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

Submission Title : Initial Proposal of P-FSK based NG-SUN PHY for TG4ad

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Source : Sangsung Choi, Seonghyeon Chung (A2UICT), Tae-Joon Park(ETRI), Jaemin Ahn(Chungnam University), Minjung Im(Dongguk University)

Re : TG4ad Next Generation SUN PHYs

Abstract : This is an initial proposal of P-FSK based NG-SUN PHY for TG4ad

Purpose: Discussion

Introduction

- **This is an initial proposal of P-FSK based NG-SUN PHY for TG4ad**
- **This document includes**
  - NG-SUN PHY Application
  - NG-SUN PHY Requirements
  - Operating Frequency Bands
  - PHY Channel Plan
  - PHY Proposal Consideration
  - Channel Model & Link Budget
  - Symbol Rate & Data Rate
  - FEC & Data Whitening
  - PHY Frame Format
  - Conclusion

NG-SUN PHY 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.
- **The NG-SUN PHY requires improved performance over the existing SUN PHY for emerging future monitoring applications that consider harsh wireless network environments.**
  - Developing low-power wireless communications to deploy new IoT networks connecting to SAN(Ship Area Network) on large ships with complex steel bulkhead structures is a very challenging task.
  - Due to the high metallic (shielding) nature of the container environment, it is difficult to secure sufficient wireless link budget for the container area network.

NG-SUN PHY Requirements

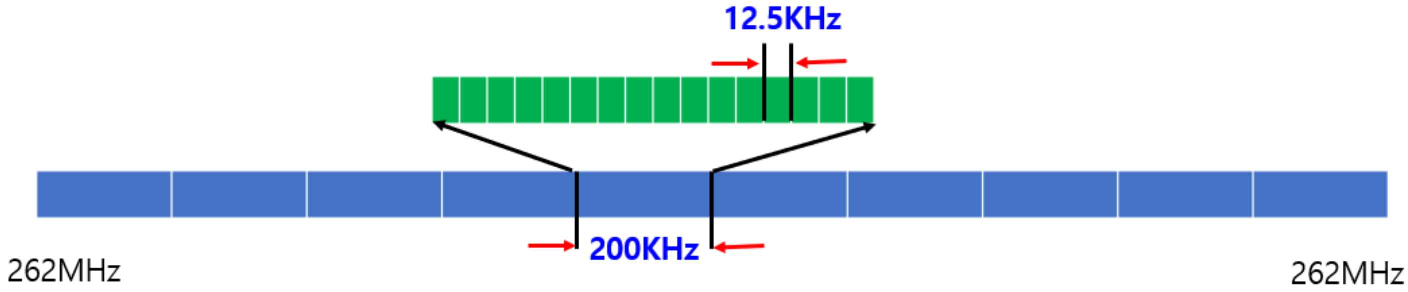
- **The PHY enhancements address the needs of emerging applications where additional data rates expand the usefulness of the SUN PHYs.**
  - Seamless wireless connectivity for IoT Applications
    - ☞ Ultra low complexity
    - ☞ Ultra low cost
    - ☞ Ultra low power consumption
  - NG-SUN PHY defines new data rate extensions by
    - ☞ increasing the occupied bandwidth
    - ☞ adding new modulation and coding schemes (MCSs)
    - ☞ extending the SUN PHYs to provide long-range communication in congested environments

Operating Frequency Bands for NG-SUN PHY

- **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)



917 MHz ~ 923.5 MHz

- **Center Frequency:**

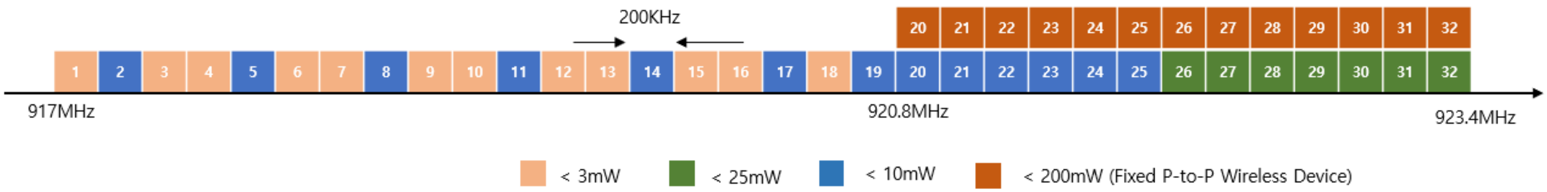
  917.1 MHz + [200 KHz x (N-1)], 1 ≤ N ≤ 32, N=integer of channel number

- **Radiated power including absolute antenna gain :**

  ≤ 3mW, 10mW, 25mW, 200mW

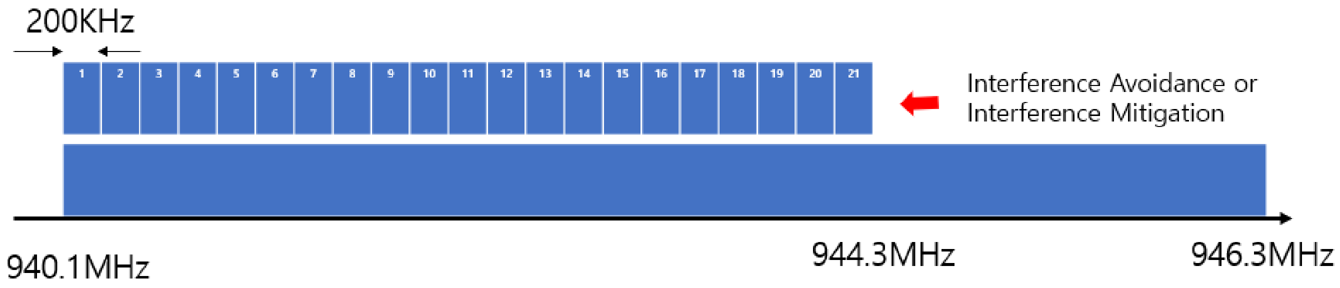
- **Occupied Frequency Bandwidth :** within 917~923.5 MHz.

- **Interference Avoidance**
  - Frequency Hopping or
  - LBT(Listen Before Transmission)
  - Other method(Occupied Time)



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
- **Occupied Frequency Bandwidth :** ≤ 200KHz
- **Must use interference avoidance or mitigation technique**
  - Frequency Hopping or
  - LBT(Listen Before Transmission)
- **Sum of the transmission time :** within 5% of any one minute



NG-SUN PHY Channel Plan

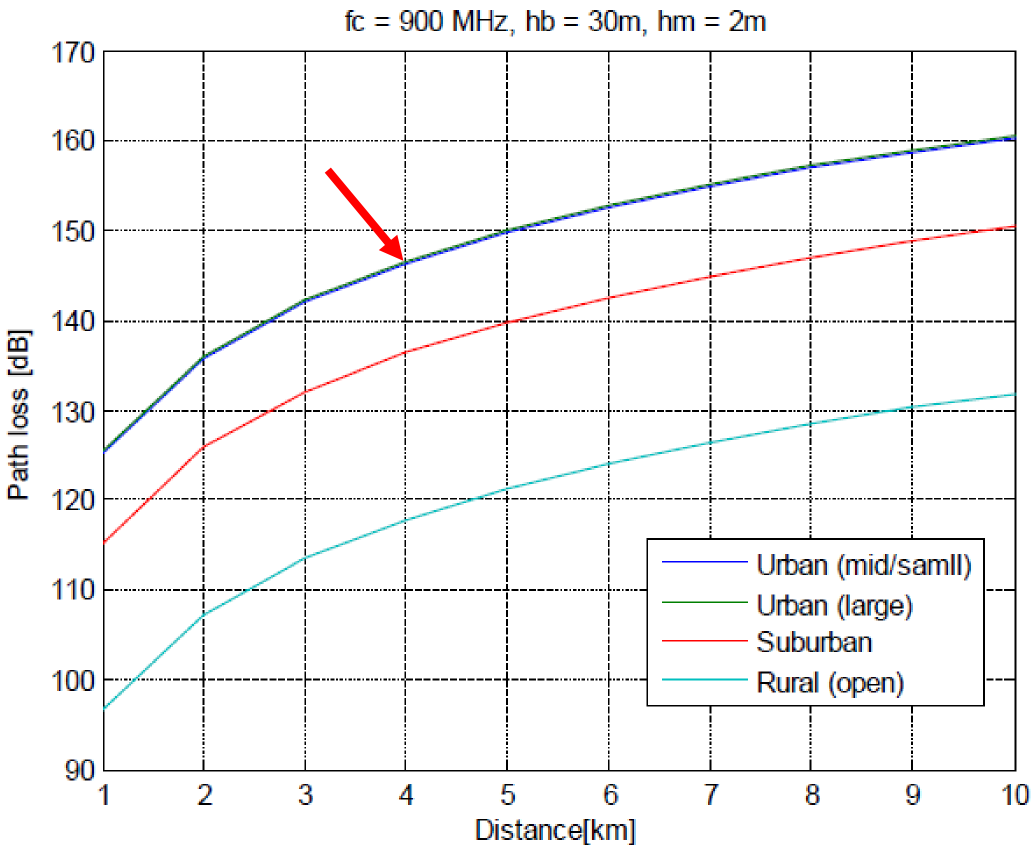
- **Number of channels per band**
  - Symbol rate 12.5 KHz : 50KHz channel spacing
  - Symbol rate 25 KHz : 100KHz channel spacing
  - Symbol rate 50 KHz : 200KHz channel spacing
  - Symbol rate 100 KHz : 400KHz channel spacing

Frequency Band	Number of Channels			
	12.5KHz	25KHz	50KHz	100KHz
262 ~ 264 MHz	40	20	10	5
*917 ~ 923.5 MHz	14	14	14	7
940.1 ~ 944.3 MHz	21	21	10	5

* Channel No.19 ~ No.32 (14 channels)

NG-SUN Channel Model in Large Urban

- **Okumura-Hata Path loss models at 900MHz frequency band**
  - Path Loss in large urban area : 146.7dB @ 4Km



RX Power Calculation in Large Urban

Channel Model Parameters		Note
Frequency (MHz)	900	Valid Range 150-2400 MHz
TX Antenna Height(m)	30	Valid Range 30-200 m, including terrain
RX Antenna Height (m)	2	Valid Range 1-10 m,
Distance (Km)	4	Valid Range 1-20 km

Path Loss Calculation		Note
TX Power(dBm)	33	Subject to Tx Power Regulations
TX Antenna Gain(dBi)	2	Subject to Tx Power Regulations
Path Loss(dB)	-147	Must reference the right path loss from the Hata worksheet
Shadowing Margin (dB)	-10	To buffer against variable shadowing loss
Penetration Loss (dB)	0	For underground vaults, etc.
Rx Antenna Gain (dBi)	2	If using same antenna for Tx, must be same as in Uplink Table
Interference(dB)	1	Rise over Thermal Interference
RX Power at endpoint(dBm)	-119	Compare against Rx sensitivity

NG-SUN Channel Model in Harsh Environment

- **Pass Loss in Container Block Stacking**
  - Because of the particularity of the container environment, well-known path loss models for outdoor environments (e.g., COST 231Walfisch-Ikegami) are an unsatisfactory fit for empirical path loss around containers.
  - Empirical path loss models by Emmeric Tanghe is considered for an environment of stacked shipping containers.(IEEE 802.15-24-0603-00-04ad)

☞ Path Loss in container block stacking environment

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

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

☞ TX Power 20dBm @869MHz

b_0 = 51.80, b_1 = 2.38, χ_s=7.98

Pass Loss @1000m

$PL(1000) = 58.10 + 2.38 \times 10 \cdot \log_{10}(1000) + 7.98 = 137.5dBm$

RX Power Calculation in Harsh Environment

Channel Model Parameters		Note
Frequency (MHz)	869	Valid Range 150-2400 MHz
TX Antenna Height(m)	30	Valid Range 30-200 m, including terrain
RX Antenna Height (m)	2	Valid Range 1-10 m,
Distance (Km)	1	Valid Range 1-20 km

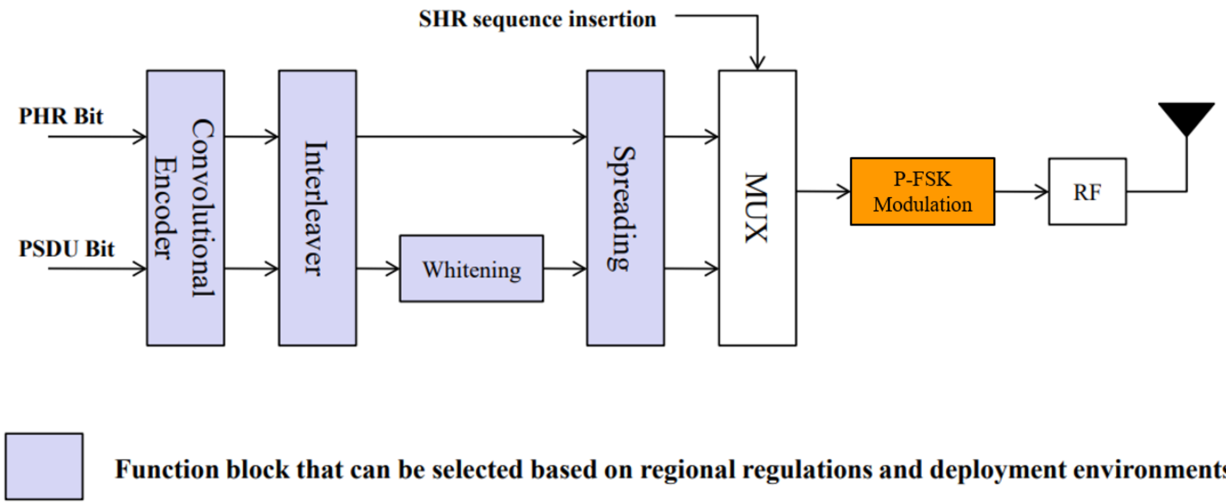
Path Loss Calculation		Note
TX Power(dBm)	20	Subject to Tx Power Regulations
TX Antenna Gain(dBi)	2	Subject to Tx Power Regulations
Path Loss(dB)	-137.5	Must reference the right path loss from the Hata worksheet
Shadowing Margin (dB)	-10	To buffer against variable shadowing loss
Penetration Loss (dB)	0	For underground vaults, etc.
Rx Antenna Gain (dBi)	2	If using same antenna for Tx, must be same as in Uplink Table
Interference(dB)	1	Rise over Thermal Interference
RX Power at endpoint(dBm)	-121.5	Compare against Rx sensitivity

NG-SUN PHY Proposal Consideration

- **NG-SUN Channel :** harsh, high path loss environment
  - 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 increased performance**
  - Channel coding gain
  - **Spreading gain**
  - Antenna gain and etc.
- **Energy efficiency (low-power consumption) at battery-powered devices is also main consideration**

Proposed NG-SUN PHY Architecture

- **System Block Diagram**
  - P-FSK Modulation
  - Spreading



Position based FSK Modulation

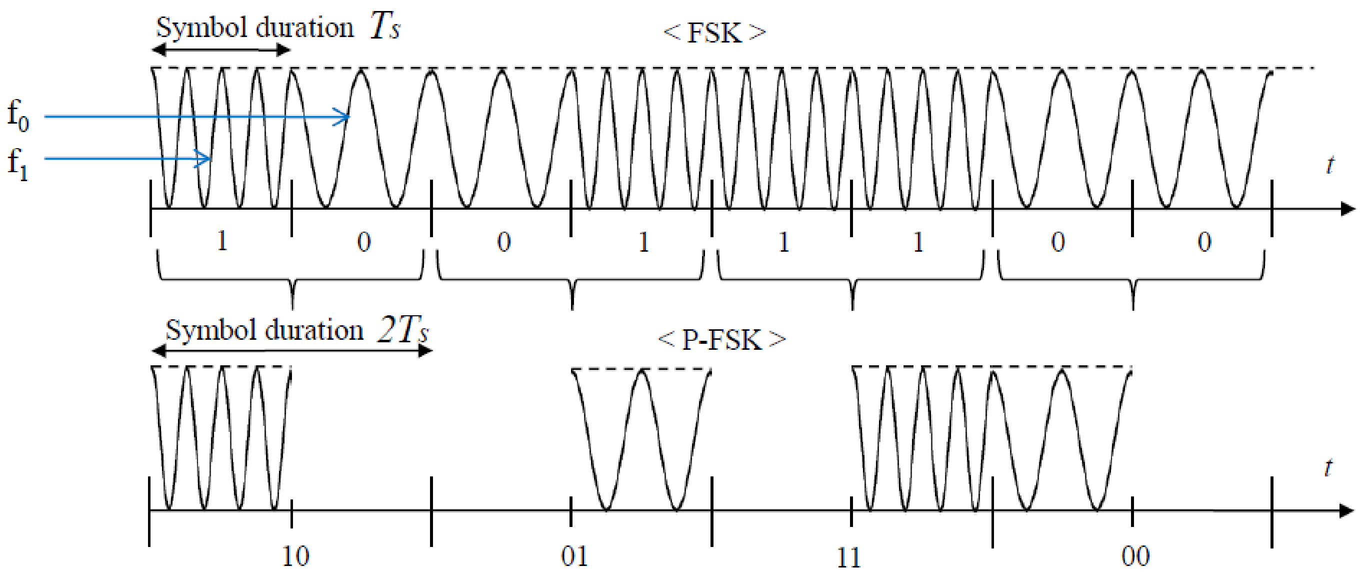
- **Benefits of FSK Modulation PHY**
  - No need of high-linearity power amplifier (PA)
  - Non-coherent receiver: low-power consumption
    - ☞ No need to track the phase of the carrier
    - ☞ Performance difference between coherent receiver and non-coherent receiver: roughly 1dB
    - ☞ Suitable for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

Position based FSK Modulation - Continued

- **Conventional FSK: relatively poor performance**
- **Reliable operation over high path loss channel**
  - SNR gain obtained from modulation is beneficial
- **High-dimension orthogonal signaling**
  - Can reduce the SNR per bit required to achieve a target BER
  - 2-level FSK: 2-dimension orthogonal signals (freq. domain)
  - 2-ary PPM (Pulse position modulation): 2-dimension orthogonal signals (time domain)
- **Combination of FSK and PPM**
  - Can construct 4-dimension orthogonal signals while keeping the same bit rate and signal bandwidth

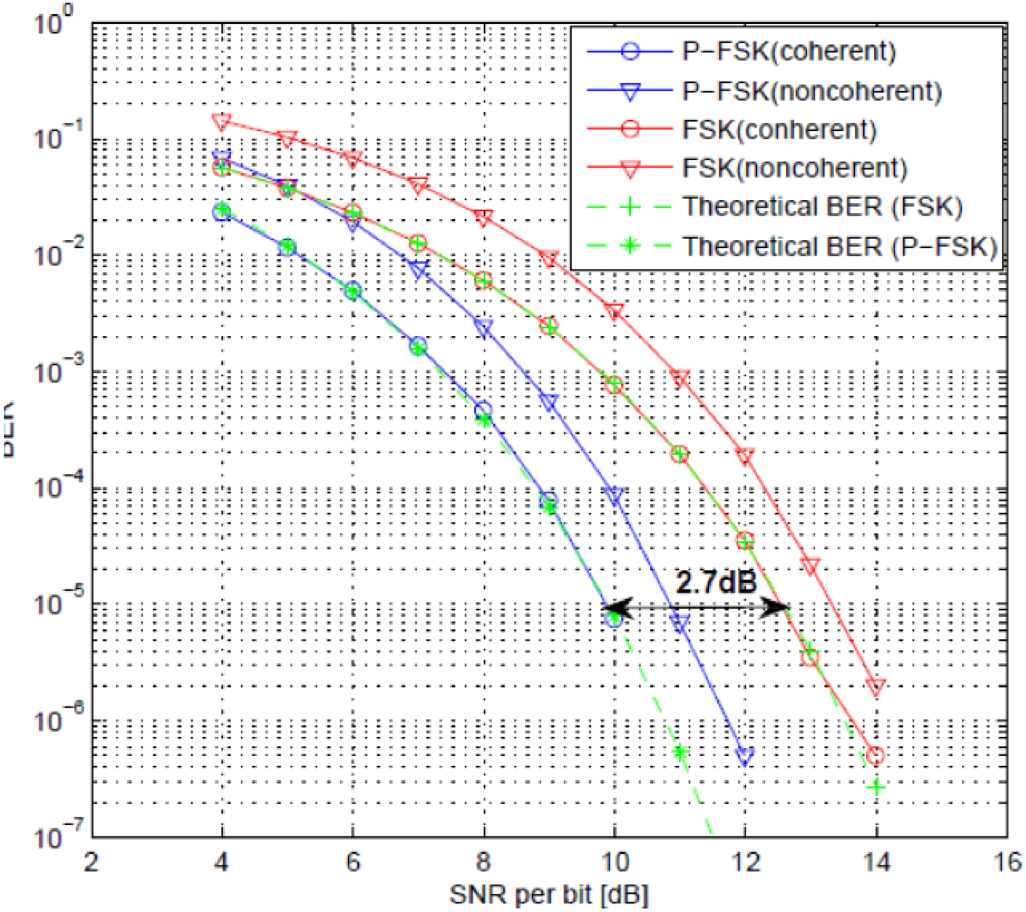
Position based FSK Modulation - Continued

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



Position based FSK Modulation - Continued

- **BER performance of P-FSK: 2.7dB gain at BER 10^{-5}**



Spreading

- **NG-SUN channel:** RF link with high path loss (>120dB)

- **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), 32(15dB)
  - Can be selected according to channel condition

Symbol Rate & Data Rate

- **Symmetric data flow between uplink and downlink**
- **Data rate depends on coding rate and spreading factor**
  - e.g., symbol rate 50KHz, coding rate 0.5

Spreading Factor	Data Rate			
	12.5KHz	25KHz	50KHz	100KHz
1	6.25 Kbps	12.5 Kbps	25 Kbps	50 Kbps
2	3.125 Kbps	6.25 Kbps	12.5 Kbps	25 Kbps
4	1.5625 Kbps	3.125 Kbps	6.25 Kbps	12.5 Kbps
8	0.78125 Kbps	1.5625 Kbps	3.125 Kbps	6.25 Kbps
16	0.390625 Kbps	0.78125 Kbps	1.5625 Kbps	3.125 Kbps
32	0.1953125 Kbps	0.390625 Kbps	0.78125 Kbps	1.5625 Kbps

Forward Error Correction

- **Long burst errors are more likely than random bit error**
- **Error correction capability is required for reliable operation in dramatically changing environments**
- **Details of FEC are TBD**
  - Propose to use the same FEC & Interleaving in SUN FSK PHY (IEEE Std. 802.15.4-2024 : 20. SUN FSK PHY)
  - Consider to add a rate 1/2 convolutional coding with constraint length K

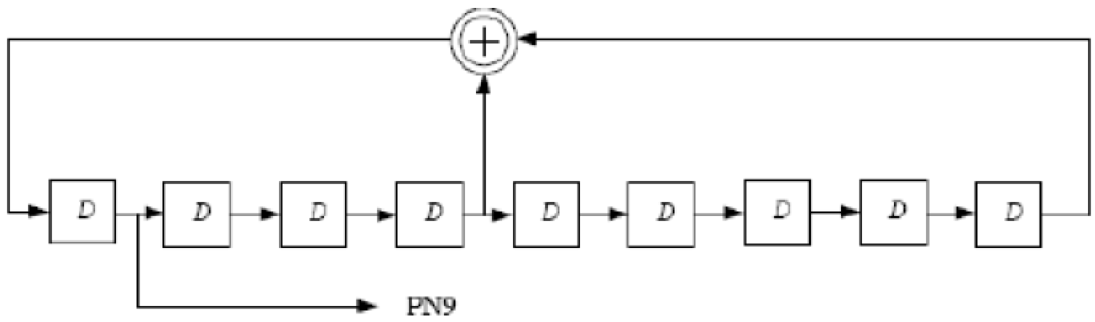
Data Whitening

- **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**

  (IEEE Std. 802.15.4-2024 : 20. SUN FSK PHY)

  – Whitened bit = XOR(incoming bit, PN9)



< Schematic of the PN9 sequence generator >

Link Budget (900MHz Large Urban)

- **Minimum Eb/No for P-FSK:**
  - Coherent receiver: 10dB @ BER 10^{-5}
  - Non-coherent receiver: 11dB @ BER 10^{-5}
  - Channel coding gain: SDD 5dB, HDD 3dB

Parameter	Unit	Value
Distance(D)	km	4
Bandwidth(BW)	KHz	50
Rx power at Endpoint(P_r)	dBm	-119
Receiver AWGN noise(N=-174+10log[BW])	dBm	-127
RF noise figure of endpoint(N_f)	dB	10
Average noise power(P_n = M + N_f)	dBm	-117
Minimum E_b/N_o(S)	dB	8
Implementation Loss(I)	dB	3
Processing Gain(PG)	dB	15
Link Margin(LM=P_r + P_n – S – I + PG)	dB	12
Proposed Minimum RX sensitivity level(P_{min})	dBm	--107

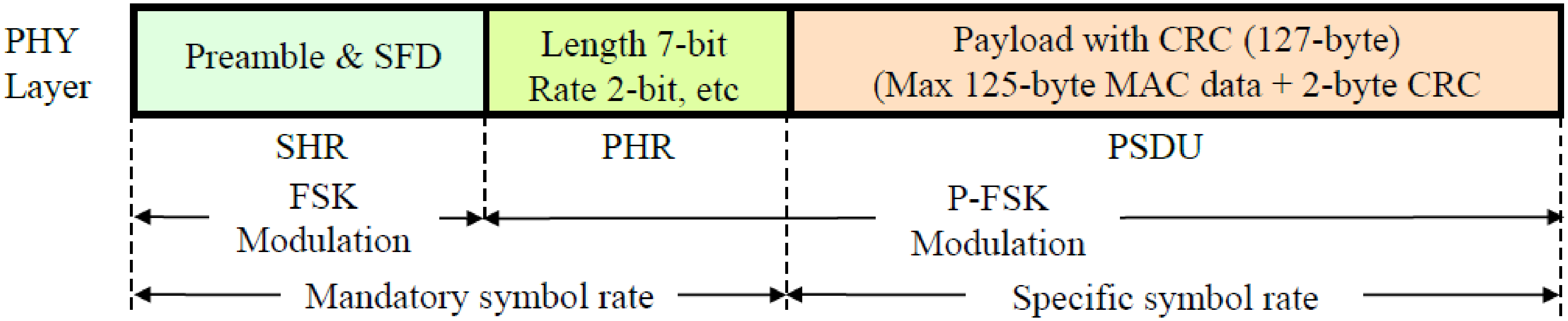
Link Budget (900MHz Harsh Environment)

- **Minimum Eb/No for P-FSK:**
  - Coherent receiver: 10dB @ BER 10^{-5}
  - Non-coherent receiver: 11dB @ BER 10^{-5}
  - Channel coding gain: SDD 5dB, HDD 3dB

Parameter	Unit	Value
Distance(D)	km	1
Bandwidth(BW)	KHz	50
Rx power at Endpoint(P_r)	dBm	-121.5
Receiver AWGN noise(N=-174+10log[BW])	dBm	-127
RF noise figure of endpoint(N_f)	dB	10
Average noise power(P_n = M + N_f)	dBm	-117
Minimum E_b/N_o(S)	dB	8
Implementation Loss(I)	dB	3
Processing Gain(PG)	dB	15
Link Margin(LM=P_r + P_n – S – I + PG)	dB	-0.5
Proposed Minimum RX sensitivity level(P_{min})	dBm	-122

PHY Packet Format

- **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 Format

- **Long preamble and SFD sequence are necessary due to harsh and high path loss channel environment**

- **Propose to use the same preamble and SFD in SUN FSK PHY**

  (IEEE Std. 802.15.4-2024 : 20. SUN FSK PHY)
  - Preamble : multiples of the 8-bit sequence "01010101" for 2-FSK
  - SFD : a 2-octet sequence selected from the values shown in the table below

	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

PHR & PSDU Field Format

- **Details are TBD**
  - The PHR field format requires the addition of at least a 3-bit Spreading Factor(SF) field to the PHR field format of the existing SUN FSK PHY.

Summary & Future Work

- **The PHY proposal is consistent with the scope of NG-SUN PHY**
  - NG-SUN channel consideration
  - Reliability enhancement
  - Energy efficiency
  - Low data rate
  - Operation in unlicensed spectrum
- **Further analysis of NG-SUN PHY is required.**
  - The PHR field to add a 3-bit SF field
  - Link budget analysis of NG-SUN at 200MHz band
  - Channel and interference analysis required by the TGD
  - etc.

Thanks for Listening !
Q&A