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

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Re: [IEEE802.15.4k call for proposal]
Abstract: [A PHY Proposal for Low Energy Critical Infrastructure Monitoring Networks Applications TG4k]

Purpose: [To be considered in IEEE 802.15.4k]

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Introduction

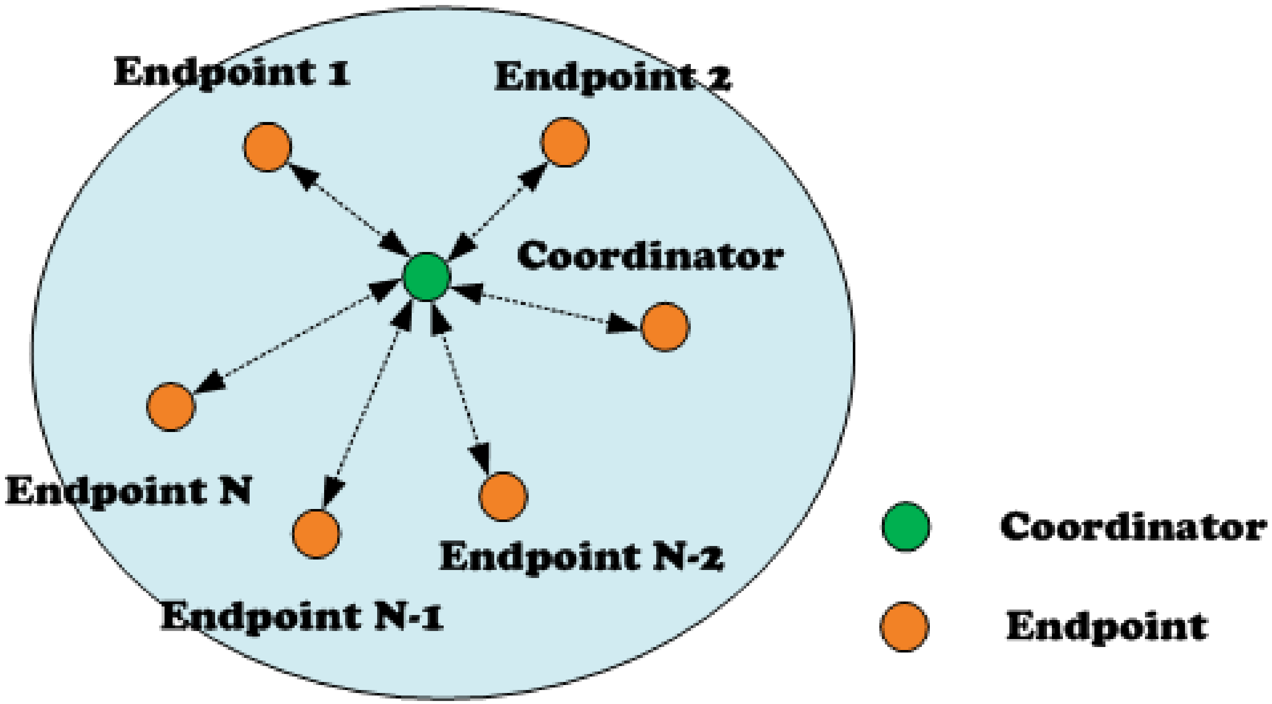
IEEE 802.15 Low Energy Critical Infrastructure Monitoring (LECIM) Task Group 4k (TG4k)

- The purpose of LECIM is to facilitate point to multi-thousands of points communications for critical infrastructure monitoring devices.

- It addresses the application's user needs of minimal network infrastructure, and enables the collection of scheduled and event data from a large number of non-mains powered end points that are widely dispersed, or are in challenging propagation environments.

- To facilitate low energy operation necessary for multi-year battery life, the amendment minimizes network maintenance traffic and device wake durations.

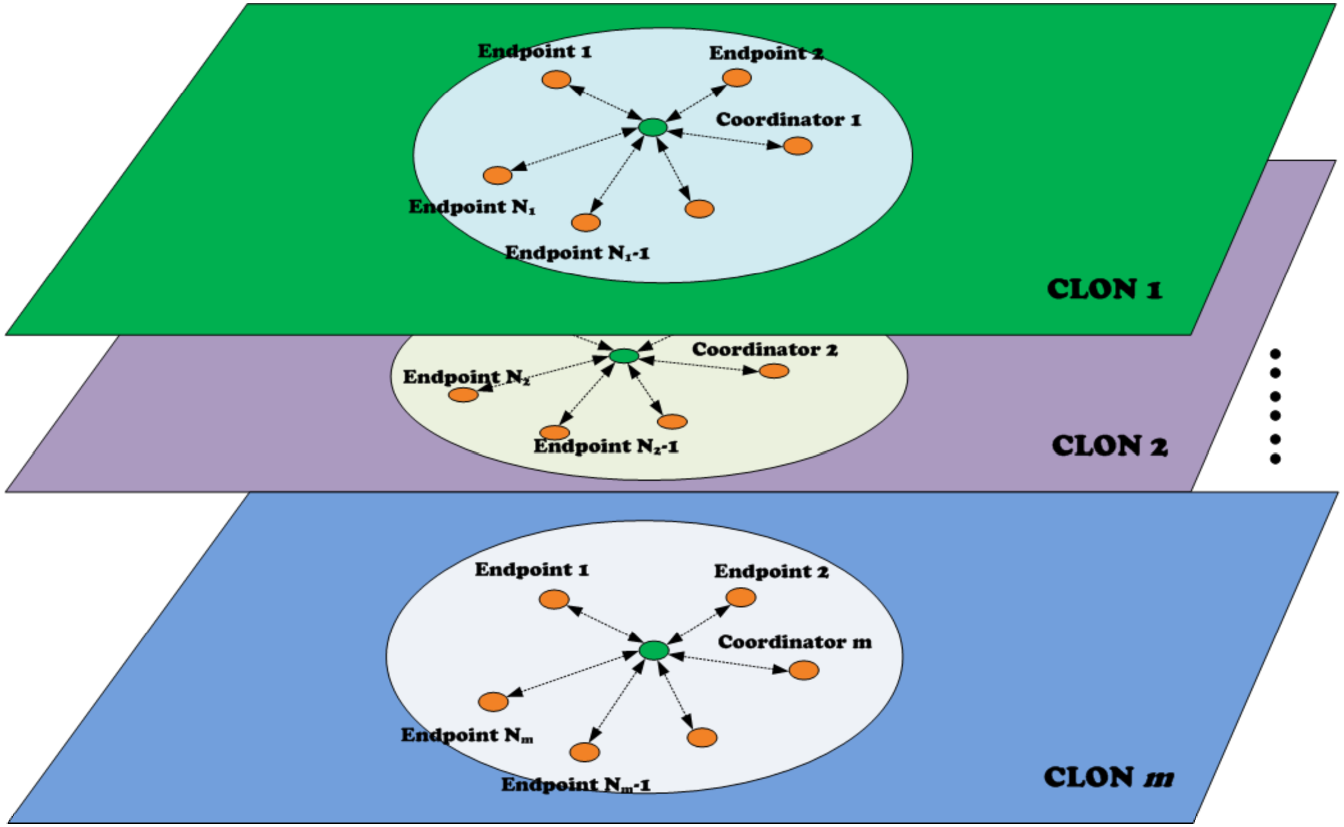
CLON Network Topology



- Each **C**o-**L**ocated **O**rthogonal **N**etworks (CLON) is composed of one coordinator and a large number of subordinate endpoints;

- Endpoints can only communicate with the coordinator.

Co-existence of up to 8 CLONs

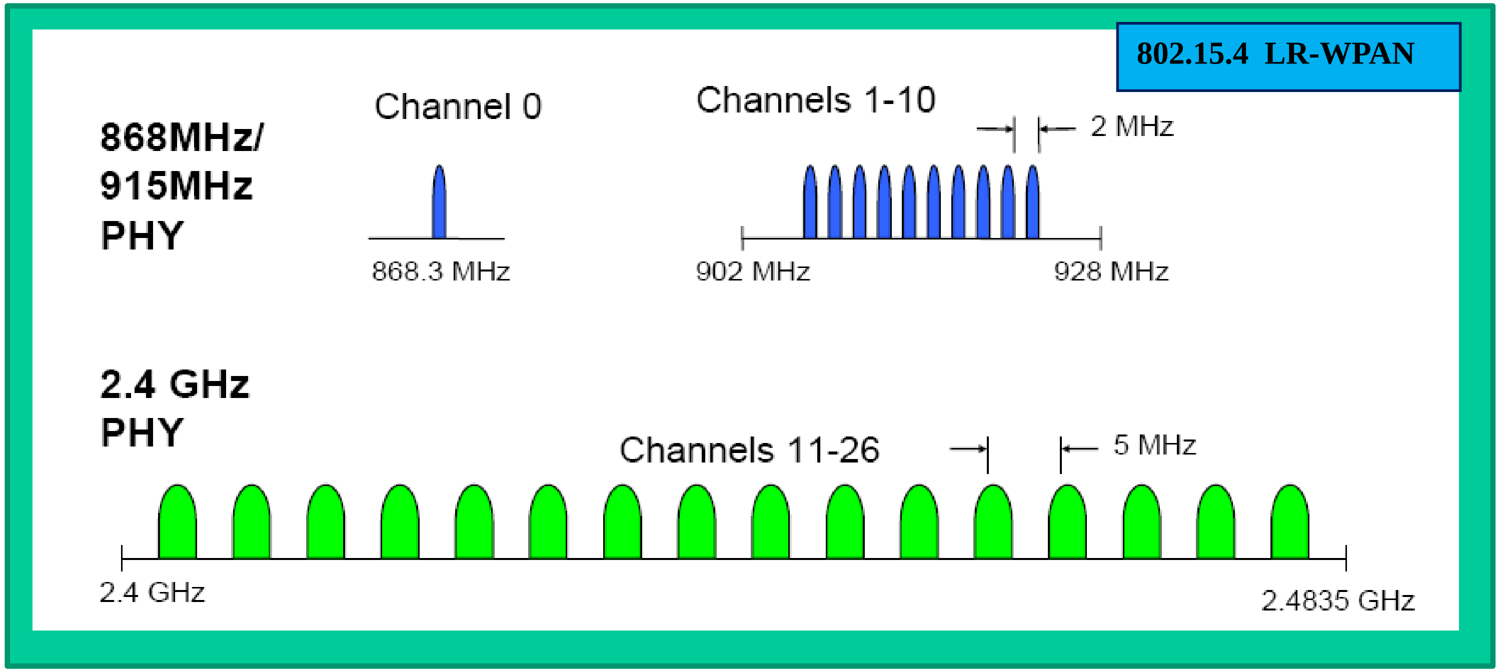


■ CLONs can use different frequency bands (channels) with different center frequencies;

■ Frequency Division Multiplexing (FDM) based orthogonality is thus utilized among CLONs.

■ Code Division Multiplexing (CDM) based orthogonality can be further adopted for multiple clusters of CLONs.

Operating Frequency Bands



■ Totally, there are **3** applicable frequency bands and **27** channels with different bandwidth

- **16** channels in the 2.4GHz frequency band,
- **10** channels in the 915 MHz frequency band, and
- **1** channel in the 868 MHz frequency band.

■ Simultaneous operation for at least **8** CLONs is feasible based on FDM mechanism.

■ TDM can be further employed for providing more logical channels.

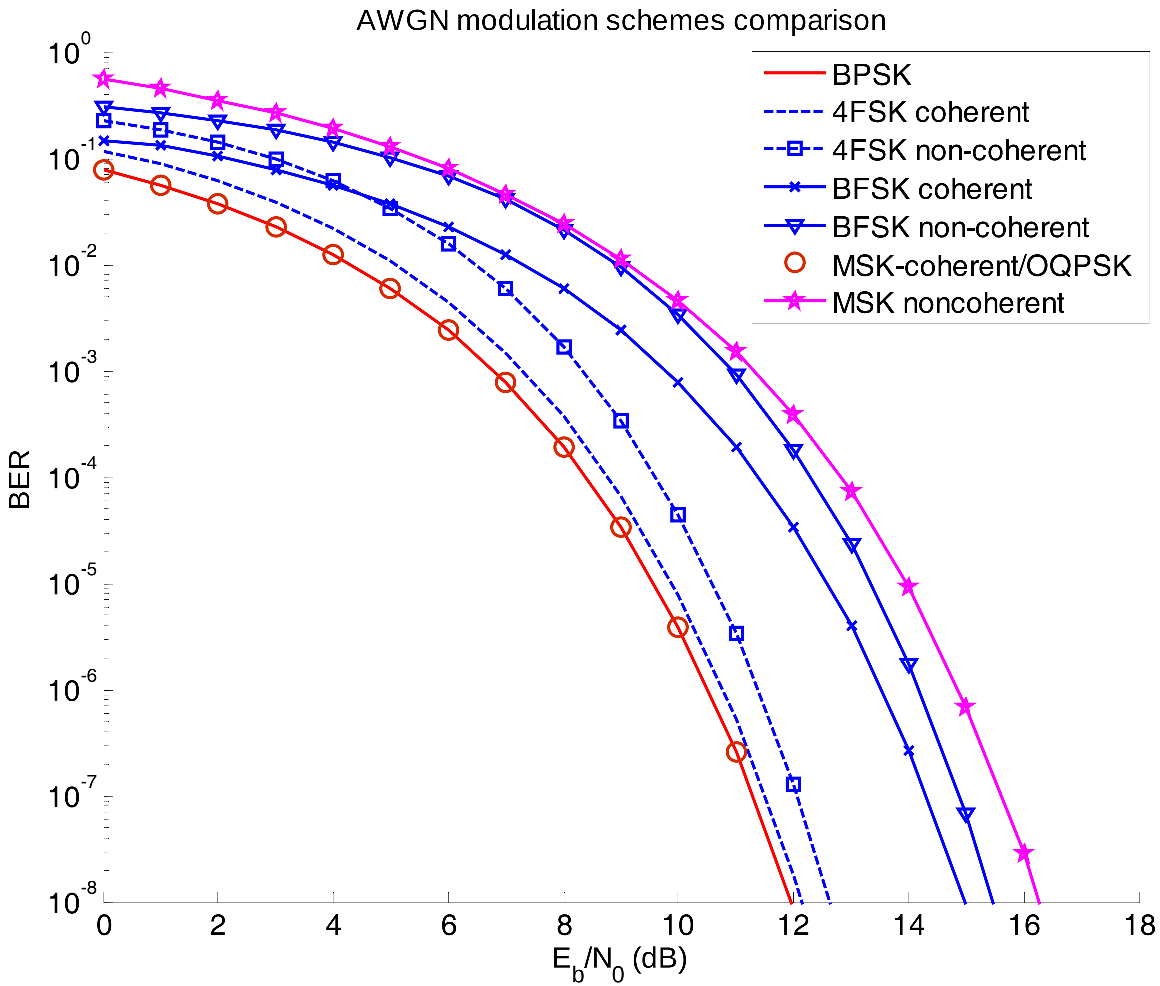
Modulation and Date rates (1)

PHY	Frequency Band	Channels	Frequency Bandwidth	Chip Rates	Parameters	
					Spreading Factors (dB)	Data Rates (kbps)
800 MHz	868 ~ 870 MHz	0	640 KHz	320 Kcps	16 (12 dB)	20
					32 (15 dB)	10
					64 (18 dB)	5
915 MHz	902 ~ 928 MHz	From 1 to 10	2.560 MHz	1.280 Mcps	32 (15 dB)	40
					64 (18 dB)	20
					128 (21 dB)	10
2.4 GHz	2.4 ~ 2.4835 GHz	From 11 to 26	2.560 MHz	1.280 Mcps	256 (23 dB)	5
					512 (27 dB)	2.5

- We keep the Data Rates flexible as 40, 20, 10, 5, and 2.5 kbps, and the Chip Rates fixed as 320 Kcps and 1.280 Mcps.
- The chip rates are slightly different from those of IEEE STD 802.15.4 – 2006.
- In practice, after we determine the processing gain required for compensating the propagation loss via channel estimation, the applicable data rate is thus chosen according to the above table.
- It is easy to implement various Spreading Factors through the **Orthogonal Variable Spreading Factor (OVSF)**.

Modulation and Date rates (3)

- **System BER performance**



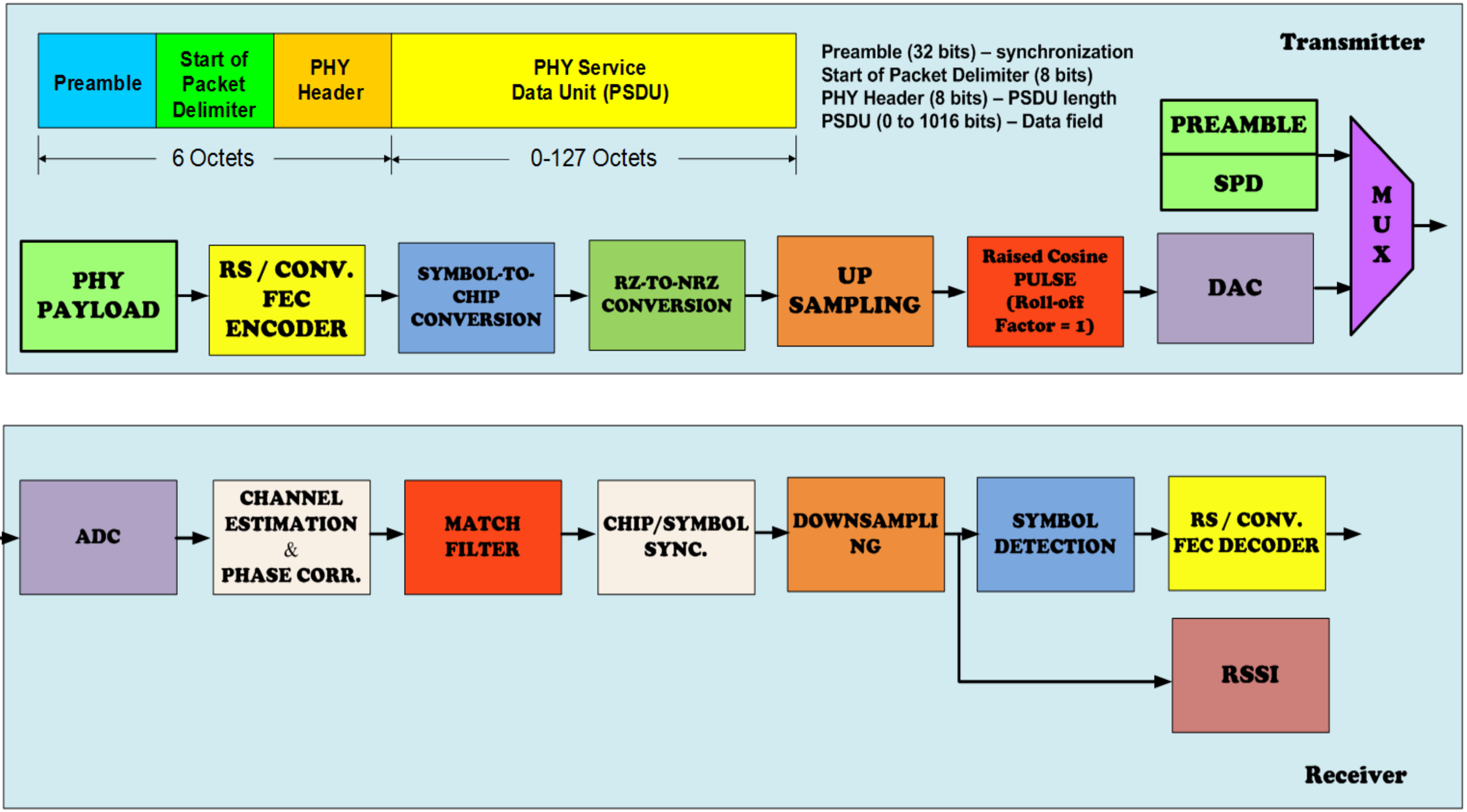
■ PSK outperforms FSK/OOK;

■ Processing gain loss is large for non-coherent reception;

■ Under coherent reception OQPSK, MSK and BPSK have the same performance in AWGN environment only.

PHY frame structure (1)

- **Transmitter and Receiver architectures**



PHY frame structure (2)

- **Modifications to the IEEE STD 802.15.4-2006 Frame Structure**

Maximum PHY frame length for 802.15.4k applications:

1) **PHY frame Head (Fixed 6 octets): 19.2 ms @ 2.5 Kbps, 1.2 ms @ 40 Kbps**
2) **PHY PSDU Maximum length is controlled according to the data rate as follows:**

PHY PSUD		40kbps		20kbps		10kbps		5kbps		2.5kbps	
		128 octets	64 octets	128 octets	64 octets	64 octets	32 octets	64 octets	32 octets	32 octets	16 octets
Frame time (ms)		25.6 ms	12.8 ms	51.2 ms	25.6 ms	51.2 ms	25.6 ms	102.4 ms	51.2 ms	102.4 ms	51.2 ms
Pay load byte	256 ms	1280 octets	1280 octets	640 octets	640 octets	320 octets	320 octets	160 octets	160 octets	80 octets	80 octets
	512 ms	2560 octets	2560 octets	1280 octets	1280 octets	640 octets	640 octets	320 octets	320 octets	160 octets	160 octets

Co-Existence Features

- **Mechanisms that enable coexistence with other systems**

□ Inter-Network Interference mitigation (Heterogeneous)

✓ Using m-sequence as an anti-interference method.

✓ Using non-overlapping channels/frequency bands in the frequency domain.

✓ Channel alignment between 15.4k and IEEE 802.11b WLAN devices.

✓ Performing dynamic channel selection by the coordinator.

□ Intra-Network Interference mitigation (Homogeneous)

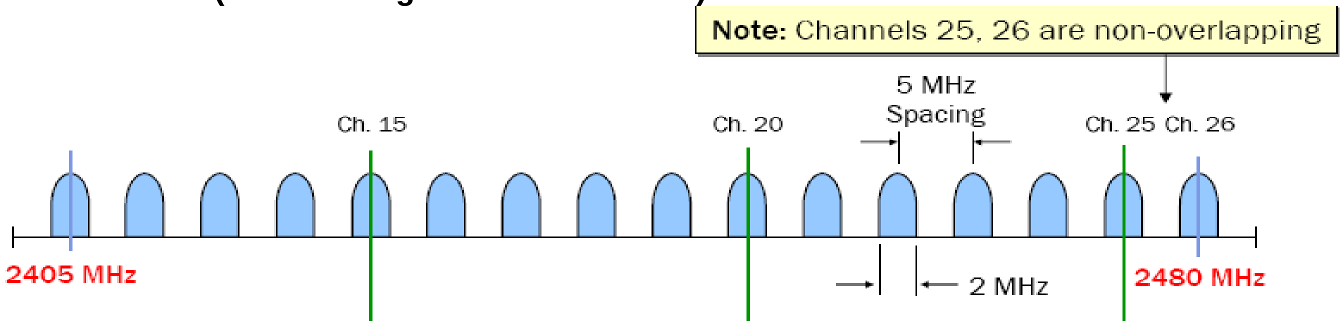
✓ Using clear channel assessment (CCA) mechanism as one proactive way for interference prevention.

✓ Using multiple access control mechanism in the MAC layer.

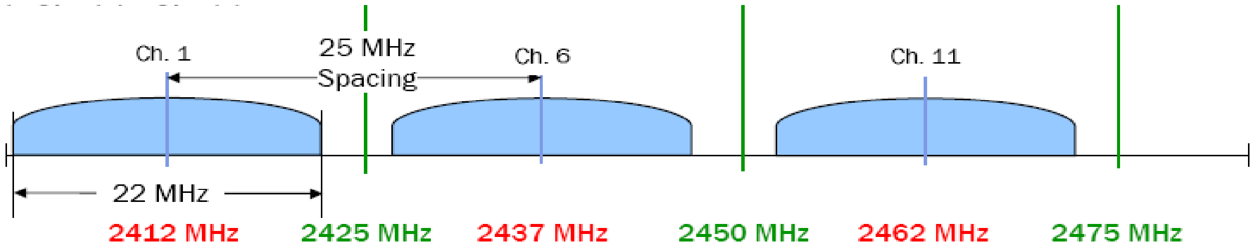
Co-Existence Features

☐ Co-Existence of IEEE 15.4k systems with WiFi and Bluetooth

- **802.15.4: Ch.11 to Ch. 26 (Channel alignment mechanism)**



- **802.11: Ch.1 to Ch. 11**



- **Bluetooth:**

79 channels, 1 MHz each (fc = 2402+K MHz; K = 0,1,….78)
Frequency hopping (1600 hops/s)

Co-Existence Features

- Dynamic channel selection by the coordinator :

✓ The coordinator performs dynamic channel selection either at network initialization or in response to an outage by using a ChannelList parameter.

✓ When dramatically performance degradation is detected by the coordinator, through the ChannelList parameter, the coordinator broadcasts the update channel to all the endpoints in order to enhance the coexistence of the networks.

✓ For the endpoint, in the sleep mode, the coordinator will inform the current channel to it after it is waken up.

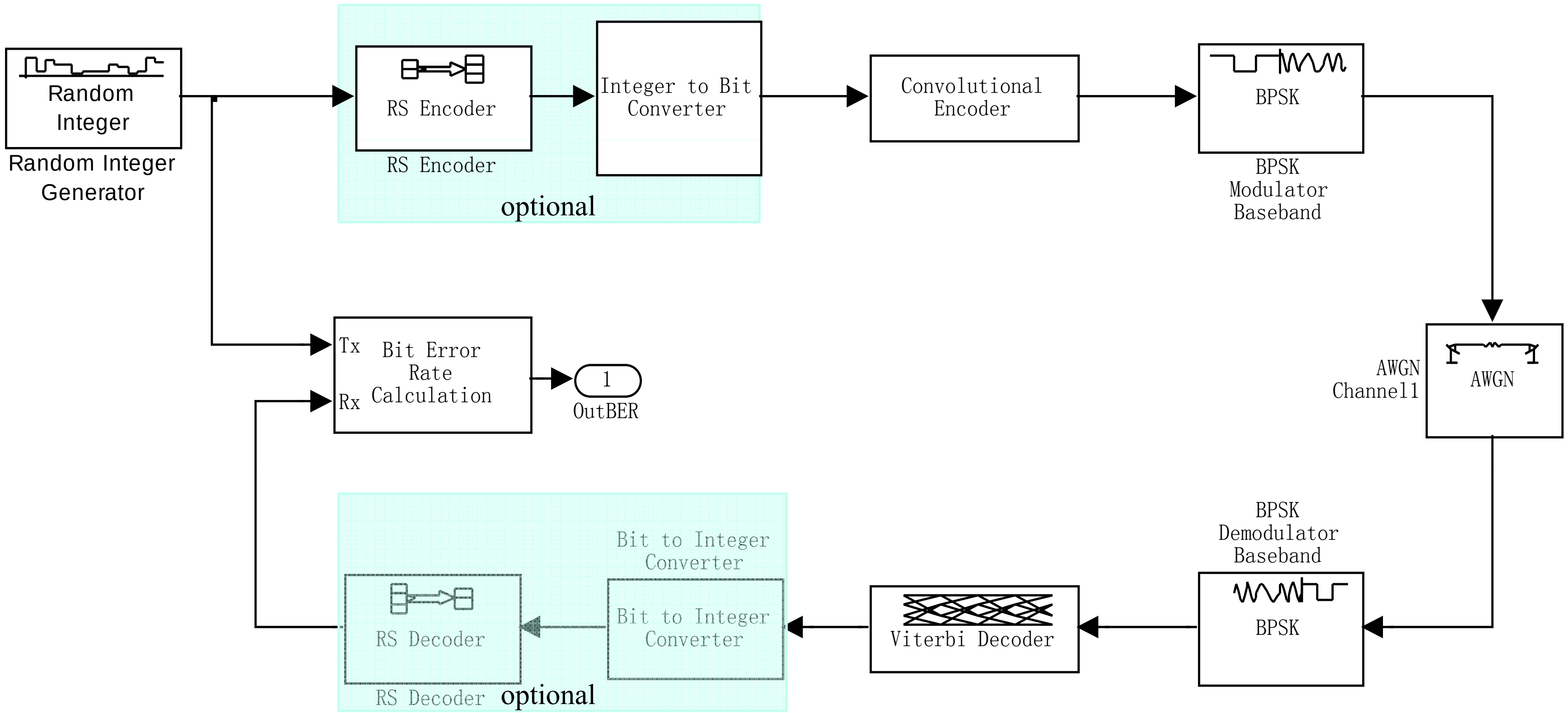
- Clear channel assessment (CCA) by the coordinator with the following methods:

✓ Using energy detection to improve coexistence by allowing transmission back off if the channel is occupied by interference from known sources or high IEEE 802.11b activity .

✓ Using detection of a signal with IEEE 802.15.4k characteristics (Coherent detection).

Transceiver Architecture with Coder

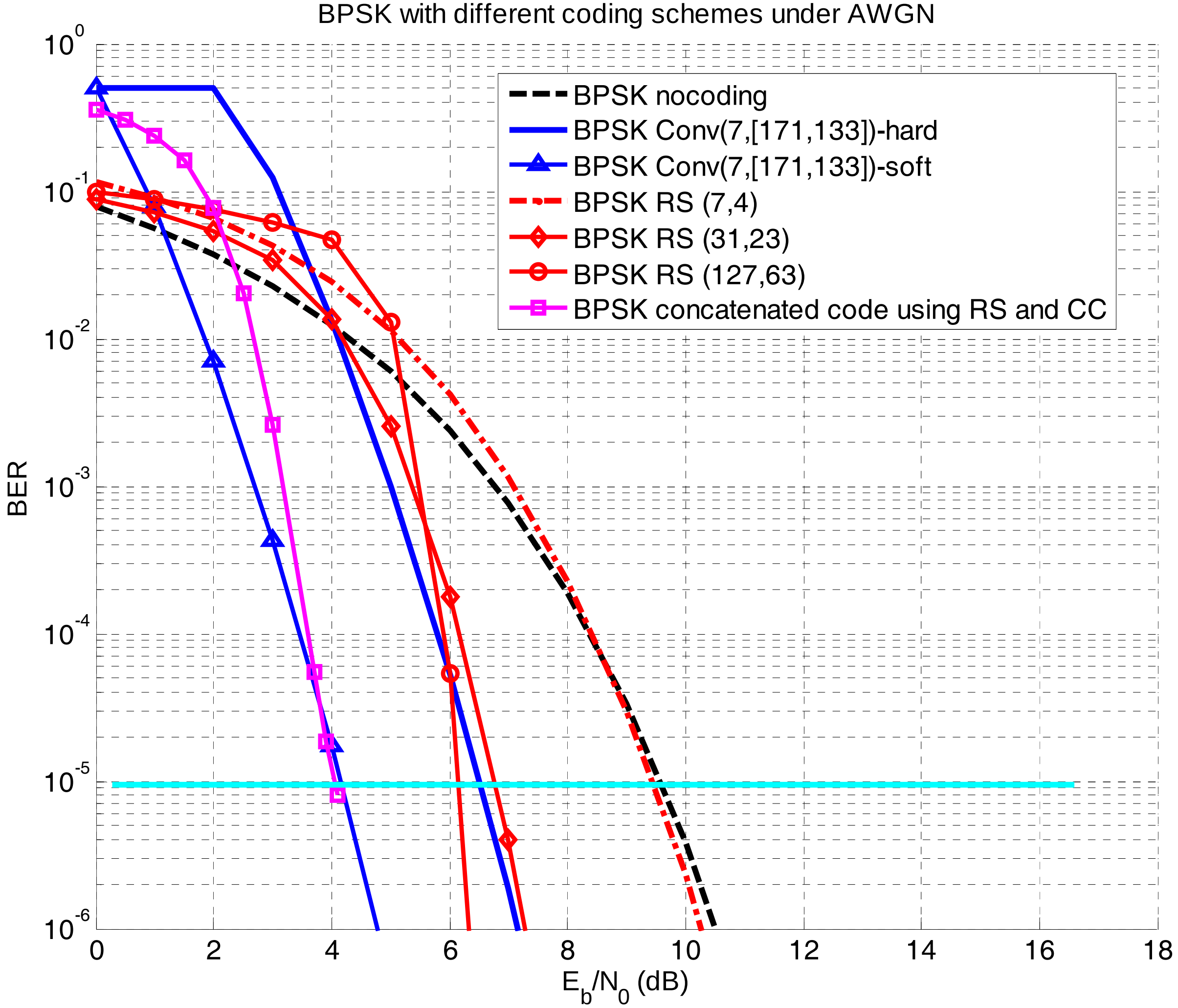
Channel coding : BCC (or Concatenated code using RS and BCC).



Specification: RS code with n=63,k=31

BCC code with code rate 1/2.

Performance Evaluation



With the BPSK Scheme

- Under BER=1.0x10^{-5}
  Concatenated code ≈
  Convolutional code >
  RS code >
  BCH code
- Considering the complexity of the receiver, Convolutional code is preferable for EEE802.15.4k.

Link Budgets

- **Propagation path loss of at least 120 dB**

□ Each device shall be capable of transmitting at least 1 mW

□ Typical devices (10 mW) are expected to cover a 1~10 km range at different achievable data rate

□ The defined transmit power steps are -25 dBm, -15 dBm, -10 dBm, -7 dBm, -5 dBm, -3 dBm, -1 dBm, 0 dBm and 10 dBm.

□ Transmitting power levels can be adjusted to save energy consumption of the endpoints by estimating the received signal strength loss.

Collector Antenna Height =30m, Endpoint Antenna Height=2m, Large Urban Scenario (1/2km):

No.	Parameters	Value		Value		Value		Units	Note
1	Frequency Band	868.0 ~ 868.6		902 ~ 928		2400~2483.5		MHz	
2	Transmission bandwidth	0.640		2.560		2.560		MHz	A0
3	Transmission power	10		10		10		dBm	A1
4	Tx/Rx Antenna Gain	2/2		2/2		2/2		dBi/dBi	A2
5	Maximum Connection Distance	2.0	1.0	2.0	1.0	2.0	1.0	km	
6	Path Loss (large urban)	135.3	124.7	137.8	125.2	152.5	141.9	dB	A3
7	Fading/Shadowing Margin	12		12		12		dB	
8	Received Power	-133.3	-122.7	-135.8	-123.2	-150.5	-139.9	dBm	A4
9	Thermal noise density	-174		-174		-174		dBm/Hz	
10	Received noise figure	5		5		5		dB	A5
11	Receiver noise power density	-169		-169		-169		dBm/Hz	
12	Receiver noise power	-111.0		-105.0		-105.0		dBm	A6
13	Required Eb/No @ BER=$1.0x10^{-5}$	4.1		4.1		4.1		dB	A7
14	Receiver sensitivity requirement	-106.9		-100.9		-100.9		dBm	A8
15	Link Margin (A1=10dBm)	26.4	15.8	34.9	22.3	49.6	39.0	dB	
17	Spreading Factor (Gain in dB)	512 (27)	64 (18)	4096 (36)	256 (24)	131072(52)	8192 (39)	(dB)	A9
18	Data rate	0.625	5	0.3125	5	0.0097	0.1563	kbps	

Collector Antenna Height =30m, Endpoint Antenna Height=2m, Rural Scenario (1/2km):

No.	Parameters	Value		Value		Value		Units	Note
1	Frequency Band	868.0 ~ 868.6		902 ~ 928		2400~2483.5		MHz	
2	Transmission bandwidth	0.640		2.560		2.560		MHz	A0
3	Transmission power	10		10		10		dBm	A1
4	Tx/Rx Antenna Gain	2/2		2/2		2/2		dBi/dBi	A2
5	Maximum Connection Distance	2.0	1.0	2.0	1.0	2.0	1.0	km	
6	Path Loss (Rural)	106.9	96.3	107.2	96.6	149.5	138.9	dB	A3
7	Fading/Shadowing Margin	12		12		12		dB	
8	Received Power	-104.9	-94.3	-105.2	-94.6	-147.5	-136.9	dBm	A4
9	Thermal noise density	-174		-174		-174		dBm/Hz	
10	Received noise figure	5		5		5		dB	A5
11	Receiver noise power density	-169		-169		-169		dBm/Hz	
12	Receiver noise power	-111.0		-105.0		-105.0		dBm	A6
13	Required Eb/No @ BER=1.0×10^{-5}	4.1		4.1		4.1		dB	A7
14	Receiver sensitivity requirement	-106.9		-100.9		-100.9		dBm	A8
15	Link Margin (A1=10dBm)	0	0	4.3	6.3	46.6	36.0	dB	
17	Spreading Factor (Gain in dB)	16 (12)	16 (12)	32 (15)	32 (15)	65728 (48)	4096 (36)	(dB)	A9
18	Data rate	20	20	40	40	0.0195	0.3215	kbps	

Collector Antenna Height =60m, Endpoint Antenna Height=2m, Large Urban Scenario (5/10km):

No.	Parameters	Value		Value		Value		Units	Note
1	Frequency Band	868.0 ~ 868.6		902 ~ 928		2400~2483.5		MHz	
2	Transmission bandwidth	0.640		2.560		2.560		MHz	A0
3	Transmission power	10		10		20		dBm	A1
4	Tx/Rx Antenna Gain	2/2		2/2		2/2		dBi/dBi	A2
5	Maximum Connection Distance	5.0	10.0	5.0	10.0	5.0	10.0	km	
6	Path Loss (large urban)	144.0	154.0	144.6	154.6	160.2	170.2	dB	A3
7	Fading/Shadowing Margin	12		12		12		dB	
8	Received Power	-142	-152.0	-142.6	-152.6	-148.2	-158.2	dBm	A4
9	Thermal noise density	-174		-174		-174		dBm/Hz	
10	Received noise figure	5		5		5		dB	A5
11	Receiver noise power density	-169		-169		-169		dBm/Hz	
12	Receiver noise power	-111.0		-105.0		-105.0		dBm	A6
13	Required Eb/No @ BER=$1.0x10^{-5}$	4.1		4.1		4.1		dB	A7
14	Receiver sensitivity requirement	-106.9		-100.9		-100.9		dBm	A8
15	Link Margin (A1=10dBm)	35.1	45.1	41.7	51.7	47.3	57.3	dB	
17	Spreading Factor (Gain in dB)	4096 (36)	32768 (45.1)	16384 (42)	131456(51)	65782 (48.2)	526526 (57.2)	(dB)	A9
18	Data rate	0.078	0.0098	0.0196	0.0097	0.0195	0.0024	kbps	

Collector Antenna Height =60m, Endpoint Antenna Height=2m, Rural (800/900MHz) and Urban (2.4 GHz) Scenario:

No.	Parameters	Value		Value		Value		Units	Note
1	Frequency Band	868.0 ~ 868.6		902 ~ 928		2400~2483.5		MHz	
2	Transmission bandwidth	0.640		2.560		2.560		MHz	A0
3	Transmission power	10		10		20		dBm	A1
4	Tx/Rx Antenna Gain	2/2		2/2		2/2		dBi/dBi	A2
5	Maximum Connection Distance	5.0	10.0	5.0	10.0	5.0	10.0	km	
6	Path Loss (Rural or Mid-urban)	115.4	125.4	115.8	125.8	158.2	168.2	dB	A3
7	Fading/Shadowing Margin	12		12		12		dB	
8	Received Power	-113.4	-123.4	-113.8	-123.8	-146.2	-156.2	dBm	A4
9	Thermal noise density	-174		-174		-174		dBm/Hz	
10	Received noise figure	5		5		5		dB	A5
11	Receiver noise power density	-169		-169		-169		dBm/Hz	
12	Receiver noise power	-111.0		-105.0		-105.0		dBm	A6
13	Required Eb/No @ BER=1.0×10^{-5}	4.1		4.1		4.1		dB	A7
14	Receiver sensitivity requirement	-106.9		-100.9		-100.9		dBm	A8
15	Link Margin (A1=10dBm)	6.5	16.5	12.9	22.9	45.3	55.3	dB	
17	Spreading Factor (Gain in dB)	16 (12)	64 (18)	32 (15)	256 (24)	32864 (45.2)	526526 (57.2)	(dB)	A9
18	Data rate	20	5	40	5	0.0389	0.0024	kbps	

Conclusions

- A simple and robust PHY scheme based on BPSK is proposed as a narrowband PHY solution operable in 868/915MHz and 2.4GHz band for LECIM.

- Using FDM and CDM make the PHY to facilitate point to multi-thousands of points communications for critical infrastructure monitoring devices.

- Concatenated forward error correction coding based on BCC/RS codes is proposed to substantially enhance the system BER performance.

- PHY PSDU Maximum length is controlled according to the data rate.

- The use of interference avoidance techniques (CCA and dynamic channel selection) enhance the coexistence of the network.

Appendix –A :

Spreading Code Design

Spreading Code Generation(1)

- **Generation of OVSF sequence**

1. Matrix notation of OVSF with different length: Let C_N be a matrix of size $N \times N$ and denote the set of N binary spreading codes of N chip length, $C_N(i)$ is the i -th row vector of N elements and N is an integral power of two.

2. The matrix C_N is generated from $C_{\frac{N}{2}}$:

$$[c_1(1)] = 1$$

$$\begin{bmatrix} c_2(1) \\ c_2(2) \end{bmatrix} = \begin{bmatrix} c_1(1) & c_1(1) \\ c_1(1) & \overline{c_1(1)} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$\begin{bmatrix} c_4(1) \\ c_4(2) \\ c_4(3) \\ c_4(4) \end{bmatrix} = \begin{bmatrix} c_2(1) & c_2(1) \\ c_2(1) & \overline{c_2(1)} \\ c_2(2) & c_2(2) \\ c_2(2) & \overline{c_2(2)} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

$$\vdots$$

$$\begin{bmatrix} c_N(1) \\ c_N(2) \\ \cdot \\ \cdot \\ c_N(N-1) \\ c_N(N) \end{bmatrix} = \begin{bmatrix} c_{N/2}(1) & c_{N/2}(1) \\ c_{N/2}(1) & \overline{c_{N/2}(1)} \\ \cdot & \cdot \\ \cdot & \cdot \\ c_{N/2}(N/2) & c_{N/2}(N/2) \\ c_{N/2}(N/2) & \overline{c_{N/2}(N)} \end{bmatrix}$$

Spreading Code Generation(2)

- **Generation of OVSF sequence**

3. In the above matrix notation, an over-bar indicates binary complement (e.g. $\bar{1} = -1$ and $\overline{-1} = 1$).
4. In our proposal, the SFs range from 32 (15 dB) to 512 (27 dB). For SF=32, we can take any row of the C_{32} matrix; whereas for SF=512, we can choose one row of the matrix C_{512}.

Coding-Tree of OVSF