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

Submission Title: [ETRI NB PHY proposal for TG4k LECIM networks]
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Re: [802.15.TG4k]

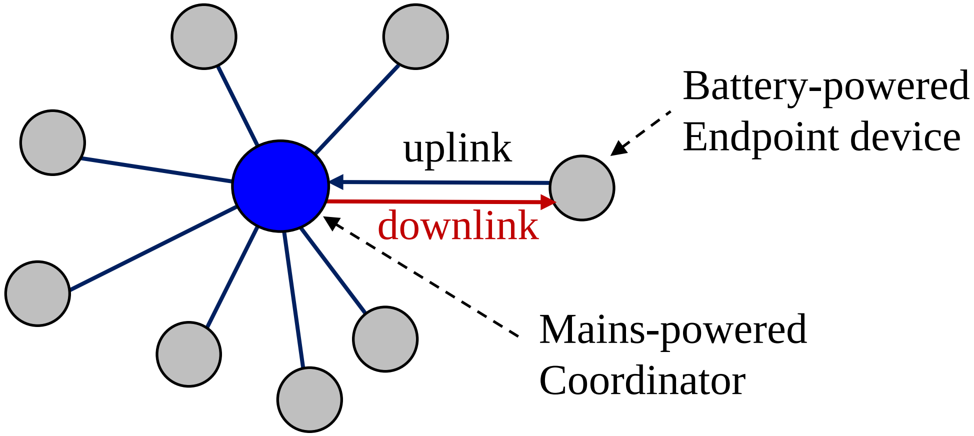
Abstract: This contribution is prepared to propose the PHY for LECIM networks

Purpose:

Contents

Requirements Overview (1/3)

- LECIM Networks
  - Mains powered coordinator should manage thousands of battery powered endpoint devices that are widely dispersed
  - Power consumption and lifetime are the major design requirements for long deployment life without human contact
  - Reliable operation against high path loss is essential



Requirements Overview (2/3)

- Operation in any of the regionally available licensed, license exempt, and special purpose frequency bands
- Simultaneous operation for at least 8 co-located orthogonal networks
- Application data rate of less than 40 kbps
- Propagation path loss of at least 120 dB
- >1000 endpoints per mains powered infrastructure
- Asymmetric application data flow

Requirements Overview (3/3)

- Extreme difference in capabilities and performance between endpoint devices and coordinating devices
  - Coordinator may support all standardized modulations (MCS) and data rates
  - Coordinator may be required to support antenna diversity or antenna beam steering
  - Endpoint must be able to conserve energy
- Reliable operation in dramatically changing environments (no control over environment)
- Mechanisms that enable coexistence with other systems in the same band(s)

Key Aspects of PHY Proposal (1/2)

Parameter	Proposed narrowband PHY
Operating band	Sub-GHz, 2.4GHz
Modulation	FSK-based orthogonal signaling
Symbol rate	40KHz (uplink), 20 KHz (downlink)
Spreading	Spreading factor: 0, 2, 4, 8,16, 32
FEC	Convolutional code with interleaving
Data whitening	XOR(PSDU,PN9 sequence)
PHY frame structure:	
- SHR	Multiples of “01010101” + 64 bit SFD
- PHY header	16-bit including length 7-bit, rate 2-bit, spreading factor 3-bit, interleaving depth 2-bit, odd parity 1-bit
- Max. PSDU	127-octet
- CRC	16-bit ITU-T CRC

Key Aspects of PHY Proposal (2/2)

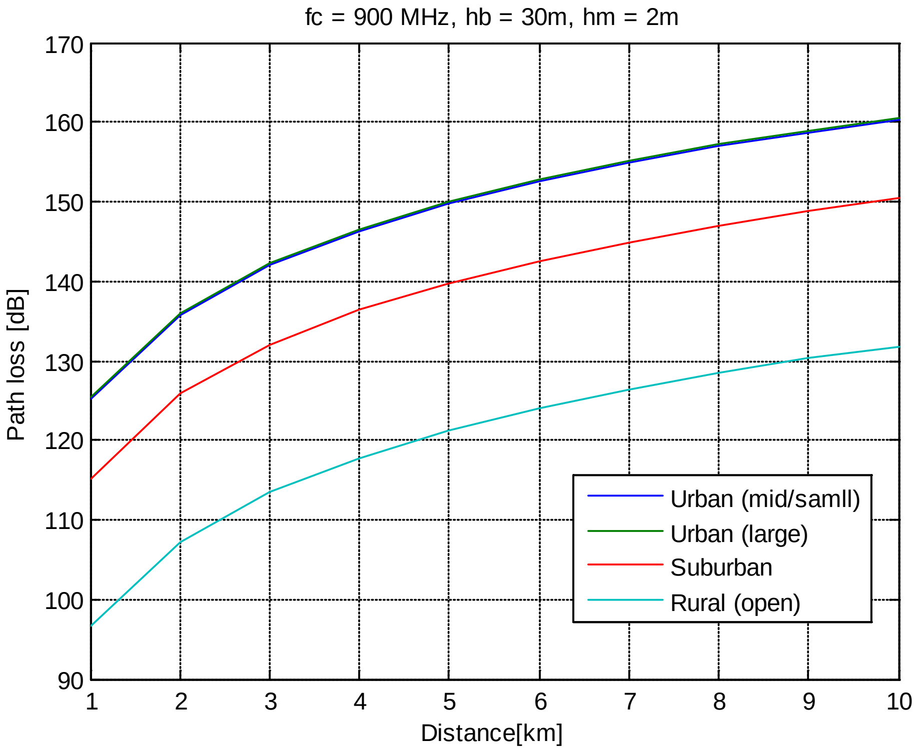
Parameter	Proposed narrowband PHY
Channel spacing	160 KHz, 80 KHz
Transmit Power	As allowed by regulatory regimes
PSD	As allowed by regulatory regimes
Link Quality Indication	RSSI
Co-located networks features	Channel diversity
Co-existence features	Channel diversity
Power efficiency features	FSK-based modulation, parity in PHR, low-power consumption endpoint device
Reliability enhancing features	FEC, whitening, spreading, long preamble & SFD sequence, etc

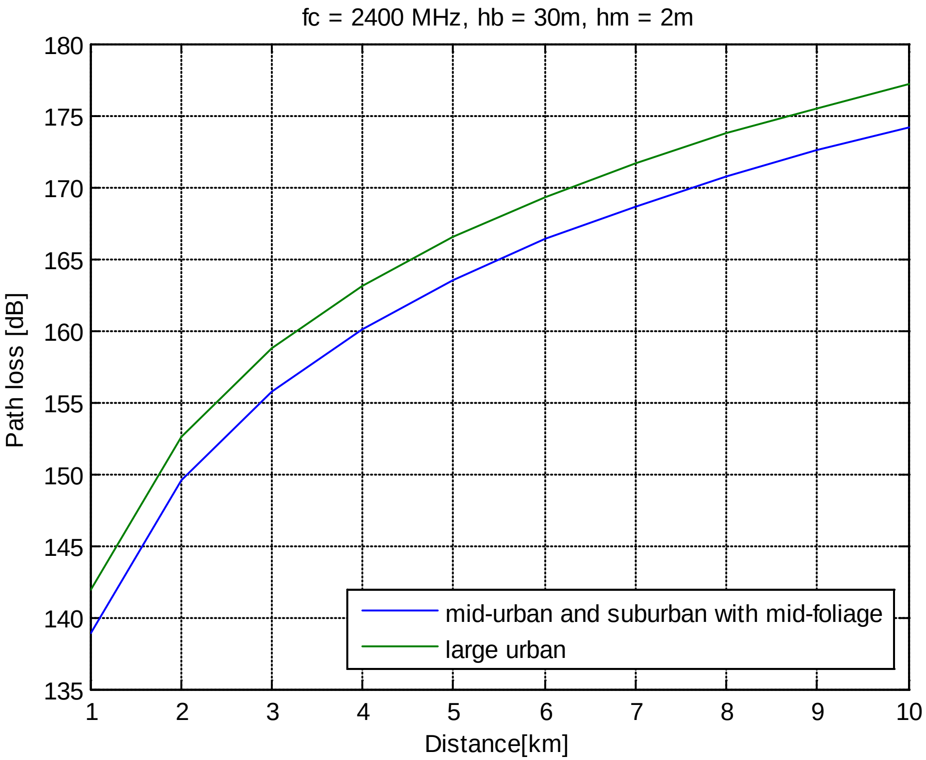
Operating Bands and TX Power

- Large number of narrowband channels across regionally available multiple bands
  - 868-870 MHz
  - 902-928 MHz
  - 2400-2483.5 MHz
  - Other available bands
- Maximum transmit power in each operating band: allowed by regulations
  - e.g., 917~923.5 MHz (Korea) : transmission power is limited by 10dBm for USN utilization

LECIM Channel

- LECIM path loss models
  - 900MHz (Okumura-Hata) v.s. 2.4GHz (COST 231-Hata) cf) Doc. 571/r0





LECIM Channel: 900MHz Large Urban

cf) Doc. 464/r1

Channel Model Parameters		Notes
Frequency (MHz)	900	Valid Range 150-2400 MHz
Collector Antenna Height (m)	30	Hata Valid Range 30-200 m, including terrain. Erceg Valid Range 10-80m, including terrain
Endpoint Antenna Height (m)	2	Hata Valid Range 1-10 m, Erceg Fixed to 2m.
Distance (km)	1	Valid Range 1-20 km

Downlink Path Loss Calculation		Notes
Collector Tx Power (dBm)	10	Subject to Tx Power Regulations
Collector Tx Antenna Gain (dBi)	6	Subject to Tx Power Regulations
Path Loss (dB)	-125.40	Must reference the right path loss from the Hata or Erceg worksheet
Shadowing Margin (dB)	-12	To buffer against variable shadowing loss
Penetration Loss (dB)	0	For underground vaults, etc.
Endpoint Rx Antenna Gain (dBi)	2	If using same antenna for Tx, must be same as in Uplink Table
Endpoint Interference (dB)	1	Rise over Thermal Interference
Rx Power at Endpoint (dBm)	**-118.40**	Compare against Rx sensitivity

Uplink Path Loss Calculation		Notes
Endpoint Tx Power (dBm)	10	Subject to Tx Power Regulations. Can be different from Collector
Endpoint Tx Antenna Gain (dBi)	2	Subject to Tx Power Regulations
Penetration Loss (dB)	0	For underground vaults, etc.
Path Loss (dB)	-125.40	Same as Downlink
Shadowing Margin (dB)	-12	Same as Downlink
Collector Rx Antenna Gain (dBi)	6	If using same antenna for Tx, must be same as in Downlink Table
Collector Interference (dB)	2	Rise over Thermal Interference
Rx Power at Collector (dBm)	**-117.40**	Compare against Rx sensitivity

* Mains powered collector: TX(RX) antenna gain includes beam-forming gain (antenna diversity gain).

PHY Proposal Consideration

- LECIM channel: harsh, high path loss environment
  - Rx power: -118.4dBm @ endpoint device
  - 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 endpoint is also main consideration

FSK-based Modulation (1/4)

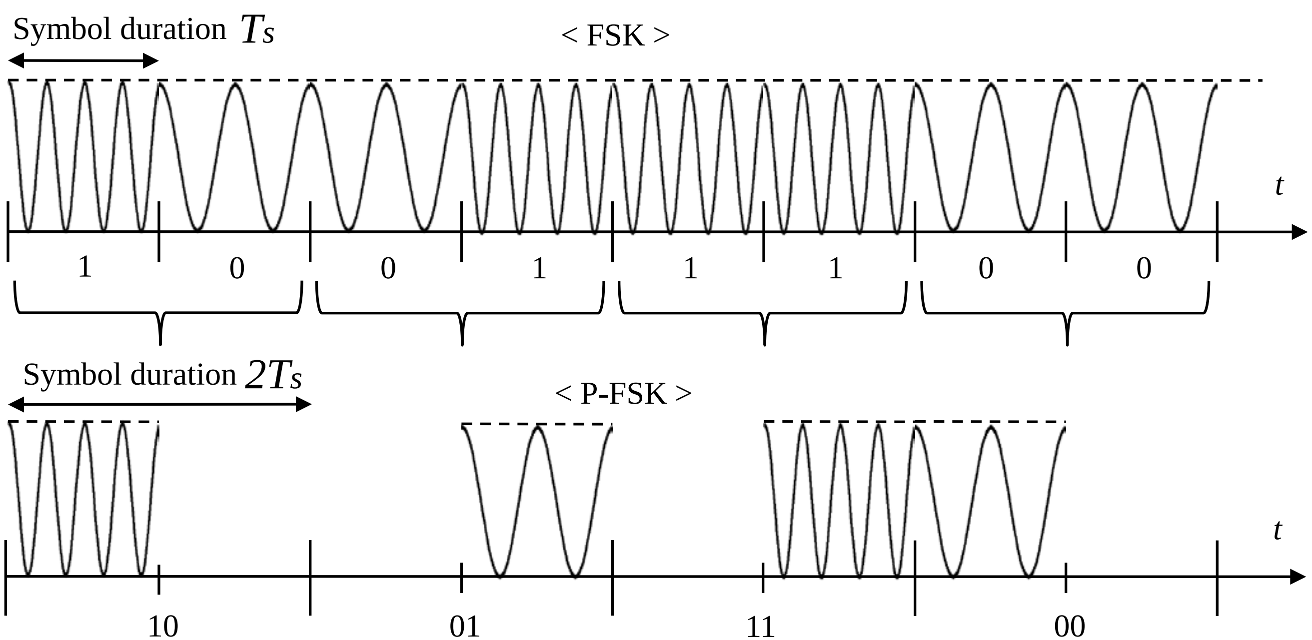
- Narrowband PHY
- Benefits
  - No need of high-linearity power amplifier (PA)
  - Non-coherent receiver: low-complexity & low-power consumption
    - No need to track the phase of the carrier
    - Performance difference between coherent receiver and non-coherent receiver: roughly 1dB
    - Suitable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

FSK-based Modulation (2/4)

- Conventional FSK: relatively poor performance
- Reliable operation over high path loss channel
  - SNR gain obtained from modulation is beneficial
- High-dimension orthogonal signals
  - 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 2-level FSK and 2-ary PPM
    - Can construct 4-dimension orthogonal signals while keeping the same bit rate and signal bandwidth

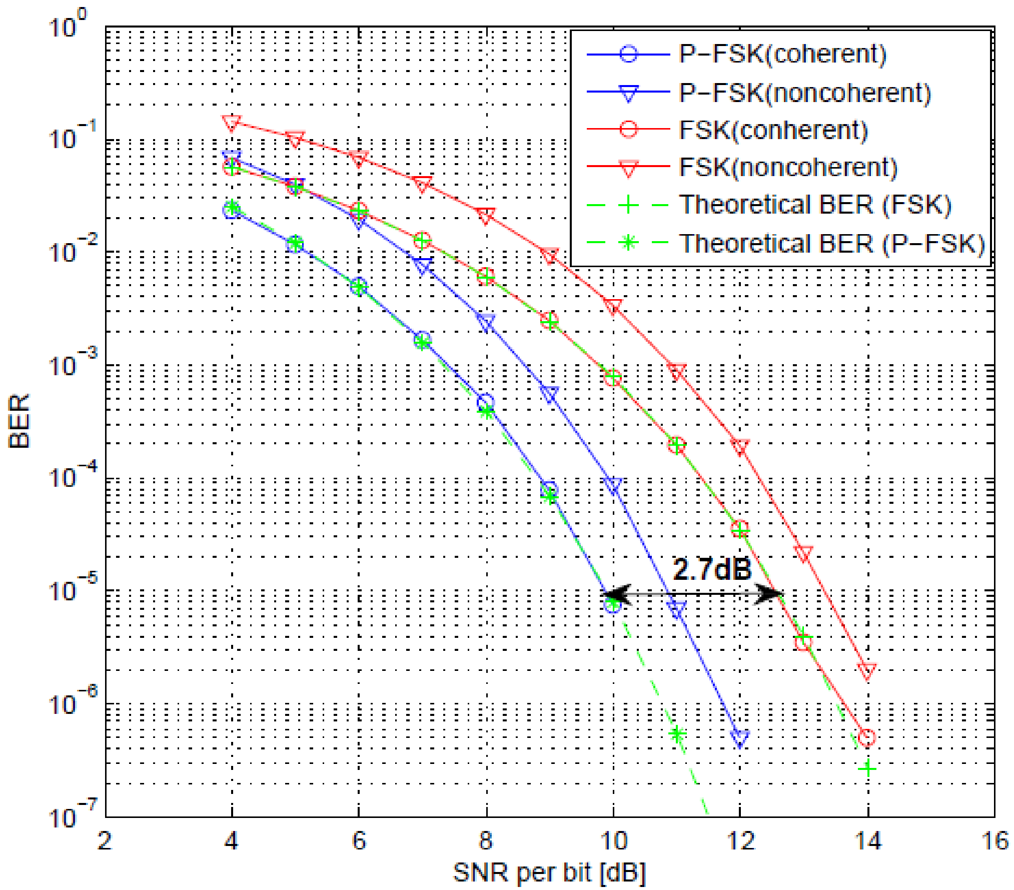
FSK-based Modulation (3/4)

- Position-based FSK (P-FSK)
  - Two bits are encoded by transmitting a FSK-modulated signal in one of two possible positions (time-shifts)



FSK-based Modulation (4/4)

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



- Mains powered coordinator
  : recommend the coherent receiver
  : performance enhancement

- Battery powered endpoint
  : recommend the non-coherent receiver
  : low power consumption

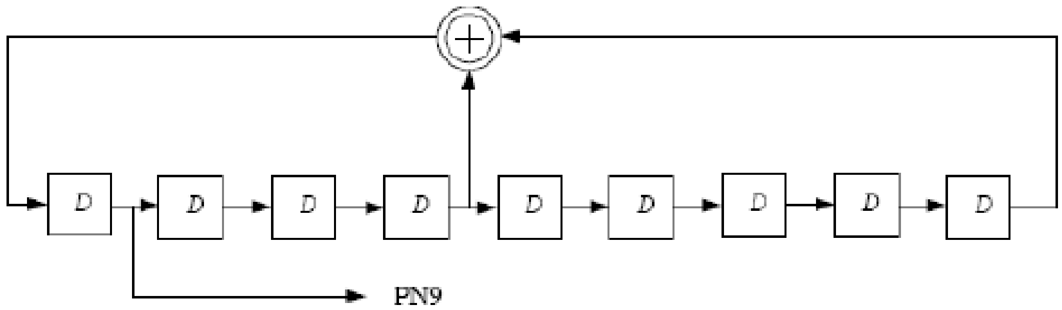
-Non-coherent receiver for P-FSK
  : same as the conventional FSK
  : computational overhead is negligible

Forward Error Correction

- Error correction capability is required for reliable operation in dramatically changing environments
- Long burst errors are more likely than random bit error
- FEC
  - Rate ½ (133,171) convolutional code with interleaving
  - Already specified in 15.4 PHYs
  - 5 dB coding gain with soft decision
- Viterbi decoder at the receiver
  - Mains powered coordinator: soft decision
  - Battery powered endpoint: hard decision
  - 2dB performance difference between SDD & HDD

Data Whitening

- Long runs of 1s and 0s in data (payload) may degrade the performance of bit timing recovery and tracking in FSK system
- PSDU Data whitening (applied to FSK-modulated bits)
  – Same as 15.4g
  – Whitened bit = XOR(incoming bit, PN9)



< Schematic of the PN9 sequence generator >

Spreading

- LECIM 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
- Spreading factor selection
  - 1(0dB), 2(3dB), 4(6dB), 8(9dB),16(12dB), 32(15dB)
  - Can be varied according to applications

Symbol Rate & Data Rate

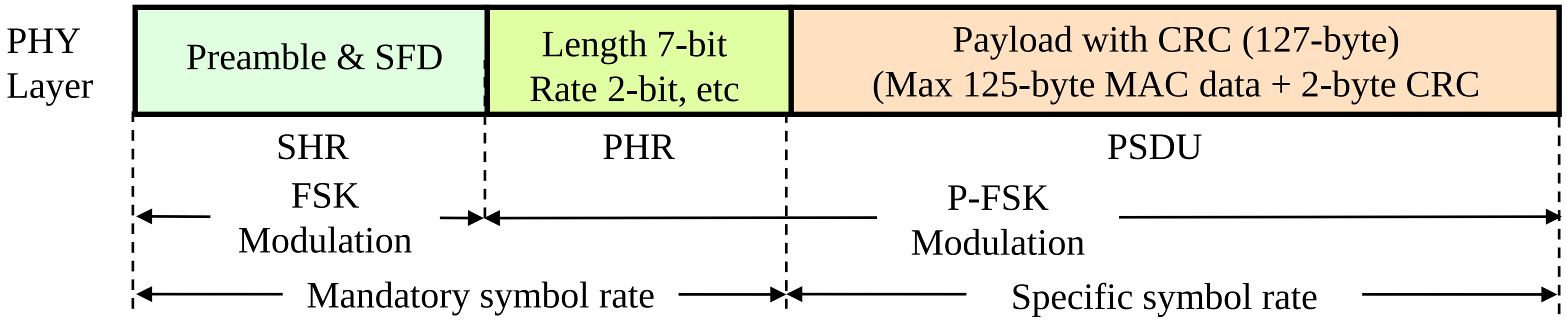
- Asymmetric data flow between uplink and downlink
  - More data from endpoint device to coordinator
- Symbol rate : 40KHz & 20KHz
  - 40KHz (Mandatory for uplink), 20KHz(Mandatory for downlink)
- Data rate depends on coding rate and spreading factor

< Data Rate Table >

SF \ Symbol Rate	40 KHz	20 KHz
1	20 Kbps	10 Kbps
2	10 Kbps	5 Kbps
4	5 Kbps	2.5 Kbps
8	2.5 Kbps	1.25 Kbps
16	1.25 Kbps	0.625 Kbps
32	0.625Kbps	0.3125 Kbps

PHY Packet Format

- Packet Structure



  - SHR including preamble and SFD: 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

Preamble & SFD

- Long preamble and SFD sequence are necessary due to harsh and high path loss channel environment
- Preamble
  - Multiples of "01010101" as specified in 15.4g
  - Enough octets for packet detection and synchronization
- SFD
  - At least 64-bit sequence
  - 4-repetition of short sequence with length 16
  - Short sequence: "0110111101001110" as specified in 15.4g
  - SFD detector at the receiver
    - Use of full SFD sequence
    - Use of part of SFD sequence

PHR

- PHR sequence
  - Length: 7-bit → max. PSDU 127-octet
  - Rate: 2-bit → symbol rate 40KHz and 20KHz
  - Spreading factor (SF): 3-bit
  - Interleaving depth (IDepth): 2-bit
    - 4 cases for PSDU interleaving depth
  - Odd parity (OP): 1-bit
    - Simply detect PHR error to stop demodulation process

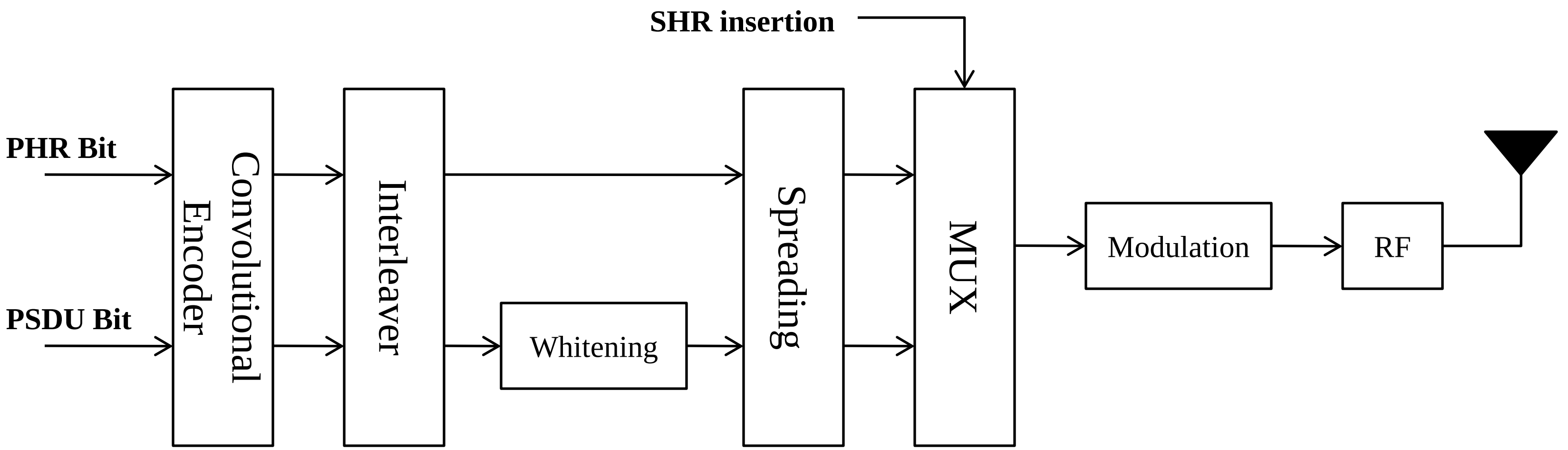
Octets: 1				1	
Bits: 1	2	3	2	1	7
OP	IDepth	SF	Rate	EXT	Length
PHR					

PHR & PSDU

- PHR and PSDU are encoded by ½ (133,171) convolutional code with interleaving to be fed into spreader
  - PHR: spreading with mandatory SF
  - PSDU: spreading with SF specified in PHR
- Interleaving depth
  - Different interleaving depth for PHR and PSDU
  - PHR: corresponding to the length of encoded PHR
    - PHR recovery without latency
  - PSDU: specified in PHR
    - Consider channel coherence time

System Block Diagram

- PHY data flow



PHY Channel Plan

- Number of channels per band
  - Symbol rate 40KHz: 160KHz channel spacing
  - Symbol rate 20KHz: 80KHz channel spacing

Band	# of Channels	
	40KHz	20KHz
868-870 MHz	12	25
902-928 MHz	162	325
2400-2483.5 MHz	521	1043

Coordinator/Endpoint Features

- Mains-powered coordinator
  - (+) Beam forming & Antenna diversity
  - (+) P-FSK modulation
  - (-) Twice increased noise level than endpoint device => 3dB loss
  - (+) Coherent receiver
  - (+) Soft decision Viterbi decoding

  } => 3dB gain
- Battery-powered endpoint device
  - (+) P-FSK modulation
  - (+) Twice lowered noise level than coordinator => 3dB gain
  - (-) Non-coherent receiver
  - (-) Hard decision Viterbi decoding

  } => 3dB loss

=> Balanced receiver sensitivity between coordinator and endpoint device

Link Budget (900MHz Large Urban)

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

Downlink		
Parameters	Unit	Value
Symbol rate [Rb]	KHz	20
Bandwidth [BW]	MHz	0.08
RX power at Endpoint [Pr]	dBm	−118.4
Receiver AWGN noise floor [N=-174+10log(BW)]	dBm	−125.0
RF noise figure of Endpoint [Nf]	dB	7.0
Average noise power [Pn=N+Nf]	dBm	−118.0
Minimum Eb/No [S]	dB	8.0
Implementation loss [I]	dB	3.0
Processing gain [PG]	dB	15
Link Margin [LM=Pr-Pn-S-I+PG]	dB	3.6
Proposed Min. Rx Sensitivity Level (Endpoint) [Pmin]	dBm	−122.0

Uplink		
Parameters	Unit	Value
Symbol rate [Rb]	KHz	40
Bandwidth [BW]	MHz	0.16
RX power at Collector [Pr]	dBm	−117.4
Receiver AWGN noise floor [N=-174+10log(BW)]	dBm	−122.0
RF noise figure of Collector [Nf]	dB	7.0
Average noise power [Pn=N+Nf]	dBm	−115.0
Minimum Eb/No [S]	dB	5.0
Implementation loss [I]	dB	3.0
Processing gain [PG]	dB	15
Link Margin [LM=Pr-Pn-S-I+PG]	dB	4.6
Proposed Min. Rx Sensitivity Level (Collector) [Pmin]	dBm	−122.0

Link Budget (900MHz Suburban)

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

Downlink		
Parameters	Unit	Value
Symbol rate [Rb]	KHz	20
Bandwidth [BW]	MHz	0.08
RX power at Endpoint [Pr]	dBm	−108.2
Receiver AWGN noise floor [N=-174+10log(BW)]	dBm	−125.0
RF noise figure of Endpoint [Nf]	dB	7.0
Average noise power [Pn=N+Nf]	dBm	−118.0
Minimum Eb/No [S]	dB	8.0
Implementation loss [I]	dB	3.0
Processing gain [PG]	dB	6
Link Margin [LM=Pr-Pn-S-I+PG]	dB	4.8
Proposed Min. Rx Sensitivity Level (Endpoint) [Pmin]	dBm	−113.0

Uplink		
Parameters	Unit	Value
Symbol rate [Rb]	KHz	40
Bandwidth [BW]	MHz	0.16
RX power at Collector [Pr]	dBm	−107.2
Receiver AWGN noise floor [N=-174+10log(BW)]	dBm	−122.0
RF noise figure of Collector [Nf]	dB	7.0
Average noise power [Pn=N+Nf]	dBm	−115.0
Minimum Eb/No [S]	dB	5.0
Implementation loss [I]	dB	3.0
Processing gain [PG]	dB	6
Link Margin [LM=Pr-Pn-S-I+PG]	dB	5.8
Proposed Min. Rx Sensitivity Level (Collector) [Pmin]	dBm	−113.0

Co-located Networks

- Channel diversity of NB PHY
  - 902MHz band: 162 Channels
  - 2.4GHz band: 521 Channels
- NB PHY with large number of available channels per band enables co-located networks

Coexistence

- Channel diversity of NB PHY
  - 902MHz band: 162 Channels
  - 2.4GHz band: 521 Channels
- 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

Power Efficiency Features

- Simple & low-power FSK based narrowband PHY
- Parity in PHR
  - Simply detect PHR error to stop payload demodulation process
- Endpoint device
  - Non-coherent FSK receiver and hard decision decoding enables endpoint device to conserve energy at PHY level

Reliability Enhancing Features

- SHR: Long preamble & SFD sequence
- PHR: protection with convolution coding and spreading
- PSDU
  - Error detection: 16-bit ITU-T CRC
  - Error correction: Convolutional coding with variable interleaving depth
  - Spreading gain
- Mains-powered coordinator
  - Antenna diversity and beam forming
  - Coherent receiver
  - Soft decision decoding

Conclusions

- The PHY proposal is consistent with the scope of LECIM PAR
  - LECIM channel consideration
  - Reliability enhancement
  - Energy efficiency
  - Low data rate
  - Operation in unlicensed spectrum

References

- **802.15-11-0061-00-004k-tg4k PAR as approved by NesCom**
- **802.15-11-0359-04-004k-tg4k technical guidance document**
- **802.15-11-0464-00-004k-tg4k hata channel model worksheet**
- **802.15-11-0465-00-004k-tg4k channel characteristics**
- **802.15-11-0571-00-004k-channel model comparison for 802.15.4k**