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

Submission Title: [Samsung Electronics (SAIT) CFP Presentation]
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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 UWB direct chaotic communications technology.]

Purpose: [Proposal for the IEEE 802.15.4a PHY standard.]

Samsung Electronics (SAIT) CFP Presentation for IEEE 802.15.4a Alternative PHY

UWB Direct Chaotic Communication System

Samsung Advanced Institute of Technology
(SAIT), Korea

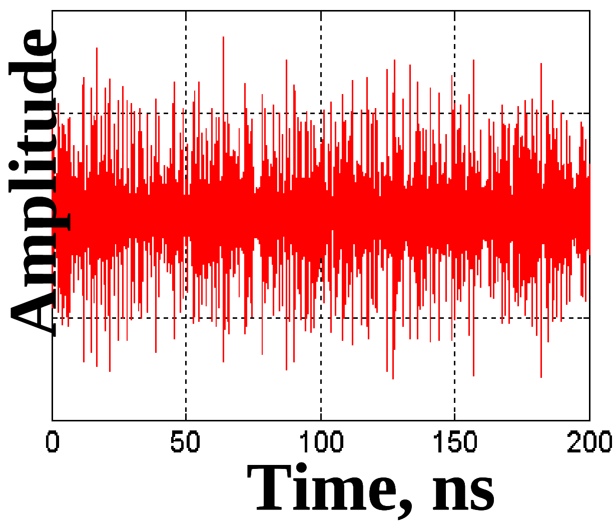
Outline

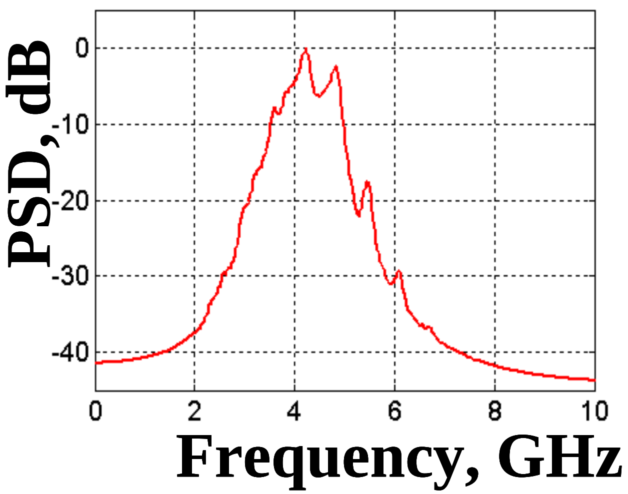
- Characteristics of Chaotic Signal
- Principle of Direct Chaotic Communications (DCC)
- PHY Layer Proposal
- System Performance
- Simultaneously Operating Piconets (SOP)
- Ranging Technique
- Power Consumption & Power Management Modes
- Link Budget & Sensitivity
- Complexity, Cost & Technical Feasibility
- Scalability
- Self-Evaluation
- Conclusion

Characteristics of Chaotic Signal (1)

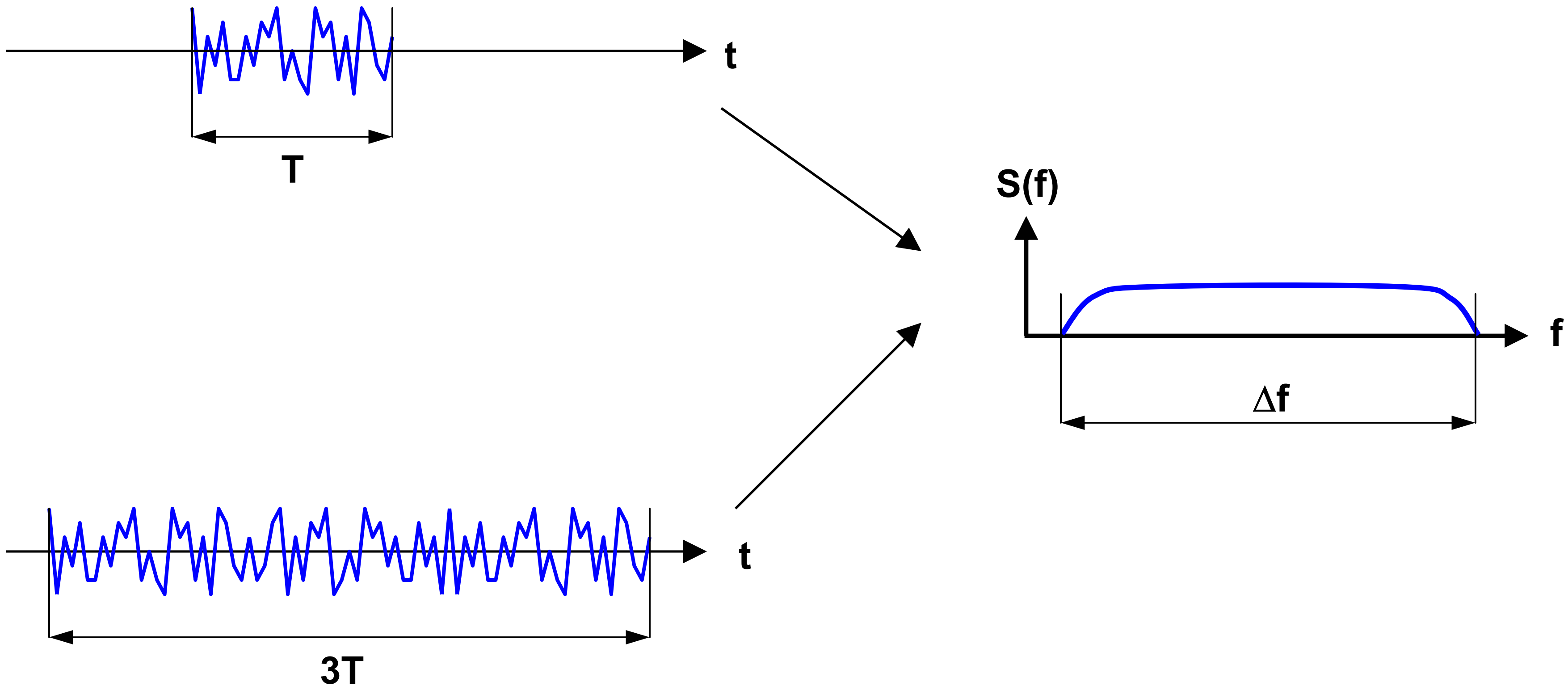
- Simple circuits
  - Chaotic signal can be generated directly into the desired microwave band by a chaotic generator
- Low cost implementation
  - The simple circuit leads to low cost product
- Multipath resistance
  - Wideband signal is very immune against multipath fading
- Good spectral properties
  - Non-periodic with a flat (or tailored) spectrum
- Flexibility
  - Chaotic radio pulse with different time duration can have the same bandwidth

Characteristics of Chaotic Signal (2)





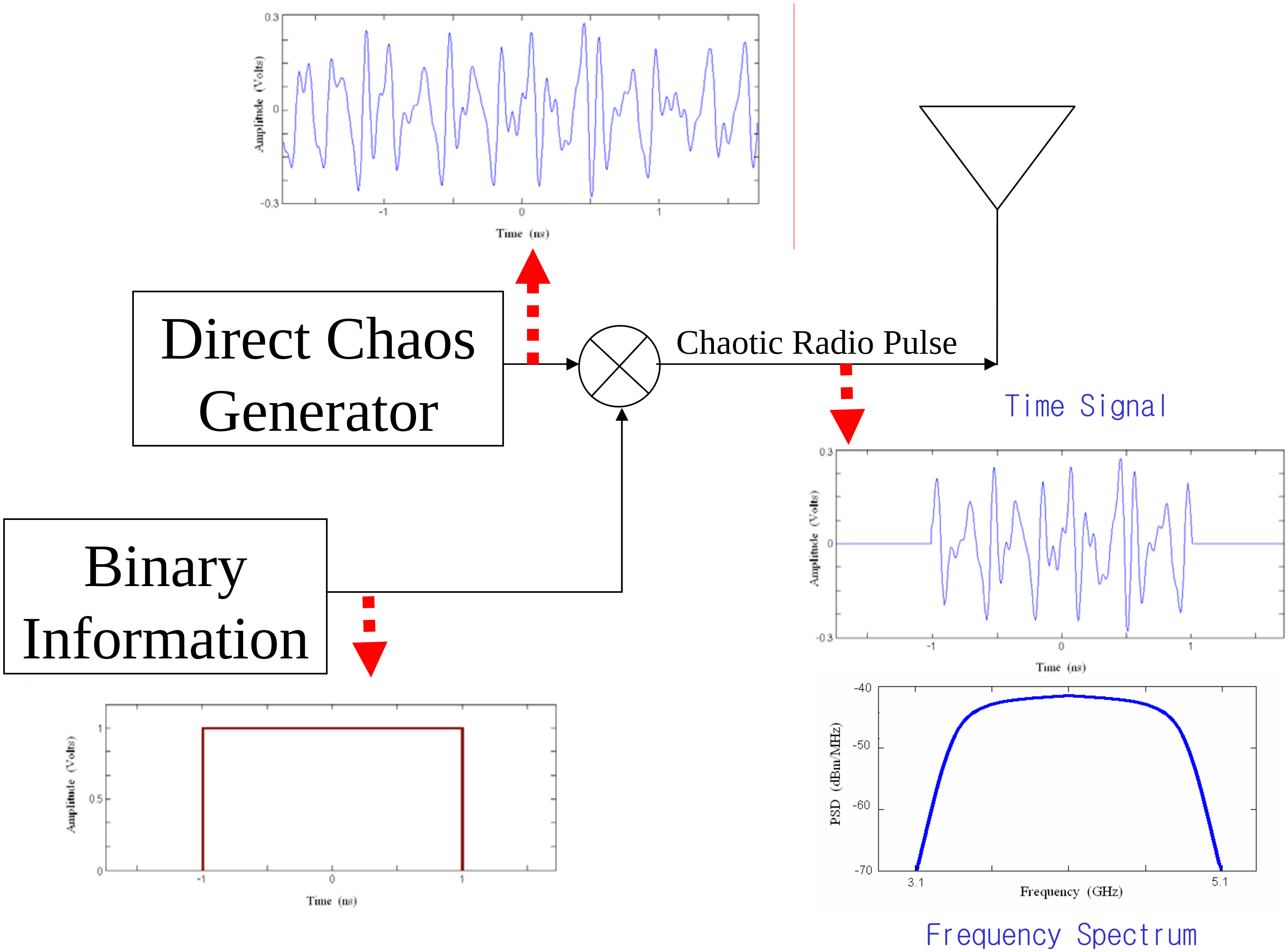
Characteristics of Chaotic Signal (3)



Direct Chaotic Communication (DCC)

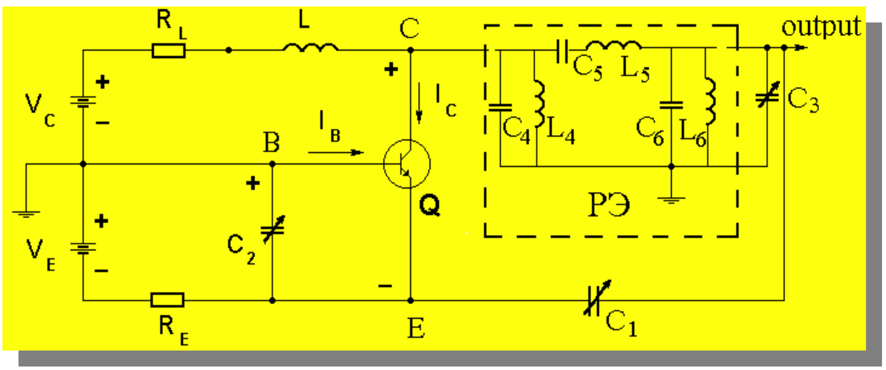
- Chaotic source generates oscillations directly in a specified microwave band.
- Information component is put into the chaotic carrier using the stream chaotic radio pulses.
- Information is retrieved from the chaotic radio pulses without intermediate heterodyning.
- Most simple non-coherent receiver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

Direct Chaotic Signal Generation

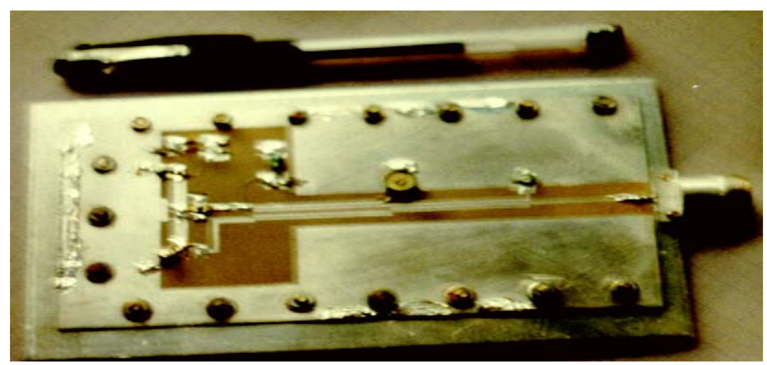


Chaotic Generator Model

Oscillator circuit



Experiment device



Chaotic Mathematical Model

- 2nd order differential equation implemented by ODE with 4.5 freedom

System Equations

$$T\dot{x}_1 + x_1 = mF(x_5)$$
$$\ddot{x}_2 + \alpha_2\dot{x}_2 + \omega_2^2 x_2 = \omega_2^2 x_1$$
$$\ddot{x}_3 + \alpha_3\dot{x}_3 + \omega_3^2 x_3 = \alpha_3\dot{x}_2$$
$$\ddot{x}_4 + \alpha_4\dot{x}_4 + \omega_4^2 x_4 = \alpha_4\dot{x}_3$$
$$\ddot{x}_5 + \alpha_5\dot{x}_5 + \omega_5^2 x_5 = \alpha_5\dot{x}_4$$

Runge-Kutta Method

y(1) = (m*Fx5 - X1)/T;
y(2) = W1*W1*(X1- X3);
y(3) = X2 - A1*X3;
y(4) = A2*y3-W2*W2*X5;
y(5) = X4 - A2*X5;
y(6) = A3*y(5)-W3*W3*X7;
y(7) = X6 - A3*X7;
y(8) = A4*y(7)-W4*W4*X9;
y(9) = X8 - A4*X9;

Nonlinearity $$F(z) = M\left[|z+e_1| - |z-e_1| + \frac{|z-e_2| - |z+e_2|}{2} \right]$$

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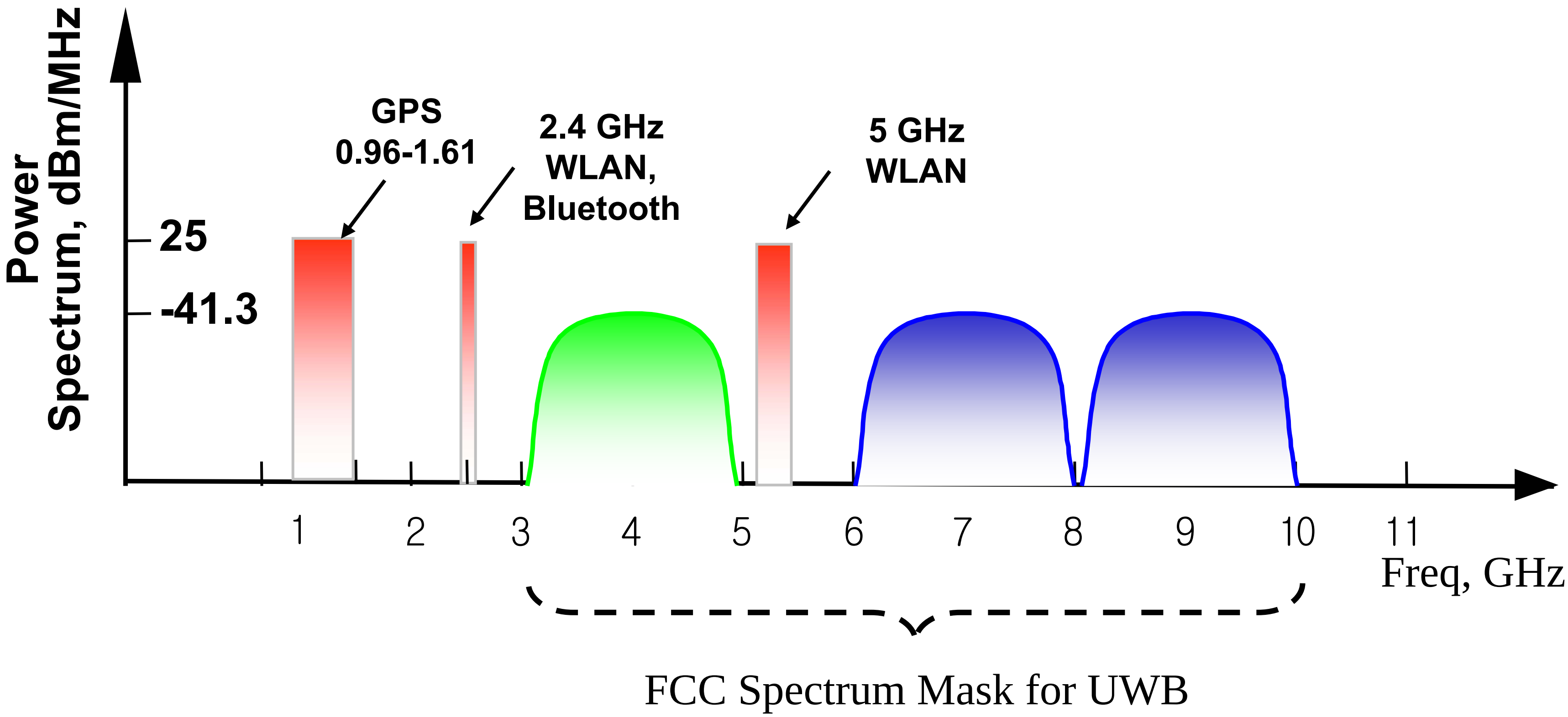
Frequency Band Plan (1)

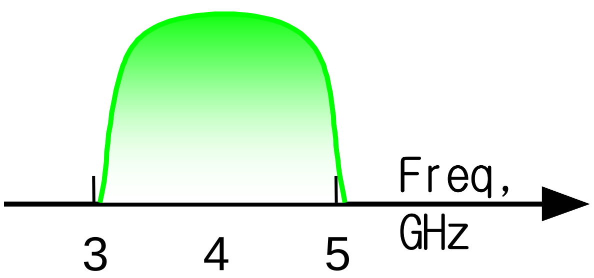


Frequency Band Plan (2)

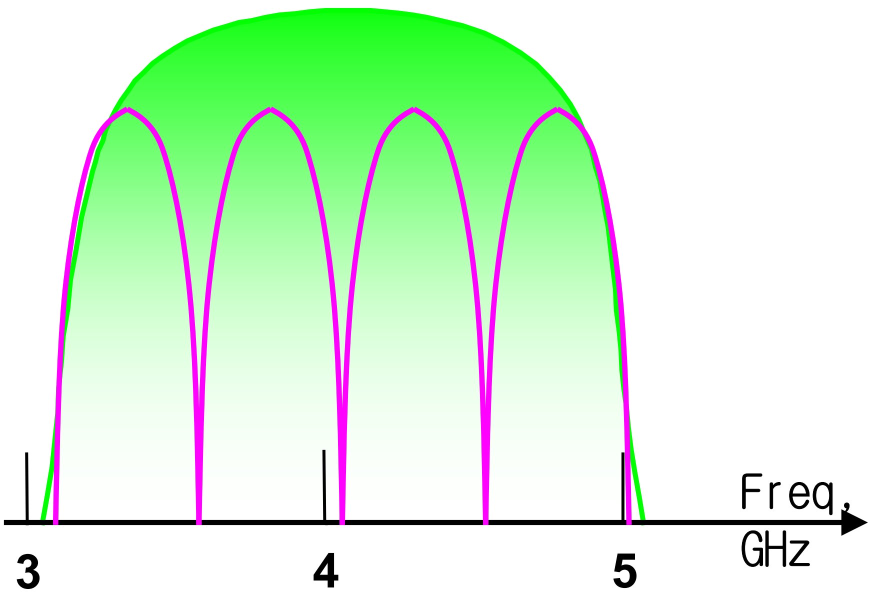
- Operating Frequency: 3.1–5.1 GHz
- Why Lower Band?
  - Limitation in the technical capabilities of integrated circuit implementation at higher frequency.
  - Limit of low cost ICs beyond 6 GHz.
  - Prevent coexistence with 5 GHz WLAN band.
  - Use as much bandwidth as possible to maximize the emitted power and follows FCC rules i.e. >500MHz.
- Can be easily change to use higher band if necessary or when cheap technologies available in the future.

Frequency Band Plan (3)

4 sub-bands for 4 simultaneously operating piconets (SOPs)

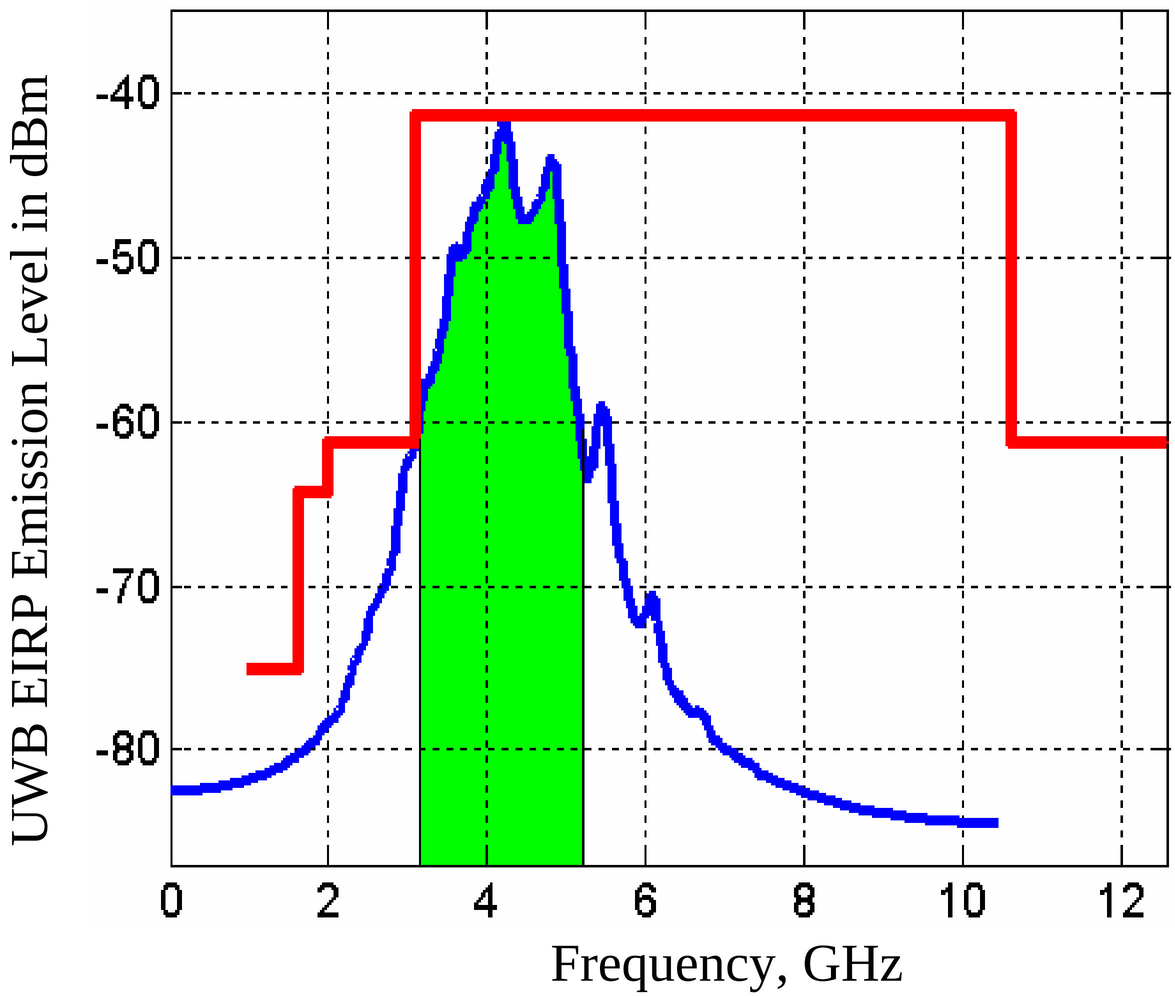


Subband	fc, GHz	fL, GHz	fR, GHz
1	3,35	3,1	3,6
2	3,85	3,6	4,1
3	4,35	4,1	4,6
4	4,85	4,6	5,1



- 500 MHz bandwidth at –10 dB
- Spaced 500 MHz away

FCC UWB Emission Mask



Modulation Schemes

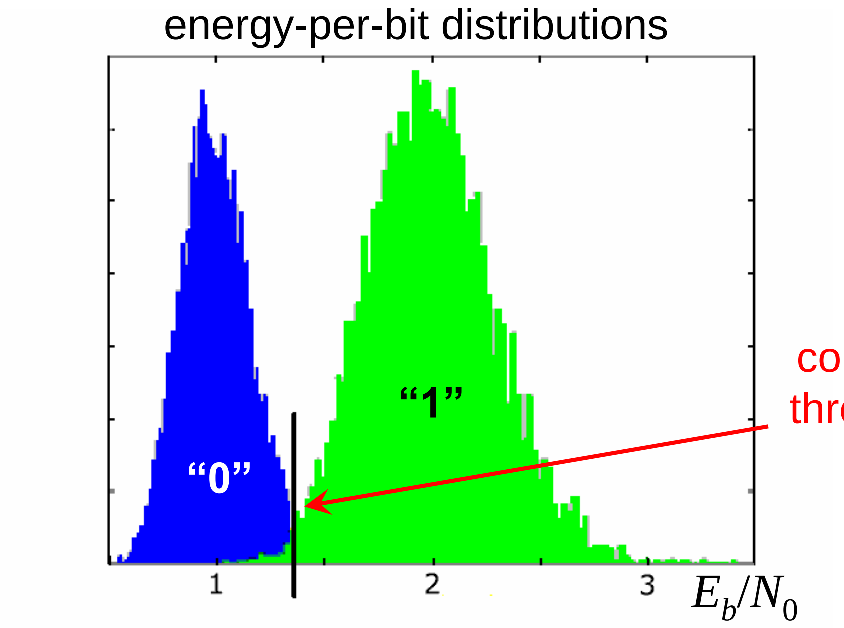
- Various modulation schemes can be deployed:
  - On-off-keying (OOK)
  - Differential-chaos-shift-keying (DCSK)
  - Pulse-position modulation (PPM)

Why OOK ?

- Advantages:
  - It has less complexity
  - It has 3 dB more energy efficiency that PPM & DCSK $\rightarrow$ battery saving
  - DCSK waste of 3 dB energy on reference pulses
- Disadvantages:
  - It requires non-zero threshold

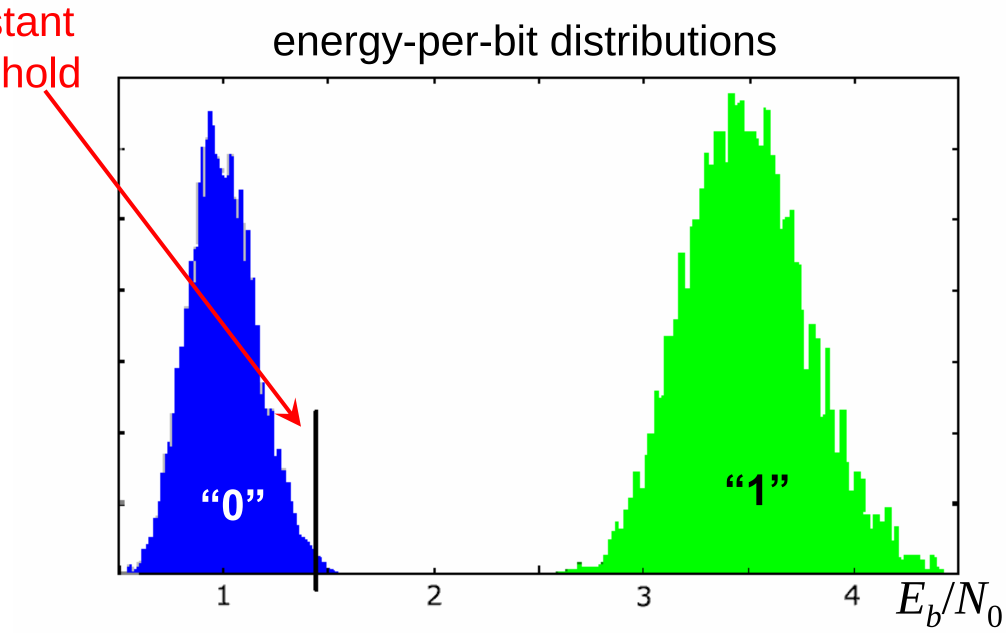
Threshold Estimation

Once set, threshold is constant!



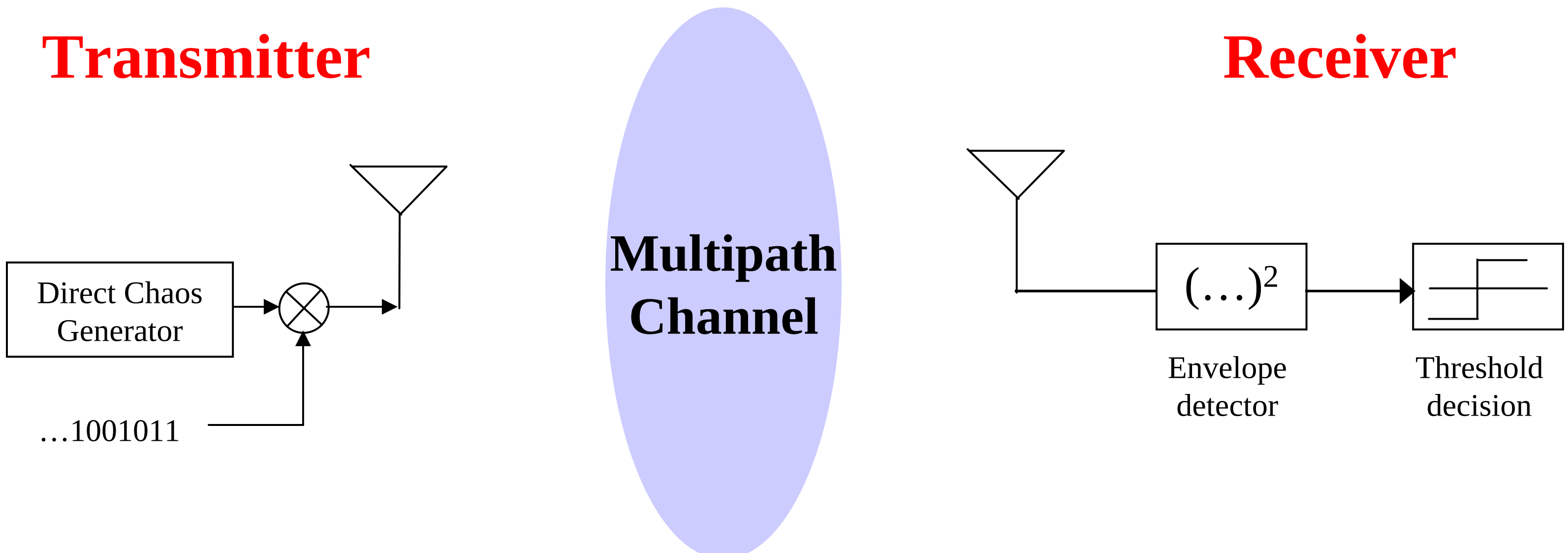
At maximum distance (i.e. 30 m) → minimum SNR

constant threshold

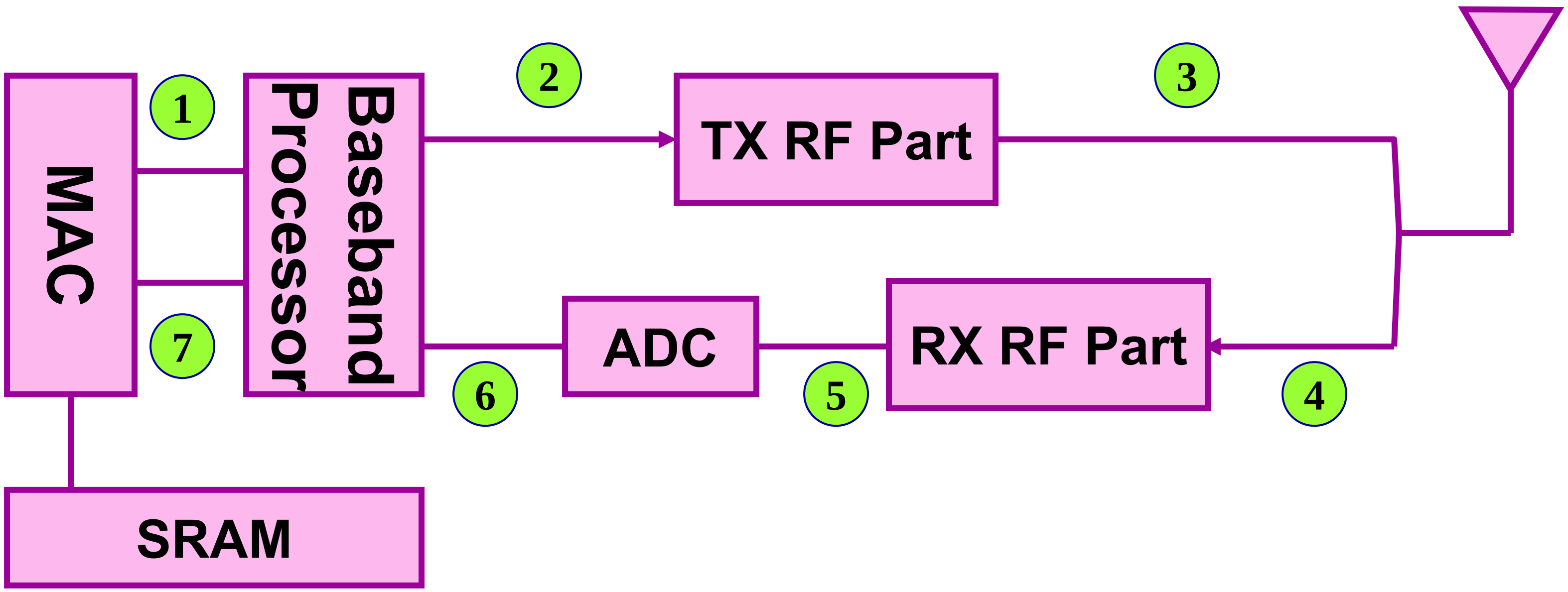


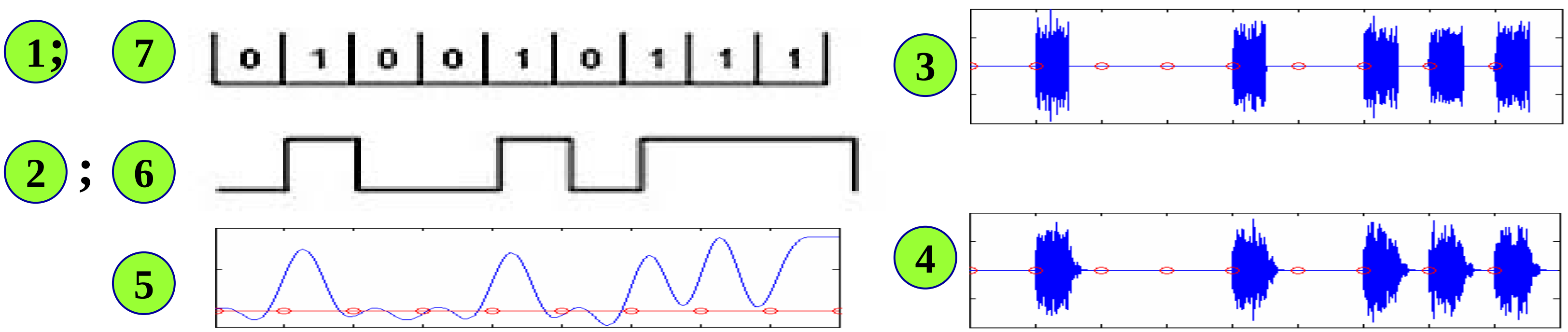
At minimum distance (i.e. 1 m) → maximum SNR

DCC-OOK Transmitter & Receiver



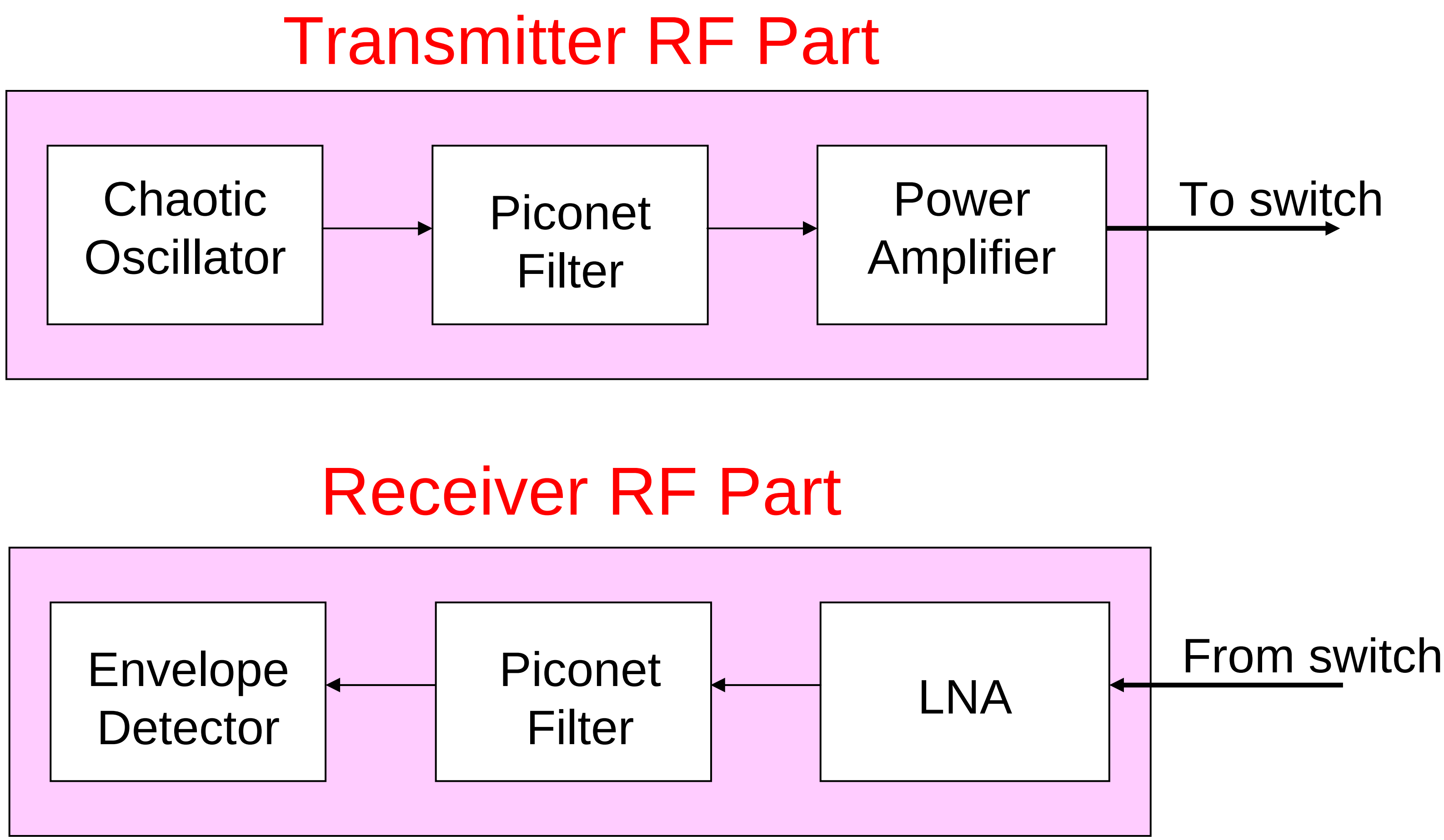
DCC-OOK Transceiver Architecture (1)





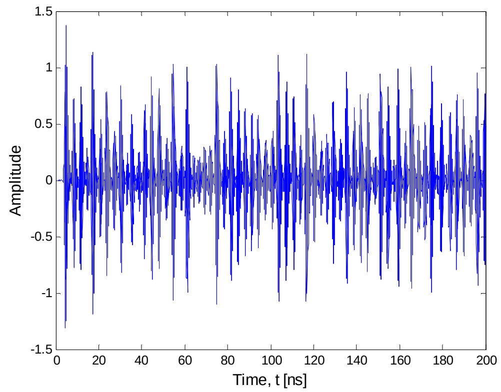
- Very simple modulation scheme: on-off power supply is used for modulation
- Additional power saving

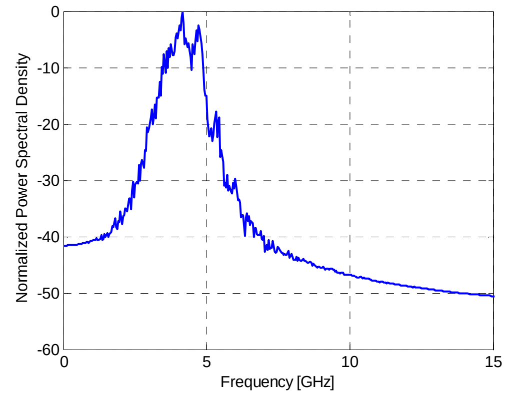
DCC-OOK Transceiver Architecture (2)



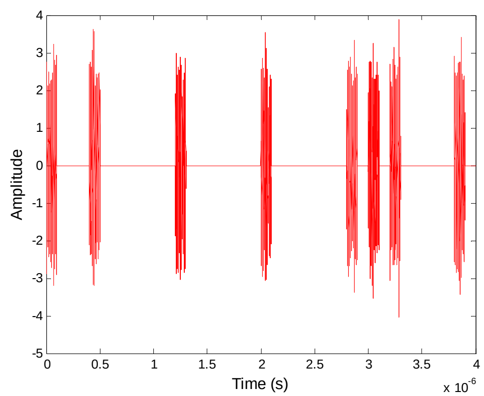
Signal Waveforms and Spectrum

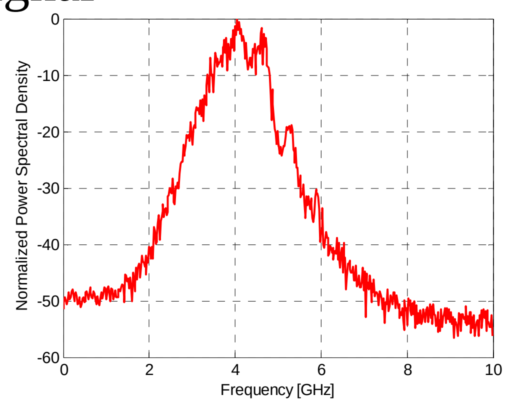
Signal of chaotic generator



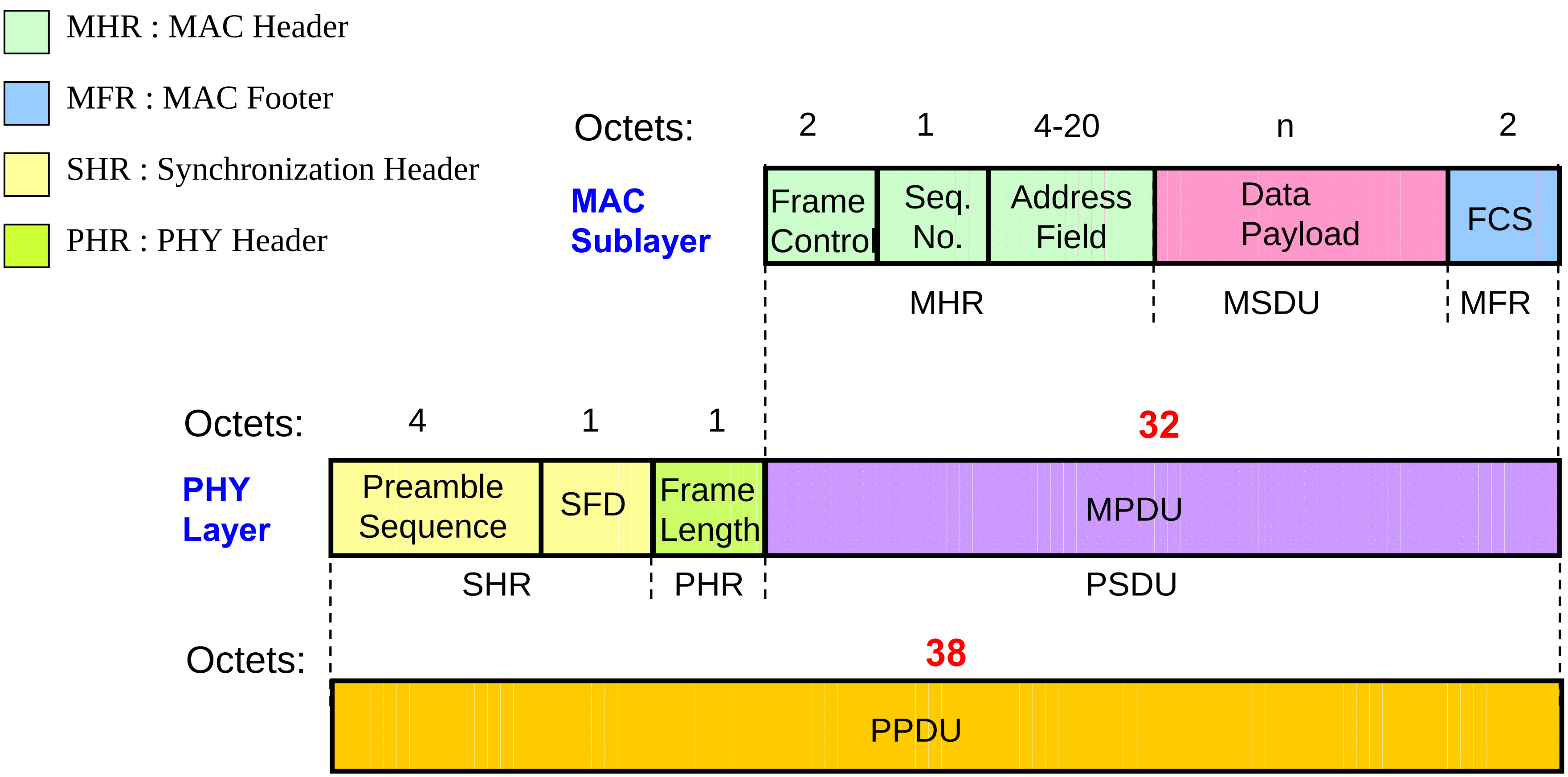


OOK modulated signal

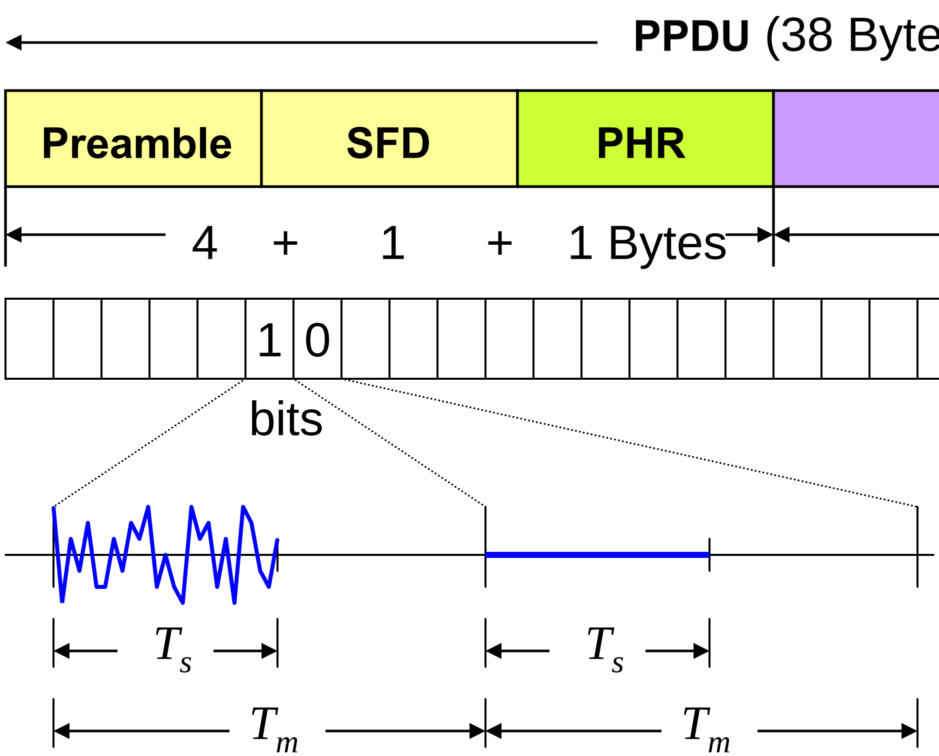




Data Frame Structure



PHY Data Frame Structure

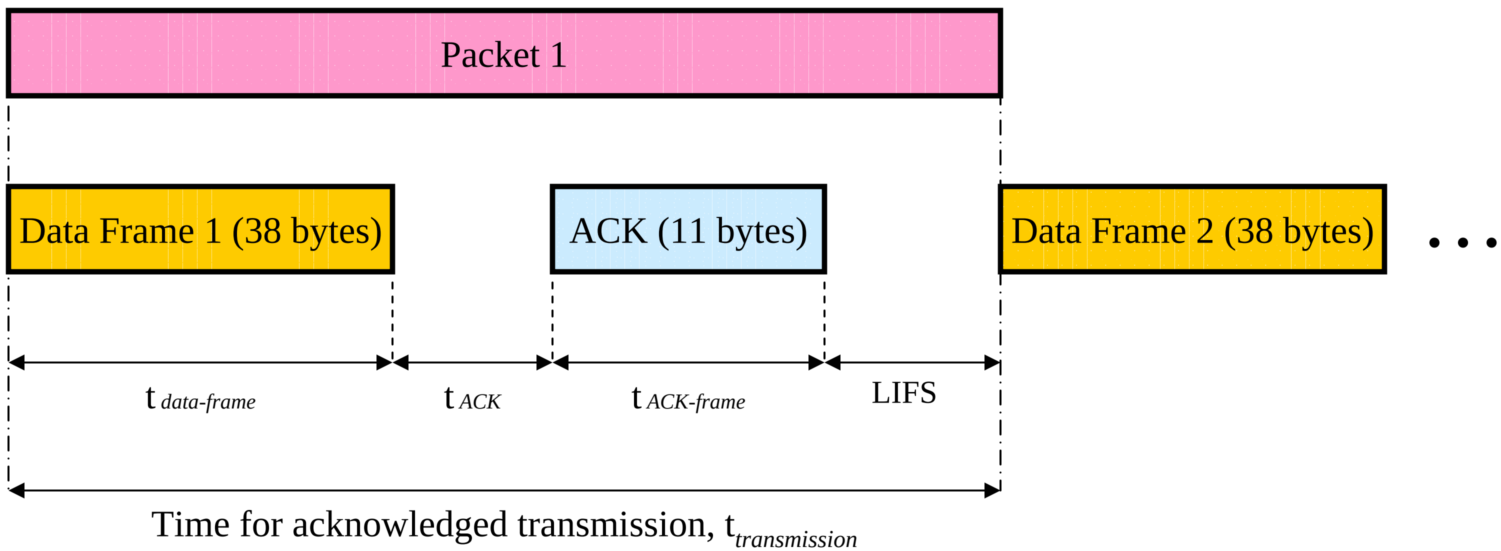


T_s = 100 ns : Pulse emission time

T_m = 200 ns : Pulse bin width or Bit period

Nominal PHY-SAP payload bit rate, X_0 = (1/200ns)×(1000/1024) = 4.88Mbps

Data Throughput



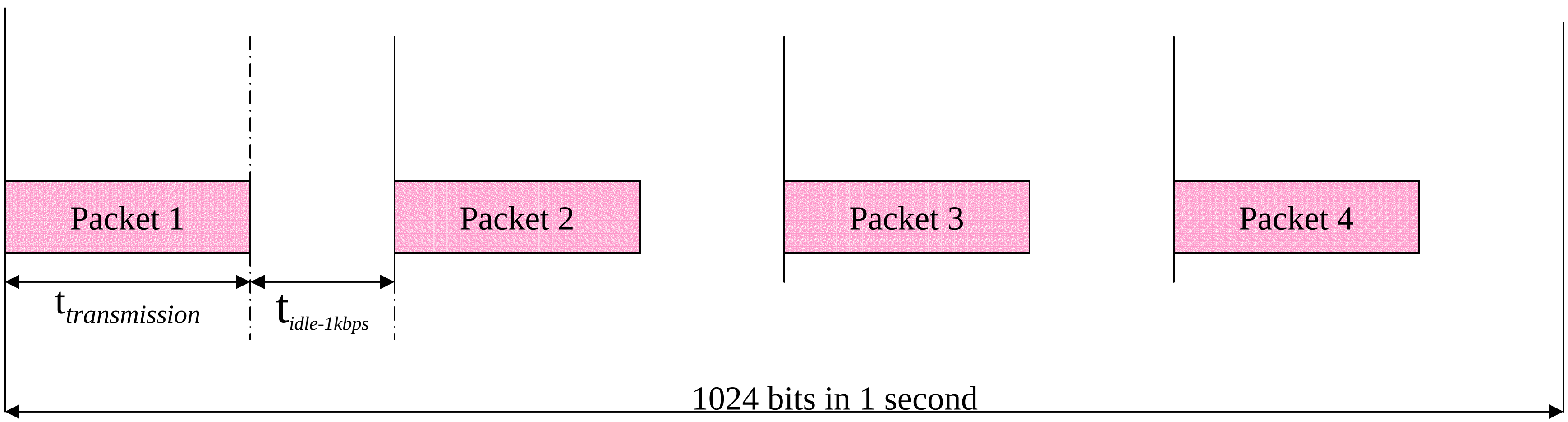
$$\begin{aligned} t_{transmission} &= t_{data\text{-}frame} + t_{ACK} + t_{ACK\text{-}frame} + \text{LIFS} \\ &= (38\times8\times200\text{ns}) + 40\mu\text{s} + (11\times8\times200\text{ns}) + 90\mu\text{s} \\ &= 208.4\mu\text{s} \end{aligned}$$

Nominal Data Throughput, T_0 = (32×8/208.4μs)×(1000/1024) = 1.2Mbps

Example of Operation at 1 kbps (1)

- There are 2 methods of operation in order to achieve 1 kbps data rate:
    1. The device transmits several packets in succession, so that the overall data volume is 1kbit i.e. 1024 bits, then falls silent till the beginning of the next second.
    2. The device transmits one packet of data at a time with long pauses between the packets, so that total data volume over 1 second is 1kbit. In the beginning of the next second the device wakes up and transmits another 1kbit portion of data.

Example of Operation at 1 kbps (2)



- To achieve effective data rates of 1 kbps using 32-bytes PSDU, 4 packets need to be transmitted in 1 second.
- The idle time for the above system is $t_{idle\text{-}1kbps} \approx 250$ ms.

Data Rates and Range

System supports data rates:

- 1 kbps
- 10 kbps
- 1 Mbps
- 40 kbps (optional)
- 160 kbps (optional)
- Aggregated bit rate up to 5 Mbps

System supports ranges:

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

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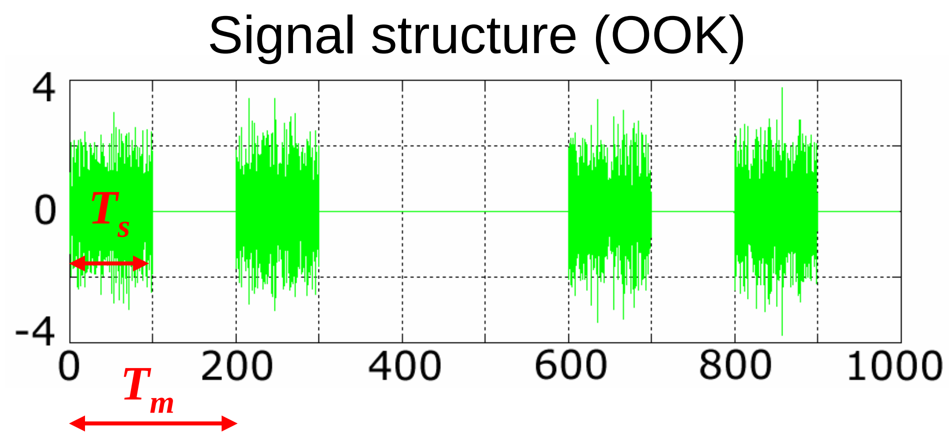
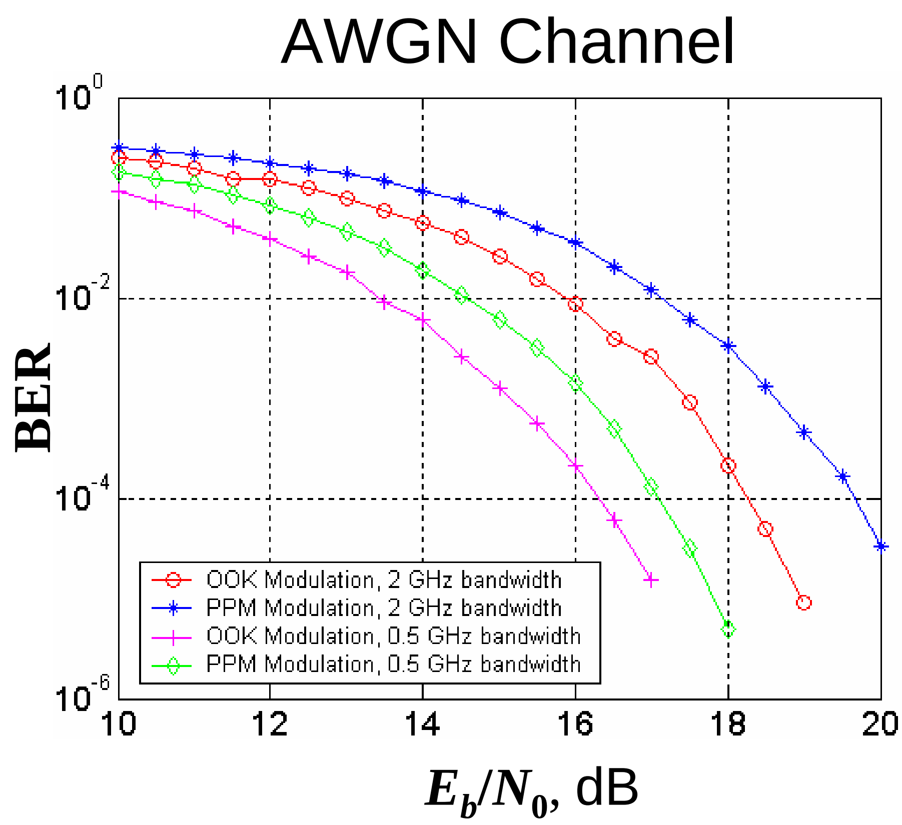
AWGN Performance

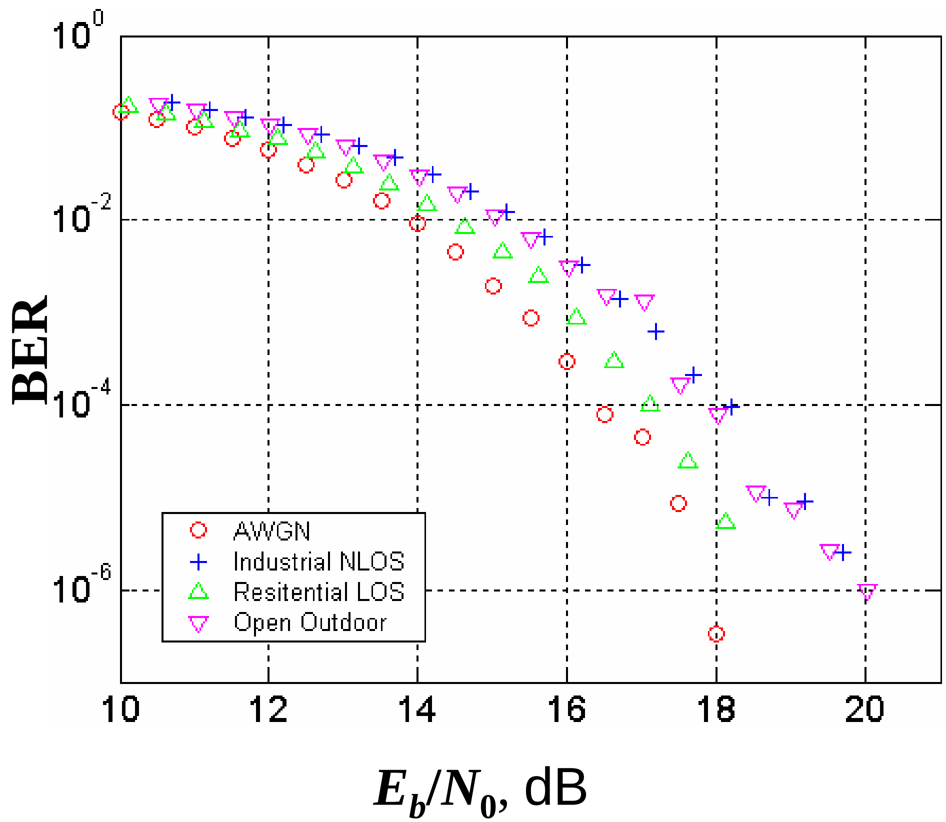


T_s = 100 ns, T_m = 200 ns

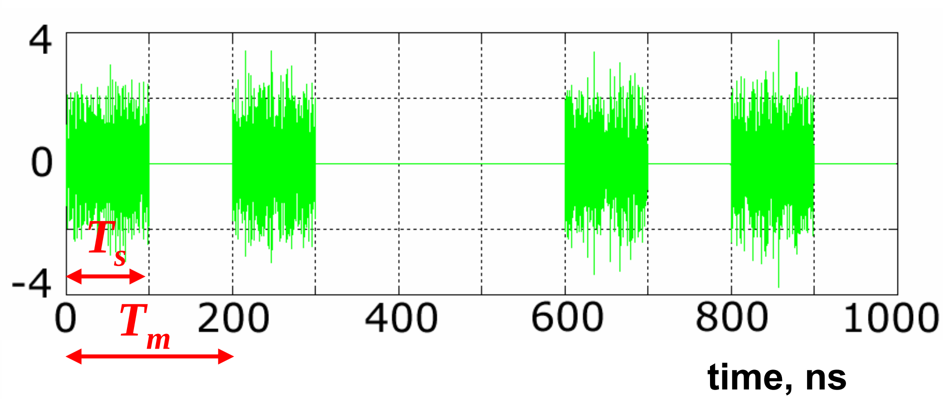


Multipath Performance (1)

Multipath channels

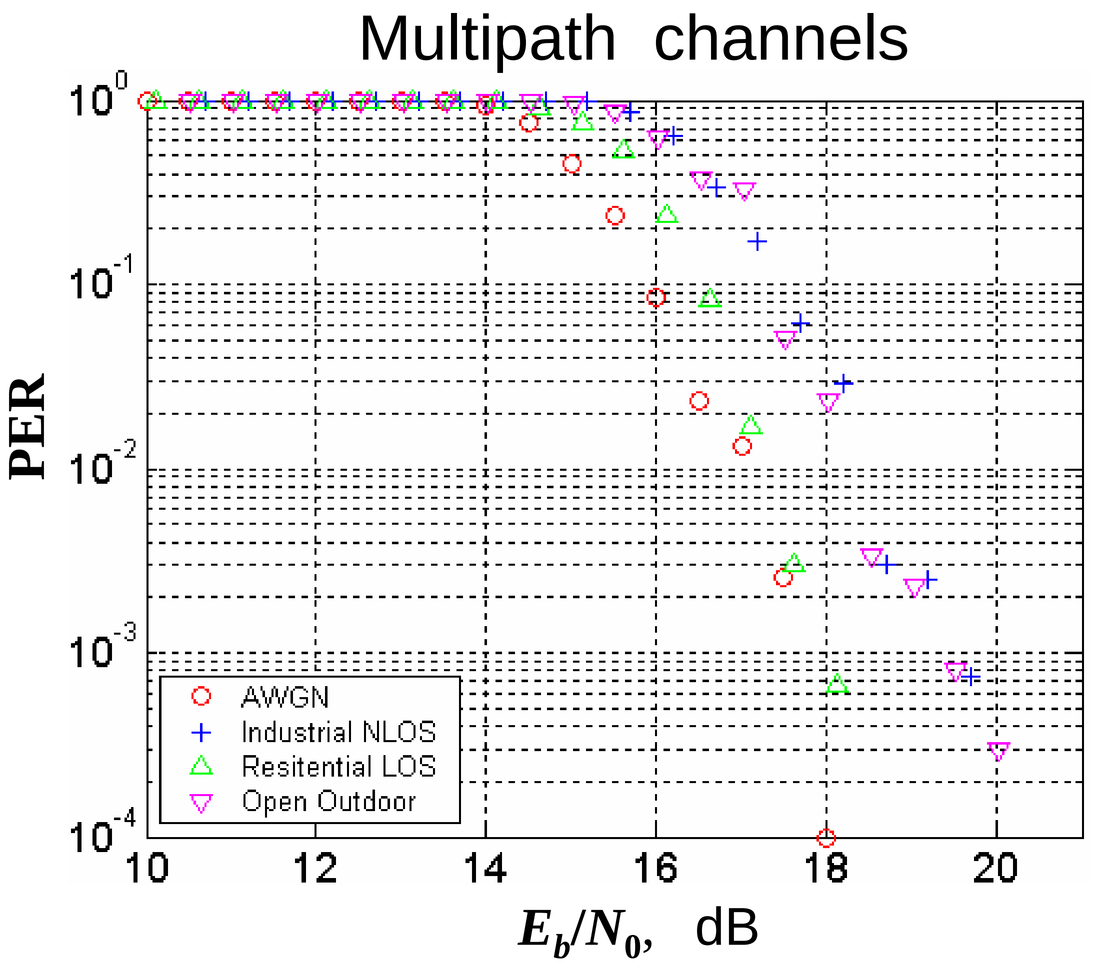


Signal structure



T_s = 100 ns, T_m = 200 ns

Multipath Performance (2)



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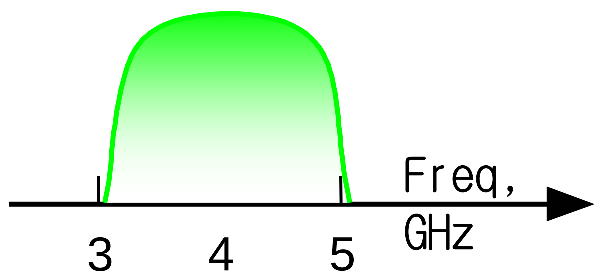
SOP

- Two methods to achieve SOP:
  1. Frequency division multiplexing (FDM)
     - Four independent frequency channels on 500 MHz guaranties simultaneously operating four piconets with aggregated bit rate up to 5 Mbps in each of them
  2. Code division multiplexing (CDM)

SOP: FDM

4 sub-bands for 4 simultaneously operating piconets (SOPs)



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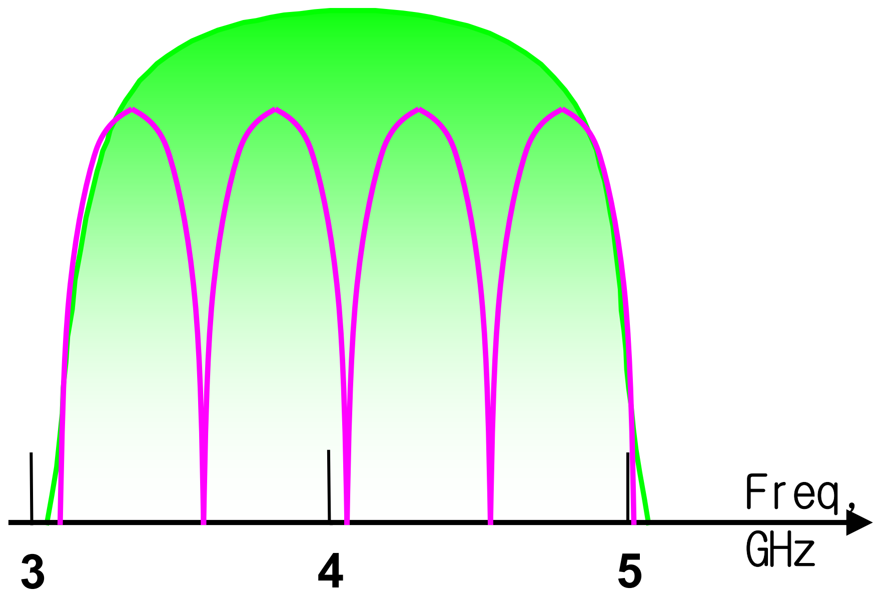
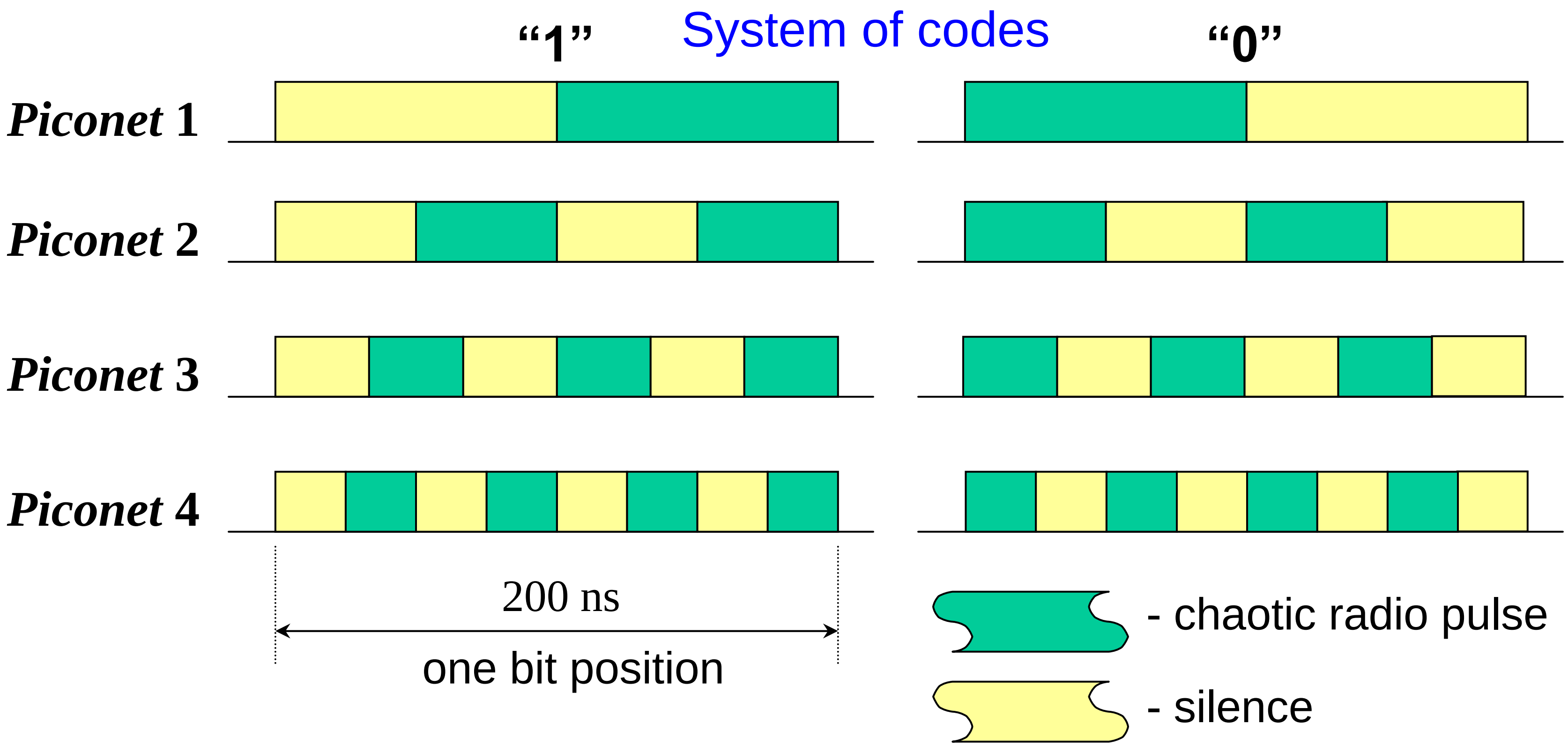


- 500 MHz bandwidth at –10 dB
- Spaced 500 MHz away

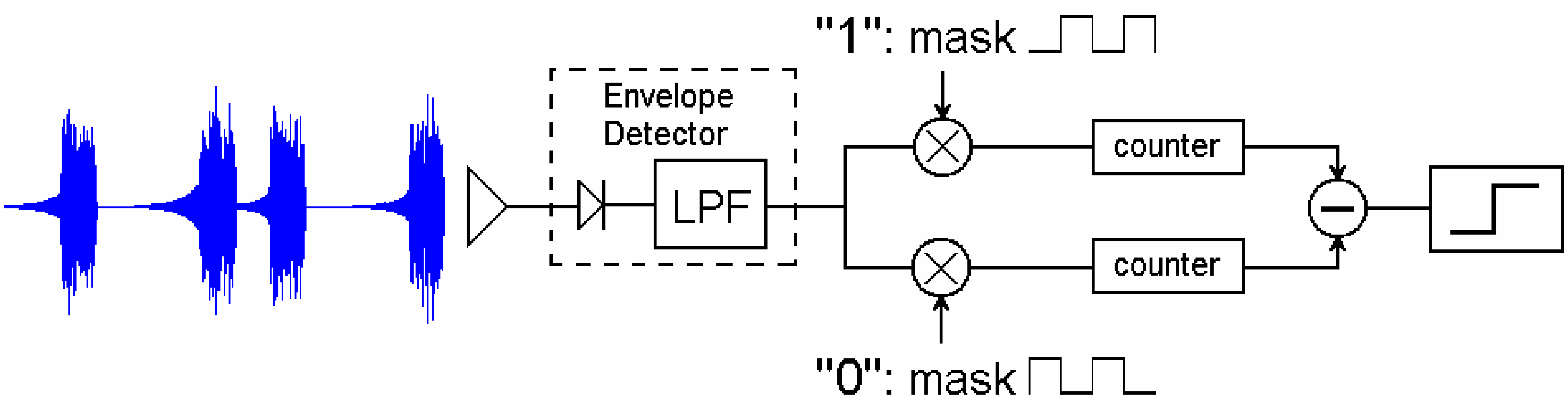
SOP: CDM



- Within each piconet, the codes are orthogonal.
- Between piconets, codes are not orthogonal, however are separable.
- Piconets are independent.
- Adding signal of one other piconet doesn't cause errors.

SOP: CDM (2)

1. Received and detected signal is divided in two branches where it is multiplied by mask corresponding to “1” or “0”. Each piconet has its own masks, defined by the piconet code.
2. Energy in every branch is measured.
3. Decision on “1” or “0” depends on which branch has higher energy.



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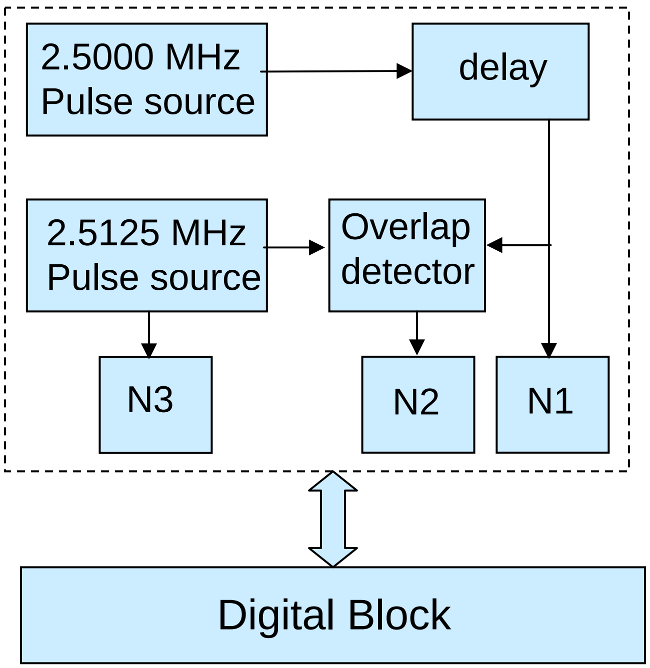
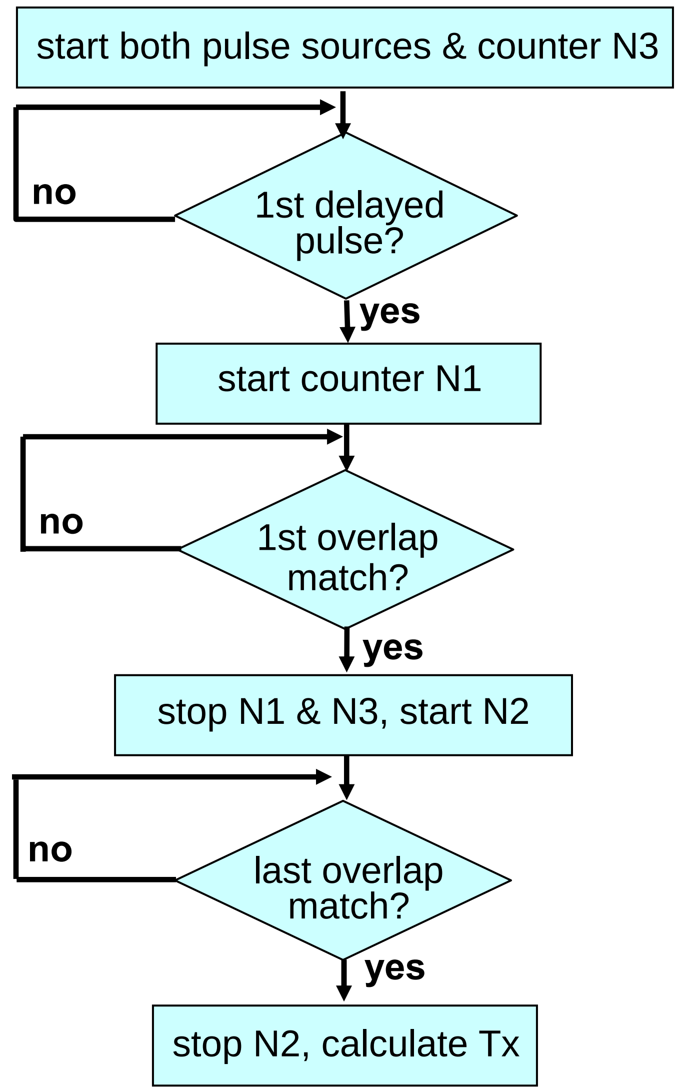
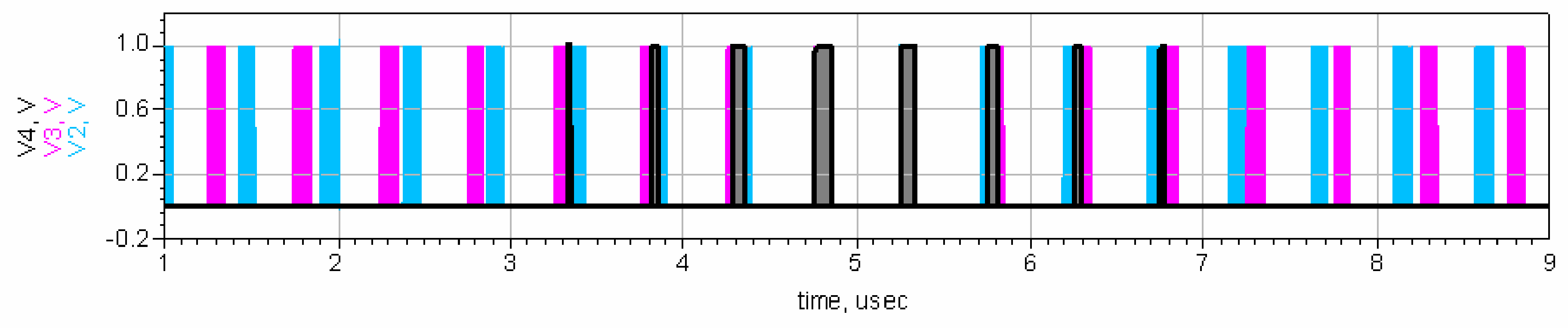
Ranging Algorithm (1)

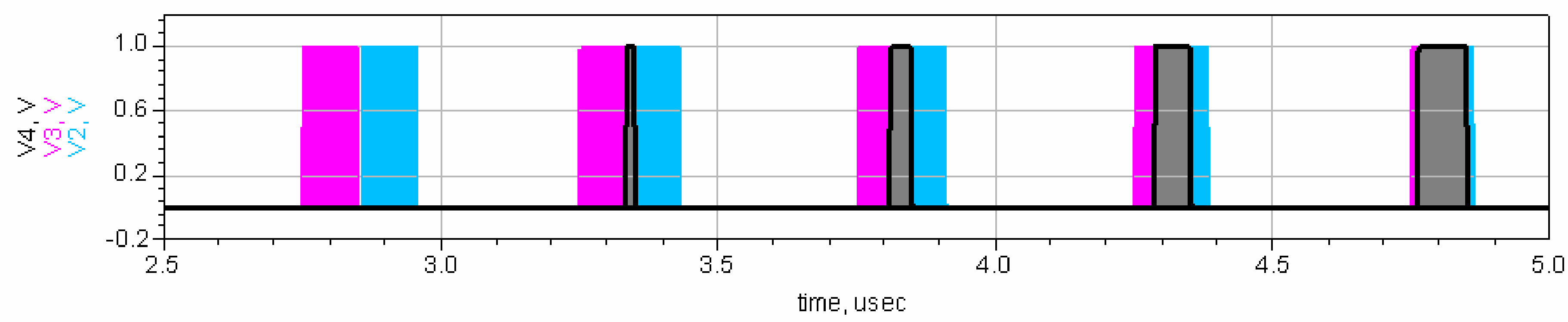




- Counter **N1** counts delayed pulses
- Counter **N2** counts overlaps between delayed pulses(2.5000 MHz) and reference pulses(2.5125 MHz)
- Counter **N3** counts reference pulses

Overlapping of Delayed & Reference Pulses



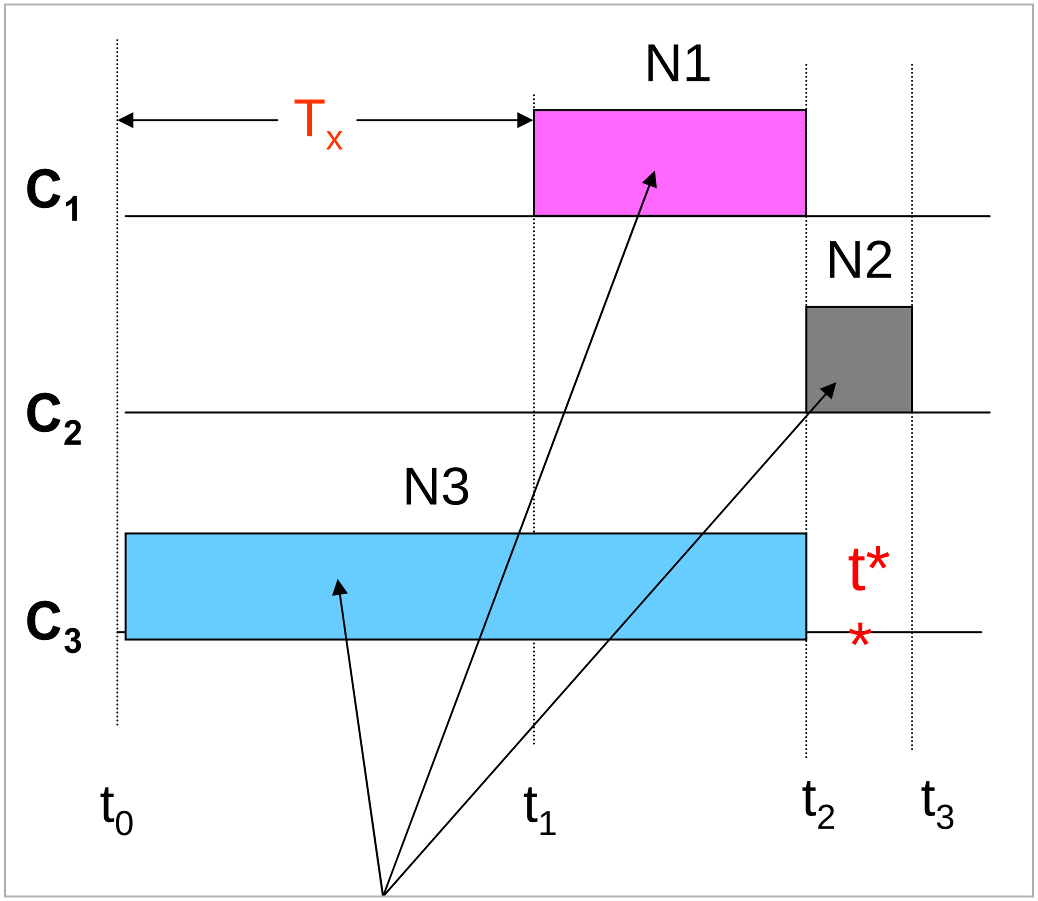


Delayed pulse

Reference pulse

Pulse overlap

Ranging Algorithm (2)



N1, N2, N3 – pulse numbers

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

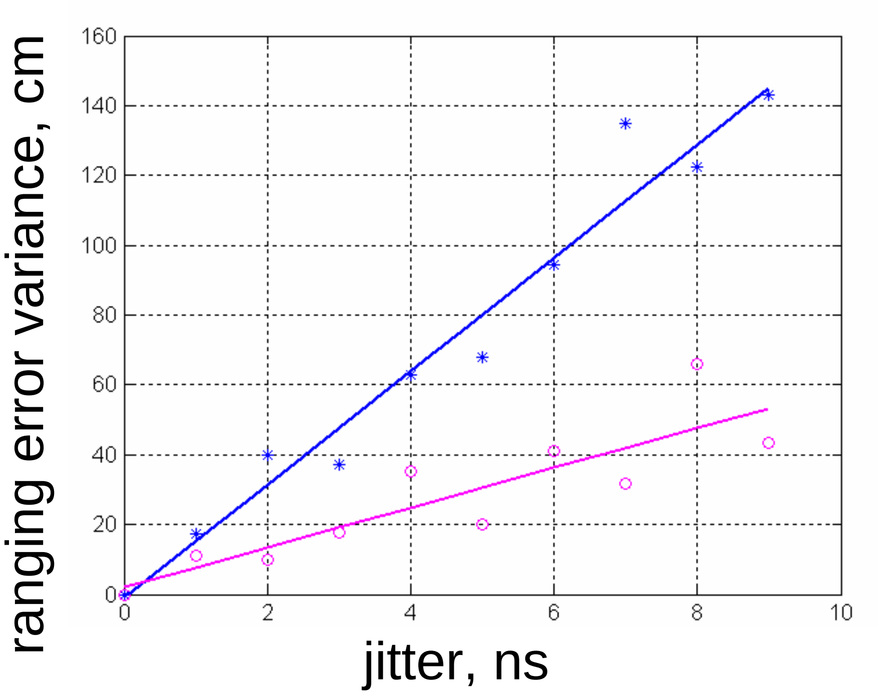
distance

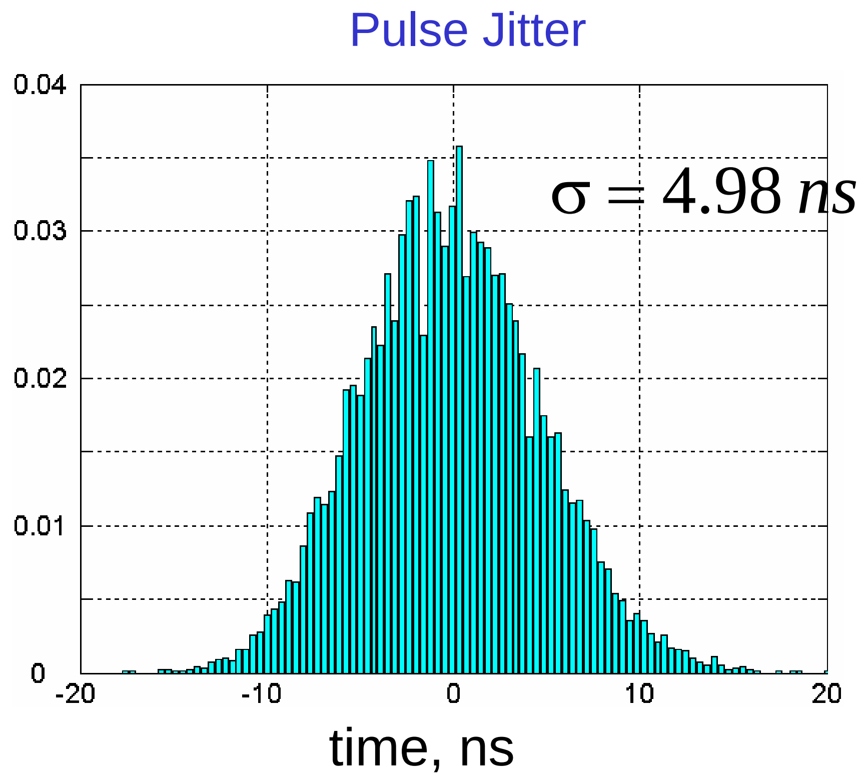
$S = 0.5*c*(T_x-\tau_0)$

τ_0 – retranslation time

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

Effect of Jitter on Ranging Precision

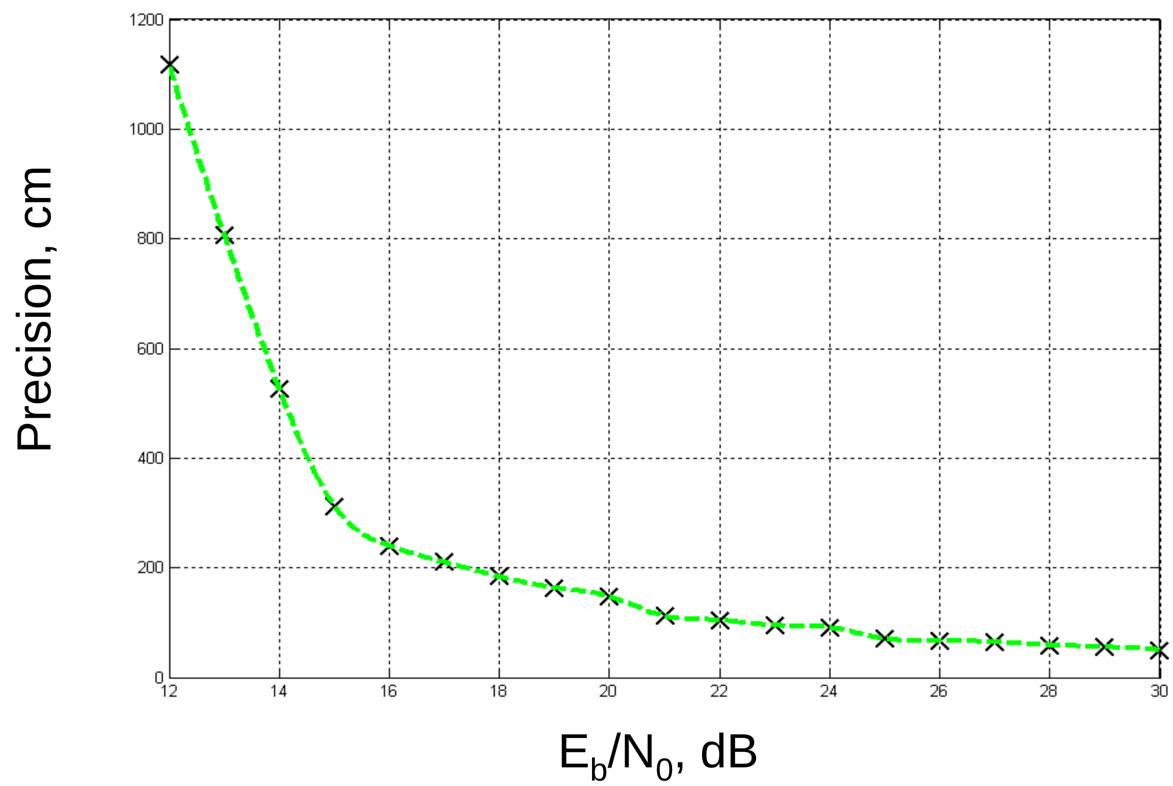




1000 estimates

100 series of 10 averaged estimates

Effect of Noise on Ranging Precision



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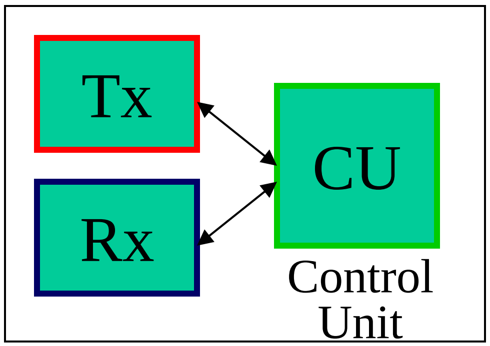
Power Consumption (1)

Transceiver



Average power consumption P_{av}

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

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

$$P_e = P_{in} \cdot T_e = 1/4 \cdot P_{in} \cdot T_{bit} \cdot V$$

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,

V is transmission rate,

C_b is battery capacity,

U_b is battery voltage.

Power Consumption (2)

Transmission Rate V, kbps	Average Emitted Power P_e, mW	Average Power Consumption P_{av} ($\eta = 5\%$)	Continuous operation time 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

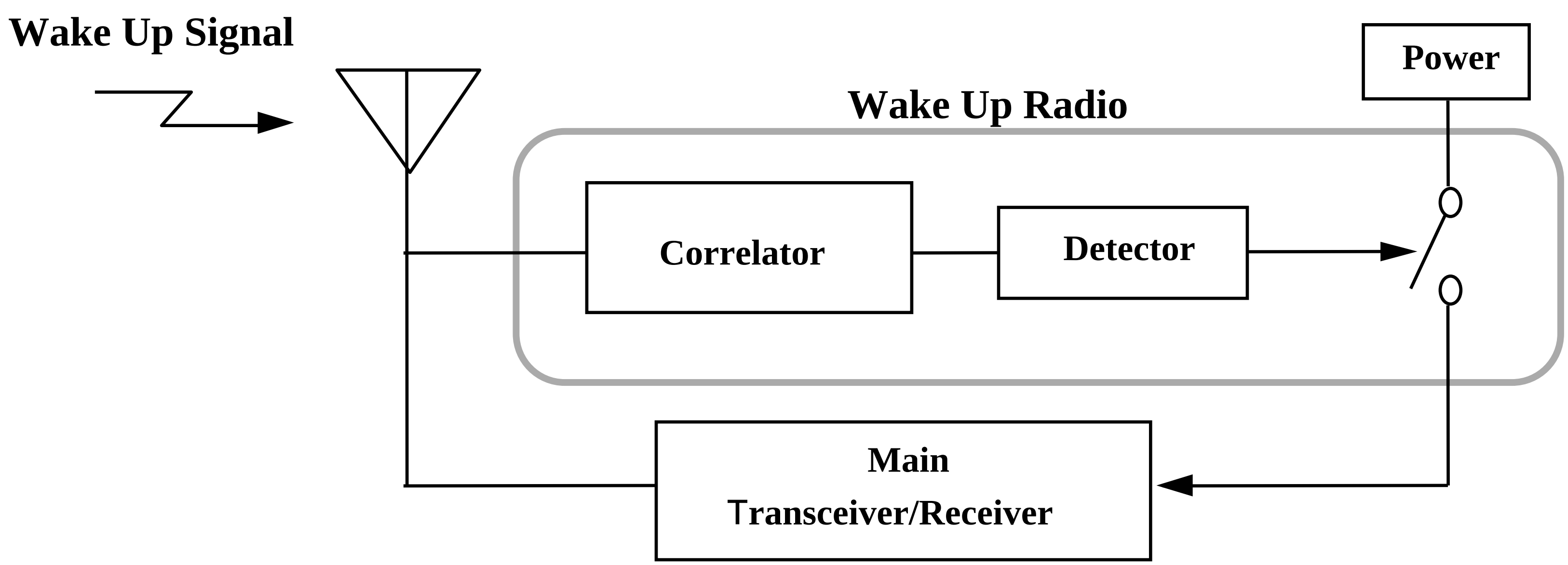
Example: V = 1 kbps; T_{bit} = 200 *ns*; η = 5%

$$P_e = 1/4 \cdot P_{in} \cdot T_{bit} \cdot V = 0.2\ \mu\text{W}$$

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

Power Management Modes

Wake Up Structure



Outline

- Characteristics of Chaotic Signal
- Principle of Direct Chaotic Communications (DCC)
- PHY Layer Proposal
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- Simultaneously Operating Piconets (SOP)
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Link Budget & Sensitivity

Parameter	Value (mandatory)
peak payload bit rate (R_b)	X_0=4880 kbps
Average Tx power (P_T)	-8.3 dBm
Tx antenna gain (G_T)	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
Path loss at 1 meter ($L_1 = 20\log_{10}(4\pi f_c' / c)$) $c = 3\times10^8$ m/s	44.43 dB
Path loss at d=30 m ($L_2 = 20\log_{10}(d)$)	29.54 dB
Rx antenna gain (G_R)	0 dBi
Rx power ($P_R = P_T + G_T + G_R - L_1 - L_2$ (dB))	-82.3 dBm
Average noise power per bit ($N = -174 + 10 * \log_{10}(R_b)$)	-107.1 dBm
Rx Noise Figure (N_F) note [1]	7 dB
Average noise power per bit ($P_N = N + N_F$)	-100.1 dBm
Minimum E_b/N_0 (S)	14 dB
Implementation Loss[1] (I)	3 dB
Link Margin ($M = P_R - P_N - S - I$)	0.8 dB
Proposed Min. Rx Sensitivity Level[2]	-83.1 dBm

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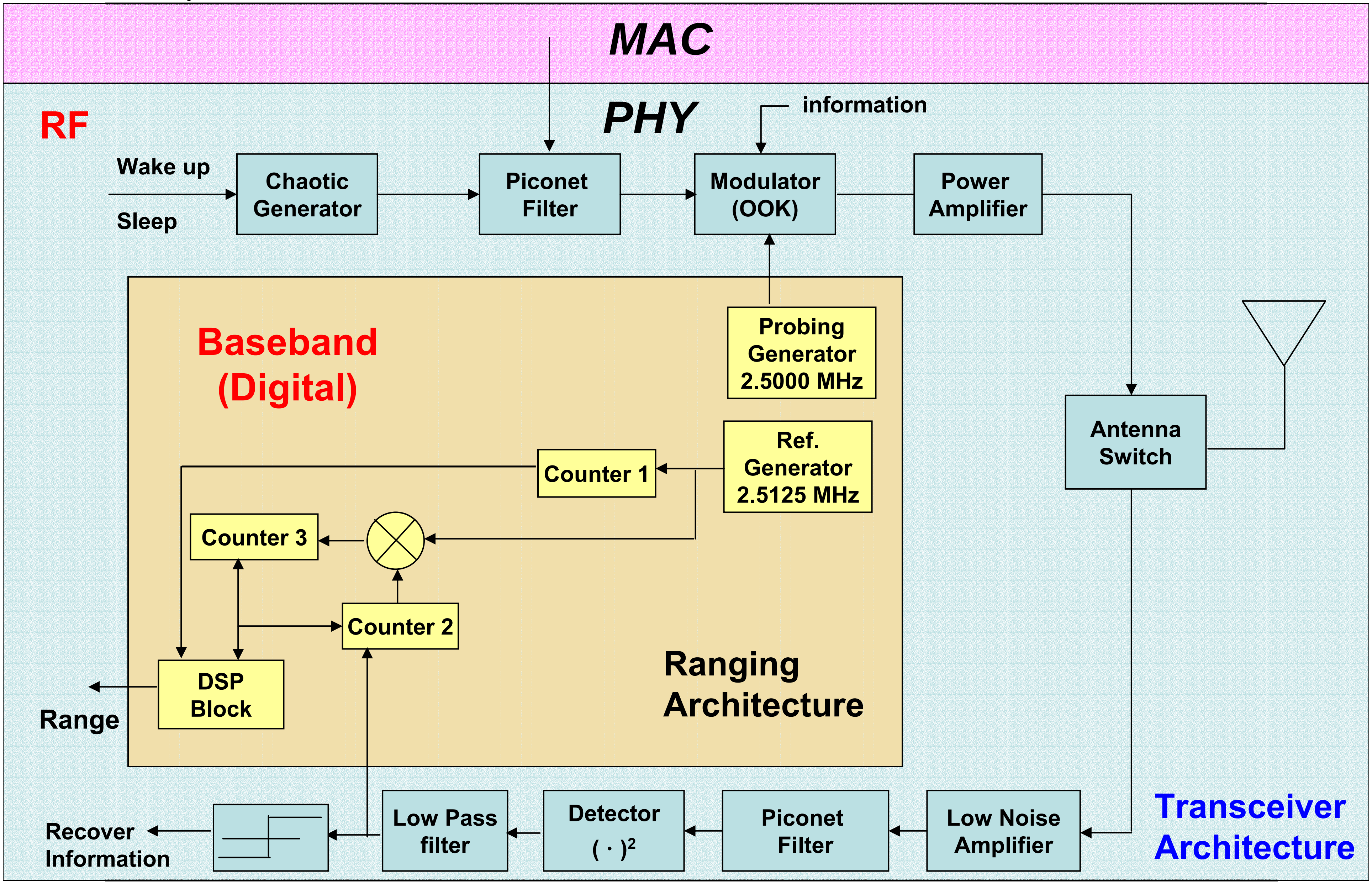
Transceiver Architecture



Unit Manufacturing Cost & Complexity (1)

- RF part of the transceiver:
  - Chaos 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)
  - **Tunable filter** with bandwidth 500 MHz (in band 3.1-5.1 GHz)
  - Envelope detector
  - Antennas
  - No: mixers, correlators, RF VCO

Unit Manufacturing Cost & Complexity (2)

- 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

Size & Form Factor

PHY–level (130 nm technology)

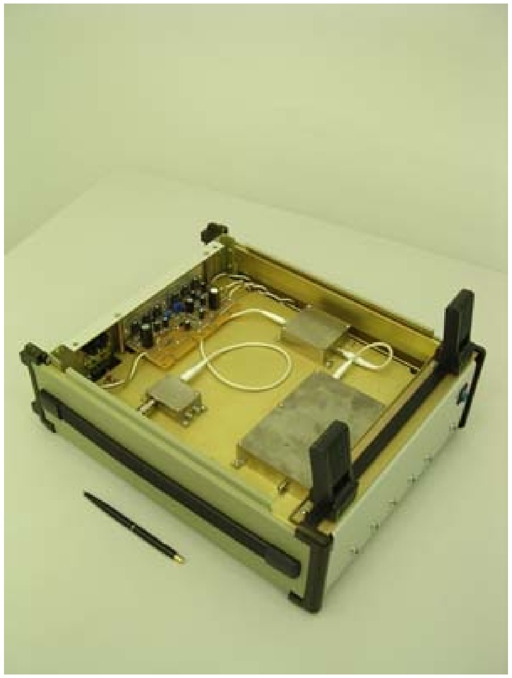
- RF part of transceiver < 0.3 mm^2
- Analog part of transceiver PHY–level baseband < 0.2 mm^2
- Digital part of transceiver PHY–level baseband < 0.3 mm^2

- Common layout square for PHY-level < 1.0 mm^2

- Antenna: 2.0 x 2.0 cm^2

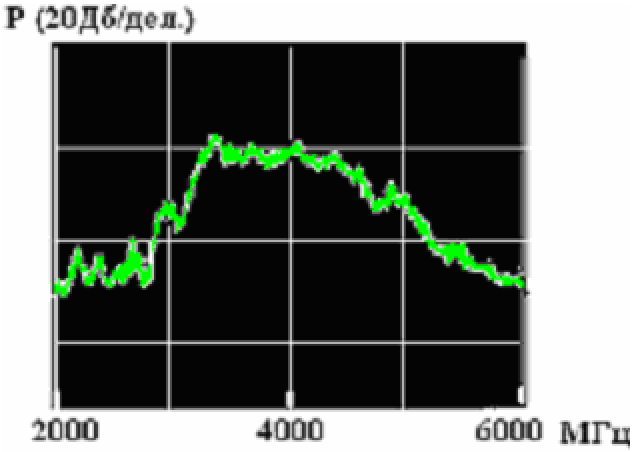
Technical Feasibility (1)

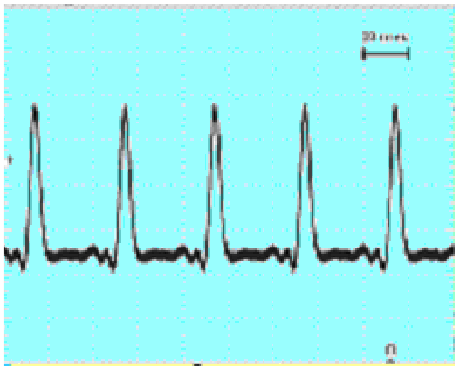
UWB DCC-OOK Test-bed

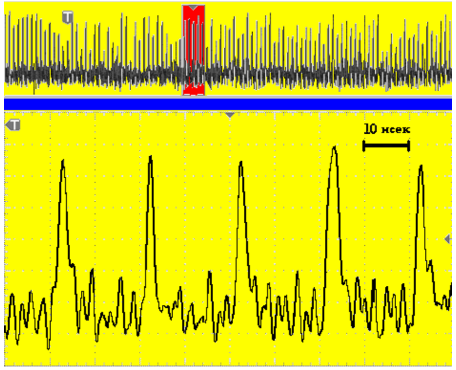




Technical Feasibility (2)

DCC-OOK Experiment: 3.1-5.1 GHz







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Scaling Parameters

- Scalability is the tradeoff between
  - Bit rate
  - Power consumption
  - Range
  - Complexity / Cost
- PHY mechanisms used
  - Transmit power control
    - Used with local Link Quality Indication/RSSI
  - Dynamic frequency selection
    - Invoked if link quality falls below some threshold
- Applications (Samsung)
  - Home usage/Smart home (1kbps - 20 to 30m)
  - Communication and networking (1kbps - 20 to 30m)
  - Directly also means type of multipath channel

What can be scaled?

- Power consumption (depending on the occupancy of the bandwidth of the chaotic signal, say 75%)
  - Scalable up to 0.11mW based on data rate and distance
  - Packet transmission followed by sleep mode
  - Duty cycle
- Data rate
  - Scalable from 1kbps – 1Mbps
- Range:
  - Scalable with coding, lower bit duration (up to the optimum value), power consumption.
- Complexity
  - Lower complexity, lower performance system possible
  - Scale with future CMOS process improvements

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Self-Evaluation

Criteria	Ref.	Importance Level	Proposer Response
Unit Manufacturing Complexity	3.1	A	+
Technical Feasibility	3.4	A	+
Scalability	3.5	A	+
Size and Form Factor	5.2	A	+
PHY-SAP Payload Bit Rate and Data Throughput	5.3.1	A	+
Simultaneous Operating Piconets	5.4	A	+
System Performance	5.6	A	+
Ranging	5.7	A	+
Link Budget	5.8	A	+
Sensitivity	5.9	A	+
Power Management & Modes	5.10	A	+
Power Consumption	5.11	A	+

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Conclusions

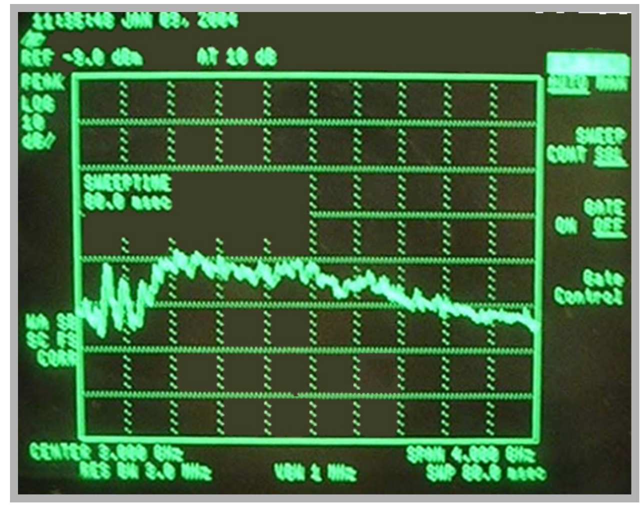
- Chaotic communications meet the low power, low cost & low complexity requirements → best suited for 15.4a applications.
- Proposed DCC-OOK compliant with FCC UWB PSD regulation.
- Feasibility and scalability are guaranteed with precision ranging and SOP capabilities.
- The implemented test bed demonstrated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

Backup Slides

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	4 channels with 500 MHz in each 2.0 GHz band		
Pulse duration	200 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 Chaos Transmitter for Wireless Communications



Transmitter consists of:

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

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

DCSK: Compatible Modulation Scheme for Direct Chaotic Communication

Outline

- General Overview
- Characteristics of DCSK
- Principle of Differential Chaotic Shift Keying (DCSK) Modulation
- Simultaneously Operating Piconets (SOP)
- Ranging Technique
- Scalability
- Complexity, Cost & Technical Feasibility
- Link Budget & Sensitivity
- Conclusion

General Overview

- Direct Chaotic Signal can be applied to the Differential Chaos Shift Keying (DCSK) modulation scheme as an alternative to OOK DCC
- The Chaotic properties are maintained as in the case of the OOK

Characteristics of DCSK

- Direct Chaotic Shift Keying (DCSK)
  - same data rate as in the proposed OOK
  - Constant decision threshold in the receiver
  - SOP can be achieved by transmitting different Chaotic pulse length

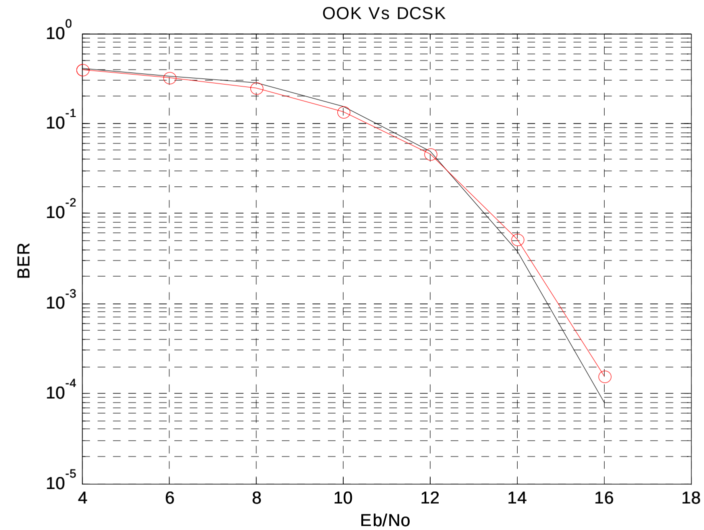
Principle of DCSK Modulation(1)

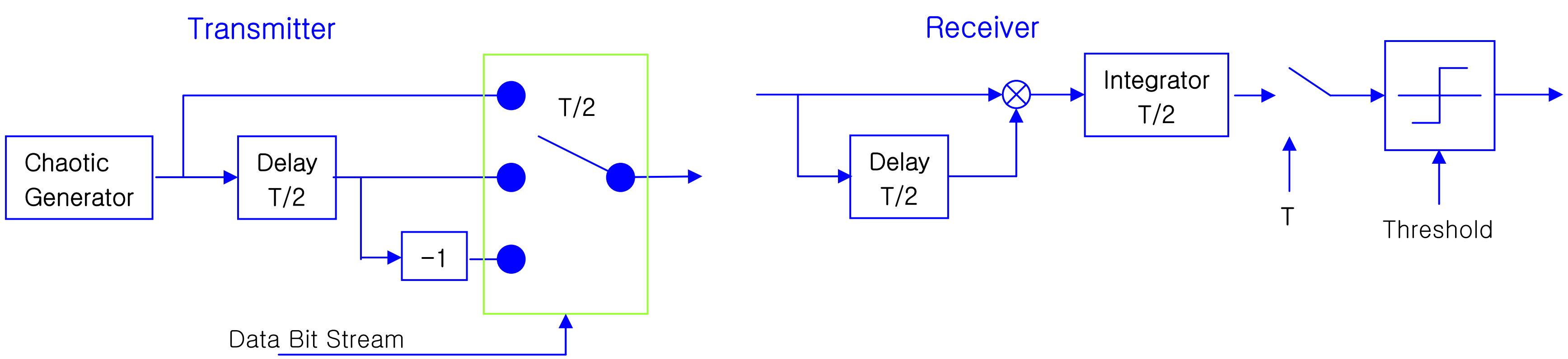
- DCSK transmits a reference chaotic pulse and an information data pulse depending on whether information bit 1 (same ref. chaotic pulse) or 0 (inverted of the chaotic pulse) is being transmitted
- The information signal can be recovered by a correlator.

Principle of DCSK Modulation (2)

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

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

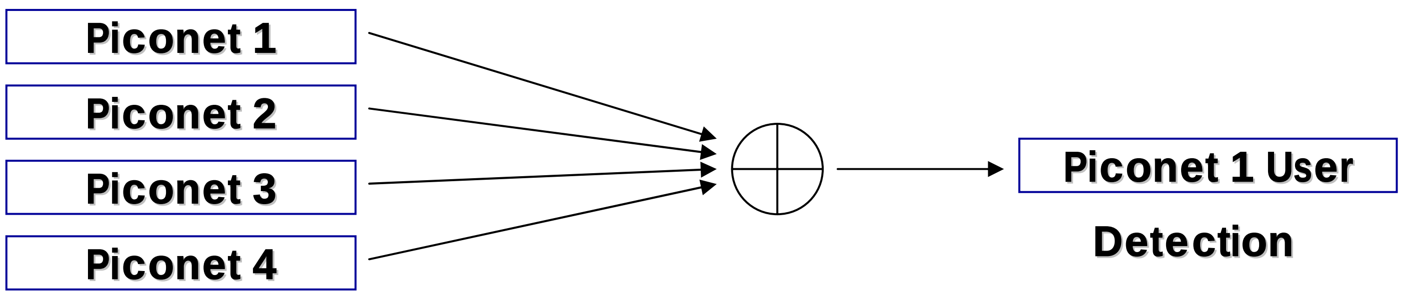


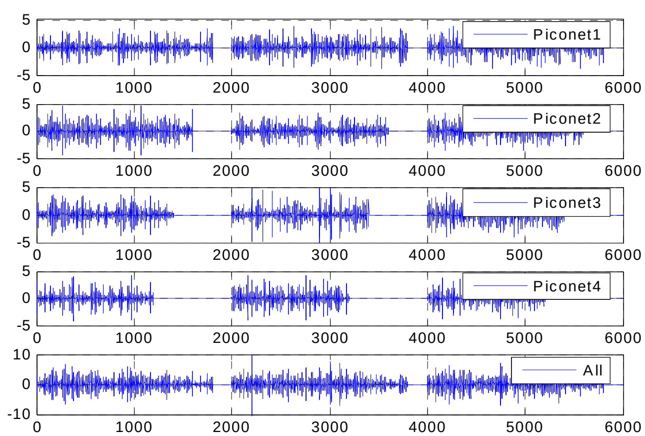


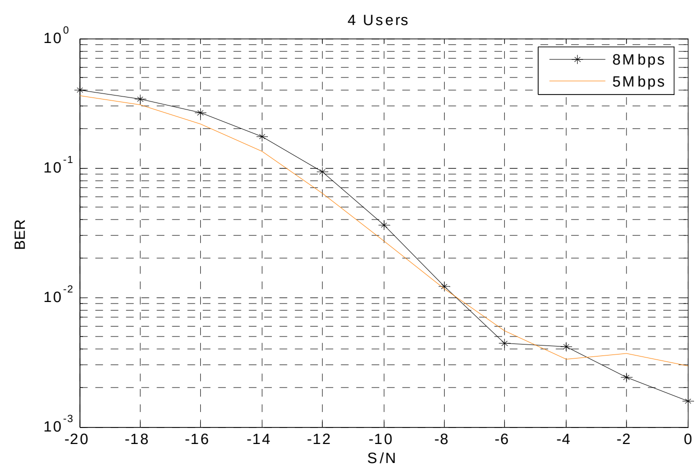
SOP (1)

- 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

SOP (2)

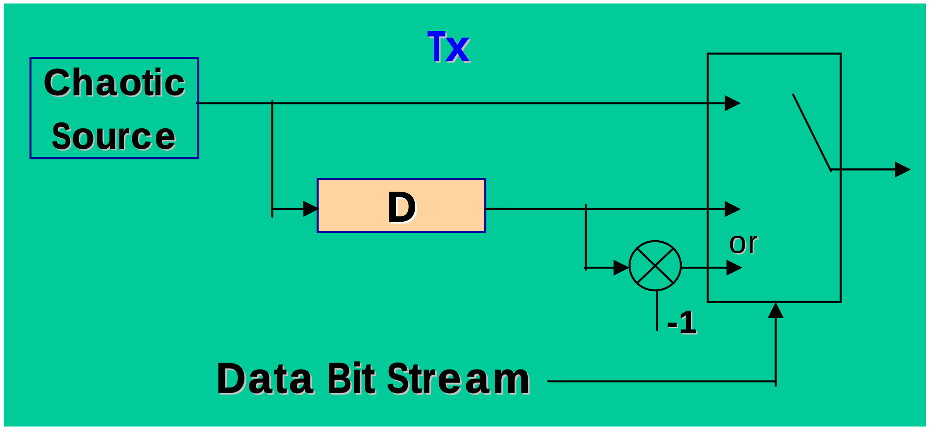

Piconet 1
Piconet 2
Piconet 3
Piconet 4
Piconet 1 User
Detection

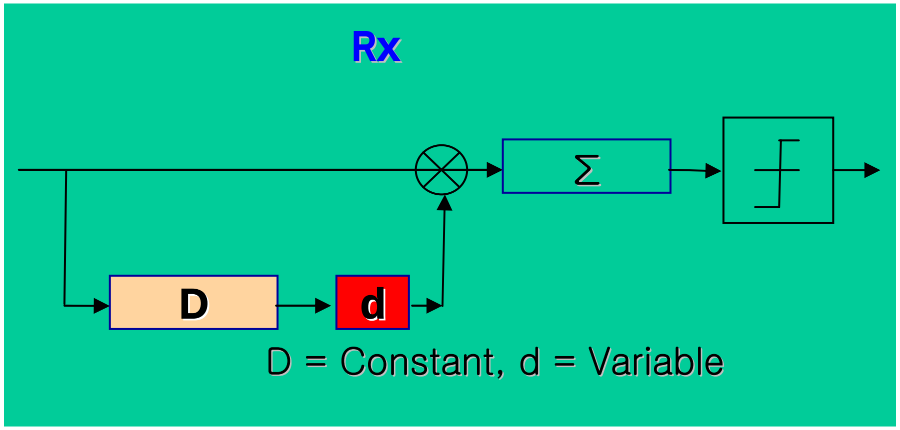

Piconet1
Piconet2
Piconet3
Piconet4
All
0
1000
2000
3000
4000
5000
6000

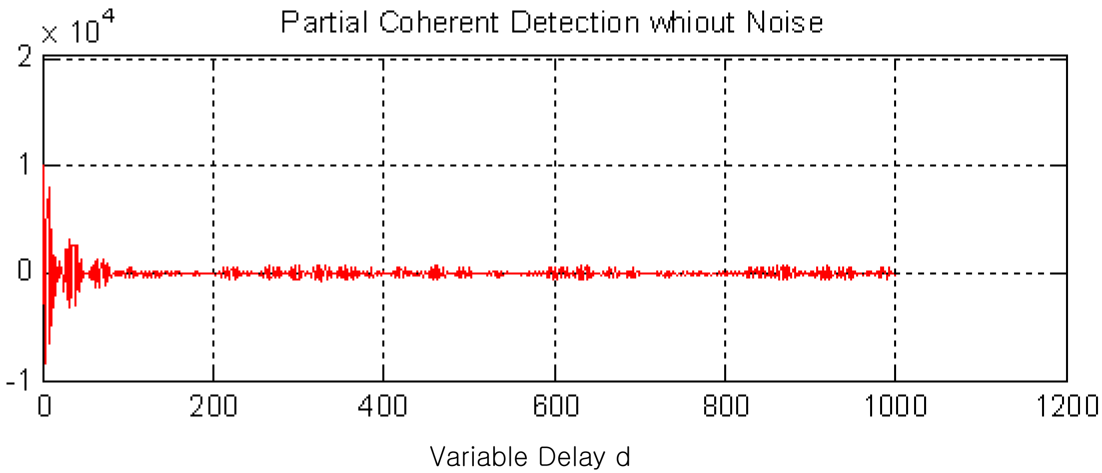

4 Users
8Mbps
5Mbps
BER
S/N

SOP (2)

Chaotic DCSK Correlation Property







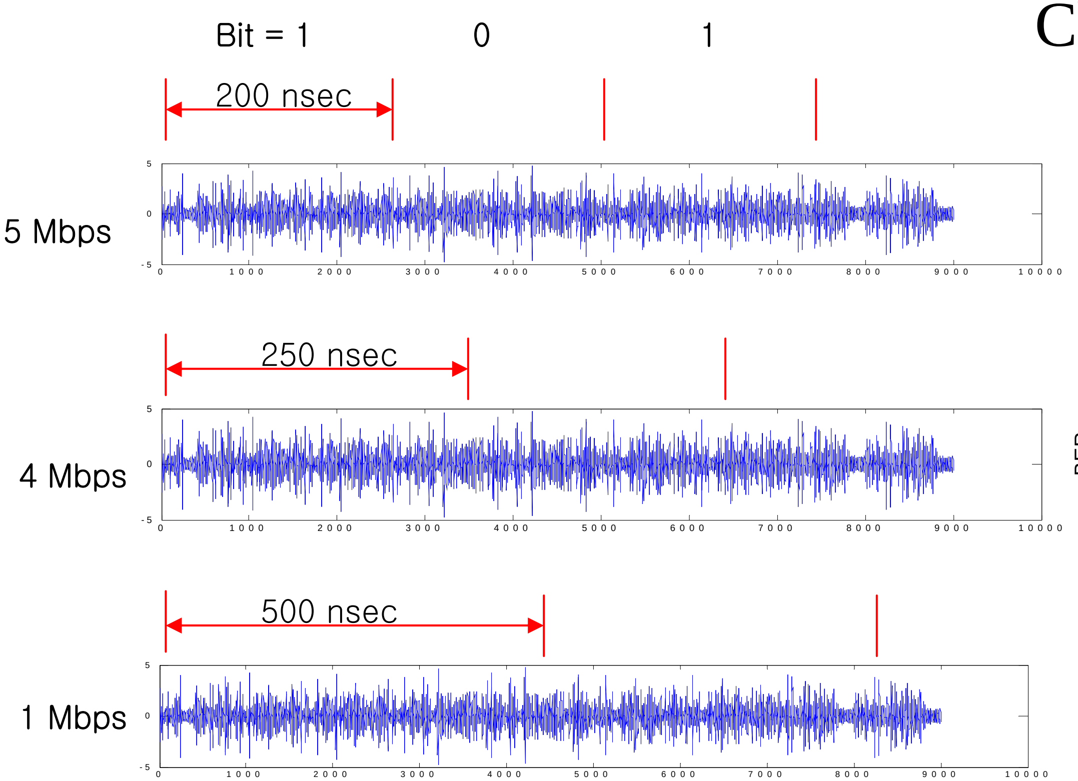
Ranging Technique

- Ranging technique used is the same as OOK proposal.

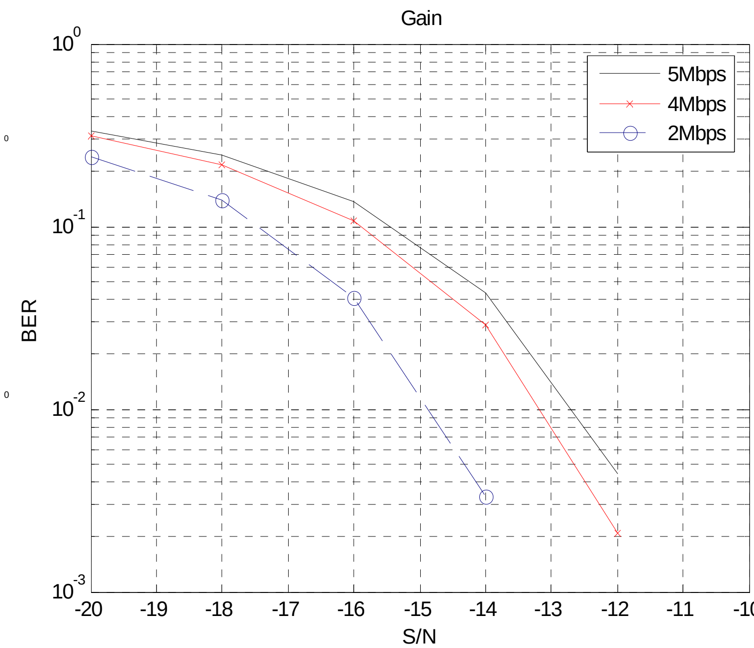
Scalability (1)

- Scalability can be achieved using
  - Chaotic gain
  - Varying bit duration
  - Duty cycle
  - Repeated transmission of information bearing chip.

Scalability (2)

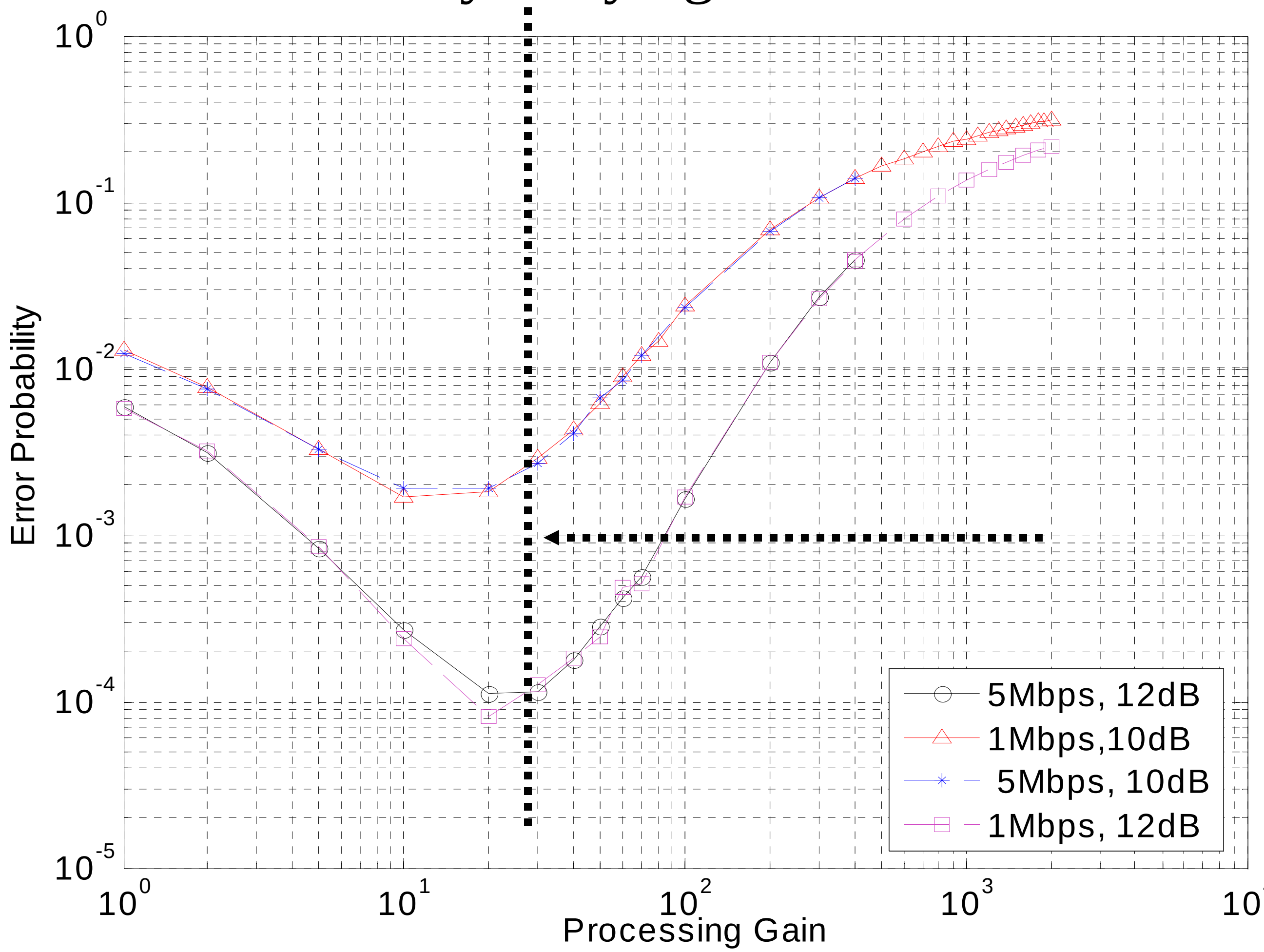


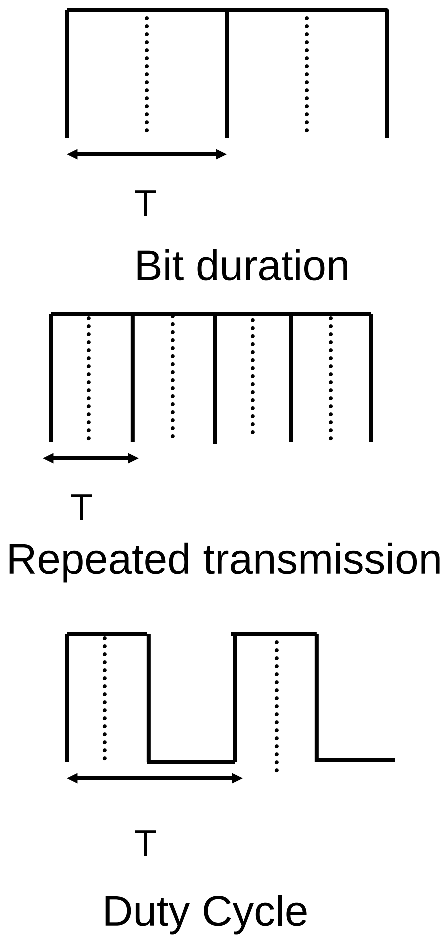
Chaotic Gain in DCSK



Scalability (3)

Scalability: varying bit duration





Complexity, Cost & Technical Feasibility

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

Link Budget & Sensitivity

Parameter	Value	Value
Throughput (R_b), Kbps	1	10
Duty cyrcle, dB	-40	-30
Average Tx Power (P_T), dBm	-30	-20
Geometric central frequency Fc, GHz	3.35	3.35
Path loss at 1 m (L_1), dB	44.5	44.5
Path loss at 30 m (L_2), dB	30	30
Tx antenna gain (G_T), dB	0	0
Rx antenna gain (G_R), dB	-3	-3
Rx Power at 30 m ($P_R=P_T+G_T+G_R-L_1-L_2$), dBm	-107.5	-97.5
Average noise power per bit ($N=-174+10*\log_{10}(R_b)$), dBm	-144.0	-134.0
Rx noise figure referred to the antenna terminal (N_F), dB	7.0	7.0
Total average noise power per bit ($P_N=N+N_F$), dBm	-137	-127
Minimum Eb/No (S), dB	14	14
Raw bit rate, kbps	2	20
Code rate	0.5	0.5
Implementation loss (I), dB	4	4
Link Margin at 30 m ($M=P_R-P_N-S-I$), dB	11.5	11.5
Rx sensitivity level, dB	-119	-109

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.