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

Submission Title: [Enhanced Noncoherent OOK UWB PHY and MAC for Positioning and Ranging]
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Re: []

Abstract: [This document proposes a proposal for the IEEE 802.15.4 alternate PHY standard.]

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

Enhanced Noncoherent OOK UWB PHY and MAC for Positioning and Ranging

KERI-SSU-KWU

Republic of Korea

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- Proposal Overview

- Band Plan

- Enhanced Noncoherent OOK UWB PHY

- Ranging and Positioning

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Proposal Overview (1)

- **Motivation of proposal**

  – To satisfy IEEE 802.15.4a technical requirements, it is essential that low power consumption in the UWB system level as well as link level must be achieved.

  – Conventional coherent UWB system based on correlator in the receiver can provide fairly good performance.

  – However, coherent UWB system is very sensitive to the signal synchronization, and the additional pulse generator with specific pulse shaping is required in the receiver.

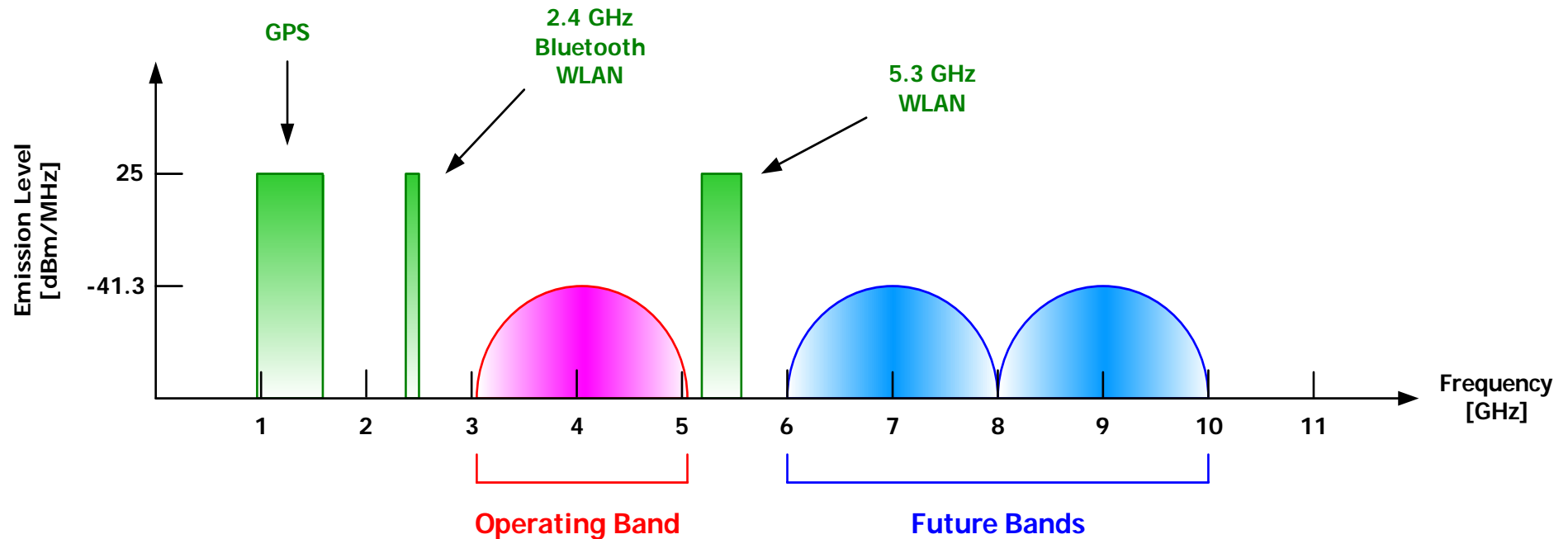 – Thus, this system may increase the implementation complexity, and consequently power consumption and system cost.

- To meet low power and low cost requirement with high precision ranging and positioning capability, we propose UWB system with OOK (On-Off Keying) modulation and noncoherent detection.

Proposal Overview (2)

- **Features**

  - In the proposed UWB system, unlike the conventional coherent UWB system, the signal demodulation is performed by simply comparing the received signal energy with detection threshold.

  - It can significantly relieve the strict synchronization requirement in the receiver and also provide simplified transceiver structure without pulse generator for the minimal power and cost demand.

  - Bit Error Rate (BER) performance of the conventional noncoherent OOK UWB system has been enhanced by adopting

    - timing, calibration, and operation mode

    - edge triggered pulse transmission
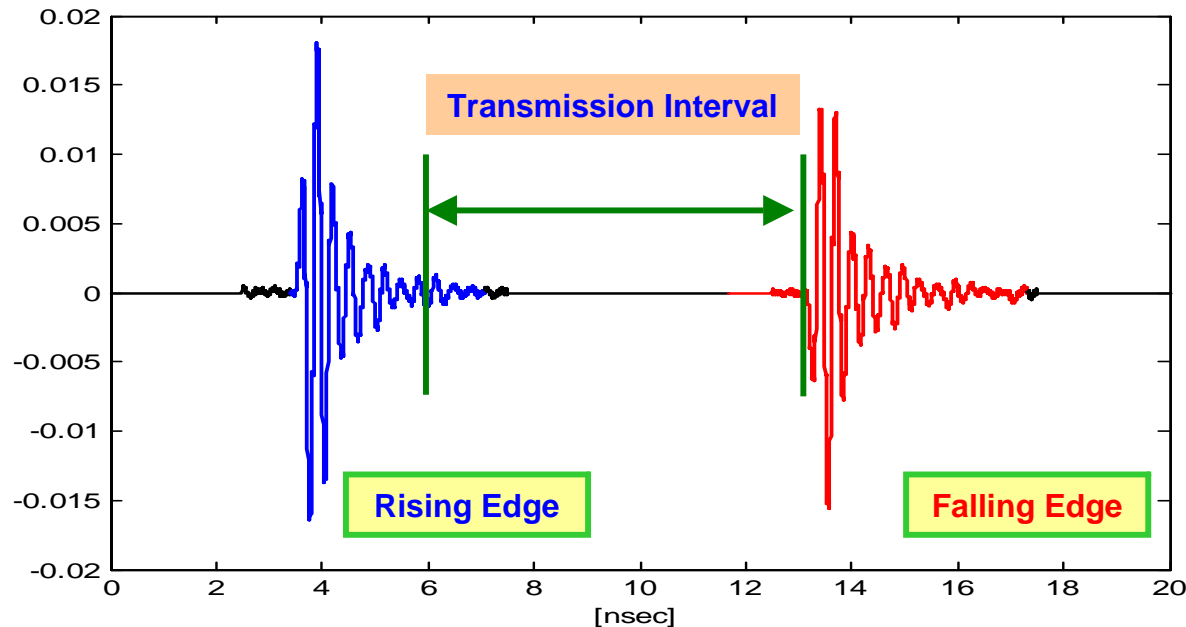
    - multipath combining and data repetition.

Band Plan

- **Proposed operating band : 3.1 ~ 5.1 GHz**

  – To avoid Interferences and victim receivers and also to fit the FCC spectrum mask for UWB systems

  – Bands for the future : Approximately 6 ~ 10 GHz

Enhanced Noncoherent OOK UWB PHY

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Edge Triggered UWB Pulse

* Measured by Tektronix, TDS8000B oscilloscope

- **Pulse duration : 2 nsec**

  – Bandwidth : 2 GHz (3.1 ~ 5.1 GHz)

  – OOK modulation can be easily implemented by generating
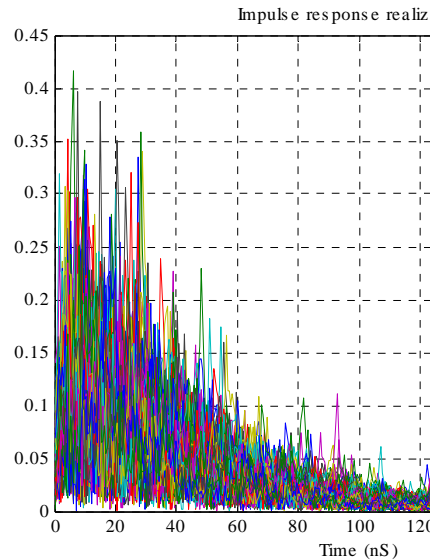   UWB pulse based on edge triggering (rising and falling edges)

Pulse Transmission Interval

Enhanced Noncoherent OOK UWB System

UWB Transmitter

Input Bit Sequence	→	Data Repetition	→	OOK Modulation	→	Pulse Generator

Calibration Mode

Threshold Control	Noise Measuring

Timing Mode

Timing and Channel Gain Estimation

Operation Mode

Receiving Data Gathering	←	Multipath Combining

Decision Stage	→	Output Bit Sequence

Energy Detection

Ranging

Analog Energy Window Bank

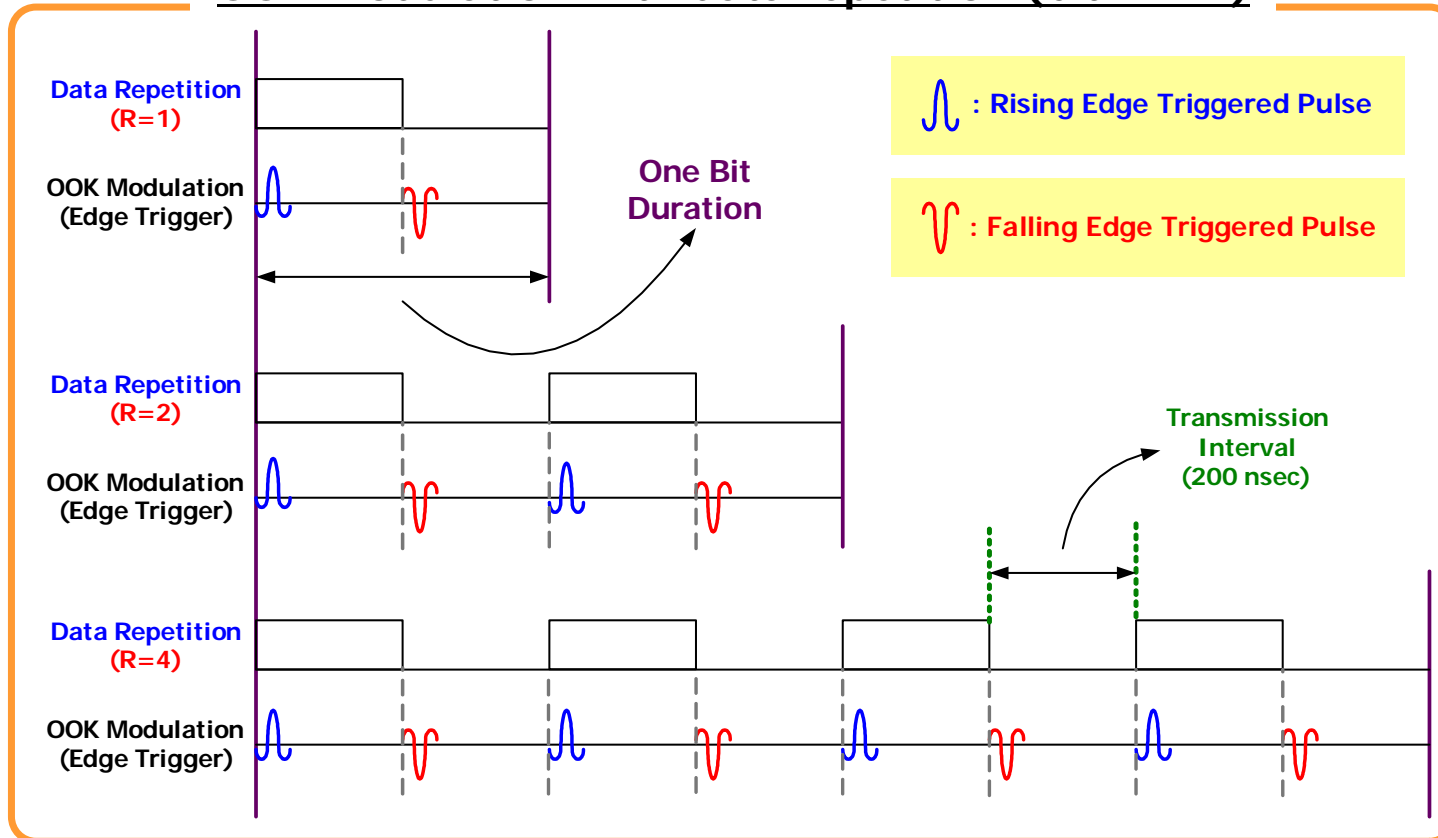**UWB Receiver**

- Non-coherent OOK UWB system based on noise power calibration and signal energy detection

- *Data repetition and multipath combining for performance improvement*

- Three modes in the receiver for compensation of performance degradation*(timing/calibration/ operation)*
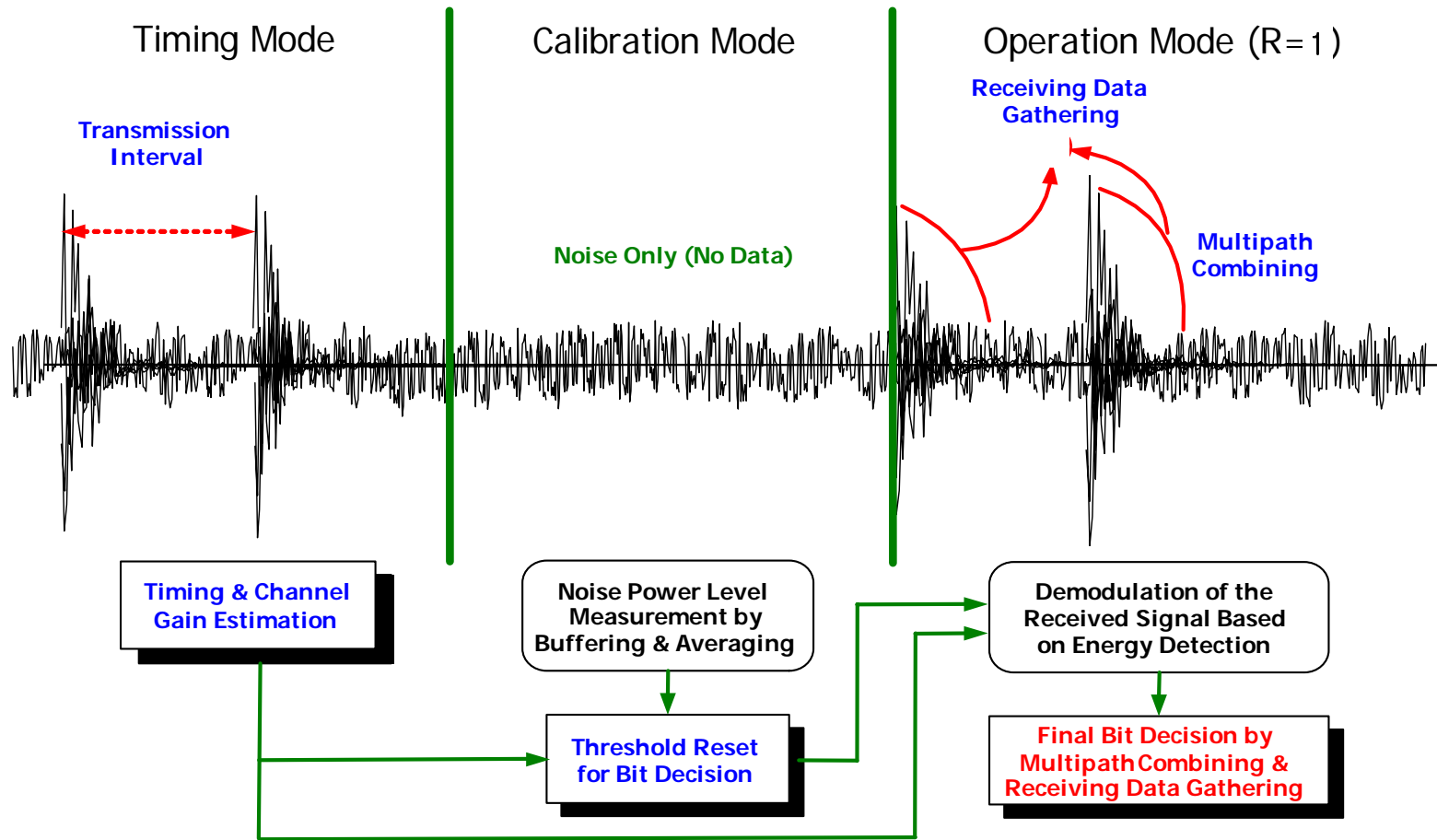
Data Transmission Based on Edge Triggering

OOK modulation with data repetition (bit = "1")

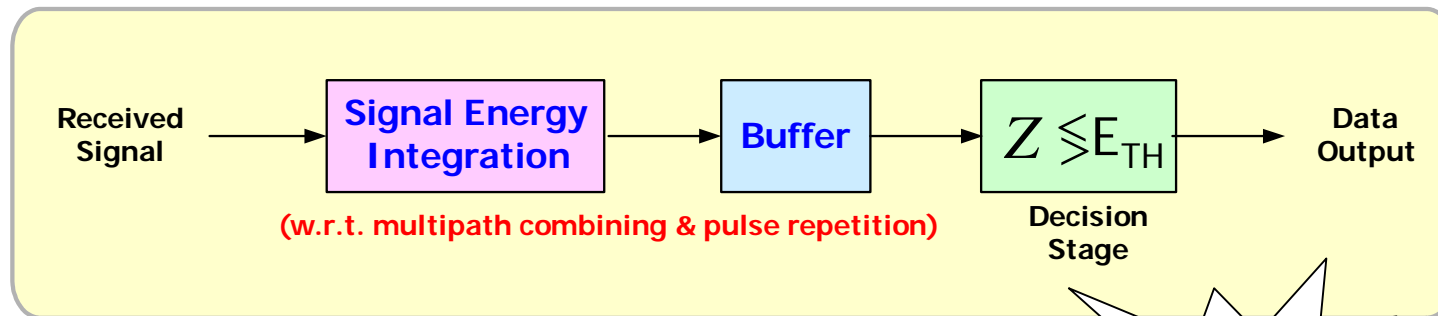**When bit = "0" for OOK, no pulse is transmitted during one bit duration**

Proposed Three Modes in the Receiver

Signal processing in three modes

More Details in the Operation Mode (1)

Operation mode description

Received Signal → **Signal Energy Integration** → **Buffer** → $Z \lessgtr E_{TH}$ → Data Output

(w.r.t. multipath combining & pulse repetition)

Decision Stage

- Decision statistics

$$Z = \sum_{n=1}^{N_s} \sum_{k=1}^{N_m} E_{s.k}^{(n)}$$

Simple

- N_s : Number of pulse repetitions per data bit
- N_m : Number of multipath components for combining
- $E_{s.k}^{(n)}$: Received signal energy corresponding to the k'th path of the n'th transmitted pulse

★***Analog energy window bank can achieve ranging accuracy improvement as well as multipath combining***

More Details in the Operation Mode (2)

- Threshold value for bit decision (no pulse repetition & no multipath combining)

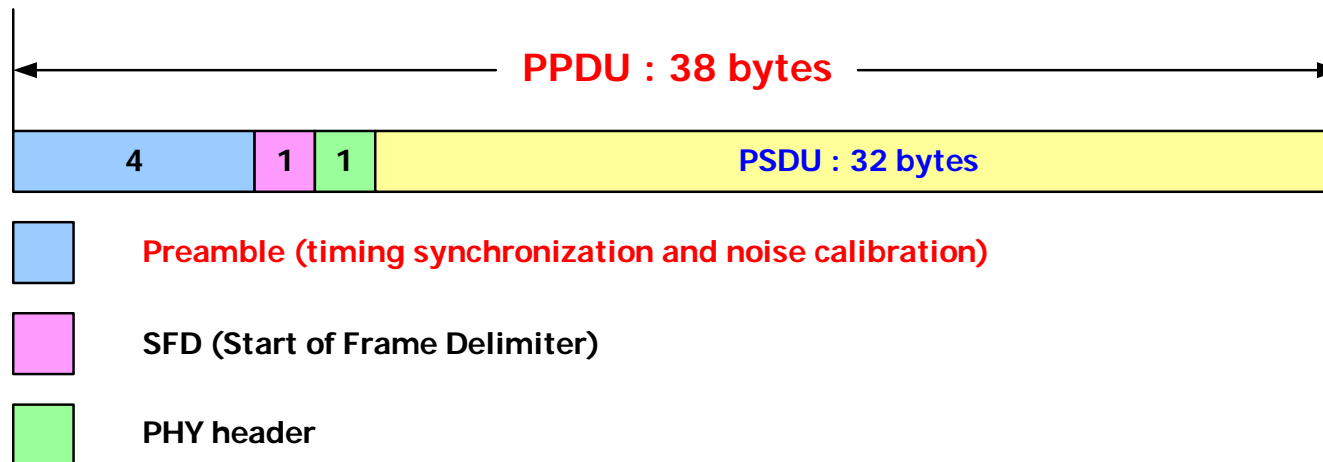$$E_{TH} = \left[\frac{\psi_{\alpha.1} + P_n}{2} \right] \times T$$

- $\psi_{\alpha.1}$: Parameter relative to the signal power of the first path (estimated in the timing mode)
- P_n : Noise power measured by noise calibration mode
- T : Pulse integration time

- Threshold value (only pulse repetition)

$$E_{TH} = N_s \times \left[\frac{\psi_{\alpha.1} + P_n}{2} \right] \times T$$

- Threshold value (pulse repetition & multipath combining)

$$E_{TH} = N_s \times \sum_{k=1}^{N_m} \left[\frac{\psi_{\alpha.k} + P_n}{2} \right] \times T$$

PHY Frame

- **PPDU data frame structure**

  - Preamble sequence for timing and calibration mode
    - Bit "1" : channel gain estimation as well as synchronization (ranging)
    - Bit "0" : noise level calibration

- *Using all bit patterns in the preamble sequence, we can appropriately set the threshold value for the energy detection*

Payload Bit Rate

- **Basic timing parameters**
  - Pulse transmission interval : **200 nsec**
    - To avoid IPI (Inter Pulse Interference) due to the excess delay spread of IEEE 802.15.4a channel models (a prioritized list for CM8, CM1, CM5)
  - Pulse repetition per bit : **2**
    - Including at least one edge triggering for easy implementation of OOK
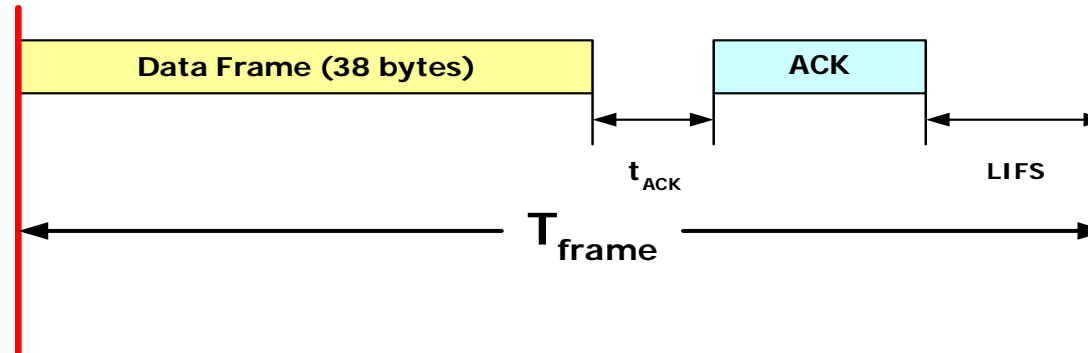
- **Payload bit rate**
  - **One bit period : 200 x 2 = 400 nsec**

  - **PHY-SAP payload bit rate (Xo)** $\Rightarrow$ $\left(\dfrac{1}{400 \times 10^{-9}}\right) \times \left(\dfrac{1000}{1024}\right) = 2.4414\,[\text{Mbps}]$
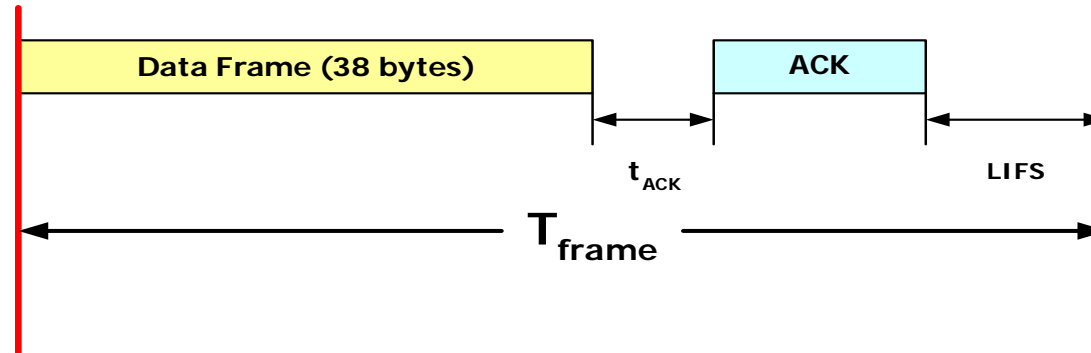
Useful Data Rate

- Useful data rate calculation for 32 byte PSDU (Xo = 2.4414 Mbps)

  – Data frame time : 38 x 8 x 400 = 121.6 µsec

  – ACK frame time : 11 x 8 x 400 = 35.2 µsec

  – t_{ACK} (considering 32 symbols) : 32 x 400 = 12.8 µsec

  – LIFS (considering 40 symbols) : 40 x 400 = 16 µsec

  – T_{frame} = 121.6 + 35.2 + 12.8 + 16 = 185.6 µsec

- **We can obtain a useful data rate** $\Rightarrow$ $\left(\dfrac{32 \times 8}{185.6} \right) \times \left(\dfrac{1000}{1024} \right) = 1.347 \, [\text{Mbps}]$

Payload Bit Rate (Optional)

- **Optional timing parameters**

  - **Pulse transmission interval : 200 nsec**

    - To avoid IPI (Inter Pulse Interference) due to the excess delay spread of IEEE 802.15.4a channel models (a prioritized list for CM8, CM1, CM5)

  - **Pulse repetition per bit : 8**

    - Including four data repetition based on edge triggered UWB signal

- **Payload bit rate**

  - **One bit period : 200 x 8 = 1.60 μsec**

  - **PHY-SAP payload bit rate (Xo) $\Rightarrow$ 610.35 [Kbps]**

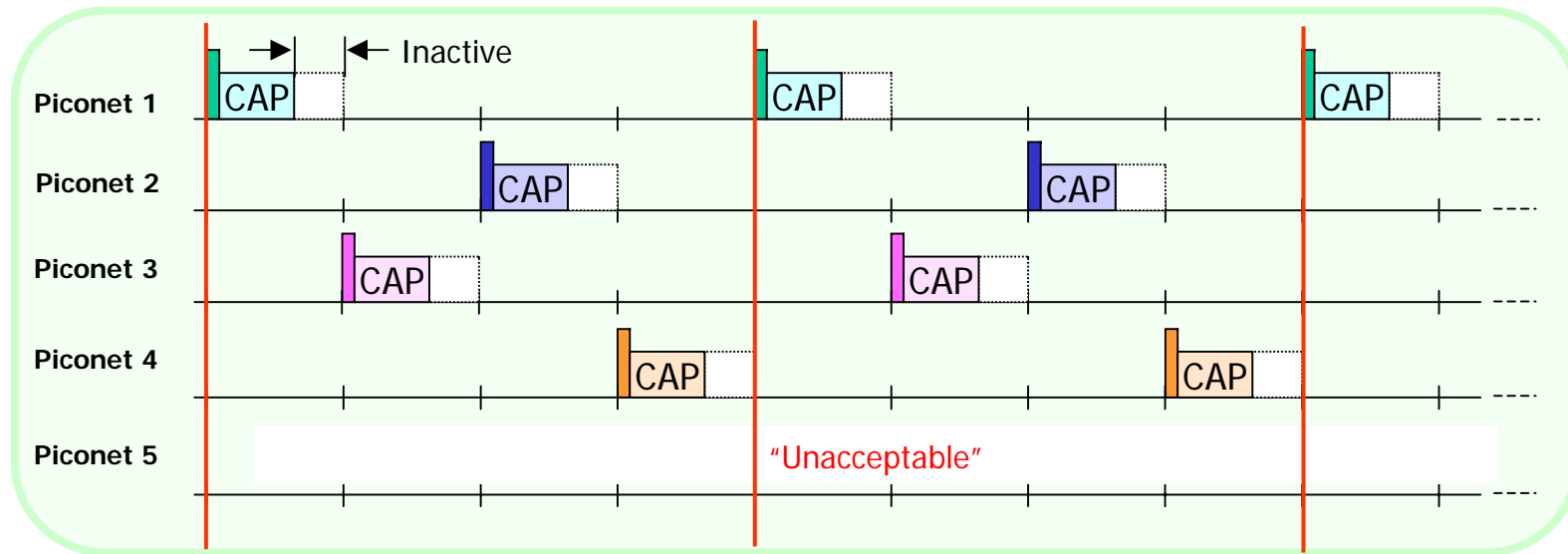**K. Kim, S. Choi, Y. Park, H. Oh, Y. Shin, W. Lee, and H. Jeon**

Useful Data Rate (Optional)

- Useful data rate calculation for 32 byte PSDU (Xo = 610.35 Kbps)

    - Data frame time : 38 x 8 x 1600 = 486.4 µsec

    - ACK frame time : 11 x 8 x 1600 = 140.8 µsec

    - t_{ACK} (considering 32 symbols) : 32 x 1600 = 51.2 µsec

    - LIFS (considering 40 symbols) : 40 x 1600 = 64 µsec

    - T_{frame} = 742.4 µsec

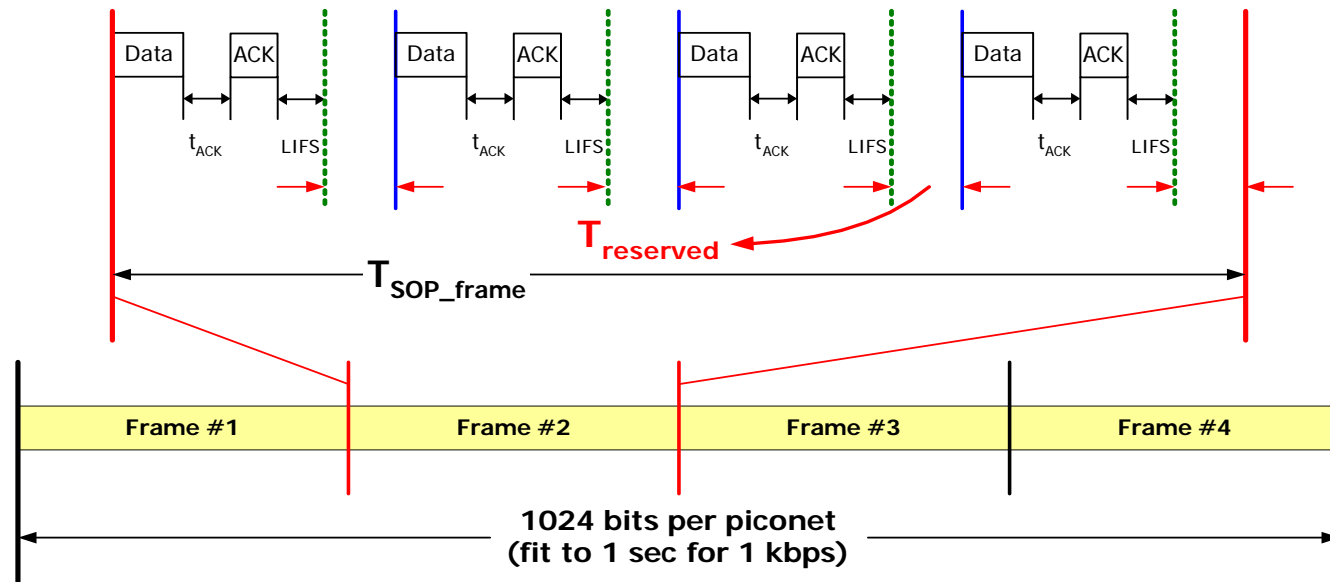- **We can obtain a useful data rate $\Rightarrow$ 336.7 Kbps**

Multiple Piconets

- **Example : if we assume 4 uncoordinated piconets**
  - Considering the roughly synchronized TDM technique for SOP
  - After CCA, each piconet decides randomly or sequentially its time slot for the CAP period of the super frame.
  - Multiple devices can communicate in each piconet based on CSMA/CA.
  - MAC has to provide the information of the number of SOPs within the

Inactive

Piconet 1	CAP		CAP		CAP
Piconet 2	CAP		CAP	
Piconet 3	CAP		CAP	
Piconet 4	CAP		CAP	
Piconet 5	"Unacceptable"

Checking Required Data Throughput

- **The reserved time in order to satisfy 1 kbps**
  - Considering the previous useful data rate 1.347 Mbps, the reserved time may become $T_{reserved}$ **= 62.3 msec**
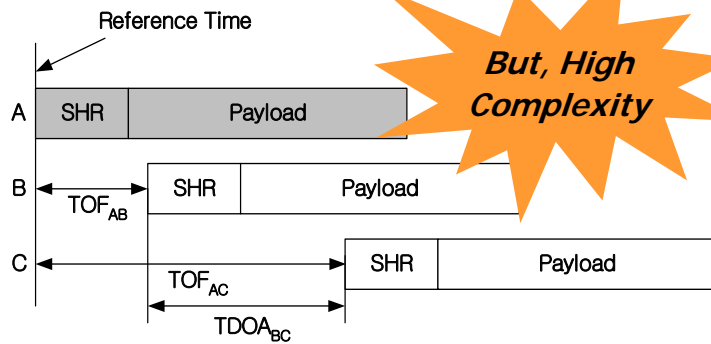

- *This long reserved time can sufficiently accommodate multiple devices (up to 100) with CSMA/CA within the same piconet.*
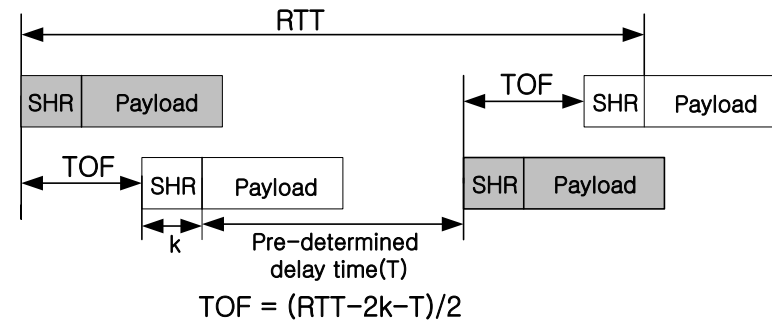
Ranging and Positioning

Asynchronous Ranging Scheme

- Synchronous ranging
  - One way ranging
  - Simple TOA/TDOA measurement
  - Universal external clock

- **Asynchronous ranging**
  - Two way ranging
  - TOA/TDOA measurement by RTTs
  - Half-duplex type of signal exchange

▨	Transmitted packets
▢	Received packets

TOF : Time Of Flight

RTT : Round Trip Time

SHR : Synchronization Header

But, High Complexity

Synchronous Ranging

Asynchronous Ranging

$$TOF = (RTT - 2k - T)/2$$

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Proposed Positioning Scheme

- Features
  - Sequential two-way ranging is executed via relay transmissions
  - PAN coordinator manages the overall schedule for positioning
  - Inactive mode processing is required along the positioning
  - PAN coordinator may transfer all sorts of information such as observed
  - TDOAs to a processing unit (PU) for position calculation

P_FFD2 P_FFD3

TOA_{24}

TOA_{34}

RFD

PAN coordinator

PU

TOA_{14}

P_FFD1

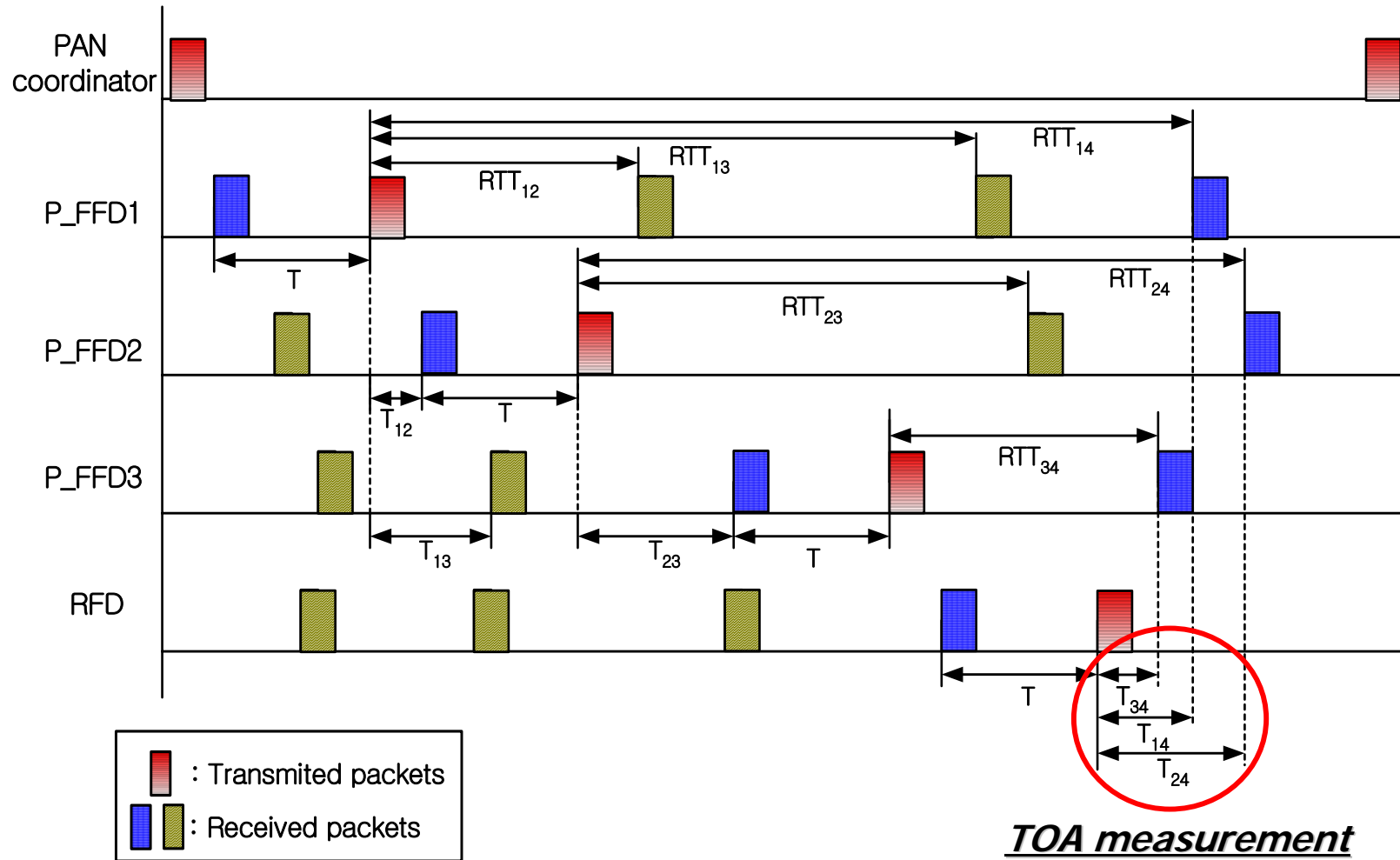P_FFD : Positioning Full Function Device
RFD : Reduced Function Device

Benefits

- It does not need pre-synchronization among the devices
- *Positioning in mobile environment is partly accomplished*

Process of Proposed Positioning Scheme

TOA measurement

More Details for obtaining TDOAs

- Distances among the positioning FFDs are calculated from RTT measurements and known time interval T

$$RTT_{12} = T + 2T_{12}$$
$$RTT_{23} = T + 2T_{23}$$
$$RTT_{13} = T_{12} + 2T + T_{23} + T_{13}$$

$$T_{12} = (RTT_{12} - T)/2$$
$$T_{23} = (RTT_{23} - T)/2$$
$$T_{13} = (RTT_{13} - T_{12} - T_{23} - 2T)$$

- Using observed RTT measurements and calculated distances, TOAs/TDOAs are updated

$$RTT_{34} = T_{34} + T + T_{34}$$
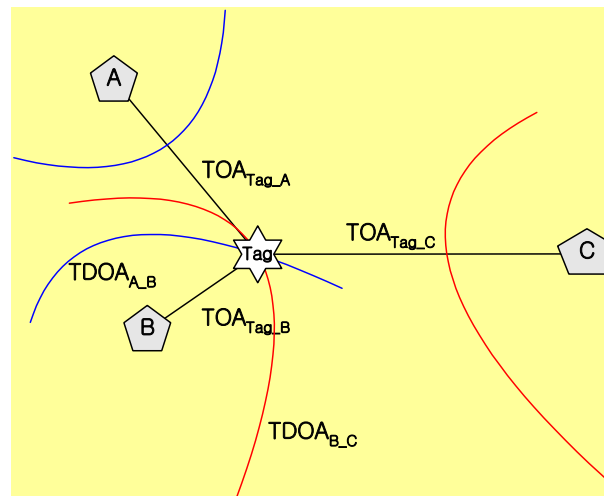$$RTT_{24} = T_{23} + T + T_{34} + T + T_{24}$$
$$RTT_{14} = T_{12} + T + T_{23} + T + T_{34} + T + T_{14}$$

$$TOA_{34} = (RTT_{34} - T)/2$$
$$TOA_{24} = (RTT_{24} - T_{23} - TOA_{34} - 2T)$$
$$TOA_{14} = (RTT_{14} - T_{12} - T_{23} - TOA_{34} - 3T)$$

$$TDOA_{12} = TOA_{14} - TOA_{24}$$

$$TDOA_{23} = TOA_{24} - TOA_{34}$$

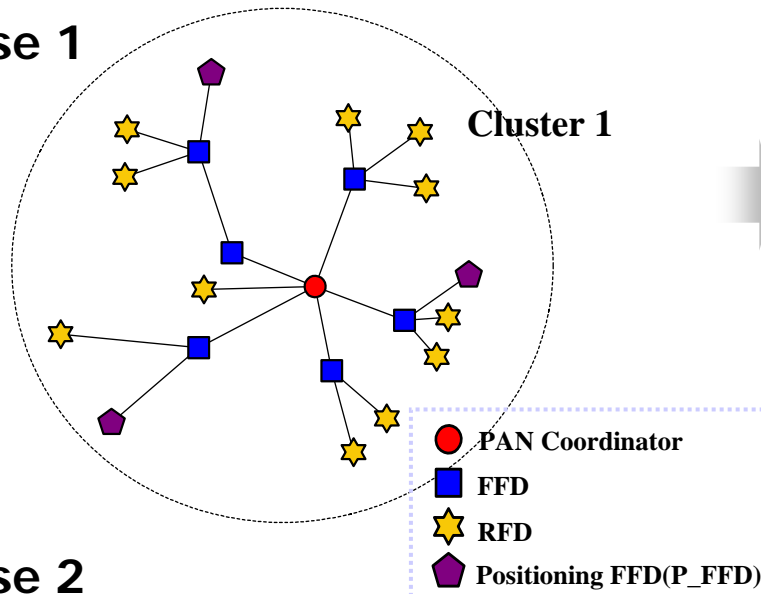# Position Calculation using TDOAs

- The range difference measurement defines a hyperboloid of constant range difference

- When multiple range difference measurements are obtained, producing multiple hyperboloids, the position location of the device is at the intersection among the hyperboloids
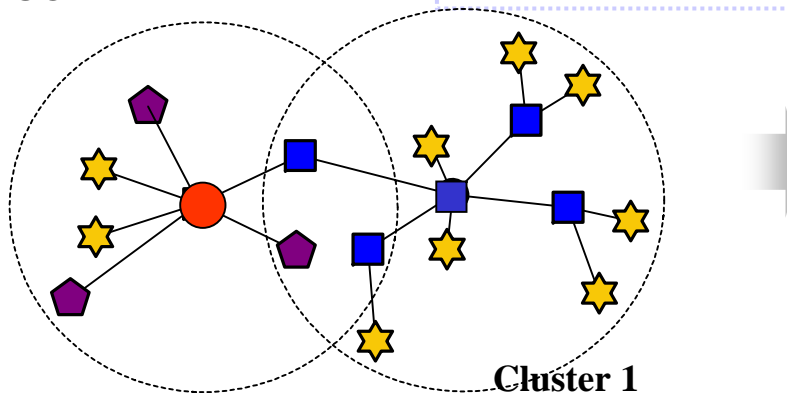

$$R_{i,j} = c \times TDOA_{i,j} = c \times (TOA_i - TOA_j) = \sqrt{(X_i - x)^2 + (Y_i - y)^2} - \sqrt{(X_j - x)^2 + (Y_j - y)^2}$$

Positioning Scenario Overview

■ **Case 1**

Cluster 1

- **PAN Coordinator**
- **FFD**
- **RFD**
- **Positioning FFD(P_FFD)**

■ **Case 2**

Cluster 1

- **Using static reference nodes in relatively large scaled cluster :**
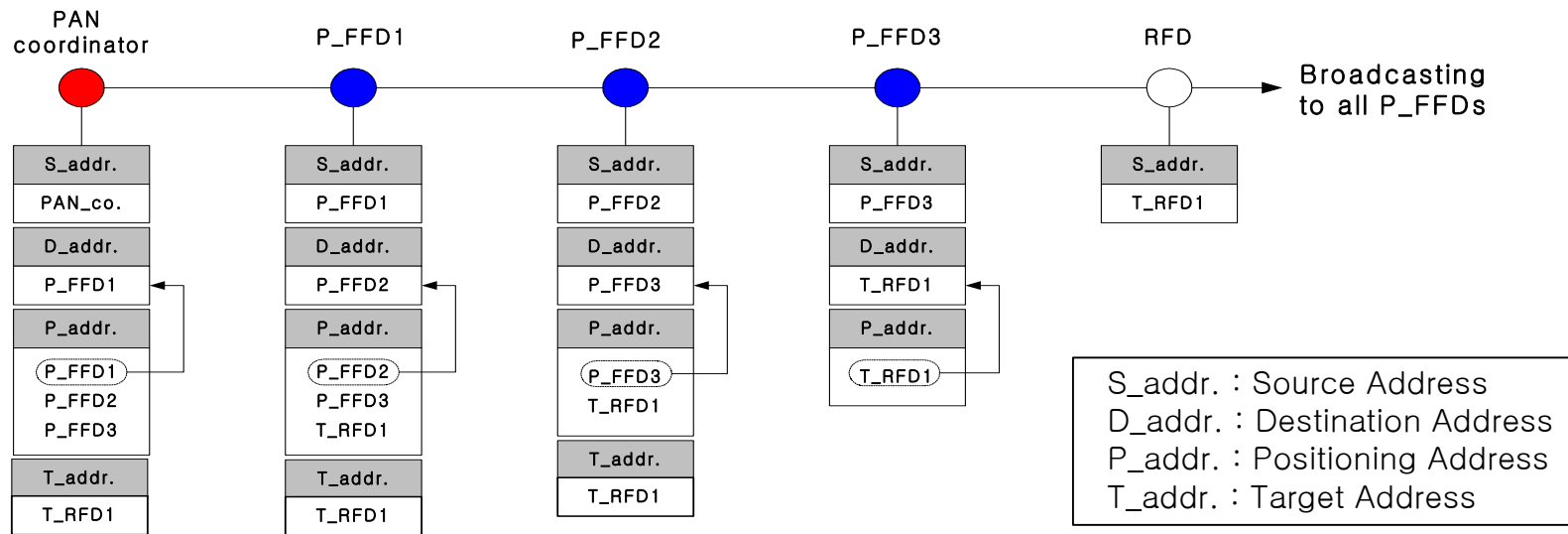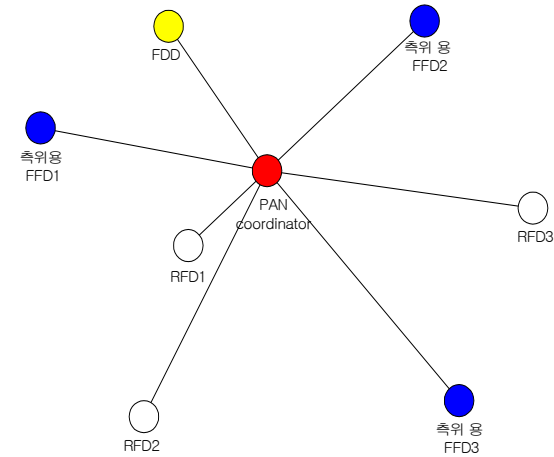 - Power control is required
  - Power consumption increases
  - All devices in cluster must be in inactive data transmission mode

- **Using static and dynamic nodes in overlapped small scaled sub-clusters :**
  - Sequential positioning is executed in each sub-cluster
  - Low power consumption
  - Associated sub-cluster in positioning mode should be in inactive data transmission mode
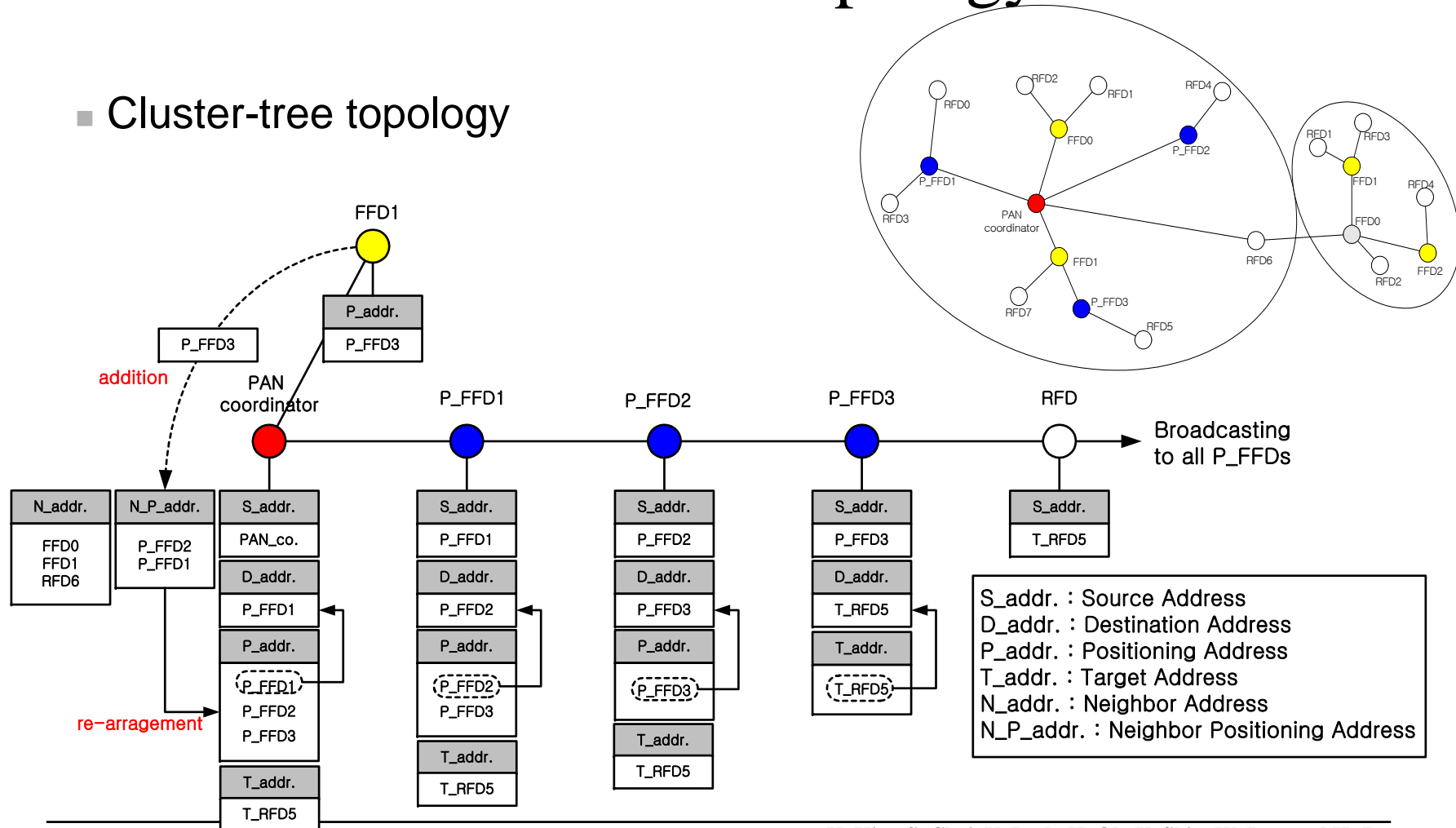
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Positioning Scenario for Star topology

- ## Star topology
  - ### PAN coordinator activated mode
    - Positioning all devices
    - Re-alignment of positioning FFD's list is not required
  - ### Target device activated mode
    - Positioning is requested from some device
    - Re-alignment of positioning FFD's list is required

S_addr. : Source Address
D_addr. : Destination Address
P_addr. : Positioning Address
T_addr. : Target Address

Positioning Scenario for
Cluster-tree Topology

■ **Cluster-tree topology**

Modifying MAC

Modifications of MAC Command Frame (1)

- Features
  - Frame control field
    - frame type : positioning (new addition using a reserved bit)
  - Command frame identifier field
    - Positioning request/response (new addition)
  - Positioning parameter information field
    - Absolute coordinates of positioning FFDs
    - POS range
    - List of positioning FFDs and target devices
    - Power control
    - Pre-determined processing time (T)

Octets : 2	1	0/4/8	1	variable		2
Frame control	Sequence number	Addressing fields	command frame identifier	Positioning parameter	Command payload	FCS
MHR			MAC payload			MFR

Modifications of MAC Command Frame (2)

- Frame Control

bits : 0~2	3	4	5	6	7~9	10~11	12~13	14~15
Frame type	Security enabled	Frame pending	Ack. request	Intra-PAN	Reserved	Dest. addressing mode	Reserved	Source addressing mode

Frame type value	Description
000	Beacon
001	Data
010	Acknowledgment
011	MAC command
100	Positioning
101~111	Reserved

- Command frame identifier

Command frame identifier	Command frame
0x01	Association request
0x02	Association response
0x03	Disassociation notification
0x04	Data request
0x05	PAN ID conflict notification
0x06	Orphan notification
0x07	Beacon request
0x08	Coordinator realignment
0x09	GTS request
0x0a	Positioning request
0x0b	Positioning response
0x0c~0xff	Reserved

- Positioning parameter

Fixed coordinate	POS range	positioning FFDs Address & Target devices lists	Pre-determined processing time(T)	Power Control

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Analog Energy Window Bank

Ranging Accuracy Improvement

- Technical requirement for positioning

  - *"It can be related to precise (tens of centimeters) localization in some cases, but is generally limited to about **one meter** "*

- **Parameters for technical requirement**

  - Minimum required pulse duration :

$$\frac{1\,[m]}{3\times 10^{\,8}[m\,/\,\sec]} = 3.333\,[\text{nsec}]$$

  - Minimum required clock speed for the correlator in the conventional coherent systems

$$\frac{1}{3.333\,[\text{nsec}]} = 300\,[MHz]$$

  High Cost !

  - ★ *Fast ADC clock speed in the conventional coherent receiver must be required for the digital signal processing*

Analog Energy Window Bank (1)

- **Digital signal processing with fast clock can be replaced by using analog energy window bank with low clock speed**

- **Why analog energy window bank?**

  – Conventional single energy window may support the energy detection for data demodulation in the operation mode

  – However, this cannot guarantee the correct searching of the signal position in the timing mode (that also means the ambiguity of ranging accuracy)

- **Analog energy window bank can sufficiently support timing and calibration as well as operation mode**

  – Integration time of each energy window : **2 nsec** (pulse duration)

  – The number of energy windows in a bank : **20**

  – Operation clock speed of each energy window : **25 MHz**

  – Number of the required energy windows : depend on the power delay profile of the multipath channel (**effective multipath components**)

Analog Energy Window Bank (2)

Simulation Results

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Simulation Conditions
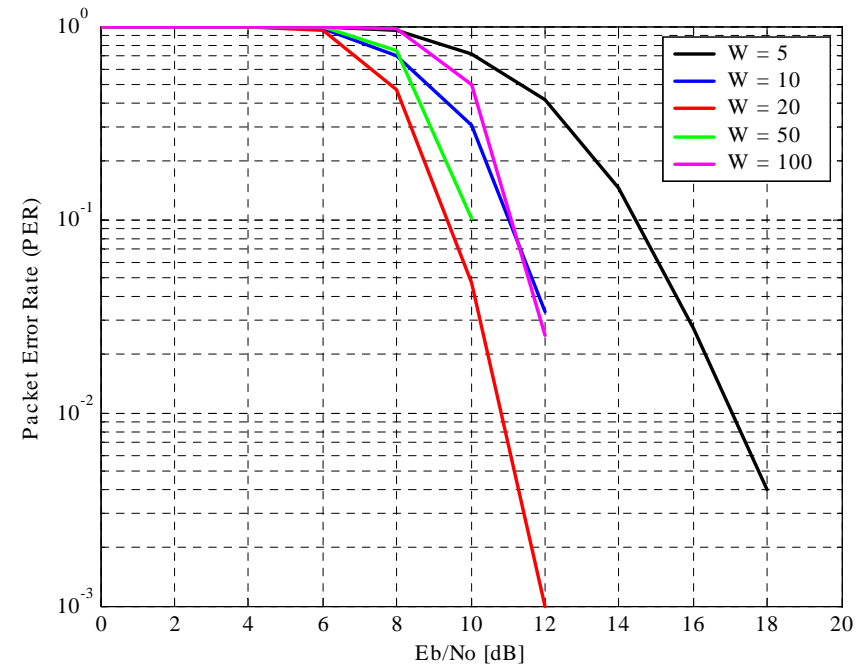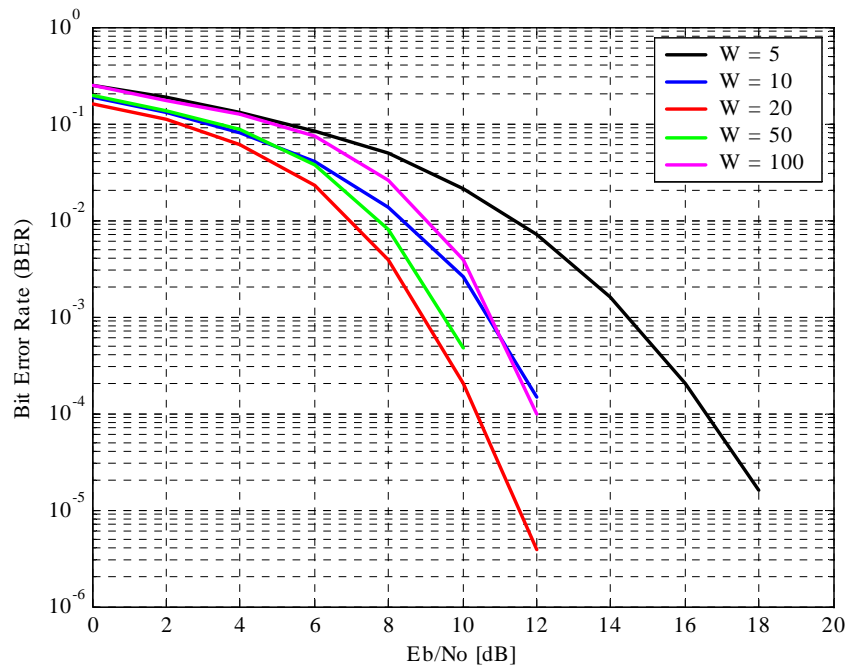
- **Simulation Parameters**
  - Number of bits for channel gain C estimation within timing mode :
    - ⇒ **8 bits** (1 byte in the preamble sequence)
  - Number of bits for noise level N measurement in calibration mode :
    - ⇒ **8 bits** (1 byte in the preamble sequence)

  - **Threshold value** for the signal energy detection : $$Th = \frac{(C + N)}{2}$$

  - Number of bit repetition (a bit consists of two (rising & falling edge) pulses) :
    - ⇒ **R = 1, 2, 4**

- **Channel models**
  - A prioritized list provided in P802.15.4a Alt PHY Selection Criteria document (doc #04/581r7)
    - ⇒ IEEE 802.15.4a **CM8** (NLOS Industrial)
    - ⇒ IEEE 802.15.4a **CM1** (LOS Residential)
    - ⇒ IEEE 802.15.4a **CM5** (LOS Outdoor)

Simulation Results (1)

- **Simulation environments**

    - IEEE 802.15.4a UWB channel model : **CM8**

    - Number of bit repetition : **1**

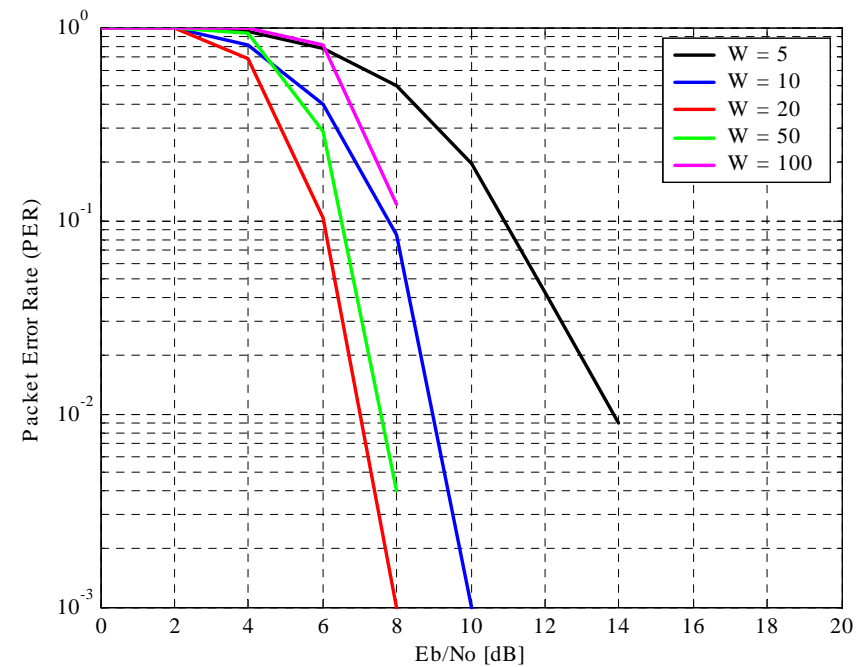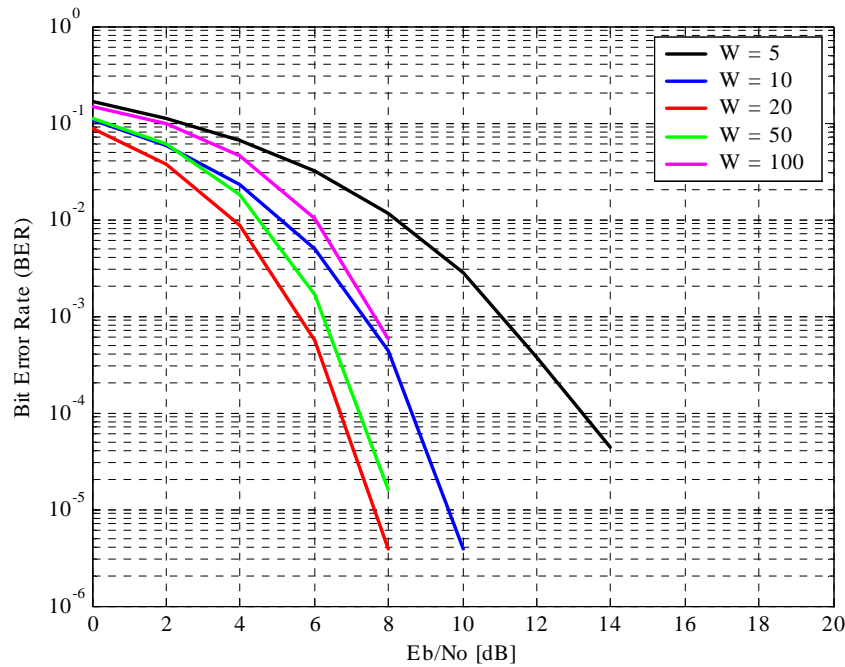   - Number of integrators in the bank : **W**

Simulation Results (2)

- **Simulation environments**

  - IEEE 802.15.4a UWB channel model : **CM8**

  - Number of bit repetition : **2**
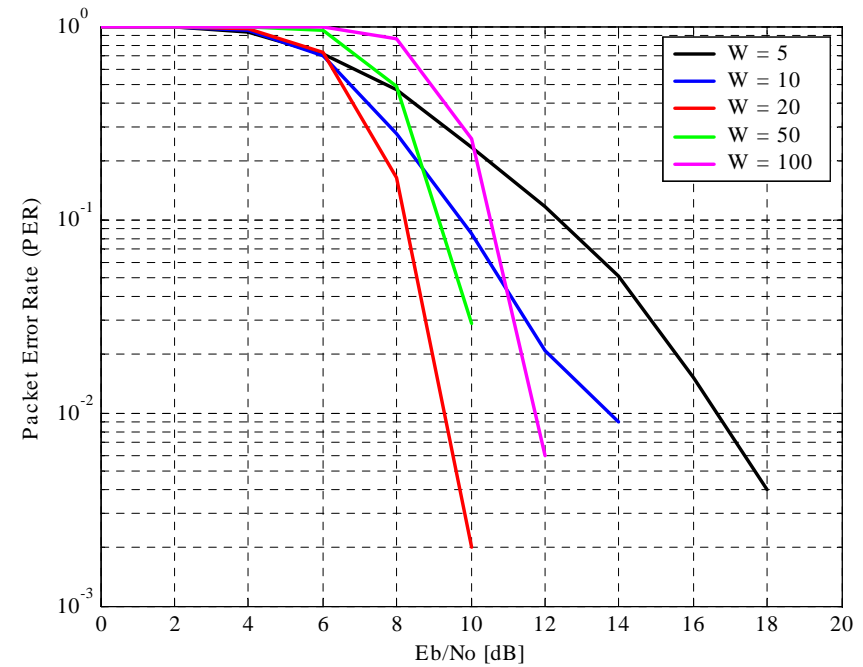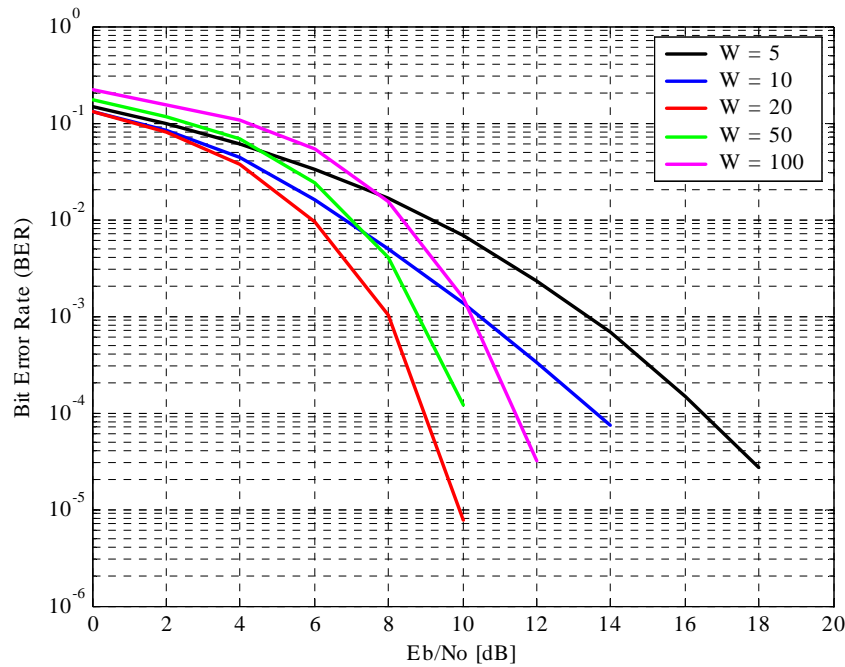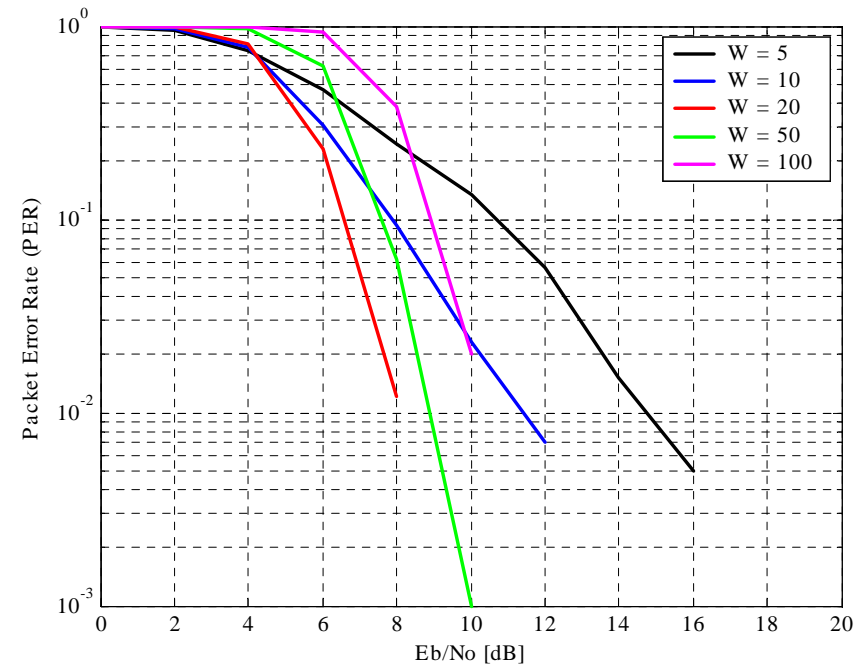
  - Number of integrators in the bank : **W**

Simulation Results (3)

- **Simulation environments**
    - IEEE 802.15.4a UWB channel model : **CM8**
    - Number of bit repetition : **4**
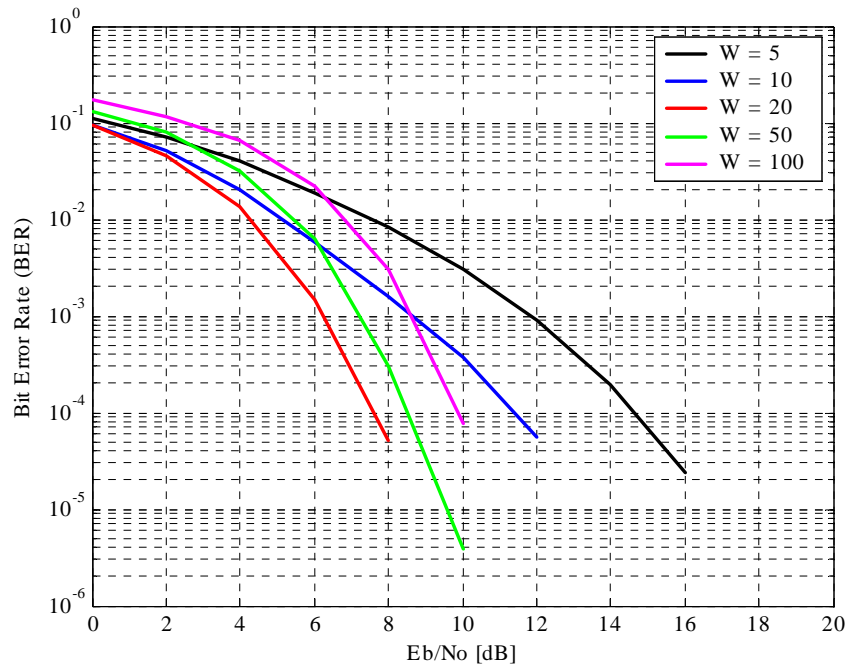   - Number of integrators in the bank : **W**

Simulation Results (4)

- **Simulation environments**

  - IEEE 802.15.4a UWB channel model : **CM1**

  - Number of bit repetition : **1**

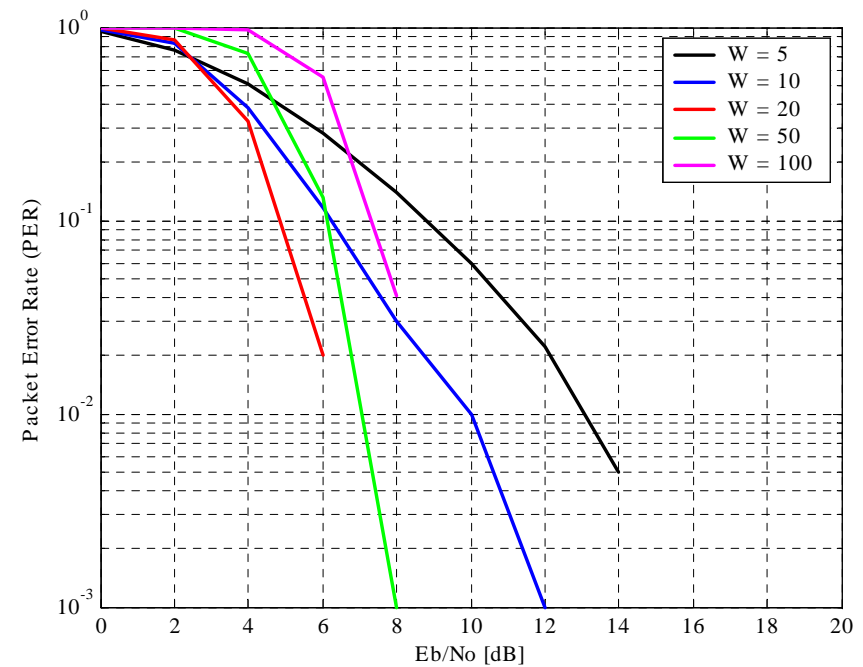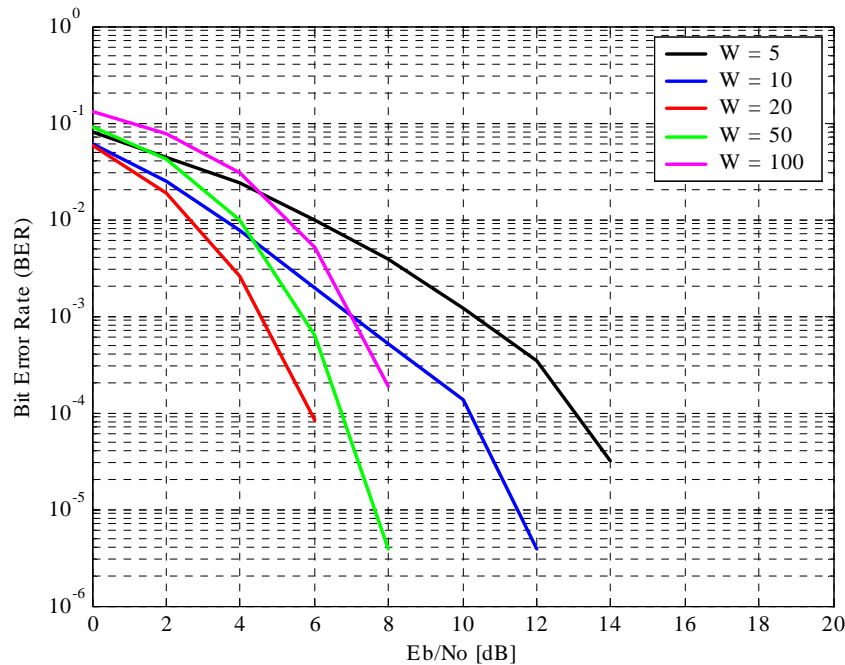 - Number of integrators in the bank : **W**

Simulation Results (5)

- **Simulation environments**
  - IEEE 802.15.4a UWB channel model : **CM1**
  - Number of bit repetition : **2**
  - Number of integrators in the bank : **W**

Simulation Results (6)

- **Simulation environments**

  – IEEE 802.15.4a UWB channel model : **CM1**

  – Number of bit repetition : **4**

  – Number of integrators in the bank : **W**

Simulation Results (7)

- **Simulation environments**

    - IEEE 802.15.4a UWB channel model : **CM5**

    - Number of bit repetition : **1**

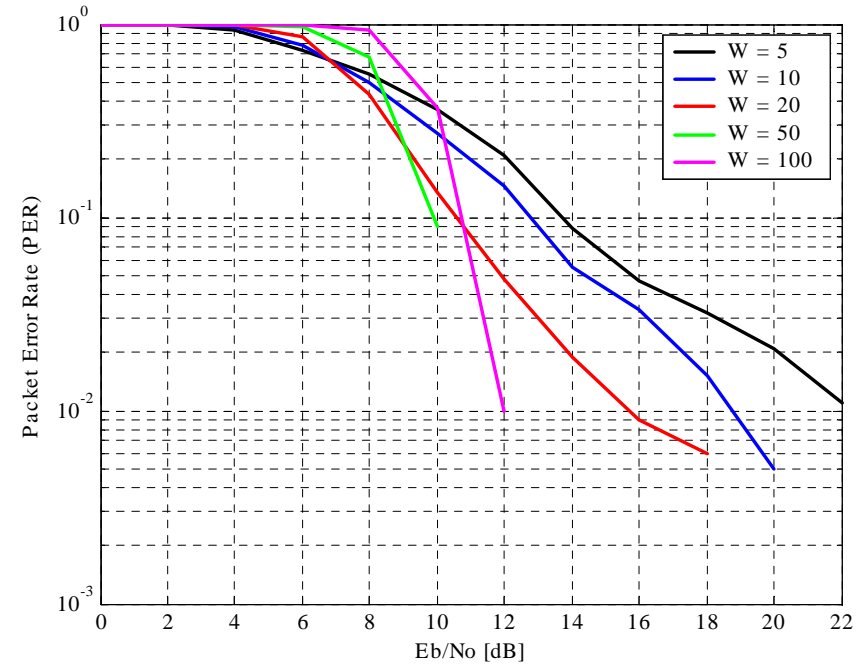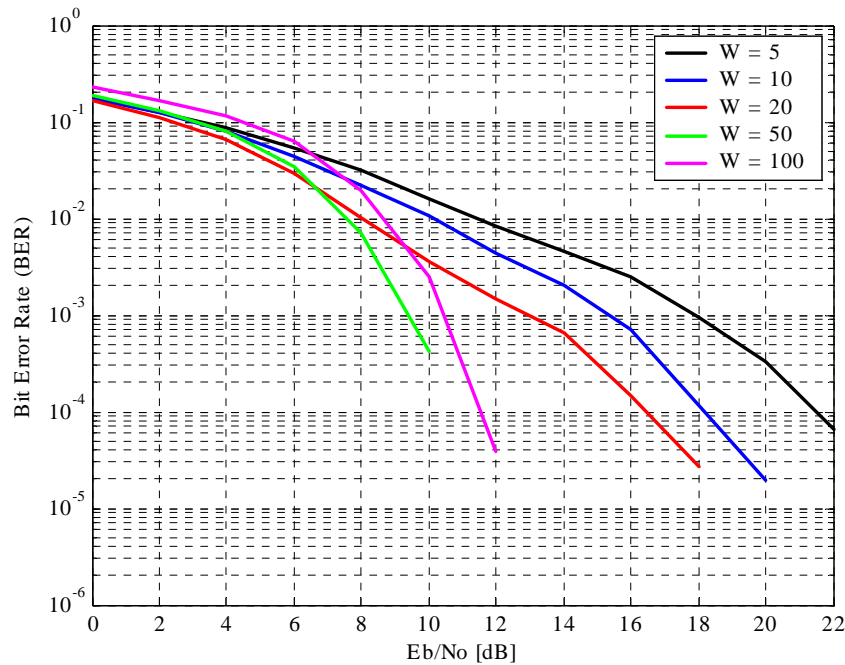   - Number of integrators in the bank : **W**

Simulation Results (8)

- **Simulation environments**

    – IEEE 802.15.4a UWB channel model : **CM5**

    – Number of bit repetition : **2**

    – Number of integrators in the bank : **W**

Simulation Results (9)

- **Simulation environments**

  - IEEE 802.15.4a UWB channel model : **CM5**

  - Number of bit repetition : **4**

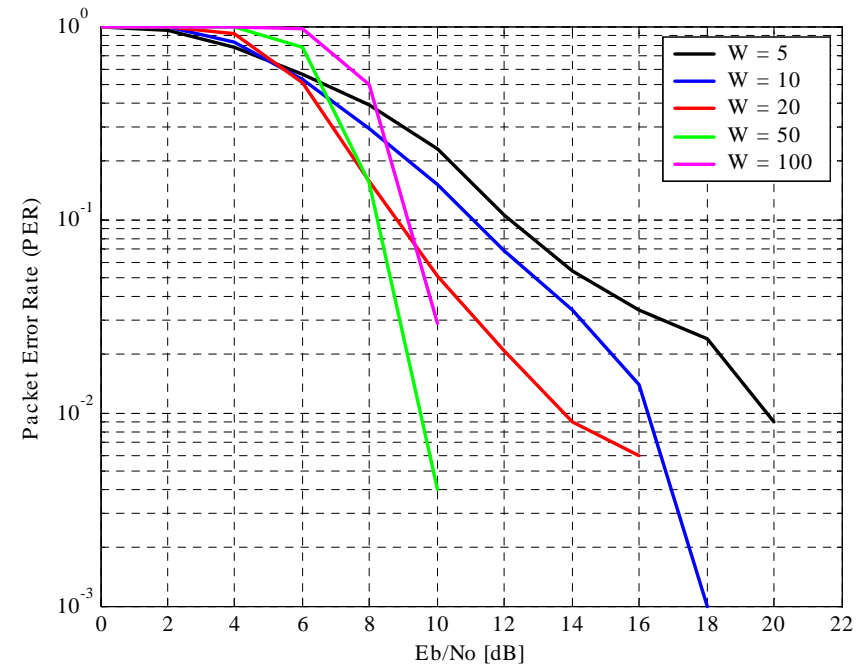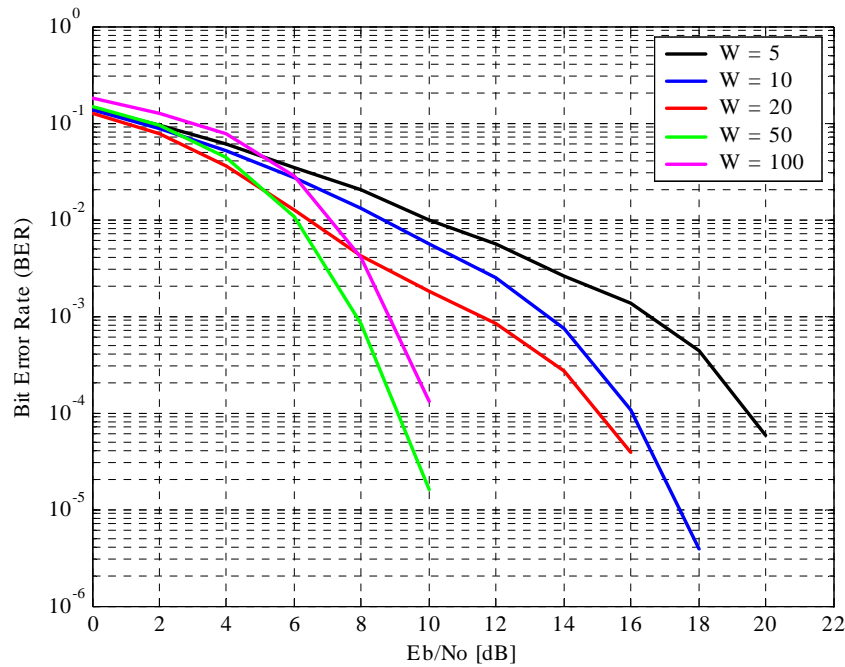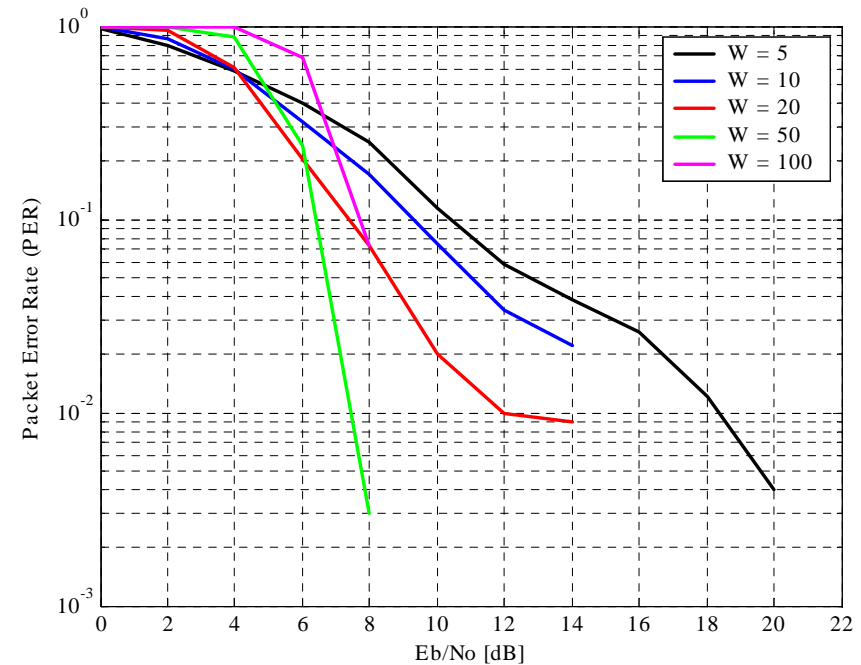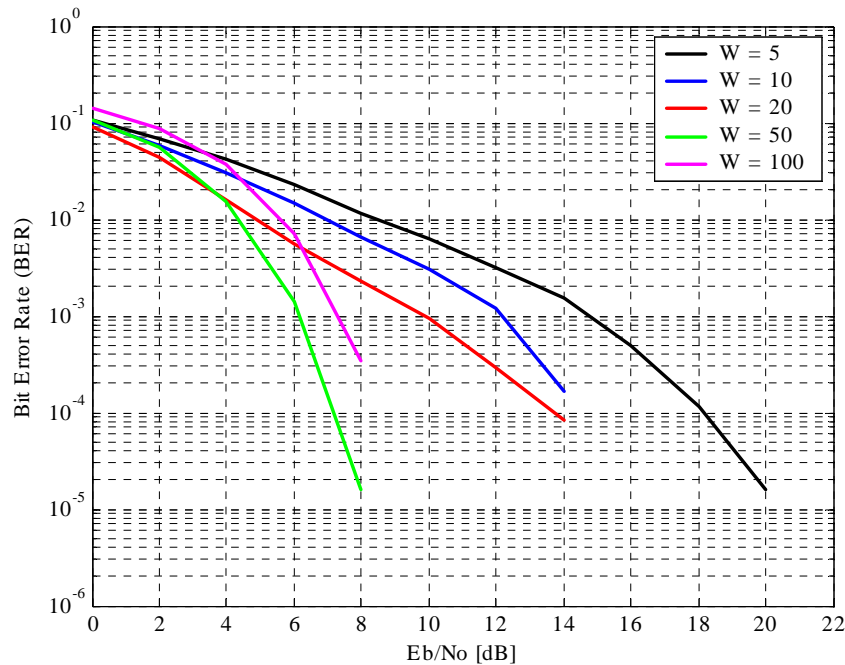 - Number of integrators in the bank : **W**

Link Budget
&
Complexity and Power Consumption

Link Budget

Parameter	Value	(optional) Value
Peak payload bit rate(R_b)	X_0= 2.4414 Mbps	X_1= 615.35 Kbps
Average Tx power (P_T)	-8.2 dBm	-8.2 dBm
Tx antenna gain (G_T)	0 dBi	0 dBi
Geometric center frequency of waveform (f_c)	4 GHz	4 GHz
Path loss at 1 meter (L_1)	44.48 dB	44.48 dB
Path loss at d m (L_2)	29.54 dB at d=30 meter	29.54 dB at d=30 meter
Rx antenna gain (G_R)	0 dBi	0 dBi
Rx power (P_R) at 10 m	-72.7 dBm	-72.7 dBm
Rx power (P_R) at 30 m	-82.3 dBm	-82.3 dBm
Average noise power per bit (N)	-110.1 dBm	-116.1 dBm
Rx noise figure (N_F)	7 dB	7 dB
Average noise power per bit (P_N)	-103.1 dBm	-109.1 dBm
Minimum Eb/No (S) @ BER=10^{-5}	12 dB	8 dB
Minimum Eb/No @ PER=1%	11 dB	7 dB
Implementation Loss (I)	5 dB	5 dB
Link Margin at 10 m	13.4 dB	23.4 dB
Link Margin at 30 m	3.9 dB	13.8 dB

Complexity and Power Consumption

• Preliminary Evaluation

    – Assumption: 500Msps

Detection Approaches	Using 1 bit ADC& S/H		Using 2 bit ADC& S/H	
	Power Consumption	Complexity	Power Consumption	Complexity
Coherent OOK Detector	2.5mW	200 TR	7.5mW	500 TR
Enhanced Non-coherent Detector	0.5mW	50 TR	5mW	350 TR

Conclusions

- Enhanced Noncoherent OOK UWB transceiver with energy detection can meet the low power, low cost, and simple architecture
  - Edge-triggered OOK signals and data repetition for better detection
  - Three modes (timing/calibration/operation) in the receiver for system performance improvement
  - Roughly synchronized TDM, randomly or sequentially allocated for SOP
- TDOA/TWR positioning & ranging techniques
  - Asynchronous ranging by round trip time
  - Positioning based on sequential relay transmission
  - Positioning scenarios according to network topologies
  - Modifying MAC command frame for SOP and positioning
  - Energy window bank with low clock speed for energy detection and ranging accuracy improvement