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

Submission Title: [Legacy based PHY Design for LECIM]

Date Submitted: [September, 2011]

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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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- Operating Bands and Channelization
- Modulation and Data Rates
- PHY frame structure
- Co-Existence Features
- Error Coding Schemes
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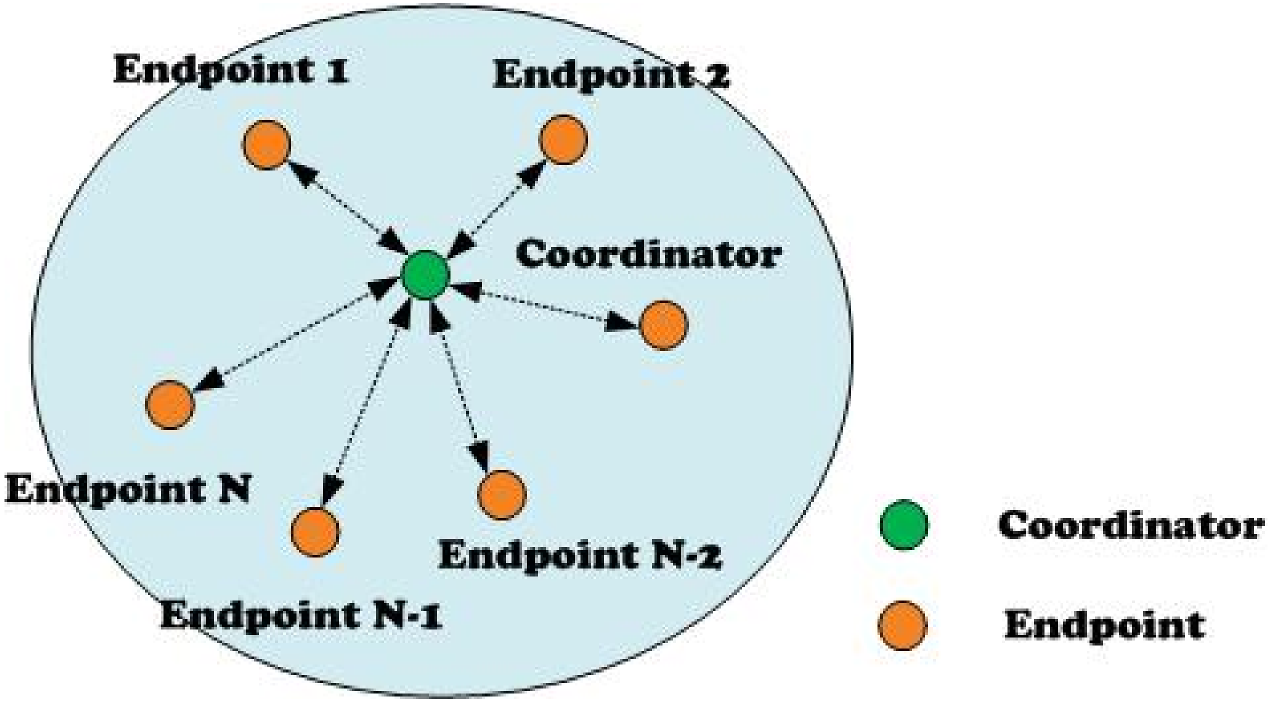
Introduction

- 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.

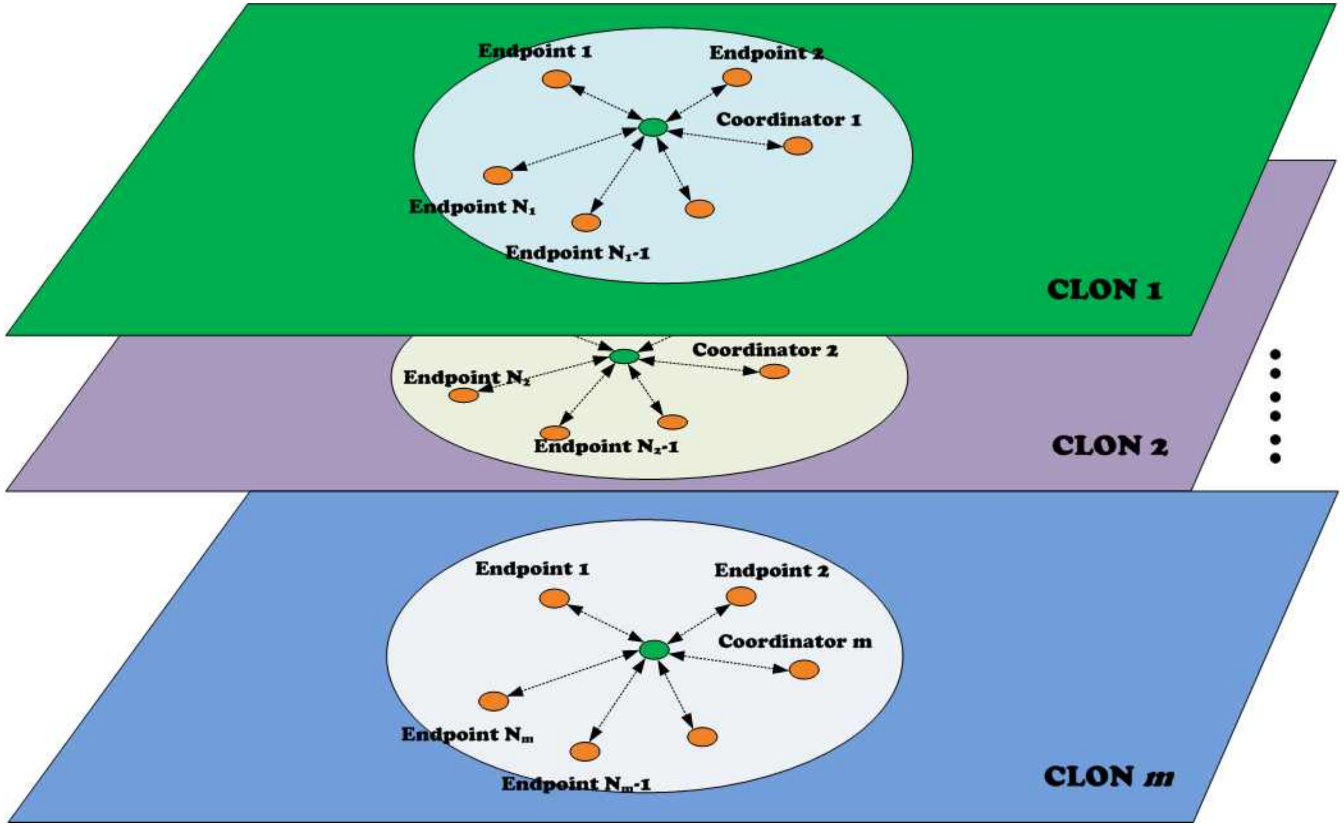
- To facilitate low energy operation necessary for multi-year battery life, this amendment minimizes network maintenance traffic and device awake durations.

CLON Network Topology



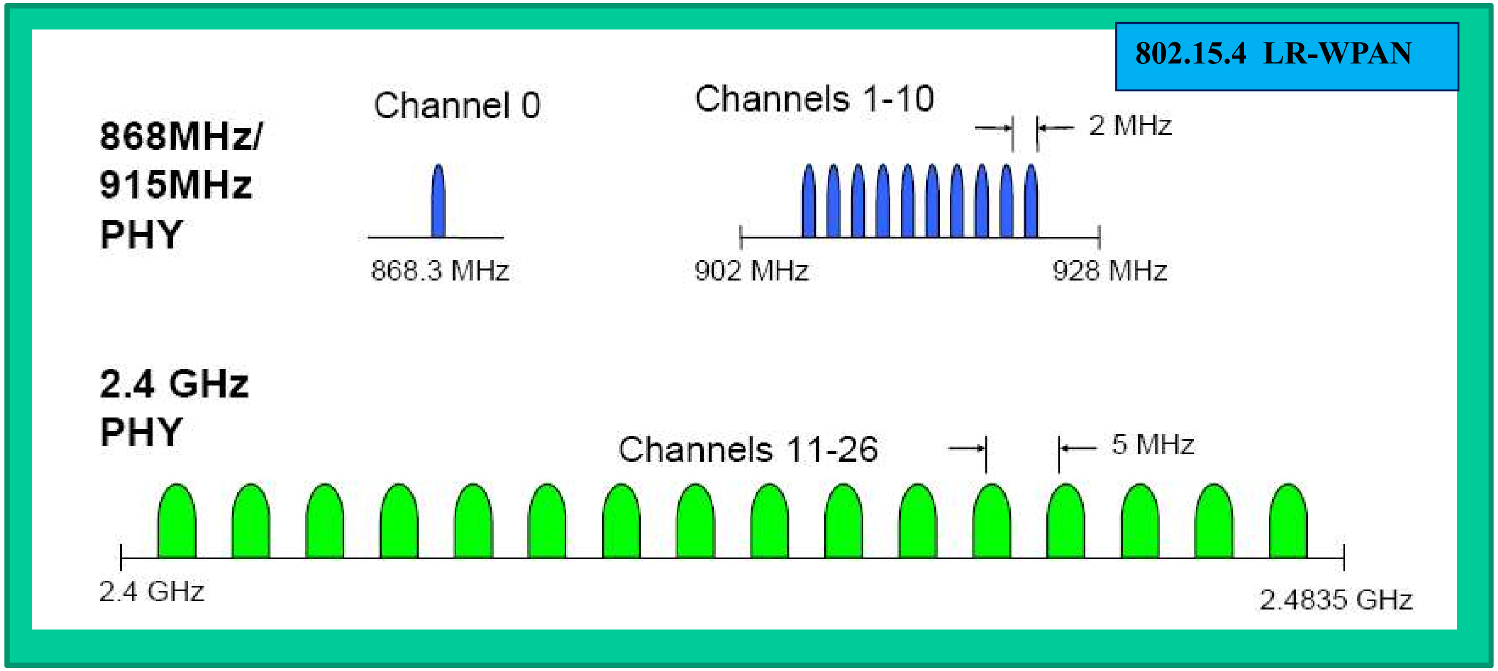
- Each **C**o-**L**ocated **O**rthogonal **N**etworks (CLON) is a star topology composed of one coordinator and a large number of endpoints;
- Endpoints can only communicate with the coordinator.

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.(e.g., Walsh codes for multi-cluster idetification)

Operating Frequency Bands(1)



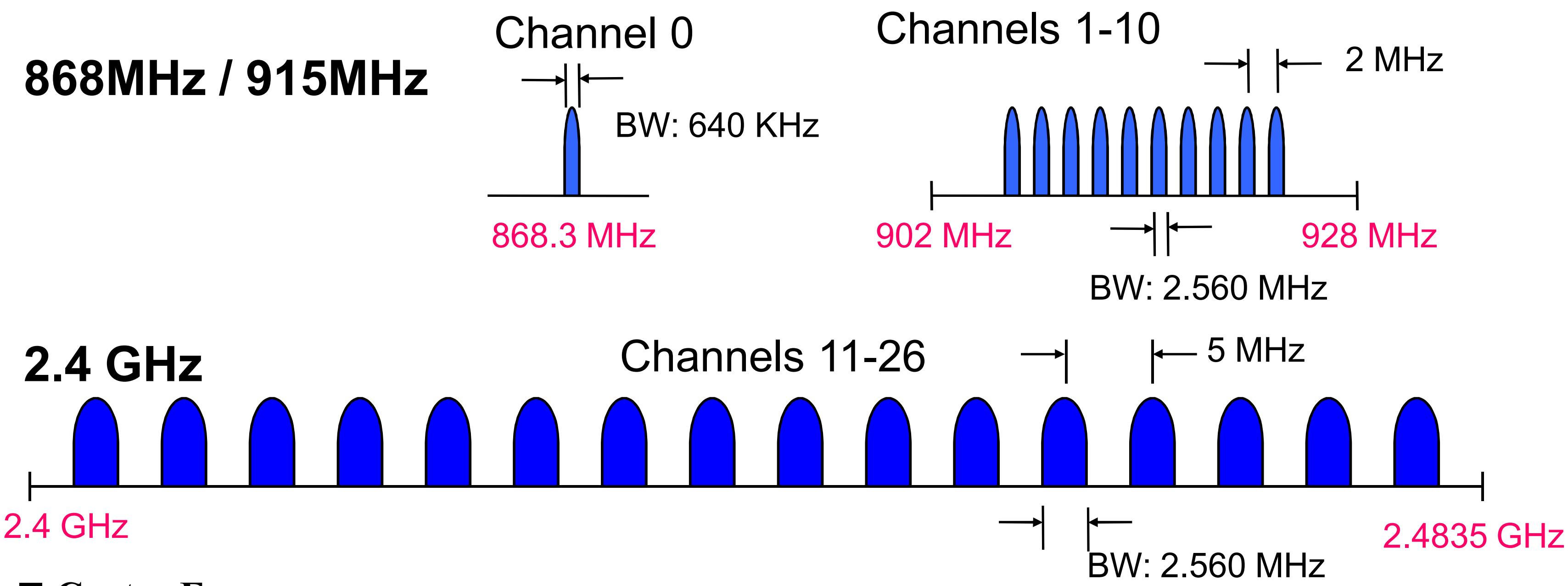
■ Totally, there are **3** applicable frequency bands and **27** channels with different bandwidth

- **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 for a certain application

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

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

Operating Frequency Bands(2)



■ **Center Frequency:**

$$f_c = \begin{cases} 868.3\text{ MHz, Channel Number } k \in \{0\} \\ 906 + 2(k-1)\text{ MHz, Channel Number } k \in \{1, 2, \cdots, 10\} \\ 2405 + 5(k-11)\text{ MHz, Channel Number } k \in \{11, 12, \cdots, 26\} \end{cases}$$

■ **Like the IEEE STD 802.15.4 – 2006, if we use a roll-off coefficient $\beta = 1$, the RF bandwidth will be correspondingly 640 KHz and 2.560 MHz, respectively.**

■ **If we want to keep the RF channel bandwidth identical to those of IEEE STD 802.15.4 – 2006, i.e. 600 KHz and 2.0 MHz, we need to set β as 0.875 and 0.5625, respectively.**

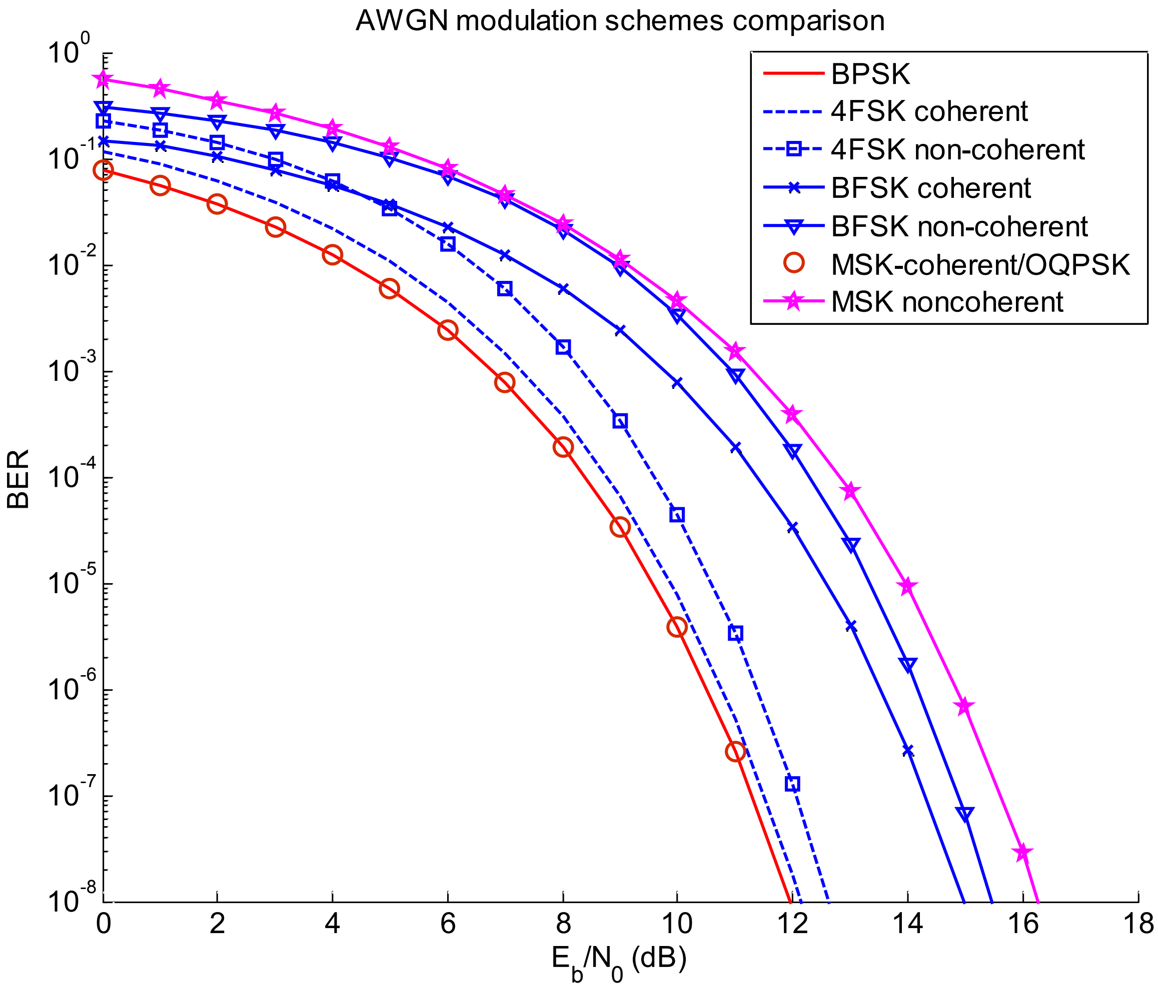
Modulation and Date rates (1)

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	10	2.56MHz	1.28 Mcps	32 (15 dB)	40
					64 (18 dB)	20
2.4 GHz	2.4 ~ 2.4835 GHz	16(8)	2.56 MHz	1.28Mcps	128 (21 dB)	10
					256 (23 dB)	5

- We keep the Data Rates flexible as 40, 20, 10, 5 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)** or **Long m-sequence.**

Modulation and Date rates (2)

- **System BER performance**



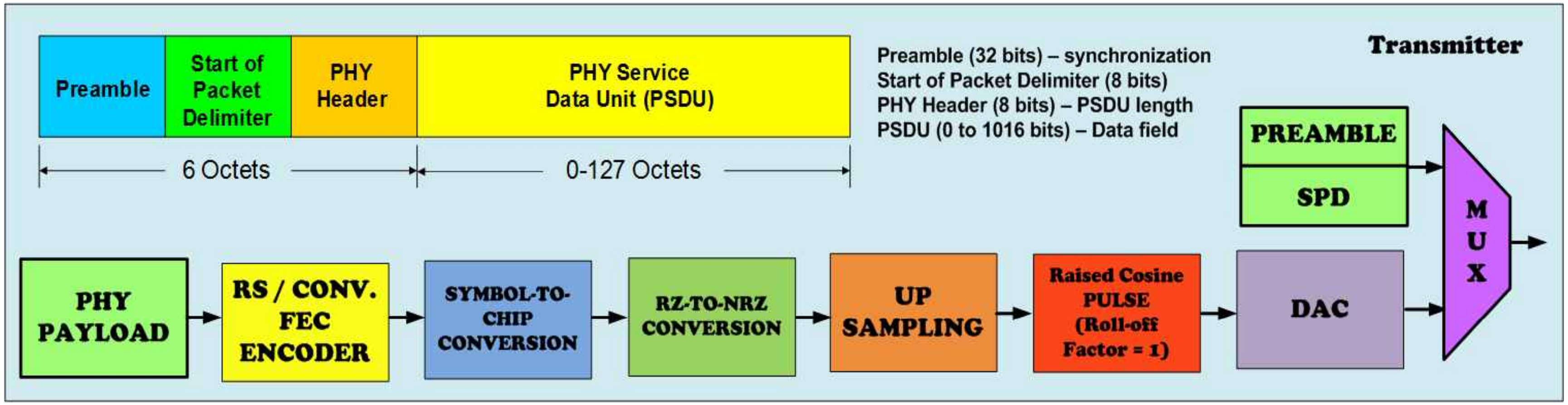
■ PSK outperforms FSK/OOK;

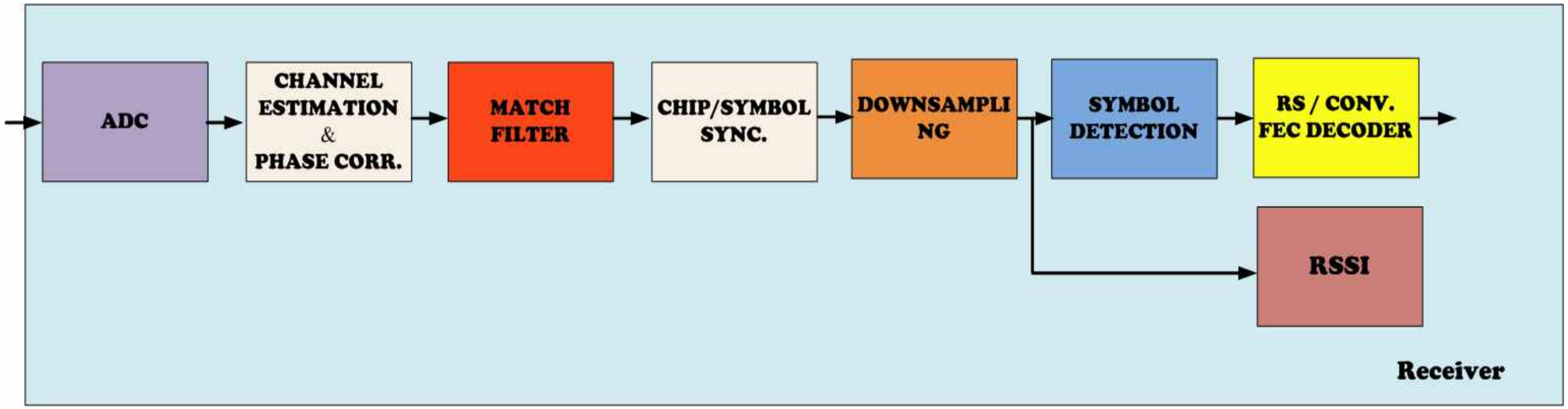
■ Processing gain loss is large for non-coherent reception;

■ 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 PSDU		40kbps	20kbps	10kbps	5kbps	2.5kbps
		128 octets	128 octets	64 octets	64 octets	32 octets
PSDU Time (ms)		25.6 ms	51.2 ms	51.2 ms	102.4 ms	102.4 ms
Super-Frame Time	256 ms	1280 octets	640 octets	320 octets	160 octets	80 octets
	512 ms	2560 octets	1280 octets	640 octets	320 octets	160 octets

Co-Existence Features

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

☐ Inter-Network Interference mitigation (Heterogeneous)

- ✓ Using PN 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.

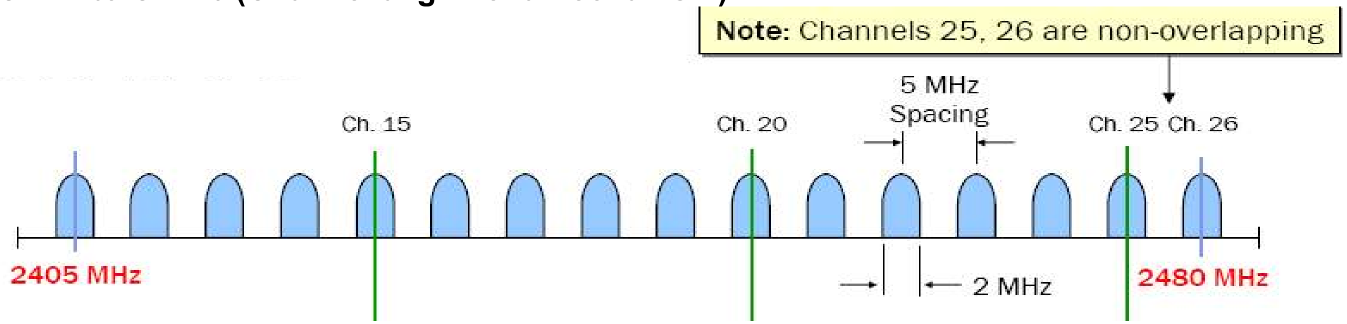
☐ Intra-Network Interference mitigation (Homogeneous)

- ✓ Using multiple access control mechanism in the MAC layer
- ✓ Using better channel assessment (CCA/LQI/RSSI)) mechanism as one proactive way for interference prevention.
- ✓ Using uniform randomization for interference prevention.
- ✓ Using DSSS by its inherited characteristics

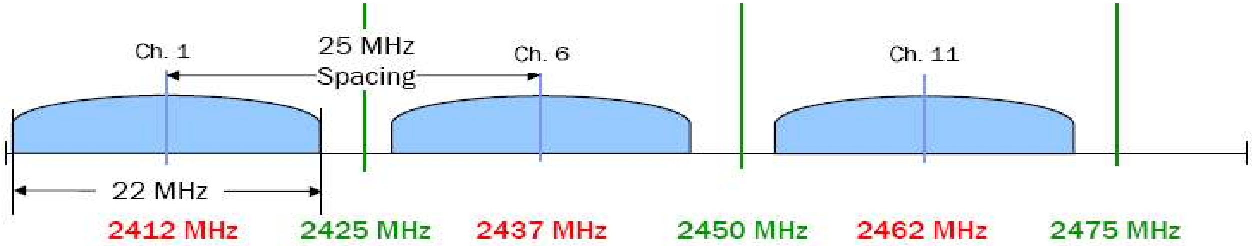
Co-Existence Features

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

- **802.15.4k: 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 :

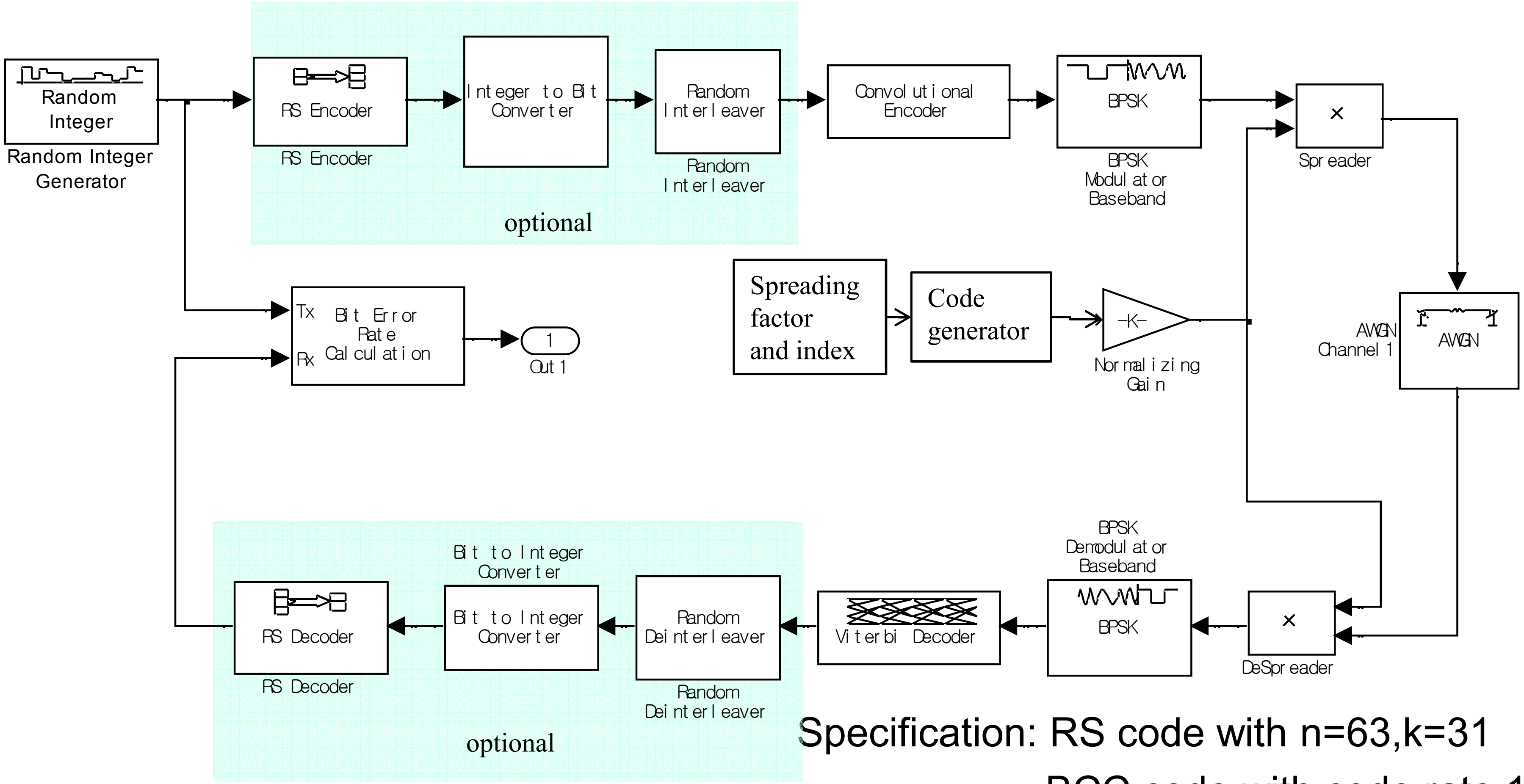
✓ The coordinator performs dynamic channel selection either at network initialization or in response to an outage by using a ChannelList parameter.

✓ 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.

Transceiver Architecture with Coder

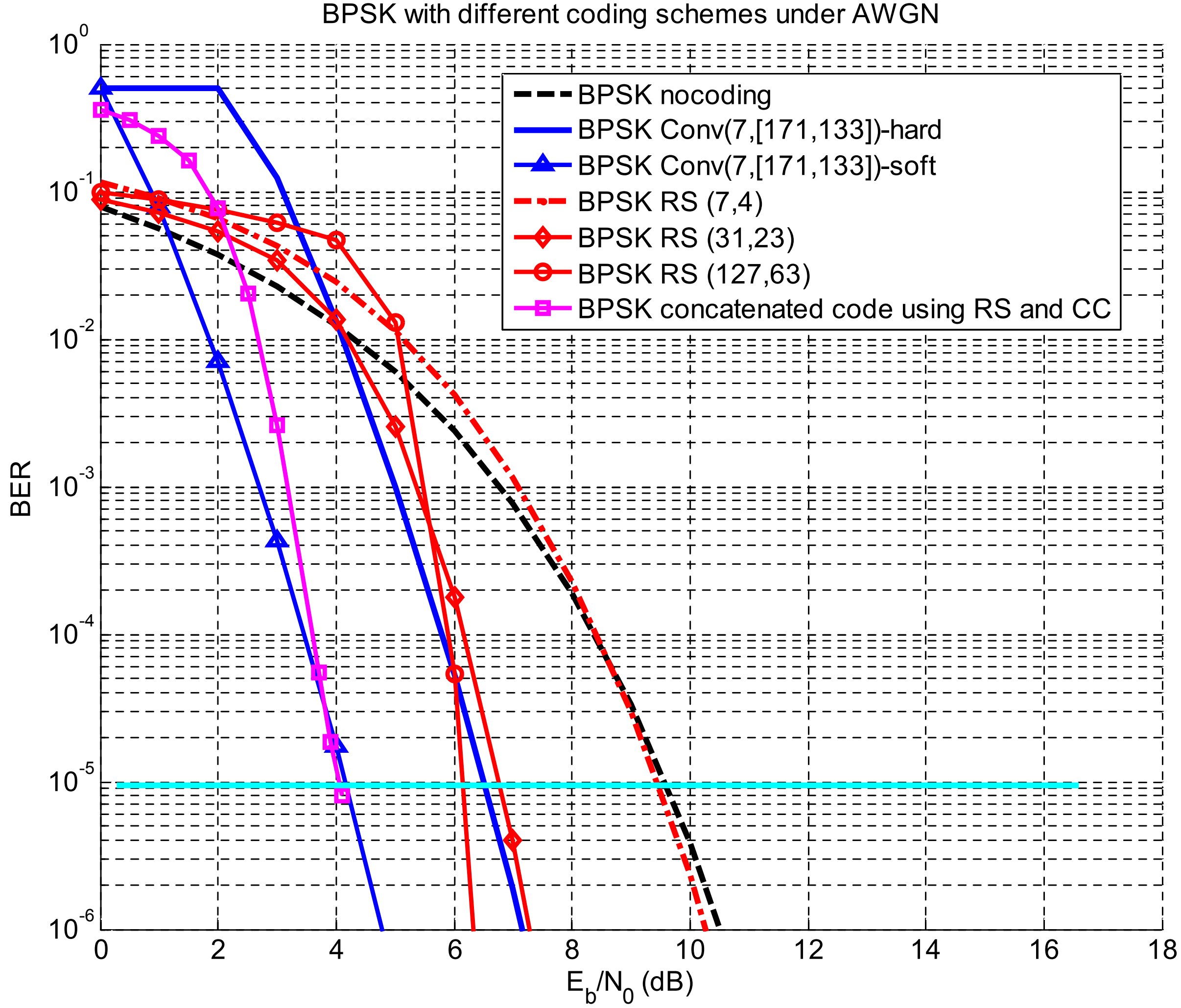
Channel coding : BCC (or Concatenated code using RS and BCC).



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 rates.

☐ 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.

☐ Maximum transmit power levels for the targeted frequency bands varies in different geographical regions(see Appdix-B)

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=$1.0x10^{-5}$	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)	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, 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=$1.0x10^{-5}$	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)	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	

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	6/2		6/2		6/2		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	-109.4	-119.4	-109.8	-119.8	-142.2	-152.2	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)	2.5	12.5	8.9	18.9	41.3	51.3	dB	
17	Spreading Factor (Gain in dB)	16 (12)	32 (15)	32 (15)	128 (21)	16384 (42)	262144 (54)	(dB)	A9
18	Data rate	20	10	40	10	0.0781	0.0049	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.
- Service of 2.4GHz band with current channelization is infeasible to be practical. New methods are necessary; e.g.; Tx antenna gain increased.

- Utilization of FDM and CDM facilitates 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 (DSSS coding 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 $C_{\frac{N}{2}}$:

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

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

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

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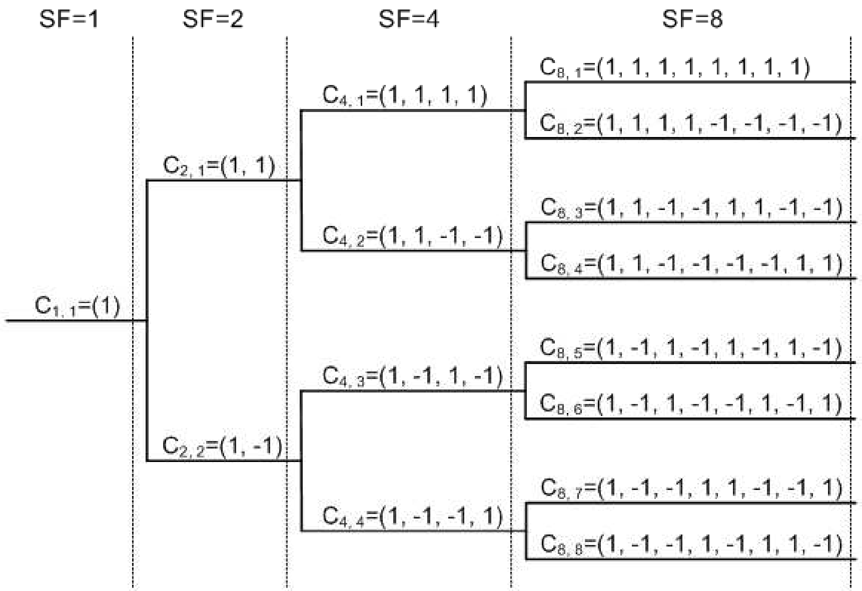
$$\begin{bmatrix} c_N(1) \\ c_N(2) \\ . \\ . \\ c_N(N-1) \\ c_N(N) \end{bmatrix} = \begin{bmatrix} c_{N/2}(1) & c_{N/2}(1) \\ c_{N/2}(1) & \overline{c_{N/2}(1)} \\ . & . \\ . & . \\ c_{N/2}(N/2) & c_{N/2}(N/2) \\ c_{N/2}(N/2) & \overline{c_{N/2}(N)} \end{bmatrix}$$

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 16 (12 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



Note that for better system performance in interference mitigation, robustness in multipath fading, and synchronization, Gold or m sequence based scrambling can be jointly used with OVSF.

Appendix –B :

Transmit Power Levels
in geographical regions.

Maximum transmit power levels

The table below summarizes the known maximum transmit power levels for the targeted frequency bands in various geographical regions.

Frequency band	Geographical region	Maximum conductive power/ radiated field limit	Regulatory document
2400 MHz	Japan	10 mW/MHz	ARIB STD-T66 [B22]
	Europe (except Spain and France)	100 mW EIRP or 10 mW/MHz peak power density	ETSI EN 300 328 [B26] and [B27]
	United States	1000 mW	Section 15.247 of FCC CFR47 [B29]
	Canada	1000 mW (with some limitations on installation location)	GL-36 [B32]
902–928 MHz	United States	1000 mW	Section 15.247 of FCC CFR47 [B29]
868 MHz	Europe	25 mW	ETSI EN 300 220 [B25]