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

Submission Title : Proposal of NG-SUN FSK PHY for IEEE 802.15.4ad

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Re : TG4ad Next Generation SUN PHYs

Abstract : This is a final proposal of NG-SUN FSK PHY for TG4ad

Purpose: Discussion

Introduction

- **This is a final proposal of P-FSK based NG-SUN PHY for TG4ad**

- **This document includes**
  - Target of Applications
  - NG-SUN PHY Requirements
  - Operating Frequency Bands
  - Channel Plan
  - Channel Models
  - PHY Proposal Consideration
  - NG-SUN PHY Architecture
  - Symbol Rate & Data Rate
  - FEC & Data Whitening
  - PHY Frame Format
  - Link Budget

Target Applications

- **SUN is widely used to deploy large-scale outdoor IoT networks in various industries.**
  - Early SUN focused on wireless metering services for utilities such as electricity, water, and gas.
  - Recently, SUN applications are expanding into various monitoring services in smart grids, smart cities, smart homes, and smart factories.
- **For future industrial IoT applications, the NG-SUN PHY requires better performance than existing SUN PHYs in harsh wireless network environments.**
  - NG-SUN PHY can be used to wirelessly connect new IoT devices to the Ship Area Network (SAN) on large vessels with complex steel bulkhead structures.
  - NG-SUN PHY can be used to deploy wireless networks in harsh environments such as container yards and shipyards where it is difficult to secure sufficient wireless link budget due to high metallicity (shielding) characteristics.
  - .

NG-SUN PHY Requirements

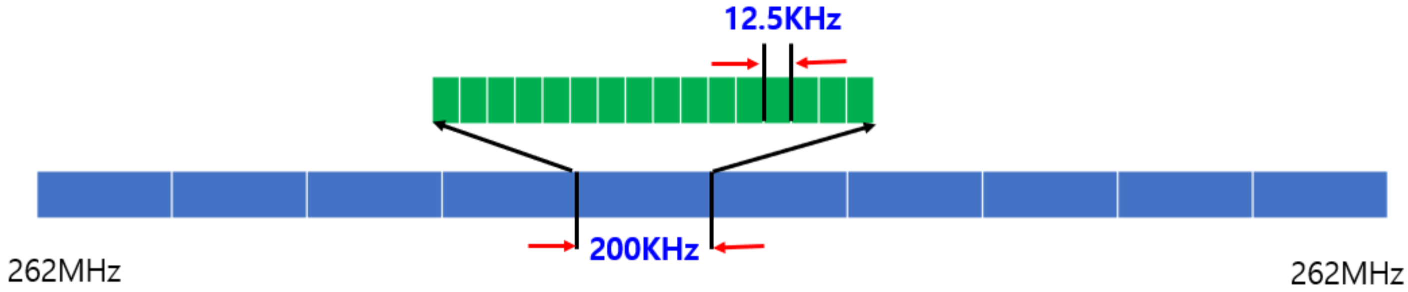
- **NG-SUN PHYs address the requirements of emerging IoT applications in harsh wireless network environments**
  - Seamless wireless connectivity for IoT Applications
    - ☞ Ultra low complexity
    - ☞ Ultra low cost
    - ☞ Ultra low power consumption
  - Data rate extensions by
    - ☞ increasing the occupied bandwidth
    - ☞ adding new modulation and coding schemes (MCSs)
    - ☞ providing long-range communication in congested environments

Operating Frequency Bands

- **Locally available sub-1GHz frequency bands in the world, e.g.,**
  - 902 MHz ~ 928 MHz(North and South America)
  - 863 MHz ~ 870 MHz(Europe)
  - 915 ~ 918 MHz(Japan)
  - 755 ~ 787 MHz(Chana)
  - Other available frequency bands
- **NG-SUN operating frequency bands proposed in Korea**
  - **262 MHz ~ 264 MHz**
  - 917 ~ 923.5 MHz
  - **940.1 ~ 944.3 MHz**
  - Other available frequency bands

262 MHz ~ 264 MHz

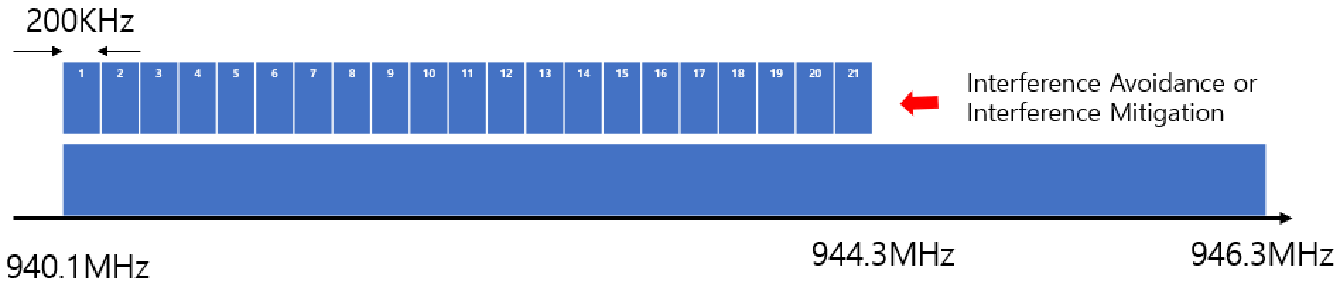
- **Center Frequency**
  - 262.00625 MHz + [12.5KHz x (N-1)], 1 ≤ N ≤ 160, N=integer of channel number
- **Effective Radiated Power :** ≤ 100mW
- **Occupied Frequency Bandwidth :** within 200KHz
- **Interference Avoidance**
  - Frequency Hopping or
  - LBT(Listen Before Transmission)



940.1 MHz ~ 944.3 MHz

- **Center Frequency**
  - 940.2 MHz + [(0.2 MHz x (N-1)], 1 ≤ N ≤ 20, N=integer of channel number
- **Radiated power including absolute antenna gain :** ≤ 200mW
- **Sum of the transmission time :** within 5% of any one minute
- **Occupied Frequency Bandwidth :** ≤ 200KHz

  If device use frequency sweep , within 940.1~944.3 MHz
- **Must use interference avoidance or mitigation technique**
  - Frequency Hopping or
  - LBT(Listen Before Transmission)



Channel Plan

- **Number of channels per band**

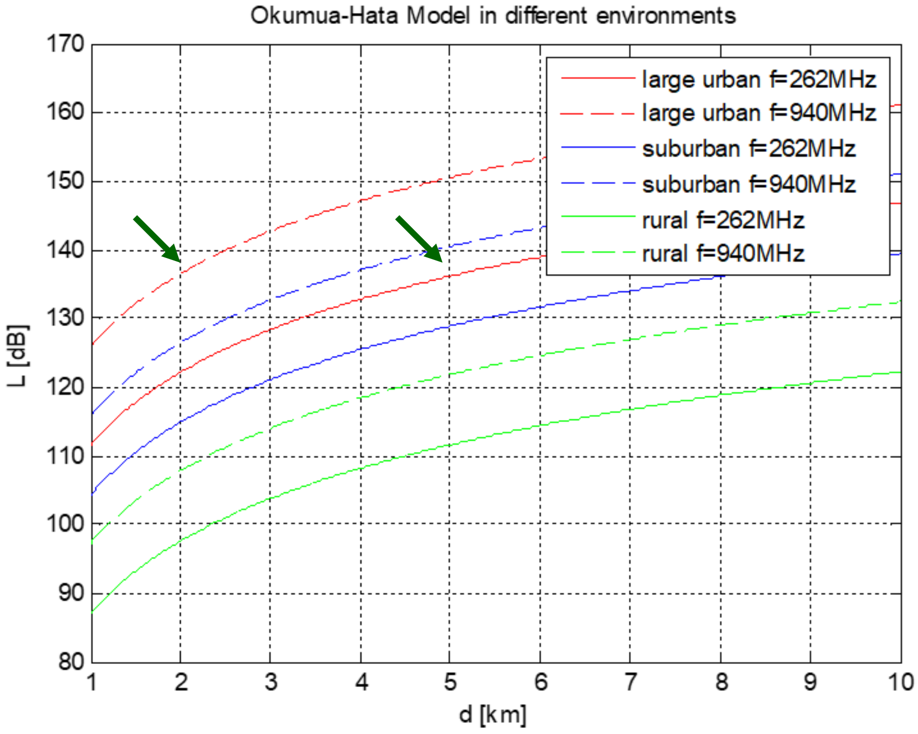
Number of Channels					
Frequency Band	Channel Spacing				
	12.5KHz	25KHz	50KHz	100KHz	200KHz
262 ~ 264 MHz 1)	160	80	40	20	10
940.1 ~ 944.3 MHz 2)	21	21	21	21	21

1) 12.5KHz channel spacing. Max. Occupied Frequency Bandwidth ≤ 200KHz

2) 200KHz channel spacing , Max. Occupied Frequency Bandwidth ≤ 200KHz

Channel Model

- **Pass Loss Model**
  - Okumura-Hata Model(Large Urban, Sub-urban, Rural)
    - Large Urban Pass Loss at 5Km for 262MHz : 136.14dB
    - Large Urban Pass Loss at 2Km for 940MHz : 136.47dB



Channel Model - Continued

- **Well-known path loss models for outdoor environments are an unsatisfactory fit for empirical path loss in harsh environments**
  - Empirical path loss models is considered for an environment of stacked shipping containers.
  - Emmeric Tanghe, Wout Joseph et. al., ‘Intra-, Inter-, and Extra-Container Path Loss for Shipping Container Monitoring Systems’, IEEE Antennas And Wireless Propagation Letters, Vol. 11, 2012
  - Link Budget Analysis of NG-SUN PHY for IEEE 802.15.4ad Preliminary Proposal(IEEE 802.15-24-0603-00-04ad)
- **Path Loss in container environment**

$$P_L(d) = b_0 + b_1 \cdot 10\log_{10}(d) + \chi_s$$

where, d is distance between TX and RX

b_0 and b_1 are regression parameters,

χ_s assumes a normal distribution with standard deviation

Channel Model - Continued

- **Container Row Stacking:**
  - 868MHz, Vent-mounted
  - Path Loss Model Parameters

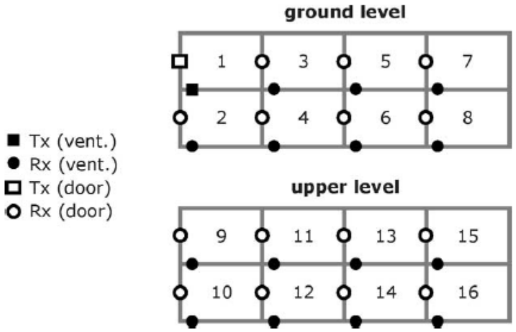
    $b_0 = 47.64$, $b_1 = 2.09$, $\chi_s = 6.56$
  - Pass Loss @500m

    $PL(500) = 47.64 + 2.09 \times 10 \cdot \log_{10}(500) + 6.56 = 110.61$ dBm

- **Container Block Stacking:**
  - 868MHz, Door-mounted
  - Path Loss Model Parameters

    $b_0 = 43.93$, $b_1 = 3.25$, $\chi_s = 4.94$
  - Pass Loss @500m

    $PL(200) = 43.93 + 3.25 \times 10 \cdot \log_{10}(500) + 4.94 = 136.59$ dBm



RX Power for 262MHz Large Urban

- **TX Power : 100mW(20dBm)**
  - RX Power@5Km : -121.14 dBm

Channel Model Parameters		
Frequency (MHz)	262	150 MHz to 1500 MHz
TX Antenna Height(m)	30	30 m to 200 m
RX Antenna Height (m)	2	1 m to 10 m
Distance (Km)	5	1 km to 20 km

RX Power Calculation		
TX Power(dBm)	20	Subject to Tx Power Regulations (200mW)
TX Antenna Gain(dBi)	2	Subject to Tx Power Regulations
Path Loss(dB)	-136.14	Reference the path loss from Okumura-Hata Model
Shadowing Margin (dB)	-10	To buffer against variable shadowing loss
Penetration Loss (dB)	0	For underground vaults, etc.
Rx Antenna Gain (dBi)	2	same antenna for Tx
Interference(dB)	1	Rise over Thermal Interference
RX Power at endpoint(dBm)	-121.14	Compare against Rx sensitivity

RX Power for 940MHz Large Urban

- **TX Power : 200mW(23dBm)**
  - RX Power@2Km : -118.47dBm

Channel Model Parameters		
Frequency (MHz)	940	150 MHz to 1500 MHz
TX Antenna Height(m)	30	30 m to 200 m
RX Antenna Height (m)	2	1 m to 10 m
Distance (Km)	2	1 km to 20 km

RX Power Calculation		
TX Power(dBm)	23	Subject to Tx Power Regulations (200mW)
TX Antenna Gain(dBi)	2	Subject to Tx Power Regulations
Path Loss(dB)	- 136.47	Reference the path loss from Okumura-Hata Model
Shadowing Margin (dB)	-10	To buffer against variable shadowing loss
Penetration Loss (dB)	0	For underground vaults, etc.
Rx Antenna Gain (dBi)	2	same antenna for Tx
Interference(dB)	1	Rise over Thermal Interference
RX Power at endpoint(dBm)	-118.47	Compare against Rx sensitivity

RX Power for Harsh Environment

- **TX Power : 100mW(20dBm)**
  – RX Power@0.5Km : -121.59dBm

Channel Model Parameters		
Frequency (MHz)	868	Operating frequency band
TX Antenna Height(m)	2.5	Container Height
RX Antenna Height (m)	2.5	Container Height
Distance (Km)	0.5	< 1Km

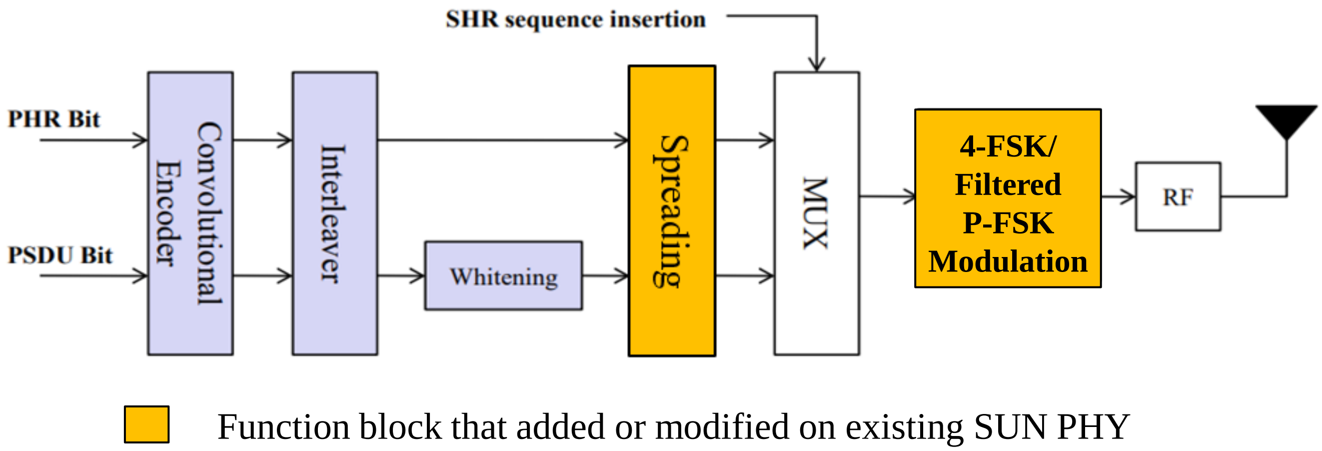
RX Power Calculation		
TX Power(dBm)	20	Subject to Tx Power Regulations (200mW)
TX Antenna Gain(dBi)	2	Subject to Tx Power Regulations
Path Loss(dB)	-136.59	Reference the path loss from the empirical path loss models
Shadowing Margin (dB)	-10	To buffer against variable shadowing loss
Penetration Loss (dB)	0	For underground vaults, etc.
Rx Antenna Gain (dBi)	2	same antenna for Tx
Interference(dB)	1	Rise over Thermal Interference
RX Power at endpoint(dBm)	-121.59	Compare against Rx sensitivity

PHY Proposal Considerations

- **NG-SUN Channel :** harsh, high path loss environment
  - TX power : 10, 20, 23 dBm
  - RX power: < -120dBm
  - SNR @ RX antenna: ~ less than 0dB
- **Reliability:** How to recover the information bit from the weak signal?
  - Narrowband PHY to lower the noise level
  - **Modified FSK modulation for improved performance**
  - Channel coding gain
  - **Spreading gain**
  - Antenna gain and etc.
- **Energy efficiency (low-power consumption) at battery-powered devices is also main consideration**
  - Modified FSK modulation for low power consumption

NG-SUN PHY Architecture

- **Trade off between 4-FSK and P-FSK**
  - 4-FSK for improved performance
  - P-FSK for low power consumption
- **Spreading**
  - Better signal reception in harsh environments by increasing the signal's duration and sensitivity



The Need for a New Modulation Scheme

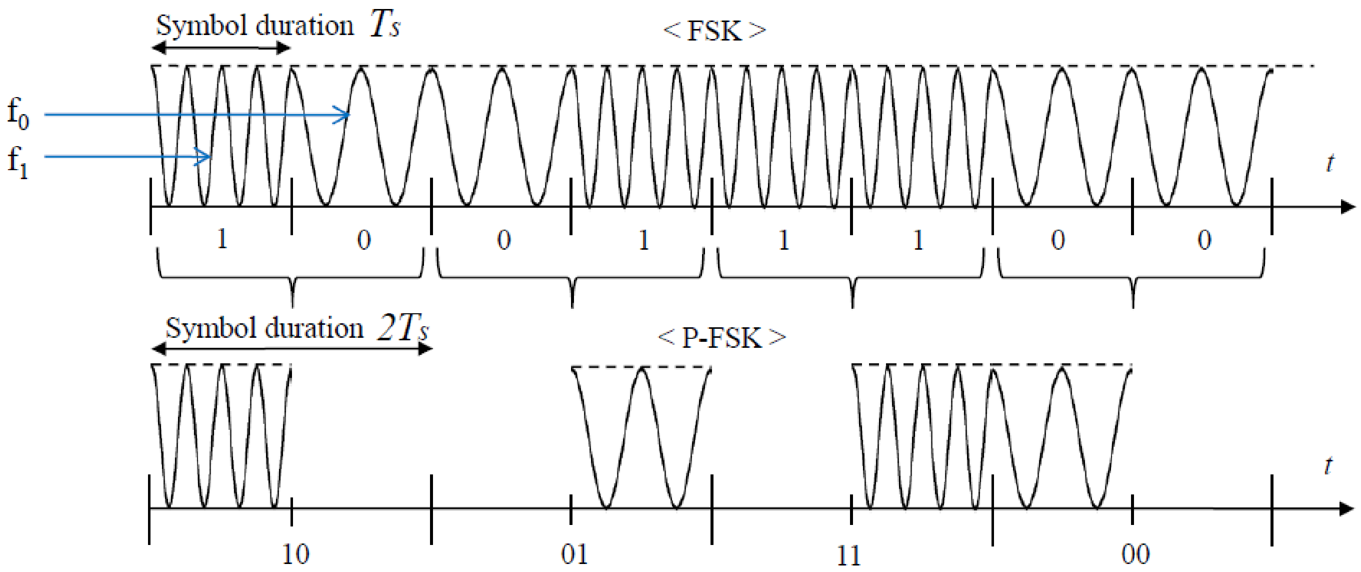
- **Benefits of FSK Modulation PHY**
  - No need of high-linearity power amplifier (PA)
  - Non-coherent receiver: low-power consumption
    - ☞ No need to track the phase of the carrier
    - ☞ Performance difference between coherent receiver and non-coherent receiver: roughly 1dB
    - ☞ Suitable for battery-powered endpoint devices
  - Simple, cheap and proven technology
- **However, conventional 2-FSK is relatively poor performance**

Position based FSK(P-FSK)

- **High-dimension orthogonal signaling**
  - P-FSK is combination of FSK and PPM
    - 2-level FSK : 2-dimension orthogonal signals (freq. domain)
    - 2-ary PPM : 2-dimension orthogonal signals (time domain)
    - Construct 4-dimension orthogonal signals while keeping the same bit rate and signal bandwidth
- **Reliable operation over high path loss channel**
  - SNR gain obtained from modulation is beneficial
  - Reduce the SNR per bit required to achieve a target BER

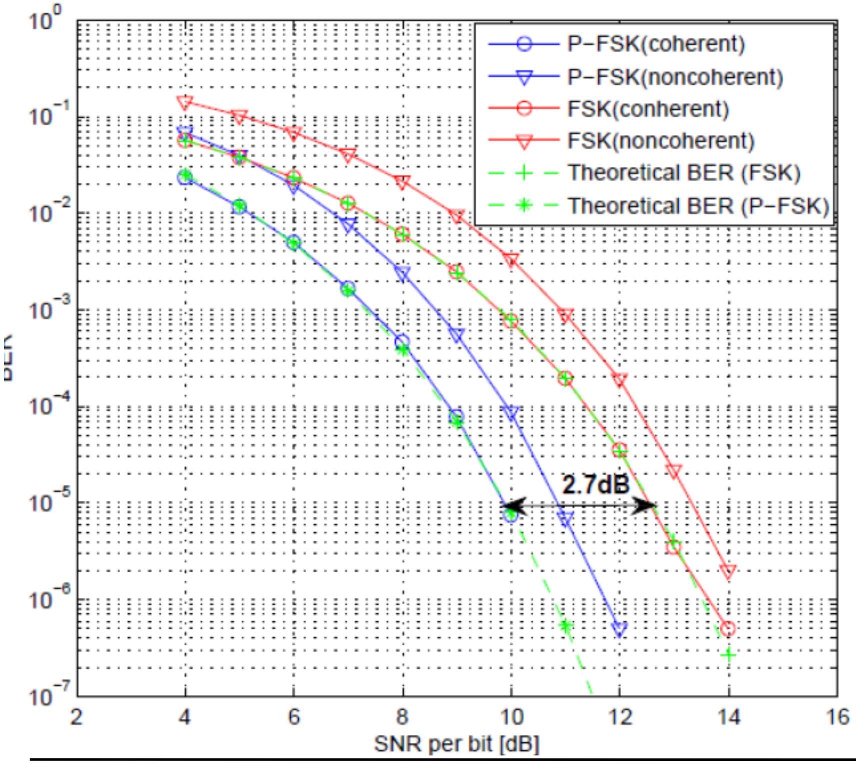
Position based FSK(P-FSK) - Continued

- **4-dimension orthogonal signaling**
  - Two bits are encoded by transmitting a FSK-modulated signal in one of two possible positions (time-shifts)
  - 4 waveforms that indicate “00”,”01”,”10”, “11”



Performance Comparison of FSK and P-FSK

- **BER performance of P-FSK : – 2.7dB gain @ BER 10^{-5} compared with FSK**
  - Coherent receiver : performance enhancement
  - Non-coherent receiver : low power consumption



- **Non-coherent receiver for P-FSK**
  - same as the conventional FSK
  - computational overhead is negligible

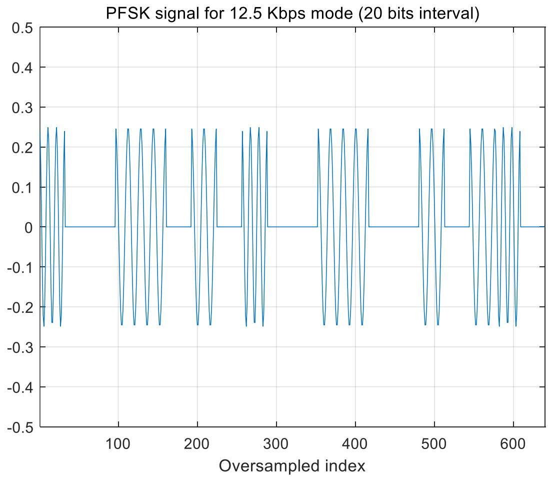
- Theoretical BER comparison

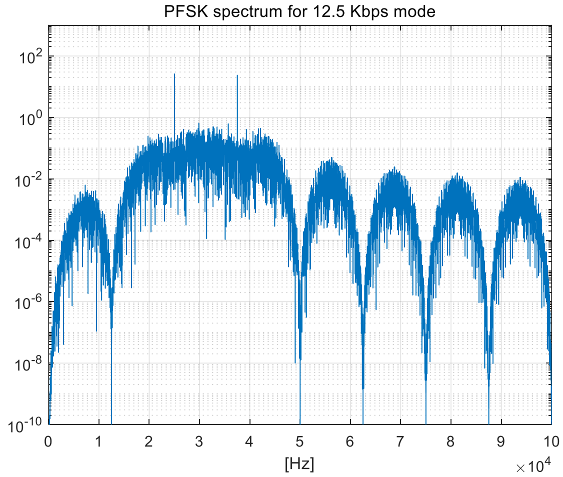
$$P_b^{\mathrm{FSK}} = Q\left(\sqrt{\frac{E_b}{N_0}}\right)$$

$$P_b^{\mathrm{P-FSK}} \leq 2 \cdot Q\left(\sqrt{\frac{E_s}{N_0}}\right) = 2 \cdot Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

Spectrum of P-FSK

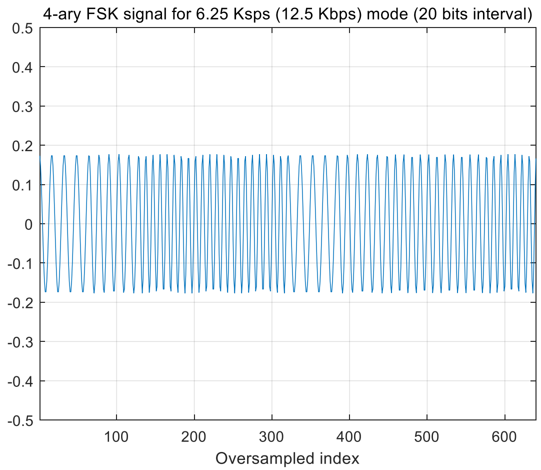
- **Potential problem with position selection mechanism**
  - Sideband regrowth
    - Need additional filter to solve the problems
    - Additional complexity in the transmitter would be unavoidable
  - Average vs. peak signal power
    - Extension of coverage
- **Pulse shaping may be required to meet strict spectral emission masks.**

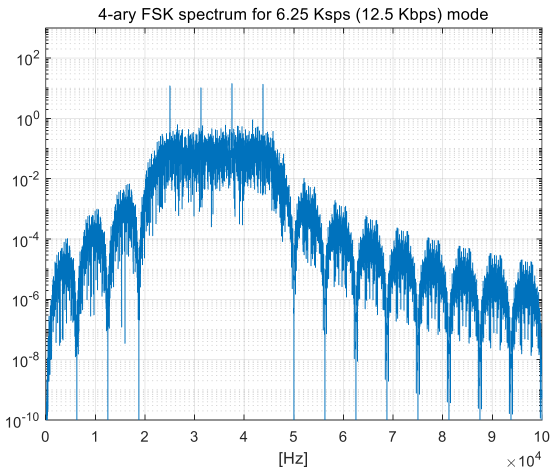




4-FSK Modulation

- **Alternative 4-ary orthogonal modulation scheme**
  - No sideband regrowth problem
    - ➢ Sidelobe of the 4-ary FSK spectrum is much lower than the PFSK
    - ➢ Spectral regulation issues would not be a problem with the 4-ary FSK
  - Reduced peak signal power with better performance than P-FSK
    - ➢ Peak power of the 4-ary FSK signal is 3-dB less than P-FSK
    - ➢ Extended coverage would be expected with the 4FSK



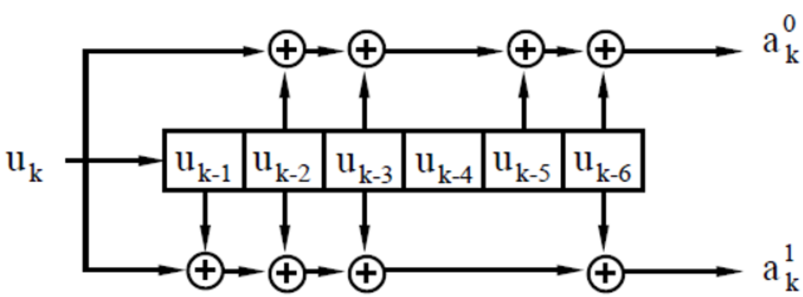


Filtered P-FSK Modulation

- **Since P-FSK and 4-FSK are four-dimensional orthogonal modulation schemes, the BER performance is exactly the same.**
  - P-FSK has 2.7 dB better BER performance than FSK while maintaining the same bit rate and signal bandwidth.
  - 4-FSK is somewhat advantageous in extending coverage because the peak power of the signal is 3 dB lower than that of P-FSK.
- **Some local regulations require very stringent spectral emission masks to protect other services in adjacent bands.**
  - 4-FSK has some advantages over P-FSK in terms of spectral emission mask control, but both schemes require pulse shaping.
  - To eliminate inter-symbol interference and achieve the objective of baseband shaping filter, propose to use Gaussian filter.
- **Since 4-FSK is already adopted in the existing SUN standard, propose to add the filtered P-FSK as an optional modulation.**

Forward Error Correction(FEC)

- **Long burst errors are more likely than random bit error**
  - Error correction capability is required for reliable operation in dramatically changing environments
- **Propose to use the same FEC of LECIM FSK PHY of IEEE Std. 802.15.4-2024**
  - Employ rate 1/2 convolutional coding with constraint length K = 7
  - $\oplus$ denotes modulo-2 addition.

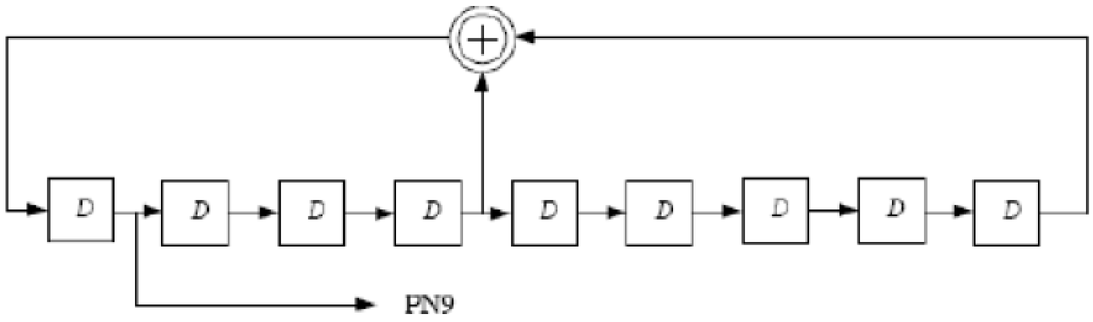


LECIM FSK PHY convolutional encoder

Data Whitening

- **Long runs of 1s and 0s in data (payload) may degrade the performance of bit timing recovery and tracking in FSK system**

- **Propose to use the same data whitening in SUN FSK PHY of IEEE Std. 802.15.4-2024**
  - Exclusive OR of the PHY Payload field with the PN9 sequence.



< Schematic of the PN9 sequence generator >

Spreading

- **NG-SUN channel :** RF link with high path loss (>120dB)
  - Require better signal reception in harsh environments
- **Simple spreading scheme**
  - A => repetition of "AĀ" where A is a symbol
    - ☞ e.g.) 0 => repetition of "01" , 1 => repetition of "10"
    - ☞ e.g.) 01 => repetition of "0110", "11" => repetition of "1100"
  - Repetition of "AĀ": useful for FSK based system
  - Repetition rate depends on spreading factor
- **Spreading factor**
  - 1(0dB), 2(3dB), 4(6dB), 8(9dB), 16(12dB)
  - Select according to channel condition

Symbol Rate & Data Rate for 4-FSK

- **The symbol rate depends on the channel spacing**
  - Mandatory : 6.25KHz & 100KHz
  - Optional : 12.5KHz, 25KHz, & 50KHz
- **The data rate depends on the coding rate and spreading**
  - Mandatory : 12.5, 25, 50, 100, 200Kbps (No coding/spreading)
  - Optional : 390.6bps ~6.25Kbps by spreading factor(Code rate ½)

Data Rate uncoded/No Spreading					
Data Rate(uncoded)	12.5Kbps	25Kbps	50Kbps	100Kbps	200Kbps
Symbol Rate	6.25KHz	12.5KHz	25KHz	50KHz	100KHz
Modulation	4-FSK	4-FSK	4-FSK	4-FSK	4-FSK
Modulation Index	0.33	0.33	0.33	0.33	0.33
Channel Spacing	12.5KHz	25KHz	50KHz	100KHz	200KHz

Symbol Rate & Data Rate for P-FSK

- **The symbol rate depends on the channel spacing**
  - Mandatory : 6.25KHz & 100KHz
  - Optional : 12.5KHz, 25KHz, & 50KHz
- **The data rate depends on the coding rate and spreading**
  - Mandatory 6.25, 12.5, 25, 50,100Kbps (No coding/spreading)
  - Optional : 195.3bps ~3.125Kbps by spreading factor(Code rate ½)

Data Rate uncoded/No Spreading					
Data Rate(uncoded)	6.25Kbps	12.5Kbps	25Kbps	50Kbps	100Kbps
Symbol Rate	6.25KHz	12.5KHz	25KHz	50KHz	100KHz
Modulation	P-FSK	P-FSK	P-FSK	P-FSK	P-FSK
Modulation Index	0.5	0.5	0.5	0.5	0.5
Channel Spacing	12.5KHz	25KHz	50KHz	100KHz	200KHz

Link Budget (262MHz Large Urban)

- **Minimum Eb/No**
  - Coherent receiver: 10dB @ BER 10^{-5}
  - Channel coding gain: SDD 5dB, HDD 3dB
- **TX Power : 20dBm(100mW)**

Parameter	Unit	Value
Distance(D)	km	5
Bandwidth(BW)	KHz	12.5
Rx power at Endpoint(P_r)	dBm	-121.14
Receiver AWGN noise(N=-174+10log[BW])	dBm	-133.03
RF noise figure of endpoint(N_f)	dB	8
Average noise power(P_n = M + N_f)	dBm	-125.03
Minimum E_b/N_o(S)	dB	10
Implementation Loss(I)	dB	8
Processing Gain(PG)+Coding Gain(SDD)	dB	17
Link Margin(LM=P_r - P_n – S – I + PG)	dB	2.89
Proposed Minimum RX sensitivity level(P_{min})	dBm	-124.03

Link Budget in 940MHz Large Urban

- **Minimum Eb/No**
  - Coherent receiver: 10dB @ BER 10^{-5}
  - Channel coding gain: SDD 5dB, HDD 3dB
- **TX Power : 23dBm(200mW)**

Parameter	Unit	Value
Distance(D)	km	2
Bandwidth(BW)	KHz	12.5
Rx power at Endpoint(P_r)	dBm	-118.47
Receiver AWGN noise(N=-174+10log[BW])	dBm	-133.03
RF noise figure of endpoint(N_f)	dB	8
Average noise power(P_n = M + N_f)	dBm	-125.03
Minimum E_b/N_o(S)	dB	10
Implementation Loss(I)	dB	8
Processing Gain(PG)+Coding Gain(SDD)	+dB	17
Link Margin(LM=P_r - P_n – S – I + PG)	dB	5.56
Proposed Minimum RX sensitivity level(P_{min})	dBm	-124.03

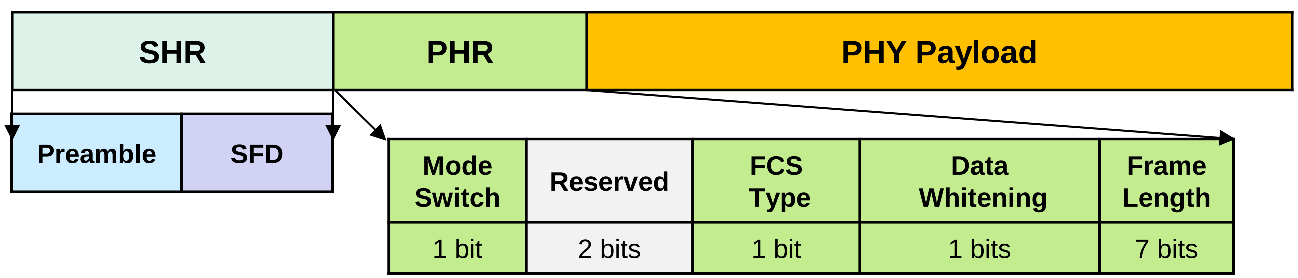
Link Budget in 868MHz Harsh Environment

- **Minimum Eb/No**
  - Coherent receiver: 10dB @ BER 10^{-5}
  - Channel coding gain: SDD 5dB, HDD 3dB
- **TX Power : 20dBm(100mW)**

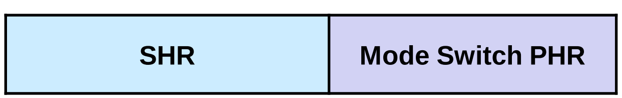
Parameter	Unit	Value
Distance(D)	km	0.5
Bandwidth(BW)	KHz	12.5
Rx power at Endpoint(P_r)	dBm	-121.59
Receiver AWGN noise(N=-174+10log[BW])	dBm	-133.03
RF noise figure of endpoint(N_f)	dB	8
Average noise power(P_n = M + N_f)	dBm	-125.03
Minimum E_b/N_o(S)	dB	10
Implementation Loss(I)	dB	8
Processing Gain(PG)+Coding Gain(SDD)	dB	17
Link Margin(LM=P_r - P_n – S – I + PG)	dB	2.44
Proposed Minimum RX sensitivity level(P_{min})	dBm	-124.03

PHY Packet Format

- **SUN FSK PHY packet format of IEEE standard 802.15.4-2024.**
  - Format of the SUN FSK PPDU (without mode switch)
    - ➢ SHR : Preamble & SFD
    - ➢ PHR : Mode Switch, FCS Type, Data Whitening, Frame Length
    - ➢ PHY Payload : transmitted at symbol rate specified in PHR

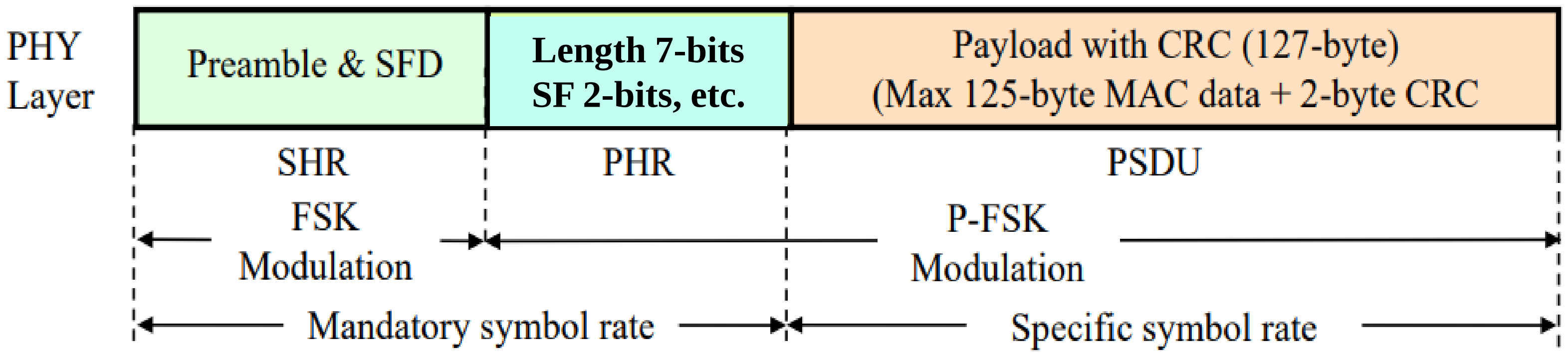


  - Format of the SUN FSK mode switch PPDU



PHY Packet Format for P-FSK

- **SHR:** modulated by FSK
- **PHR and PSDU:** modulated by P-FSK
- **SHR & PHR**: transmitted at mandatory symbol rate
- **PSDU**: transmitted at symbol rate specified in PHR



SHR Field

- **Long preamble and SFD sequence are necessary due to harsh and high path loss channel environment**
  - **Preamble**
    - ➢ Complies with IEEE802 15.4-2024 FSK SUN standard
      - ☞ Multiple 16-bit sequence “0111 0111 0111 0111” for 4-FSK
      - ☞ Multiple 8-bit sequence “10101010” for P-FSK
    - ➢ Enough octets for packet detection and synchronization

      (Default length of the preamble field : 8 Octets)

SHR Field

– **SFD**

- Complies with IEEE802 15.4-2024 FSK SUN standard
  - ☞ Coded and uncoded format for 4-FSK

	SFD value for coded format (b0–b31)	SFD value for uncoded format (b0–b31)
phySunFskSfd = 0	0111 1101 1111 1111 0111 0101 1111 1101	1101 0111 0101 0101 0111 0101 1111 1101
phySunFskSfd = 1	0111 1101 0101 1111 0101 1101 1111 0111	0111 1111 1101 1101 0101 0101 1111 1101

  - ☞ Coded and uncoded format for P-FSK

	SFD value for coded format (b0–b15)	SFD value for uncoded format (b0–b15)
phySunFskSfd = 0	0110 1111 0100 1110	1001 0000 0100 1110
phySunFskSfd = 1	0110 0011 0010 1101	0111 1010 0000 1110

- SFD detector can use full SFD sequence or part of SFD sequence according to its capability and channel condition

New PHR Format

- **PHR Sequence**
  - Length: 7-bit(max. PSDU 127-octet)
  - Rate: 3-bit (symbol rate 6.25, 12.5, 25, 50, 100KHz)
  - Spreading factor (SF): 2-bit
  - Data Whitening(DW) : 1-bit
  - Odd parity (OP) Check : 1-bit
    - ➢ Simply detect PHR error to stop demodulation process

PHR for P-FSK						
Bit: 0	1	2-4	5-6	7	8-14	15
Mode Switch	FCS Type	Symbol Rate	Spreading Factor	Data Whitening	Frame Length	Parity Check

PHR & PSDU for P-FSK

- **PHR and PSDU are encoded by ½ (133,171) convolutional code with interleaving**
- **Interleaving depth**
  - PHR: corresponding to the length of encoded PHR
    - ➢ PHR recovery without latency
  - PSDU: specified in PHR
    - ➢ Consider channel coherence time
- **Spreading**
  - PHR: spreading with mandatory spreading factor (SF)
  - PSDU: spreading with SF specified in PHR

Coexistence

- **Low Duty Cycle**
  - Small and infrequent messages
  - NB PHY with large number of available channels per band and low duty cycling property enable to coexist with other services in the same band
- **Frequency Hopping**
  - Dwell Time Limit : 400 ms max
    - ➢ US 902-928 MHz(FCC Part 15.247)
    - ➢ KR 920-923MHz (Korea)
  - **Hopping with Fragmentation**
    - ➢ Fragmentation is needed to overcome the limited PSDU transmission time to satisfy the dwell time for frequency hopping at extremely low data rates.
    - ➢ Require Fragmentation for 4-FSK PSDU

Key Aspects of PHY Proposal

Parameter		Proposed NG-SUN PHY
Operating Frequency Band		Sub-1GHz(200MHz, 400MHz, 800MHz, 900MHz)
Channel Spacing		12.5KHz, 25KHz, 50KHz, 100KHz, 200KHz
TX Power		As allowed by regulatory regimes(10mW, 100mW, 200mW, …)
Modulation		4-FSK(Mandatory), Filtered P-FSK(Optional)
Symbol Rate		Mandatory : 6.25KHz & 100KHz Optional : 12.5KHz, 25KHz, 50KHz
Spreading		Spreading Factor : 0, 2,4, 8, 16
FEC		Convolutional code Stringent Length K=7
Data Whitening		XOR(PSDU,PN9 sequence)
PHY Frame Structure	SHR	Multiple 16-bit sequence(4-FSK) , 8-bit sequence(P-FSK)
	PHR	16-bit including mode switch 1-bit, FCS 1-bit, symbol rate 3-bit, spreading factor 2-bit, Frame length 7-bits, odd parity check 1-bit
	PSDU	Max. 127-byte(Max. 125-bytes MAC data + 2-bytes CRC)
	CRC	16-bit ITU CRC
Co-existence feature		LBT or Frequency Hopping with Fragmentation

Thanks for Listening !
Q&A