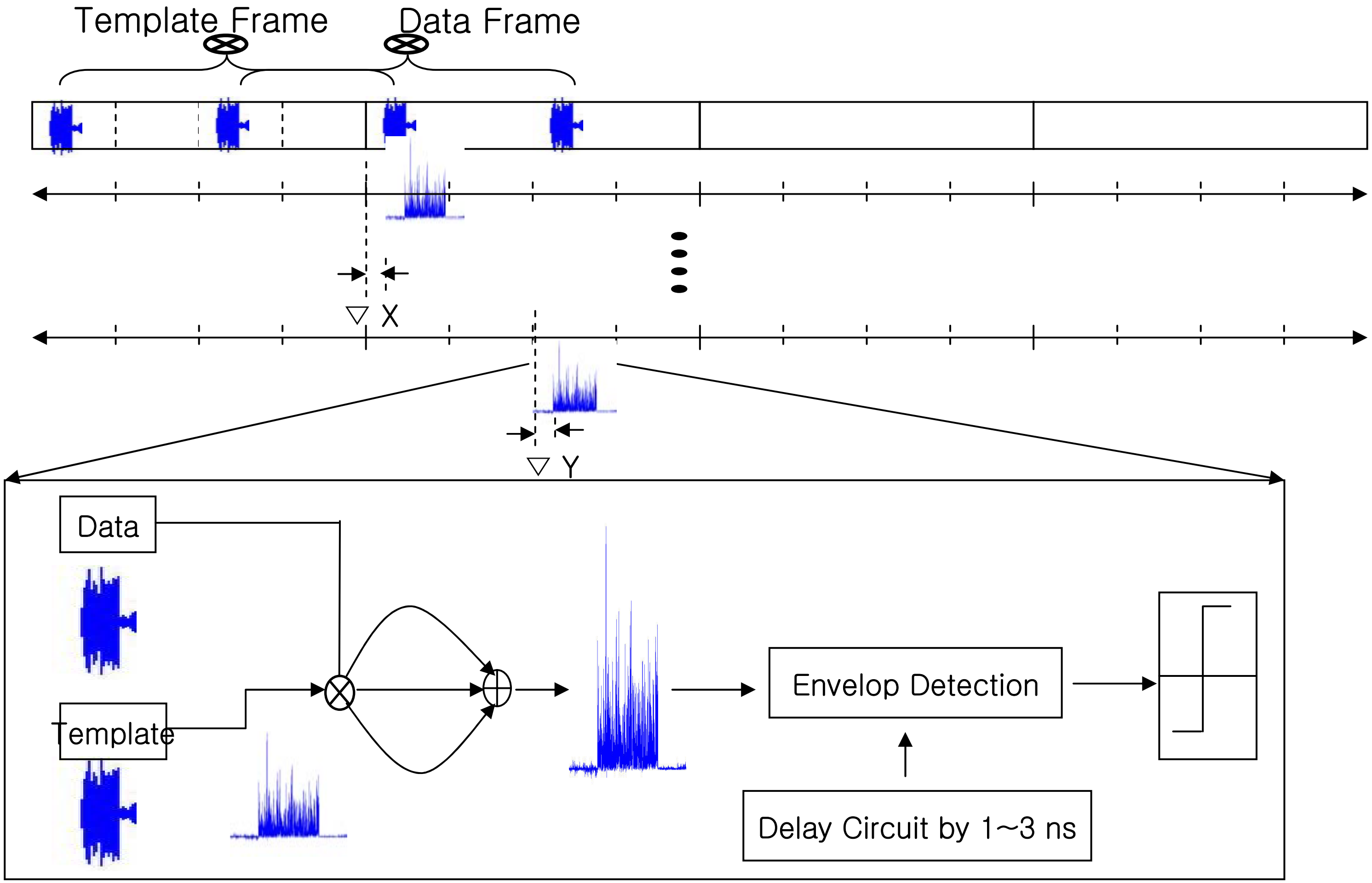
DCSK Modulation

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

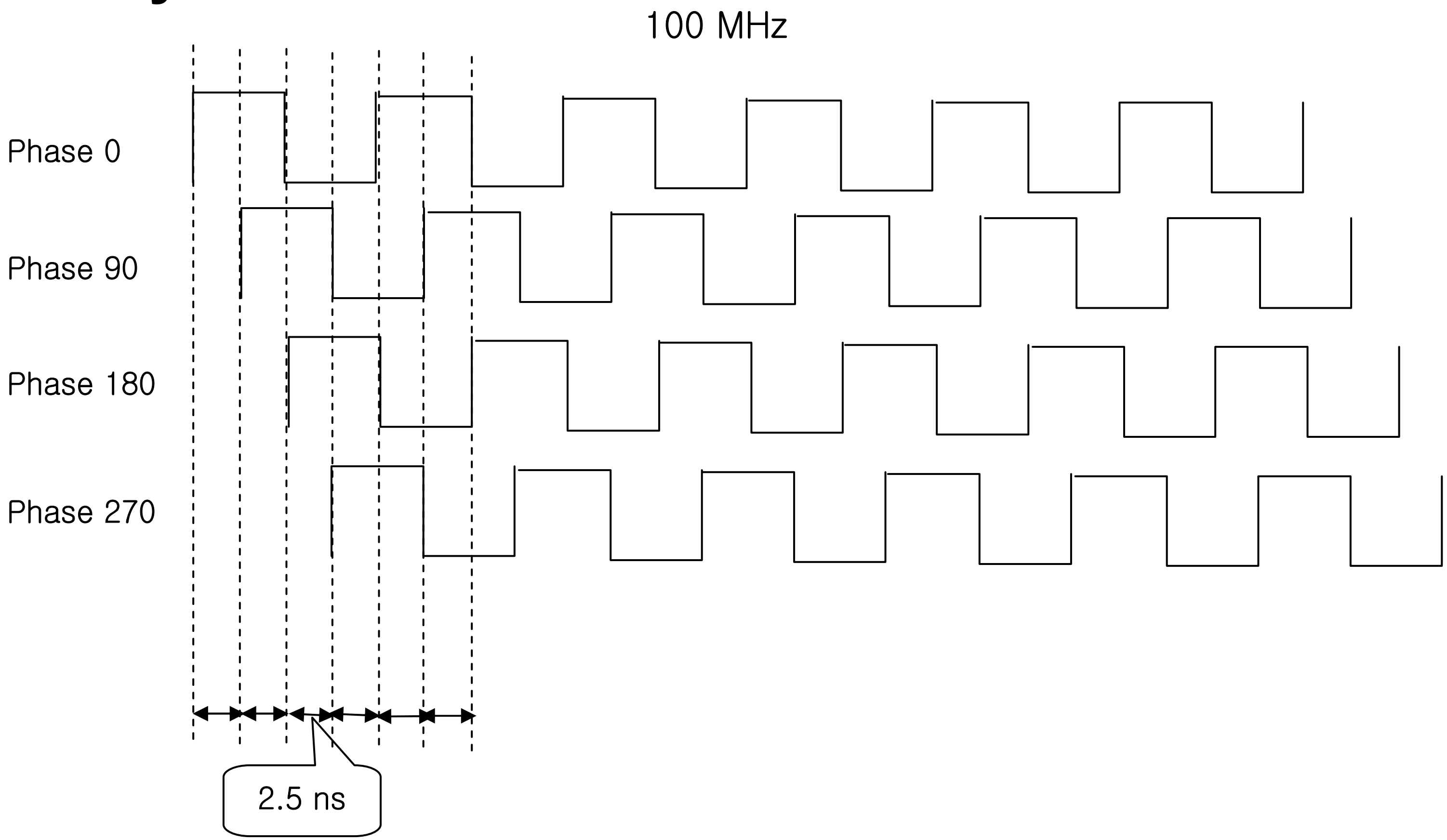
Ranging

- **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

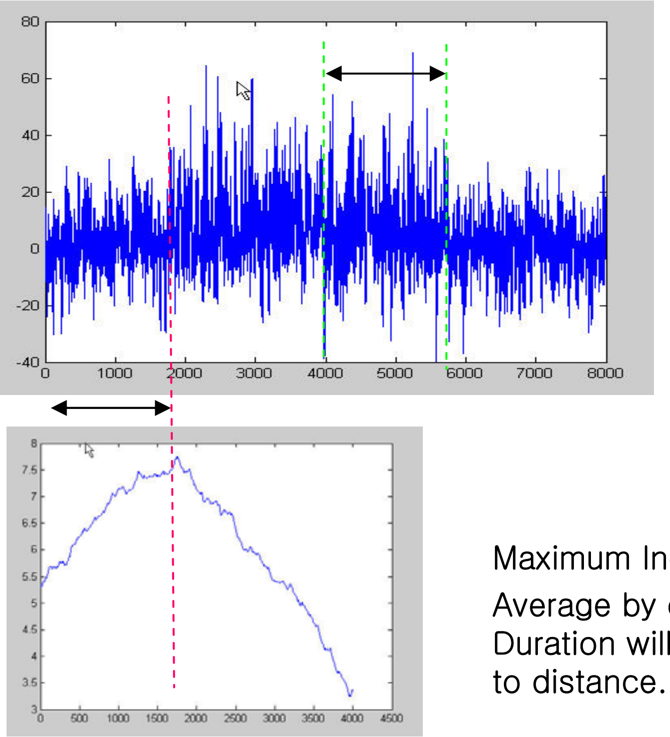
- **Delay Circuit**

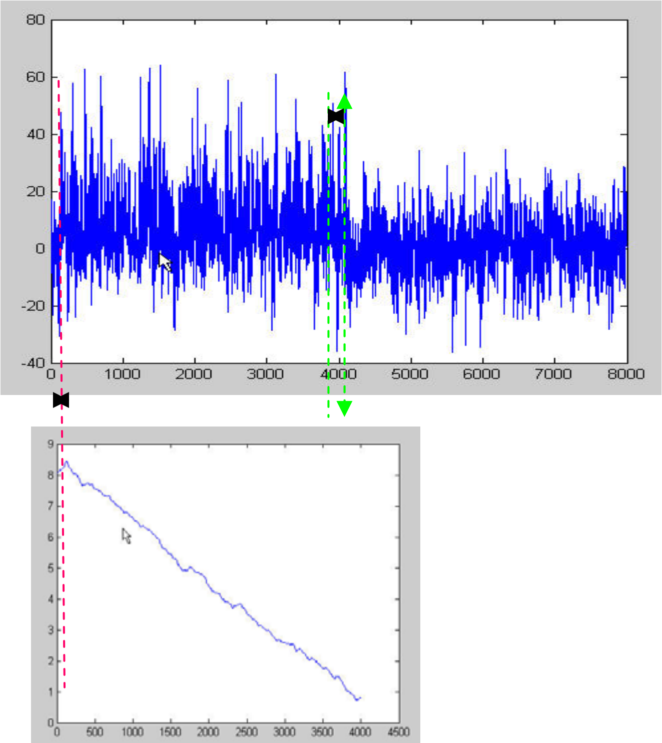


DCSK Modulation

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

M-ary Code Shift Keying/Binary PPM (MCSK/BPPM) Based Impulse Radio

Motivation

- **MCSK/BPPM increases the location/ranging capability of existing Time Hopping (TH) Impulse Radios (IRs)**
- **H/W complexity is not increased**
- **Same signal space with respect to TH-BPPM**
- **“MCSK” can be applied to other TH-IRs; eg. MCSK/BPSK**

TG4a Requirements

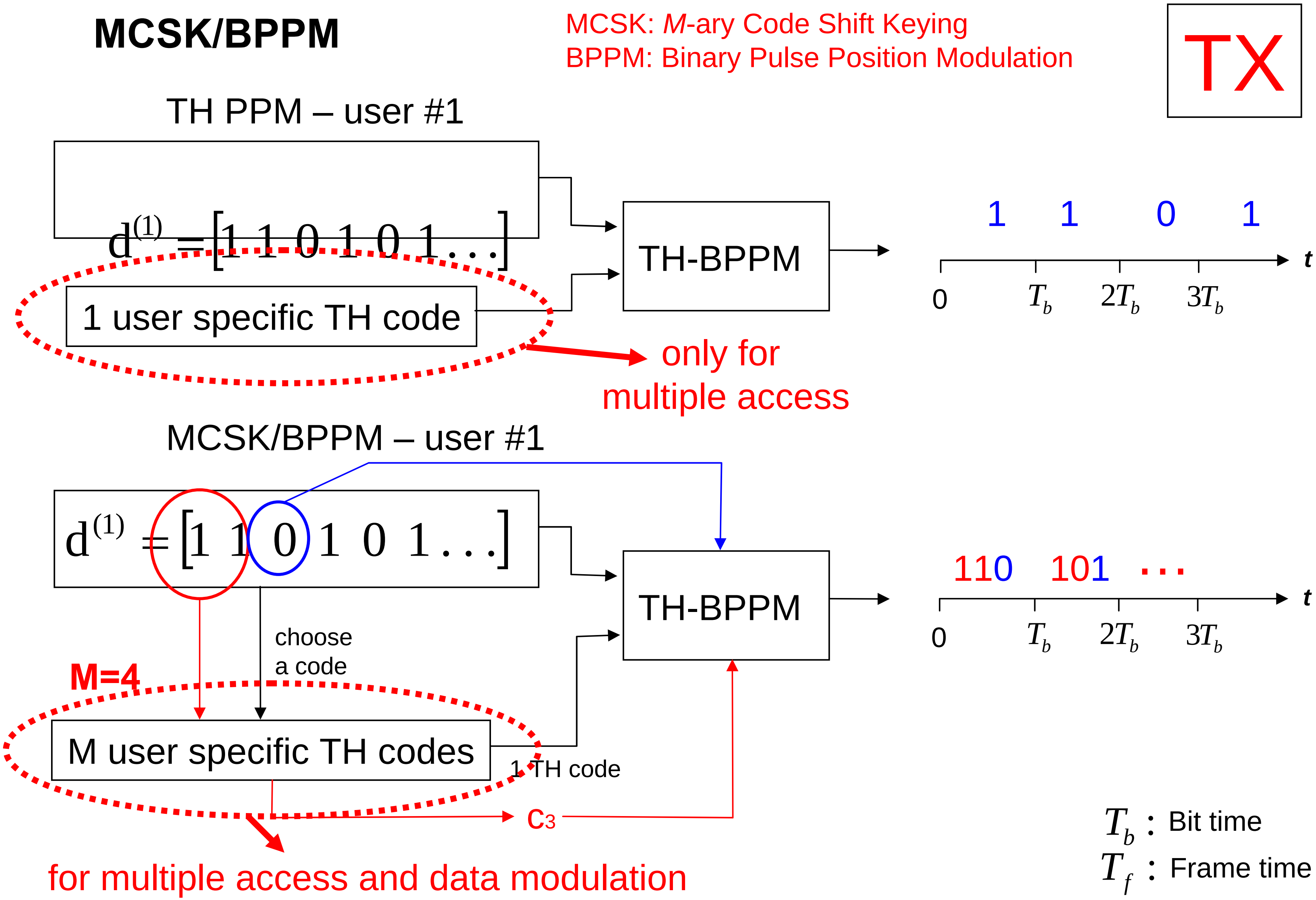
802.15.4a PHY	MCSK/BPPM compared to TH-BPPM
scalable information rates	Better BER performance **at the same/higher information rates and lower transmit power**
high precision ranging/ location	Improved ranging/location precision **capability**
low power consumption	Lower transmit power **at the same/higher information rates and better BER performance**
low complexity and cost	No new circuit **is needed /** simple transceiver **structure**

*MCSK/BPPM: *M*-ary Code Shift Keying/Binary Pulse Position Modulation

**TH-BPPM: Time Hopping Binary Pulse Position Modulation

MCSK/BPPM

MCSK: *M*-ary Code Shift Keying
BPPM: Binary Pulse Position Modulation



PHY TX Structure (1/2)

TX

M user specific TH codes

- TH codes are **periodic with N_p**
- each **pulse should be repeated N_s times**
- $N_p/N_s = k$ is an integer

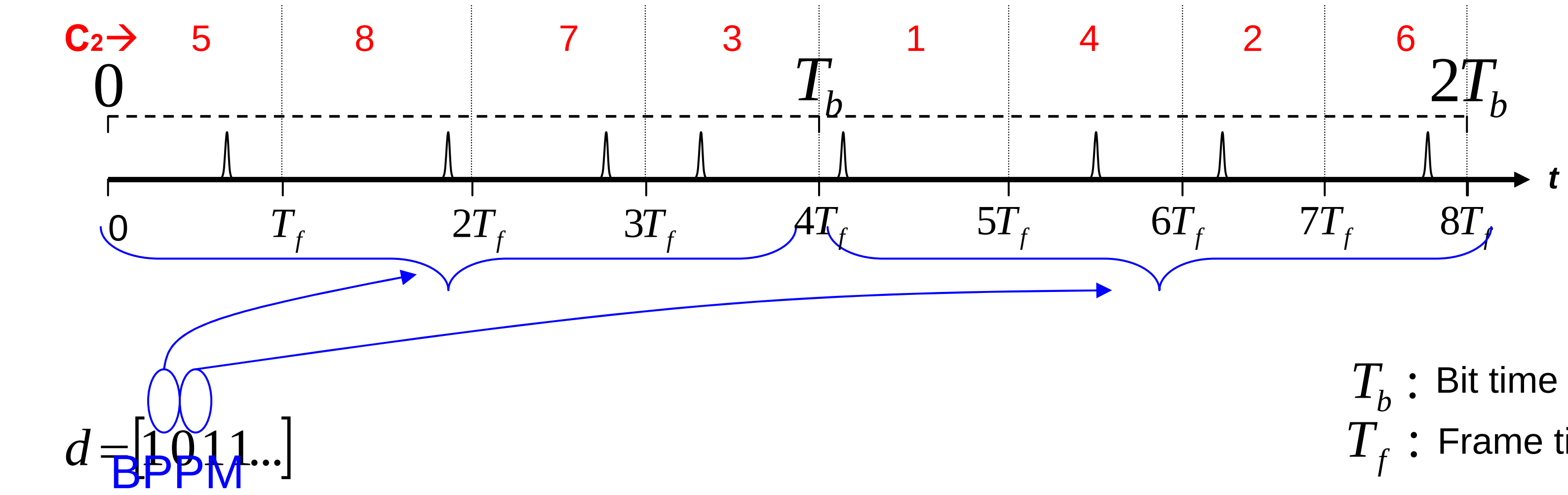
$$M = 4, N_p = 8, N_s = 4$$

Example:

$$d = [1011\ldots]$$

$$TH = \begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ c_3 \end{bmatrix} = \begin{bmatrix} 7 & 8 & 2 & 3 & 6 & 4 & 1 & 5 \\ 3 & 6 & 5 & 2 & 8 & 7 & 4 & 1 \\ 5 & 8 & 7 & 3 & 1 & 4 & 2 & 6 \\ 2 & 4 & 8 & 6 & 3 & 7 & 5 & 1 \end{bmatrix}$$

MCSK



T_b : Bit time

T_f : Frame time

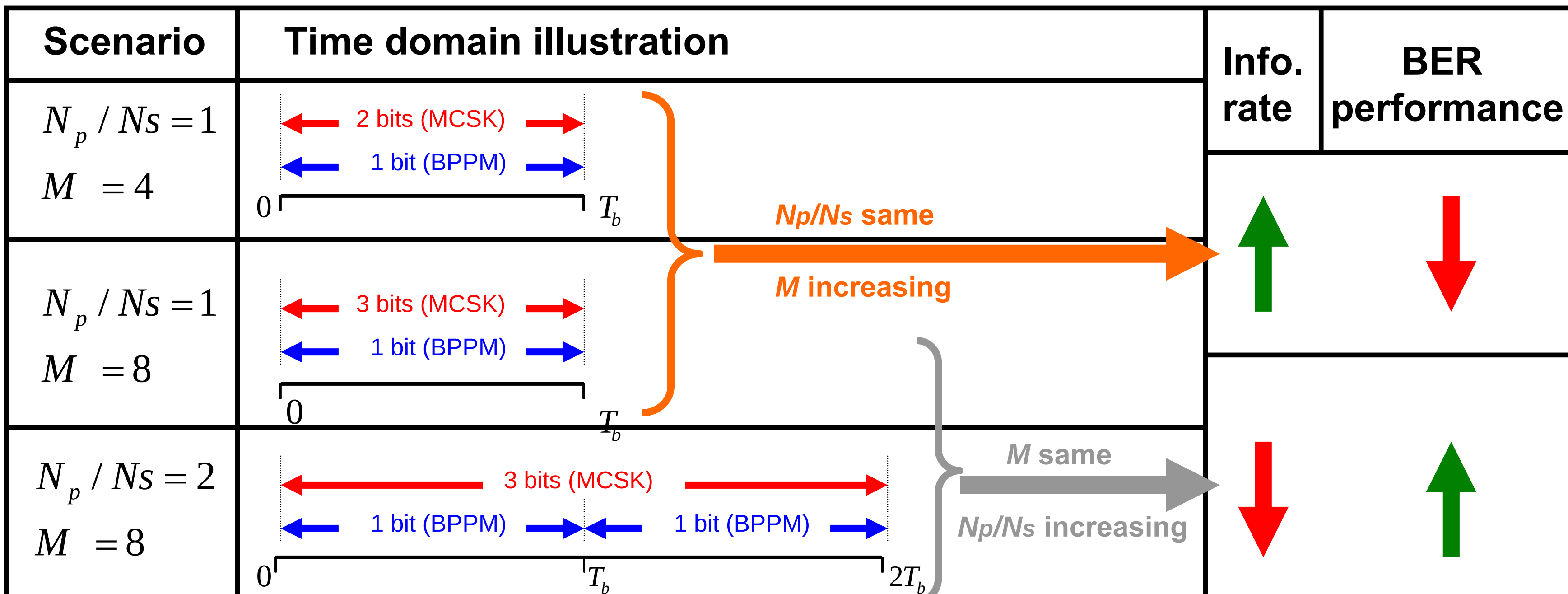
PHY TX Structure (2/2)

TX

M user specific TH codes

- TH codes are **periodic with N_p**
- each **pulse should be repeated N_s times**
- **$N_p/N_s=k$** is an integer

Information rate vs. BER performance for fixed N_s and varying N_p and M



T_b : Bit time T_f : Frame time

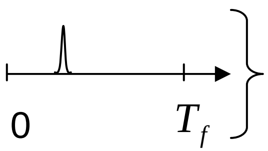
TH Code Assignment (1/2)

TX

Each user has [M user specific TH codes] → $N_u N_p M$ sample-long sequence ?

NO!

Generation of TH codes – "Case 1: random assignment"



For T_f = 100ns, T_c = 1ns:
100 slots for multiple access → $2^l \equiv N_h;\ l = 6,\ N_h = 64$

m-sequence: $[1011100101001101110100010100...]$

46 **20** **55**

$N_p = 4$
$M = 4$

$[46\ 20\ 55\ 17\ 20\ 13\ 12\ 31\ 61\ 14\ 56\ 5\ 7\ 24\ 26\ 53\ 45\ 35\ 2\ ...]$

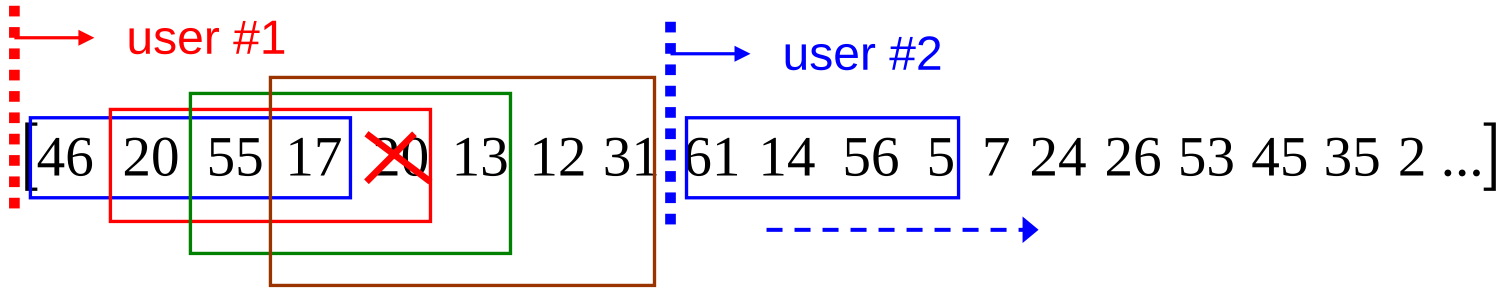
user #1: c0, c1, c2, c3
user #2: c0, c1, c2, c3

$$N_u N_p \Rightarrow N_u (N_p + M - 1)$$

TH Code Assignment (2/2)

TX

Generation of TH codes – "Case 2: no overlapping"



user #1

$N_p = 4$

$M = 4$

[46 20 55 17]

[20 55 17 20]

[55 17 20 13]

~~[17 20 13 12]~~

[17 13 12 31]

no collisions allowed within user codes

user #2 · · · **user #k**

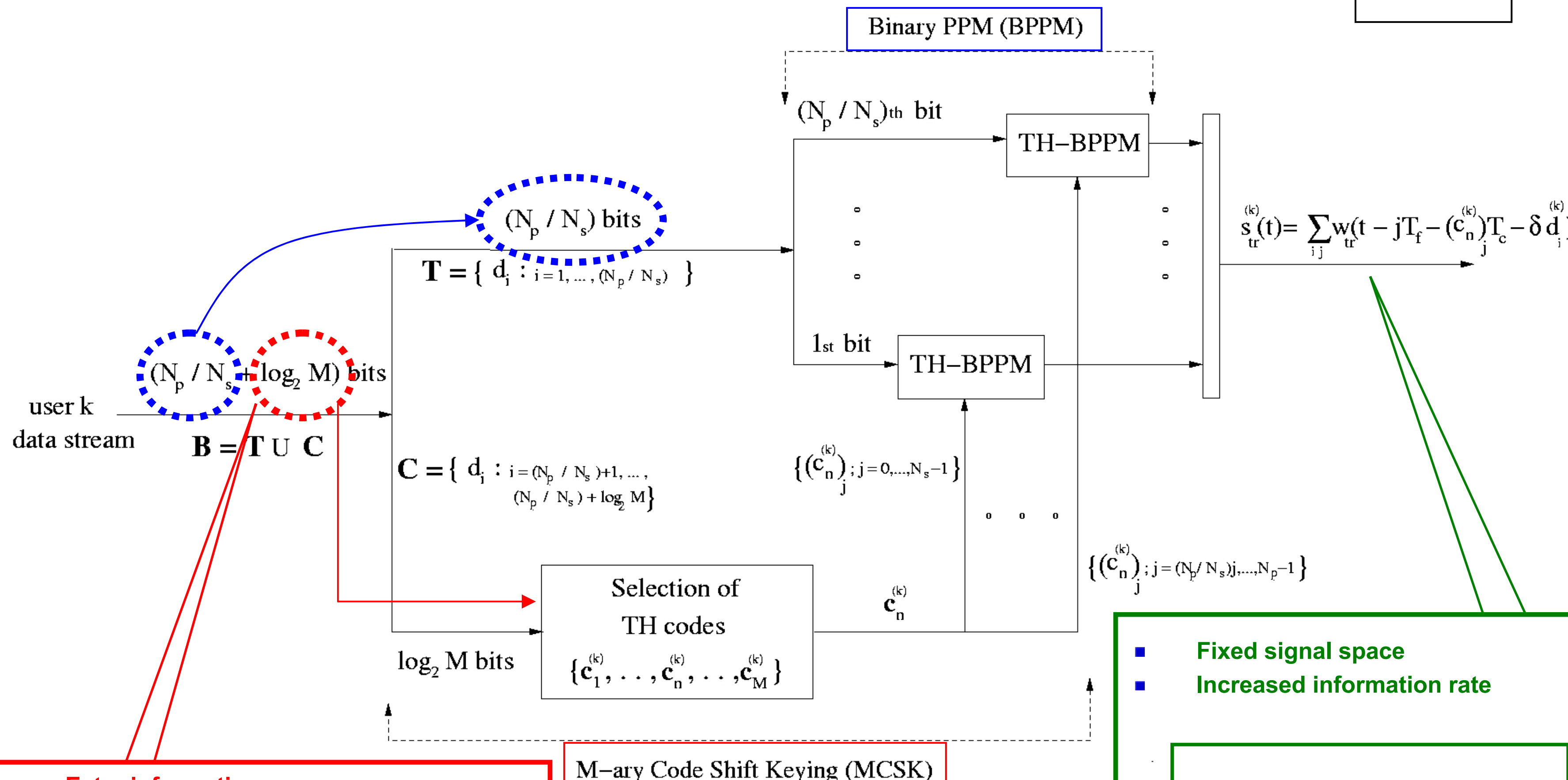
[61 14 56 5]

$$N_u N_p \Rightarrow N_u (N_p + M - 1) + n$$

n: number of overlaps

General Modulation Format

TX



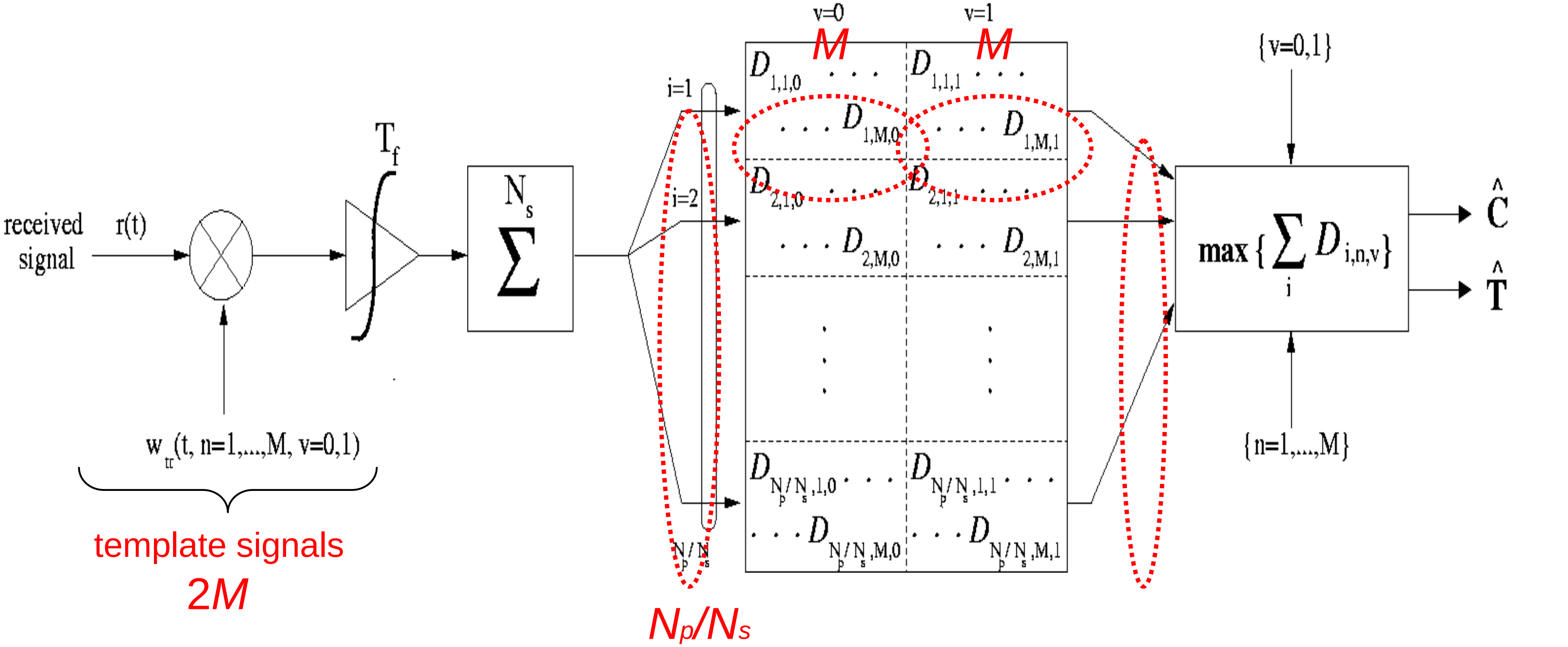
- Extra information
- Random selection of TH codes→Improved spectrum

- Fixed signal space
- Increased information rate

$$R_s = \left(1 + \frac{\log_2 M}{N_p / N_s}\right) \cdot R$$

Receiver Structure - MLSE

RX



hardware structure

1 correlator

computation complexity

$$2^{(N_p/N_s)}M$$

Information Rate (1/3)

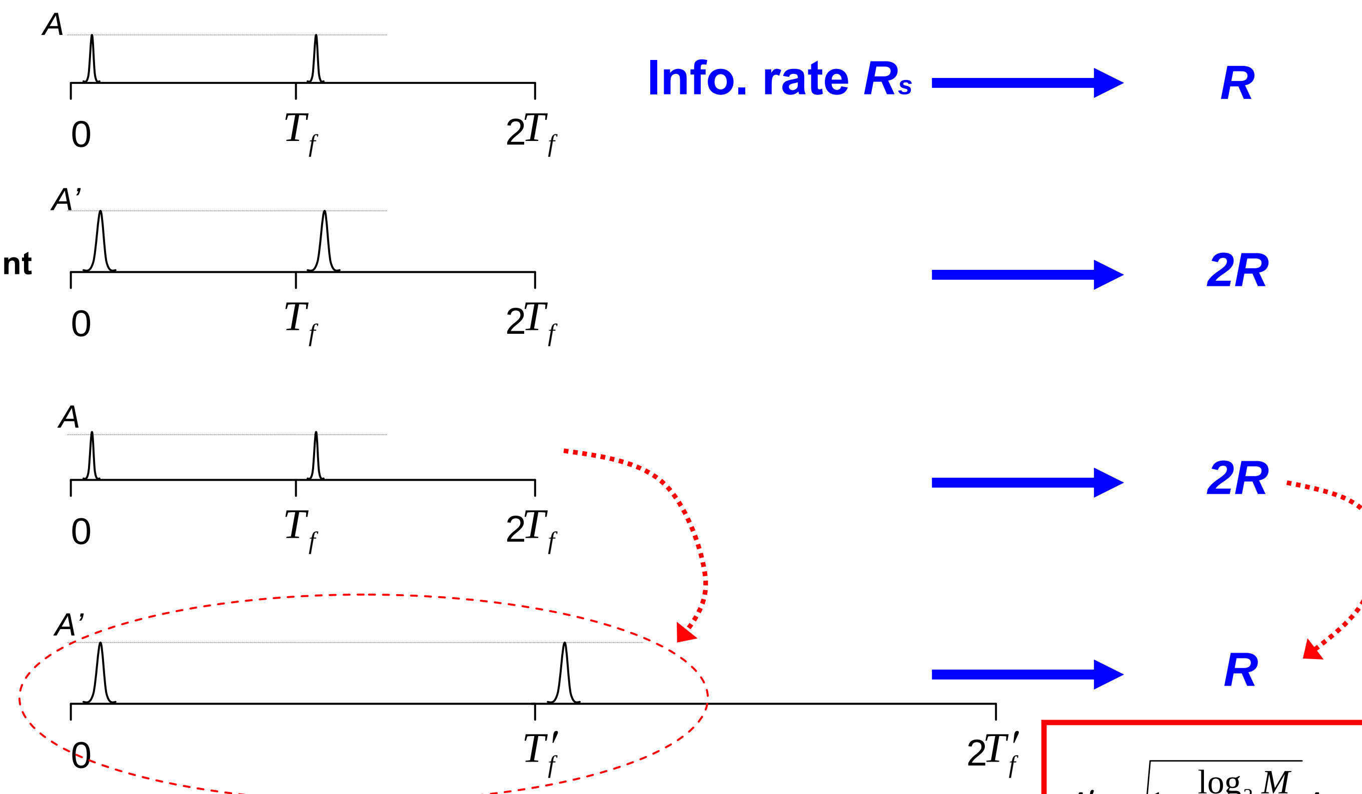
$$R_s = \left(1 + \frac{\log_2 M}{N_p / N_s}\right) \cdot R$$

TH-BPPM
Ns = 2, M=1

MCSK/BPPM
“Constant Energy/Bit” Constraint
Ns = 2, Np=2, M=2

MCSK/BPPM
“Constant Power” Constraint
Ns = 2, Np=2, M=2

MCSK/BPPM (same info. rate)
“Constant Power” Constraint
Ns = 2, Np=2, M=2



can be adjusted to achieve higher information rate at lower transmit power and still maintain better BER performance at the same time

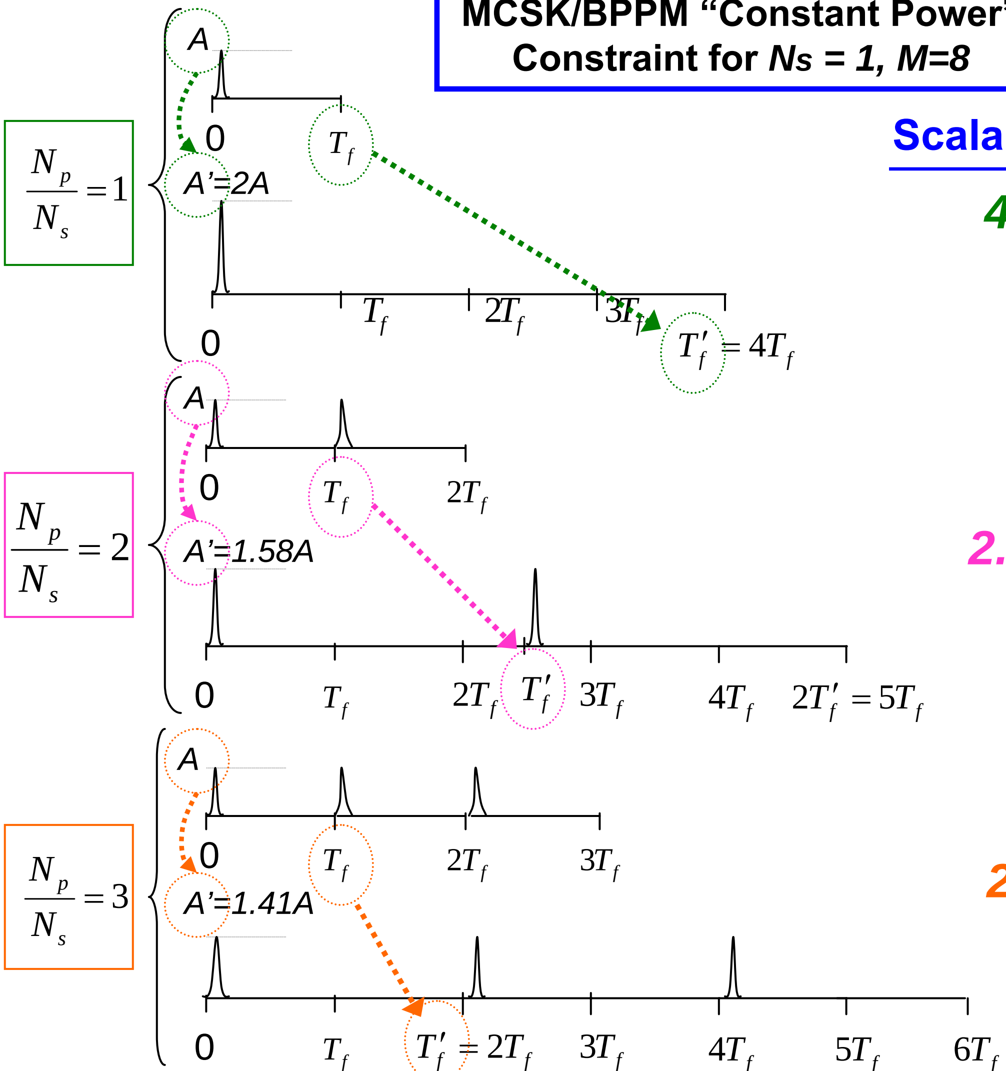
$$A' = \sqrt{1 + \frac{\log_2 M}{N_p / N_s}} A$$

$$T'_f = \left(1 + \frac{\log_2 M}{N_p / N_s}\right) T_f$$

Information Rate (2/3)

$$R_s = \left(1 + \frac{\log_2 M}{N_p / N_s}\right) \cdot R$$

MCSK/BPPM "Constant Power" Constraint for *Ns = 1, M=8*



Scalable info. rates

4R → R

2.5R → R

2R → R

BER performance (wrt TH-BPPM)

- increased SNR
- reduced collusions
- no processing gain
- not much improvement

- increased SNR
- reduced collusions
- processing gain
- improved BER
- TX power can be lowered
- info rate can be increased

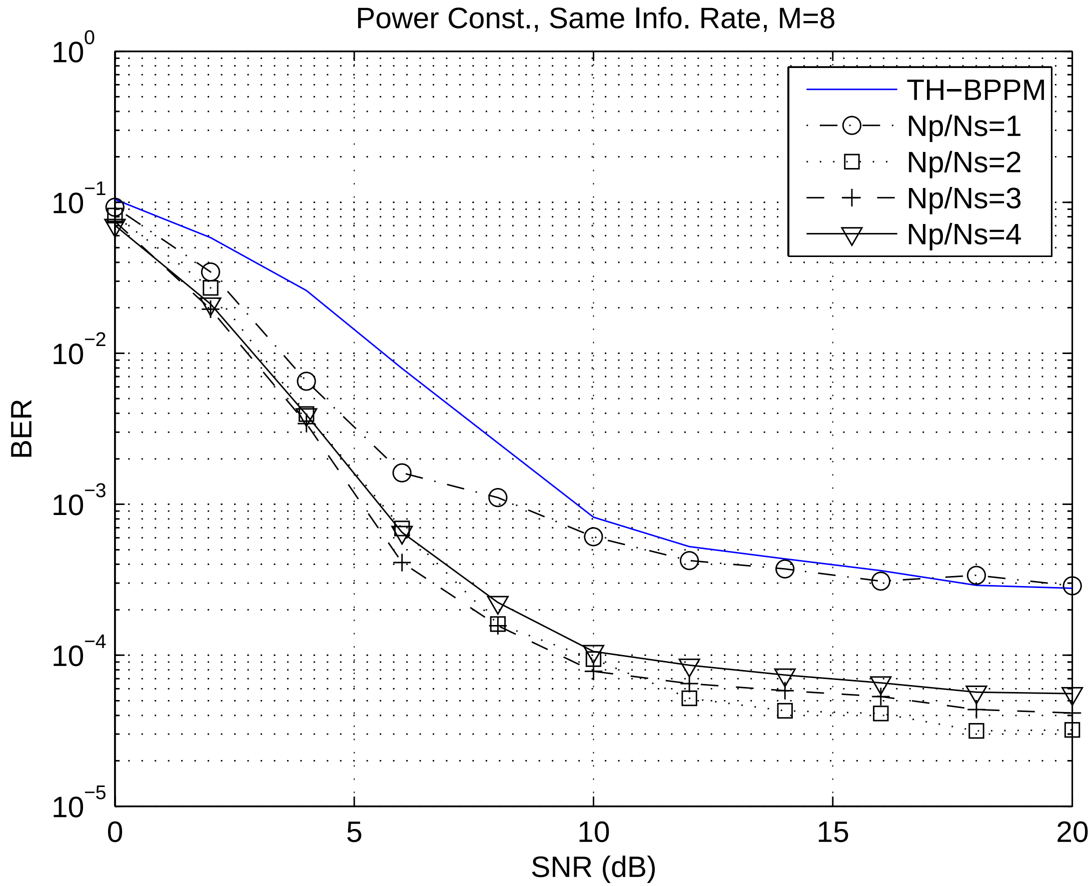
$$A' = \sqrt{1 + \frac{\log_2 M}{N_p / N_s}}\, A$$

$$T_f' = \left(1 + \frac{\log_2 M}{N_p / N_s}\right) T_f$$

Information Rate (3/3)

“Constant Power” Constraint

→ *Improved performance at the same information rate for M=8*



Location Accuracy

MCSK/BPPM
"Constant Power" Constraint

	Procedure	Result	Comment
Step 0	Initial conditions for TH-BPPM	R_0 (information rate); BER_0 (performance) TX_0 (power)	
Step 1	Increase *M*	$R_1 > R_0$; $BER_1 > BER_0$; $TX_1 = TX_0$	
Step 2	Increase *Np/Ns*	$R_1 > R_2 > R_0$; $BER_1 > BER_2$; $TX_2 = TX_0$	BER_2 may or may not be less than BER_0
Step 3	Increase *T'f*	$R_1 > R_2 > R_3 > R_0$; $BER_2 > BER_3$; $TX_0 > TX_3$	BER_3 may or may not be less than BER_0
Step 4	Increase *A'*	$R_4 = R_3 > R_0$; $BER_3 > BER_4$ & $BER_0 > BER_4$; $TX_0 > TX_4 > TX_3$	**Increased frame time with longer observation period, higher information rate, better BER performance and lower transmit power**

Accurate Ranging/Location

Conclusion

- **MCSK/BPPM provides:**
  - **→ increased information rate**
  - **→ lower transmit power**
  - **→ better BER performance**
  - **→ improved spectral characteristics**

Simultaneously!

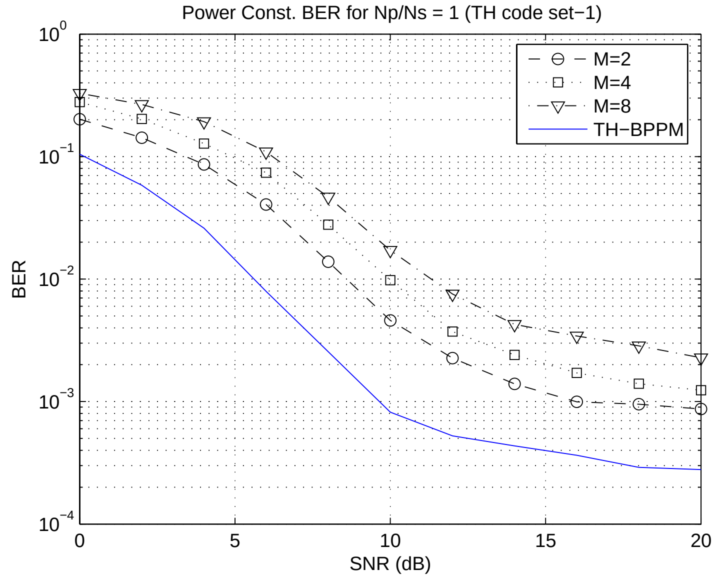
- **MCSK/BPPM is capable of:**
  - **→ information rate scalability**
  - **→ location/ranging accuracy**

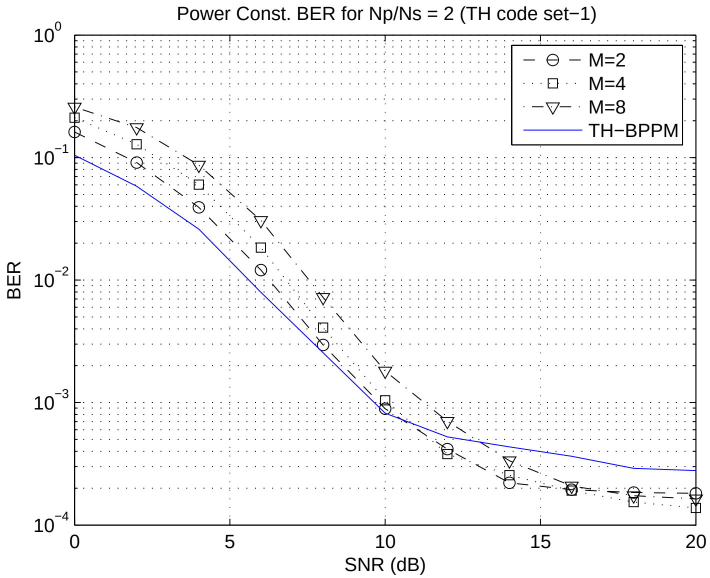
IEEE 802.15.4a PHY

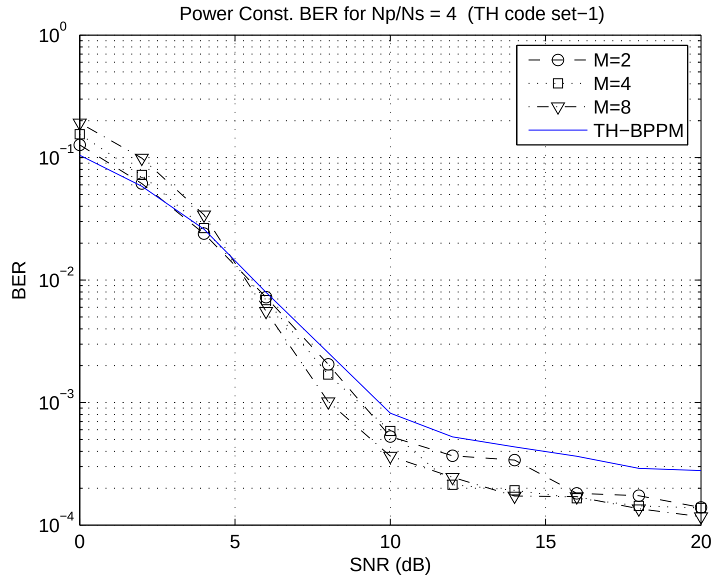
Back-up Slides

MCSK/BPPM

“Constant Power” Constraint

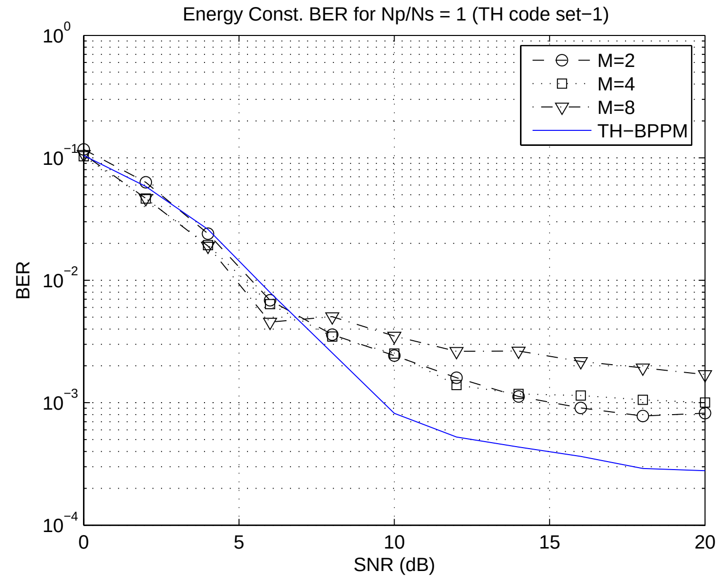


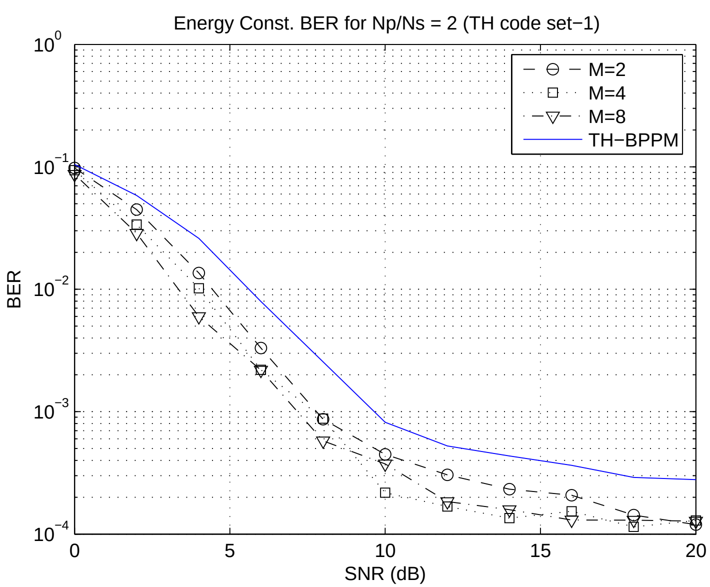


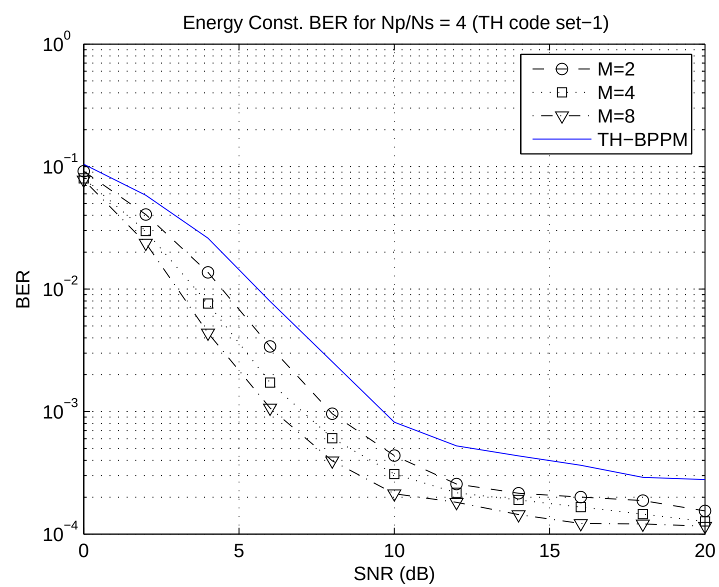


MCSK/BPPM

“Constant Energy/Bit” Constraint

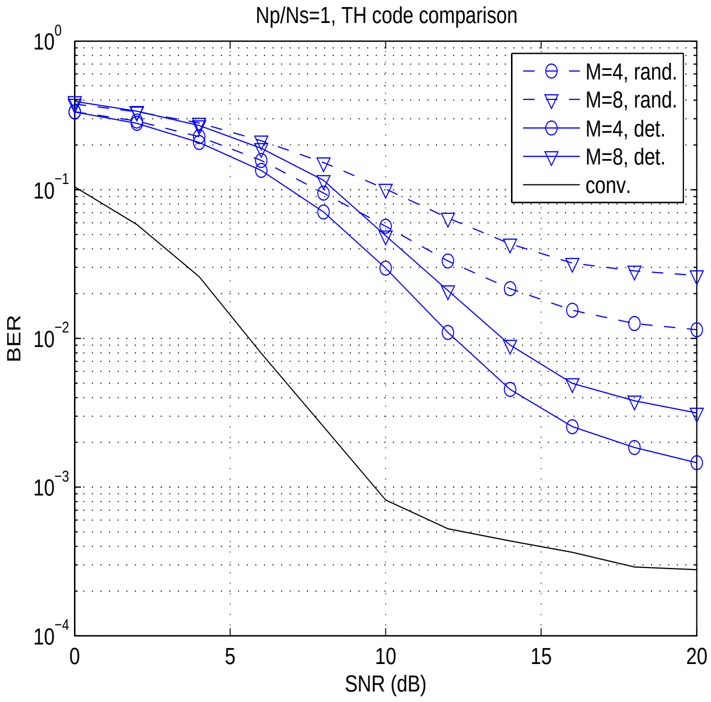


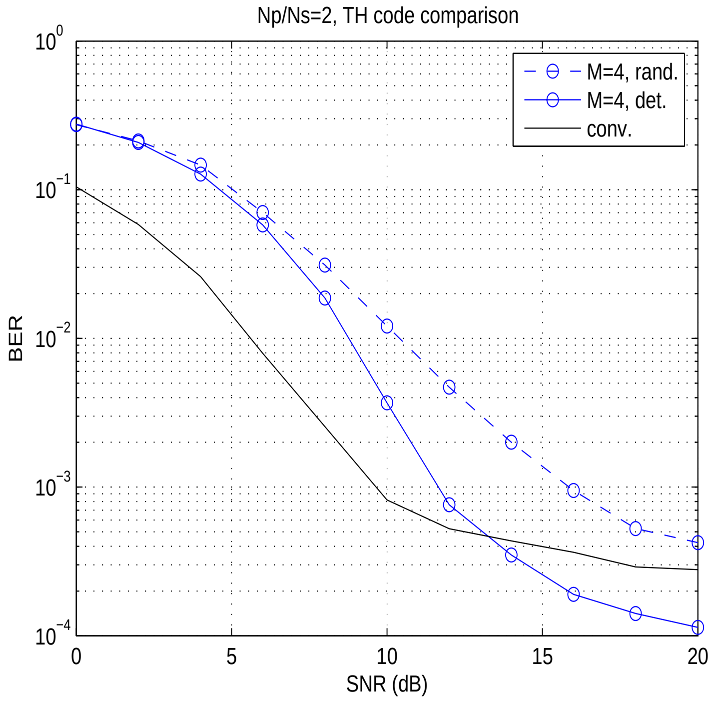




Effects of TH Code Design on the Performance

MCSK/BPPM "Constant Power" Constraint





TH Code Spectrum of:

a) TH-BPPM, N_p=10

b) ideal MCSK/BPPM, $N_p \rightarrow \infty$

c) realistic MCSK/BPPM

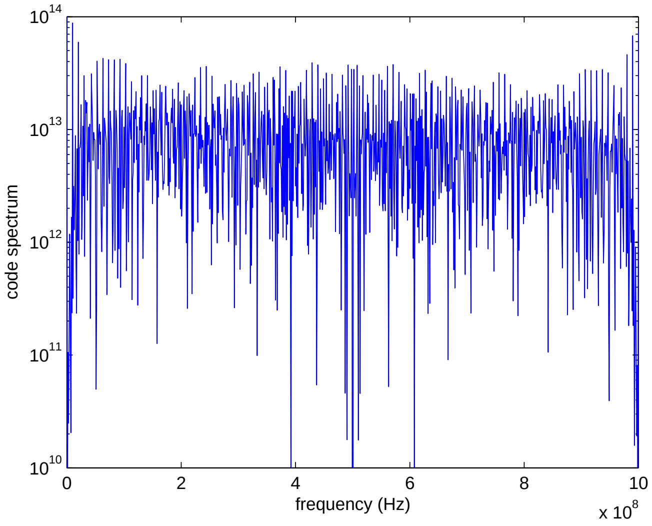


Fig. a. TH-BPPM

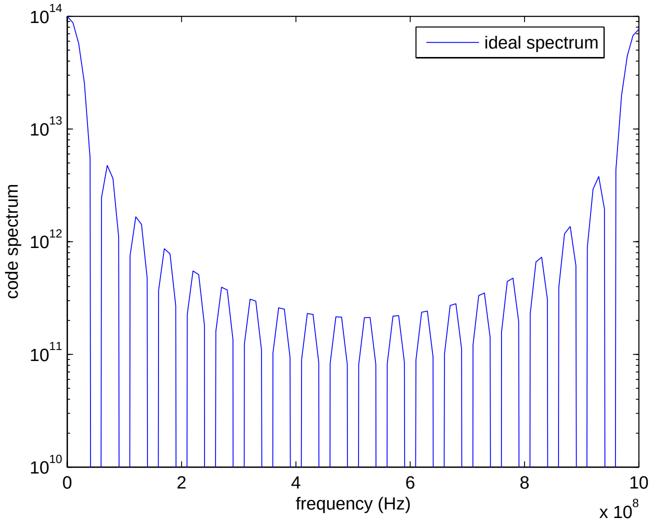


Fig. b. ideal MCSK/BPPM

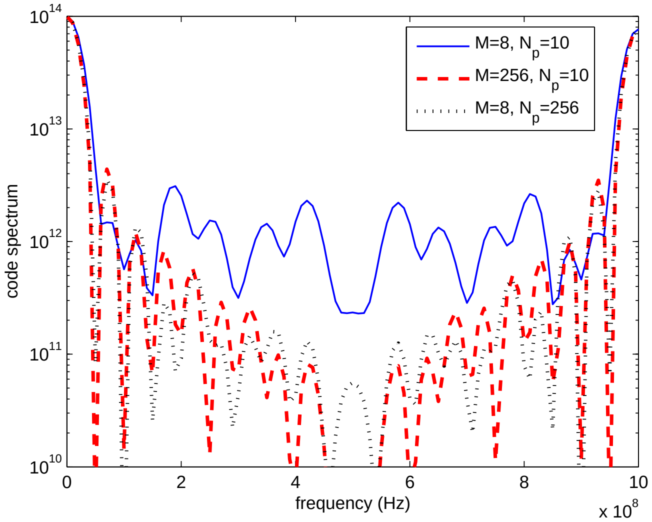


Fig. c. realistic MCSK/BPPM