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

Submission Title: [Full Proposal on PHY and MAC for IEEE 802.15.4m]
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Re: [Full Proposal on PHY and MAC Layer Designs for IEEE 802.15.4m.]

Abstract: [This document presents the NICT full proposal for TG4m PHY and MAC layer design]
Purpose: [This document provides a list of the editing staff that will be working on 802.15.4m.]
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Executive Summary

- This document presents combined PHY and MAC proposals for TG4m
- The PHY proposals consist of
  - FSK PHY based on TG4g FSK PHY with alternative FEC and Interleaver
  - Two plus Four OFDM PHY modes as options: Two are based on one-segment broadcasting system which is in service in Japan; Four are based on TG4g MR-OFDM
  - Channel plan on a consideration of FCC regulatory limits
- The MAC proposals consists of
  - TVWS Operation Enabling Protocol: to equip TG4m device with the capability to comply with TVWS rules
  - Dynamic Band Switching: to equip TG4m device with out-of-band communication capability
  - Power Saving Mechanism: to equip TG4m device with scalable power saving features
  - Direct Device-to-device Data Transfer: to equip TG4m device with peer-to-peer communication capability for network redundancy
  - Co-existence among TG4m MAC modifications

PHY PROPOSAL

Executive Outline - PHY

- FSK PHY
  - Based on TG4g FSK PHY
  - Alternate FEC and interleaver
- OFDM PHY
  - Two plus Four OFDM PHY modes proposed as options
    - Two based on one-segment broadcasting system
    - Four using TG4g MR-OFDM options
- Channel Plan
  - Based on a consideration of FCC regulatory limits

FSK PHY Proposal

Summary of TG4m FSK PHY Proposal

- Major TG4g PHY FSK specifications followed
  - Filtered 2FSK and filtered 4FSK
- Alternate FEC and Interleaver
  - Concatenated code of Reed Solomon (RS) and Convolutional Code (CC) and revised bit interleaver
- Channel Plan

  Associated with Frequency Hopping(FH) as an option
- PPDU and PHR formats

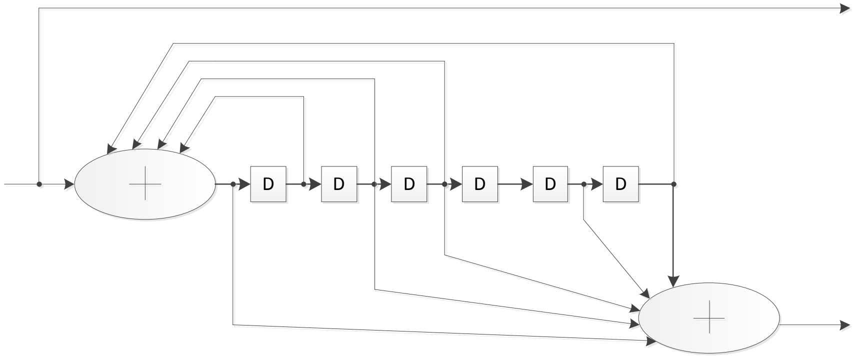
FSK PHY Modes

- Data rates and parameters supported are same as in TG4g specifications

	Mode #1	Mode #2	Mode #3	Mode #4
Data rate (kbps)	50	100	200	400
Modulation	Filtered 2 FSK	Filtered 2 FSK	Filtered 2 FSK	Filtered 4 FSK
Modulation Index	1	1	1	0.33
Channel spacing (kHz)	200	400	600	600

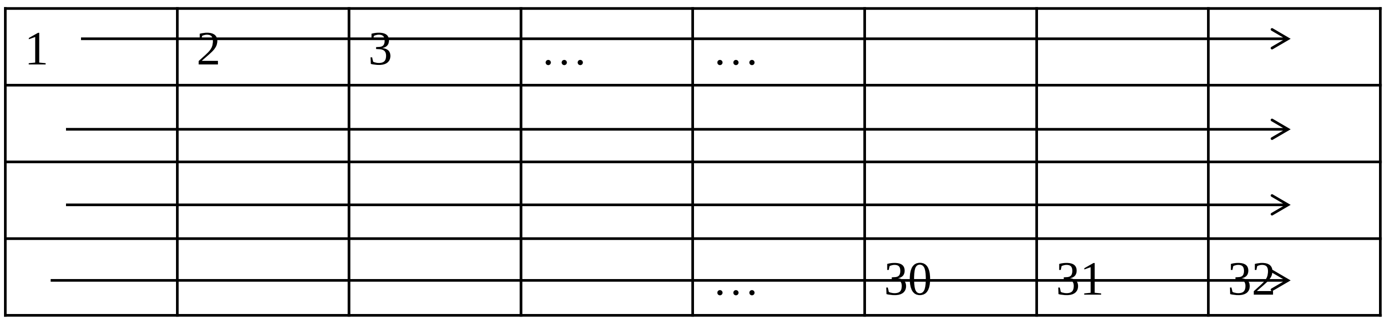
Proposed FEC for FSK PHY

- Concatenated code of RS and systematic CC
  - Outer coder: RS(204,188,8) used in DVB-T and being able to correct no more than 8 symbol (each of which is composed of 8 bits)
  - Inner coder: Systematic CC (R=1/2 & K=7) to replace the one applied in TG4g FSK
    - Only 0.2 dB degradation from non-systematic convolutional encoder (133,171)
  - As a same manner of TG4g FEC, FEC enabled and disabled selection applicable in receiver
    - 4 options to decode: Only RS decode, Only Viterbi decode, RS + Viterbi, hard decision recover without them
  - Applied to the lowest data rate mode



Proposed Bit Interleaver for FSK PHY

8 by 4 block interleaver as shown below



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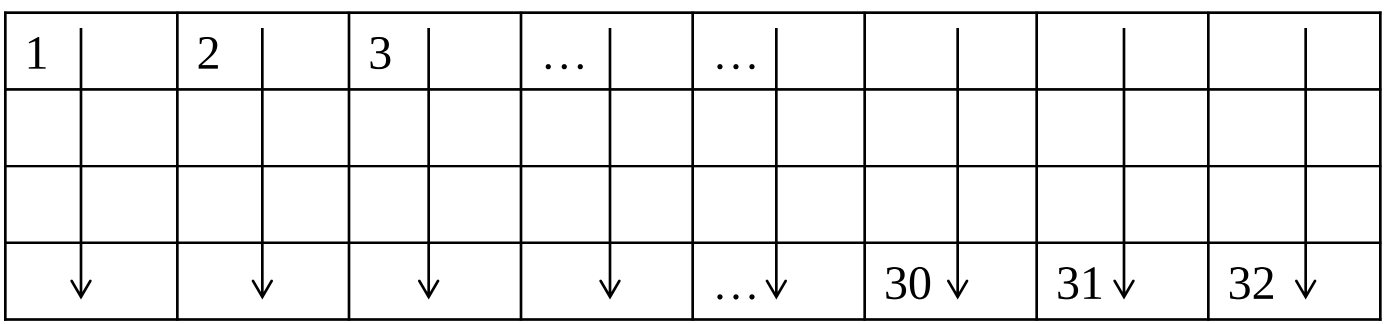


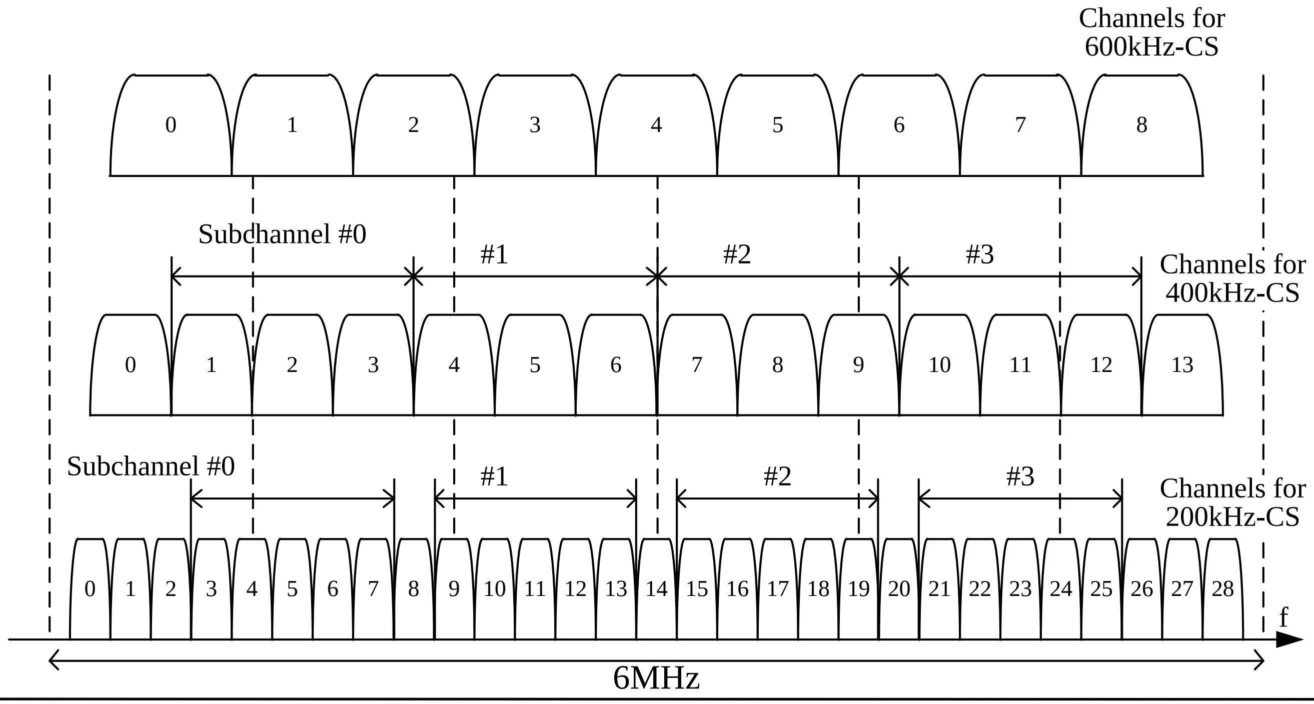
Column by column read out

Channel Plan and FH for FSK PHY (1/2)

- 6MHz bandwidth with 3 modes as follows:
  - 29 channels with center frequencies starting from 0.2MHz @Ch_{200}#0 to 5.8MHz@Ch_{200}#28 with 200kHz channel spacing
  - 14 channels with center freq. starting from 0.4 MHz @Ch_{400}#0 to 5.6MHz @Ch_{400}#13 with 400kHz channel spacing
  - 9 channels with center freq. starting from 0.6 MHz @Ch_{600}#0 to 5.4MHz @Ch_{600}#8 with 600kHz channel spacing
- FH supported for the mode using 200kHz and 400kHz channel spacing as options

Channel Plan and FH for FSK PHY (2/2)

- For the mode using 200kHz channel spacing, 6MHz channel divided into 4 subchannels and 5 hops in each
- For the mode using 400kHz channel spacing, 6MHz channel divided into 4 subchannels, and 3 hops in each



Proposed PPDU/PHR Format for FSK PHY

- PPDU Format for FSK PHY: same as of TG4g FSK PHY

Variable	2 octets	2 Octets	Variable
SHR		PHR	PPDU
Preamble	SFD		

- PHR

Bit String Index	**0**	**1-3**	**3**	**5-15**
Bit Mapping	PC	R3-R0	DW	L10-L0
Field Name	Parity Check	Reserv ed	Data Whitening	Frame length

OFDM PHY Proposal

Summary of OFDM PHY Proposal

- **Two plus Four** OFDM PHY Modes Proposed as options
  - Modes #1 and #2: one-segment broadcasting based modes
  - Modes #3 to #6: using TG4g MR-OFDM options except for some of modified channel spacing

Proposed OFDM PHY Major Specifications (1/2) -One-segment broadcasting based system-

	Mode #1	Mode #2
Channel bandwidth	6MHz	8MHz
Nominal bandwidth (kHz)	380.95	
No. of sub-channels	11	16
Channel spacing (kHz)	400	
Subcarrier spacing (kHz)	0.99206	
Guard band for each side of channel (kHz)	800kHz	
No. of effective. subcarriers per subchannel	384	
No. of pilot subcarrier per subchannel	32	
No. of data subcarriers per subchannel	352	
Effective symbol length (μs)	1008	
Guard interval length	1/32 (31.5 μs) as a default 1/16 (63.0 μs) as a option	

Proposed OFDM PHY Major Specifications (2/2) -TG4g MR-OFDM based system-

	Mode #3	Mode #4	Mode #5	Mode #6
Channel bandwidth	6MHz			
Nominal bandwidth (kHz)	1094	552	281	156
DFT size	128	64	32	16
Channel spacing (kHz)	1200	600	400	200
Subcarrier spacing (kHz)	10.4167			
Guard band				
No. of effective. subcarriers per subchannel	104	52	26	14
No. of pilot subcarrier per subchannel	8	4	2	2
No. of data subcarriers per subchannel	96	48	24	12

MCS Summary of OFDM Modes #1 and #2

- Modulation and Coding Scheme
  - Modulation:
    - BPSK QPSK, 16QAM, and 64QAM with bit block interleaving for subcarrier modulation
  - FEC: Concatenated code of RS (204,188) and systematic CC
    - Same RS as in the proposed FSK
    - Systematic CC, with variable coding rate ranging from 1/2 to 7/8 with K=7, generated from same convolutional coder in the proposed FSK

Data Rates Supported on OFDM Modes #1 and #2

- Data rates supported per 400kHz subchannel as follows
  - Outer code of RS(204,188) in all MCSs and 1/32 cyclic prefix used

MCS Index	Modulation	Inner Code: CC coding rate	Data Rate (Kbps)
MCS0	BPSK	1/2	156
MCS1	BPSK	3/4	234
MCS2	QPSK	1/2	312
MCS3	QPSK	3/4	468
MCS4	16-QAM	1/2	624
MCS5	16-QAM	3/4	936
MCS6	64-QAM	2/3	1404
MCS7	64-QAM	3/4	1248
MCS8	64-QAM	7/8	1638

Proposed Bit Interleaver of OFDM Modes #1 and #2

- Different size of bit block interleaver for 3 types of modulations (i.e., BPSK, QPSK, 16QAM, and 64QAM), which are associated with one OFDM symbol

Pilot Allocation and Subcarrier Mapping of OFDM Modes #1 and #2

Carrier Number

OFDM Symbol Number

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	...	...	...	383
0	Pilot												Pilot		...	...	...	
1				Pilot											...	...	...	
2							Pilot								...	...	...	
3										Pilot					...	...	...	
4	Pilot												Pilot		...	...	...	
⋮				Pilot											...	...	...	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	...	...	...	⋮
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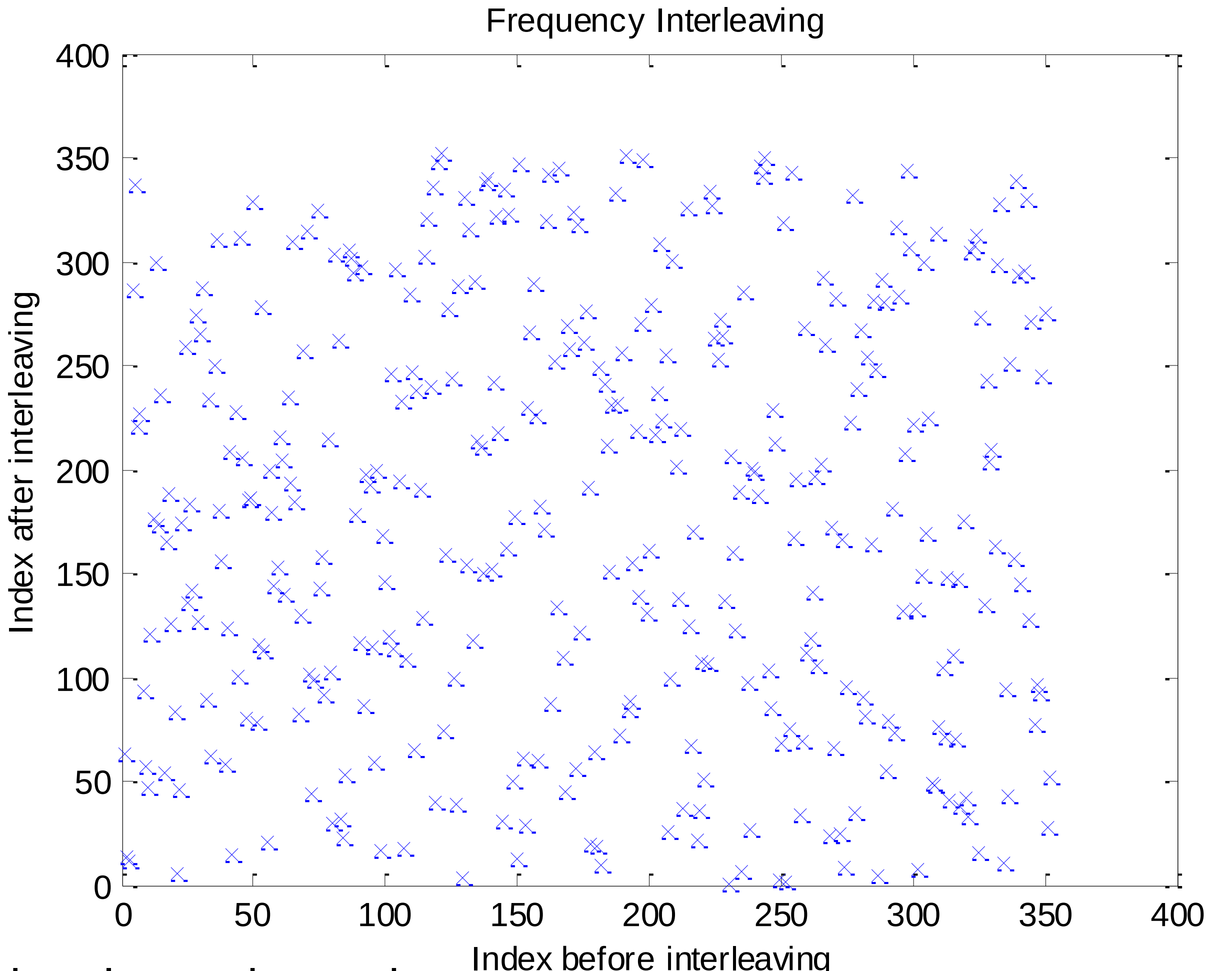
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	...	...	...	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	...	...	...	⋮
200	Pilot												Pilot		...	...	...	
201				Pilot											...	...	...	
202							Pilot								...	...	...	
203										Pilot					...	...	...	

Frequency Interleaving of OFDM Modes #1 and #2



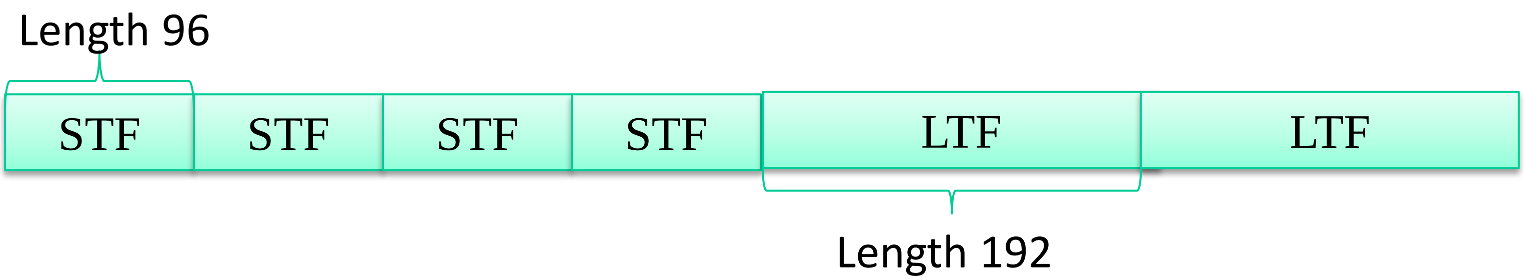
Random interleaver is used

Preamble of OFDM Modes #1 and #2 -STF and LTF proposed- (1/2)

- Sequence used: Zadoff-chu sequence
  - The sequence having ideal auto-correlation function
- 4 short training sequences of length 96 in each and 2 long training sequences of length 192 in each
  - 384 effective subcarriers in frequency domain
  - Realizing ideal auto-correlation property for ease in carrier offset estimation in frequency domain
  - The STF and LTF sequence having constant magnitude in both time and frequency domain

Preamble of OFDM Modes #1 and #2 -STF and LTF proposed- (2/2)

- Preamble consisting of 4 STFs and 2 LTFs both of which based on Zadoff Chu sequence



STF: Generated based on Zadoff Chu Sequence with length N=96,
H is a prime number, for example, H=19,
sequence a=(exp(j*H*π*k*k/N));

LTF: Generated based on Zadoff Chu Sequence with length N=192,
H is a prime number, for example, H=53,
sequence a=exp(j*H*π*k^2/N);

Data Rates Supported on OFDM Modes from #3 to #6

- Follow TG4g MR-OFDM Options for the PSD limits satisfaction
- Additional data rates modes proposed as follows

Parameter	Modulation	CC coding rate	Freq. Repetition	Mode #3	Mode #4	Mode #5	Mode #6
MCS0	BPSK	1/2	4	100	50	-	-
MCS1	BPSK	1/2	2	200	100	50	-
MCS2	QPSK	1/2	2	400	200	100	50
MCS3	QPSK	1/2	N/A	800	400	200	100
MCS4	QPSK	3/4	N/A	1200	600	300	150
MCS5	16-QAM	1/2	N/A	1600	800	400	200
MCS6	16-QAM	3/4	N/A	2400	1200	600	300

Channel Plan

Channel plan summary

- For FSK PHY with 6MHz bandwidth, there are 3 modes. 29 channels with 200kHz channel spacing; 14 channels with 400kHz channel spacing; 9 channels with 600kHz channel spacing
- For OFDM PHY mode #1 with 6MHz bandwidth, 11 channels are allocated with channel spacing 400kHz, each side of 6MHz TV channel required a guard band of 800kHz
- For OFDM PHY # 2 with 8MHz bandwidth, 16 channels are divided with channel spacing 400kHz. Each side of 8MHz TV channel required a guard band of 800kHz.

Channel Centre Frequency

- The channel centre frequency can be derived based on the formulas below
- For FSK: ***ChanCenterFreq = ChanFreq0 +(NumChan-1)* ChanSpacing***
- For OFDM

ChanCenterFreq = ChanFreq0 +floor(NumChan/11) +mod(NumChan-1, 11)* ChanSpacing *(6MHz TV Band)*

ChanCenterFreq = ChanFreq0 +floor(NumChan/16) +mod(NumChan-1, 16)* ChanSpacing *(8MHz TV Band)*

  - Where *ChanCenterFreq* is channel centre frequency
  - *ChanFreq0* is the starting channel centre frequency of every continuously available TV channel
  - *NumChan is the index of channel in every continuously available TV channel*
  - *TotalNumChan* is total number of channel in every continuously available TV Channel band
  - *ChanSpacing* is channel spacing

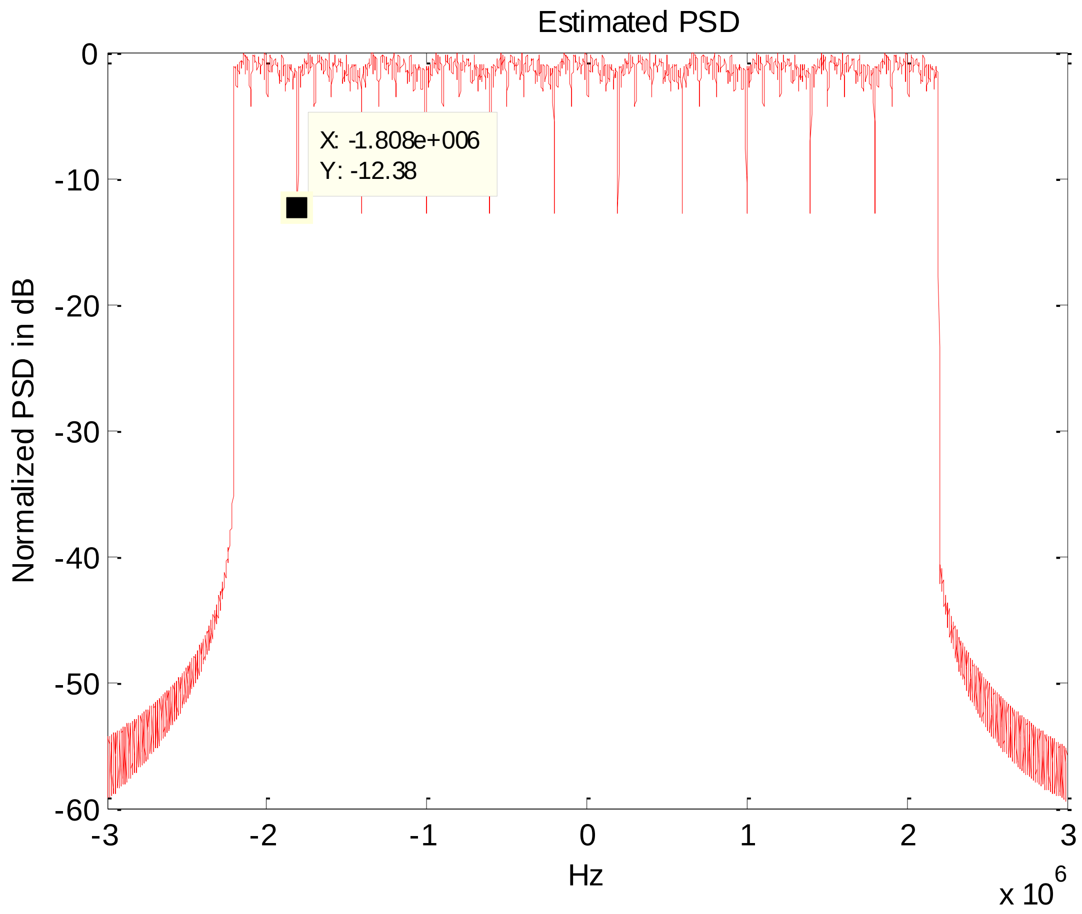
Total number of channels and first channel centre frequencies for proposed PHYs

Freq. band (MHz)	Modulation	ChanSpacing(MHz)	TotalNumChan	*ChanFreq0*
54-60	Filtered 2FSK	0.2	29	54.2
	Filtered 2FSK	0.4	14	54.4
	Filtered 2FSK and 4FSK	0.6	9	54.6
	OFDM	0.4	11	55
76-88	Filtered 2FSK	0.2	58	76.2
	Filtered 2FSK	0.4	28	76.4
	Filtered 2FSK and 4FSK	0.6	18	76.6
	OFDM	0.4	22	77
174-216	Filtered 2FSK	0.2	203	174.2
	Filtered 2FSK	0.4	98	174.4
	Filtered 2FSK and 4FSK	0.6	63	174.6
	OFDM	0.4	77	175
470-602	Filtered 2FSK	0.2	638	470.2
	Filtered 2FSK	0.4	308	470.4
	Filtered 2FSK and 4FSK	0.6	198	470.6
	OFDM	0.4	242	471
620-698	Filtered 2FSK	0.2	377	620.2
	Filtered 2FSK	0.4	182	620.4
	Filtered 2FSK and 4FSK	0.6	117	620.6
	OFDM	0.4	143	621

(based on FCC available TV Channel Table)

Channel Aggregation proposed for OFDM mode #1 and #2

For fixed device, more than one, up to 11 subchannels can be aggregated and form one channel in a 6MHz Band to support data rate of more than 10Mbps.



Conclusions of PHY proposal

- FSK PHY
  - Based on TG4g FSK PHY, concatenated code of RS and systematic CC with interleaver proposed for the lowest data rate mode for wider coverage area
- OFDM PHY
  - Two plus Four OFDM PHY modes proposed as options
  - Two modes based on one-segment broadcasting system to achieve increased flexibility and efficiency of channels
    - System parameters, FEC, bit and frequency interleavers, MCS, and preamble
    - Channel aggregation
  - TG4g MR-OFDM based system proposed
- Channel Plan
  - On a consideration of usage on 6 MHz and 8 MHz bandwidth under FCC regulatory limits, channel centre frequency and guard bandwidth proposed

MAC PROPOSAL

Executive Outline - MAC

- Proposal
  - TVWS Operation Enabling Protocol
  - Dynamic Band Switching
  - Power Saving Mechanism
  - Direct Device-to-device Data Transfer
- Expected expansion/coexistence
  - TVWS Multi-Channel Utilization (TMCU)
  - Spectrum Management
  - Ranging

Summary of MAC Proposal From NICT

- TVWS Operation Enabling Protocol
- Dynamic Band Switching
- Power Saving Mechanism
- Direct Device-to-device Data Transfer

TVWS Operation Enabling Protocol

Summary

- This document proposes an enabling protocol for IEEE 802.15.4 WPAN operating in TVWS, meeting the requirement by TVWS regulations
- What was concluded in our presentation in 2012 May Atlanta meeting, doc.12/222r0:
  - IEEE 802.15.4 network architecture is able to comply with the architecture required by TVWS regulations
  - IEEE 802.15.4 device type is able to fit into the categorization required by TVWS regulations
  - IEEE 802.15.4 functionalities is able to perform the enabling protocol with minor modification
- This document presents the details of the enabling protocol
  - Required protocol
  - Addition of IE
  - Modification of service primitives

Outline

- Summary of Major Regulatory Bodies
- Application-802.15.4-Regulation Mapping
- General State Transition Diagram
- Operational Procedure
- Detailed State Transition Diagram – Master
- Detailed State Transition Diagram – Slave
- Message Sequence Chart
- Frame Format
- Service Primitives

Summary of Major Regulatory Bodies

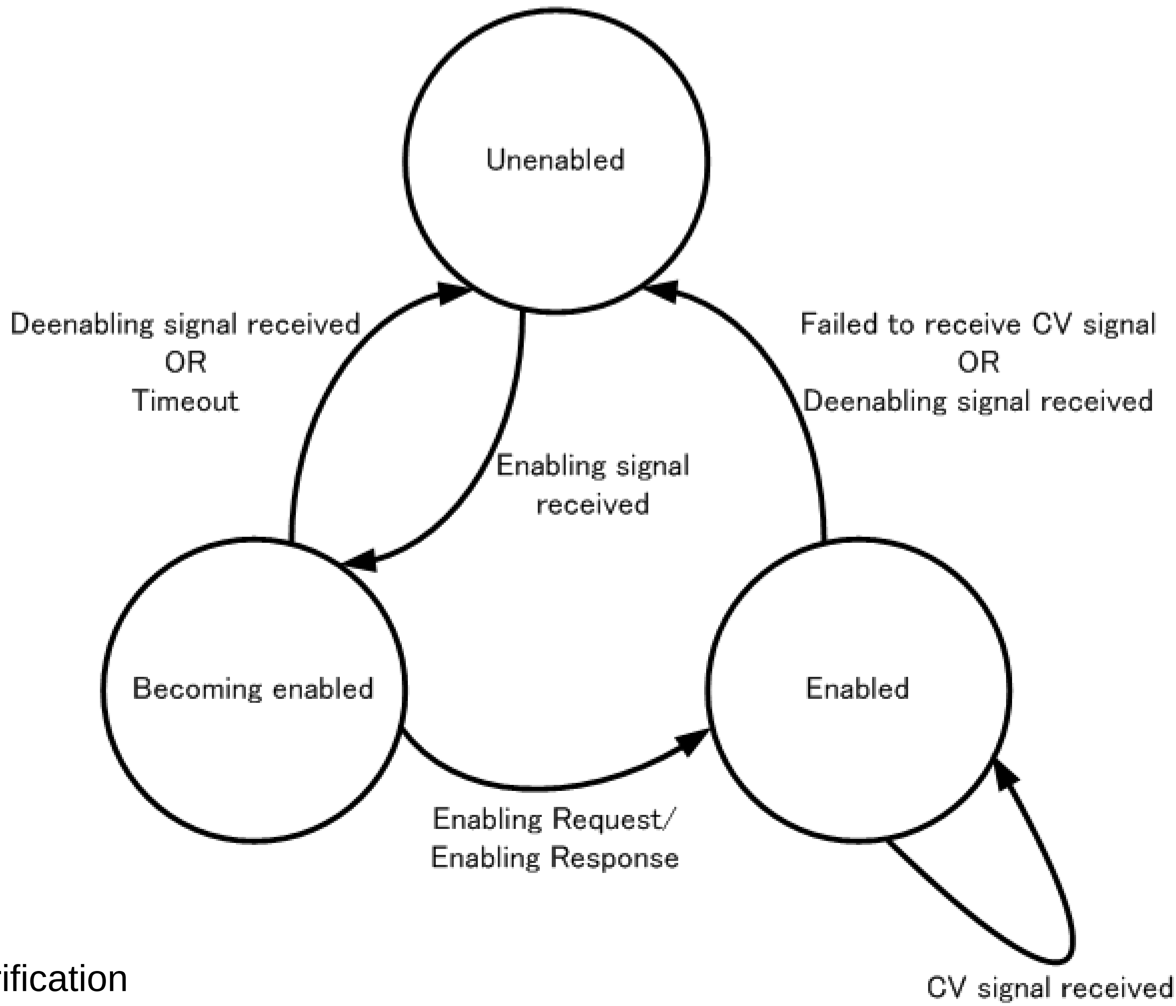
Regulatory Domains	FCC, USA	OFCOM, UK	Industry Canada, Canada	CEPT ECC, Europe
TV Channel-ization	6 MHz	8 MHz	6 MHz	8 MHz
Available TV Channels	Ch2 to Ch4: 54 to 72 MHz Ch5 to Ch6: 76 to 88 MHz Ch7 to Ch13: 174 to 216 MHz Ch14 to Ch51: 470 to 698 MHz	Ch21 to Ch60: 470 and 790 MHz	Ch2 to Ch4: 54 to 72 MHz Ch5 to Ch6: 76 to 88 MHz Ch7 to Ch13: 174 to 216 MHz Ch14 to Ch51: 470 to 698 MHz	470 to 790 MHz
Device Type	Fixed device (FD) Personal/portable device (PPD) Mode II PPD Mode I PPD Sensing-only device (SOD)	Master device (MD) Slave device (SD)	Fixed WSD (FWSD) Mobile WSD (MWSD) Mode II MWSD Mode I	Master device (MD) Slave device (SD)
TX Power	FD: 4W PPD: 100mW PPD SOD: 50mW FD disallowed in first adjacent channel PPD: 40mW (adj. channel)	DB informs the allowable transmit power	FWSD: 4W MWSD: 100mW MWSD: 40mW (adj. channel)	DB informs the allowable transmit power
Access Rules	FD: Ch2, Ch5 to Ch35, Ch39 to Ch51 PPD: Ch21 to Ch35, Ch39 to Ch51	MD and SD: Ch21 to Ch30 and Ch39 to Ch60	FWSD and MWSD: Ch2 to Ch36 and Ch38 to Ch51	–
DB Access	FD: once/day PPD Mode II: once/day, every 100m relocation PPD Mode I: not required PPD SOD: not required PPD Mode II may access DB via other PPD Mode II	MD: required SD: not required DB informs available channels and information time validity	MWSD: required FWSD: required FWSD Mode II may access DB via other FWSD Mode II	DB informs available channels and information time validity
Geo-location	FD: accuracy 50m PPD Mode II: accuracy 50m, re-establish location every 60s PPD Mode I: not required PPD SOD: not required	MD: accuracy 100m SD: not required	MWSD: required FWSD Mode II: required FWSD Mode I: not required	MD: required SD: not required
Spectrum Sensing	PPD SOD: required	DB informs whether sensing is required	–	DB informs whether sensing is required
Additional Notes	Contact Verification Signal required by PPD Mode I every 60s	–	The channels bands are currently being shared with low power apparatus (LPA) and remote rural broadband systems (RRBS)	–

Application-802.15.4-Regulation Mapping

Application	IEEE 802.15.4 Device Type	TVBD Classes	Sensing Capability	Geo-location Awareness	Maximum Transmit Power
Utility provider base station	FFD	Fixed device	Not required	Required	4 W
Data collector	FFD	Mode II independent device	Not required	Required	100 mW
Electric/gas/water meter	FFD/RFD	Mode II independent device	Not required	Required	100 mW
		Mode I client device	Not required	Not required	100 mW
Mobile data collector	FFD/RFD	Mode II independent device	Not required	Required	100 mW
		Sensing-only device	Required	Not required	50 mW

Note: This table is only an example to illustrate the mapping relationship among SUN application, 802.15.4 network and FCC requirement. Applications other than SUN and regulations other than FCC may also go through the same mapping process with IEEE 802.15.4 system

General State Transition Diagram

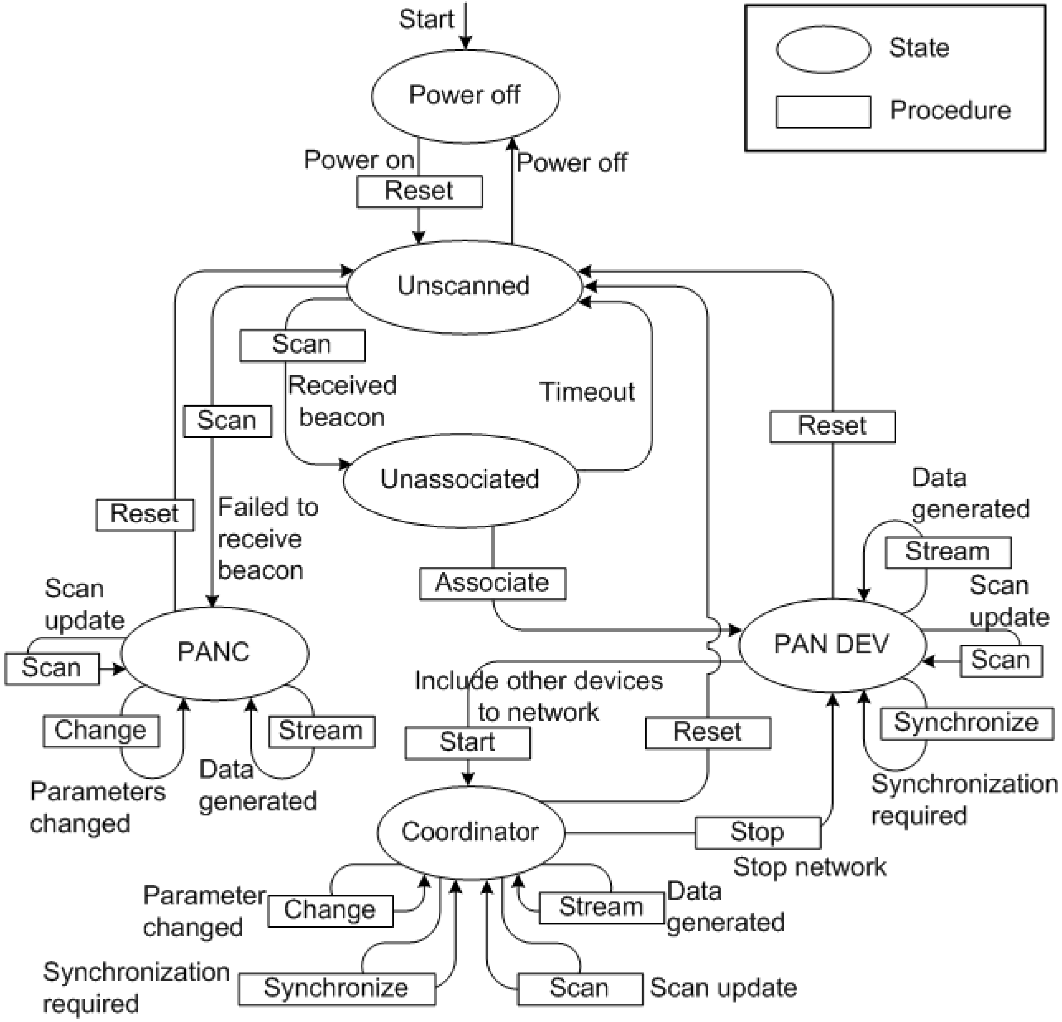


CV: contact verification

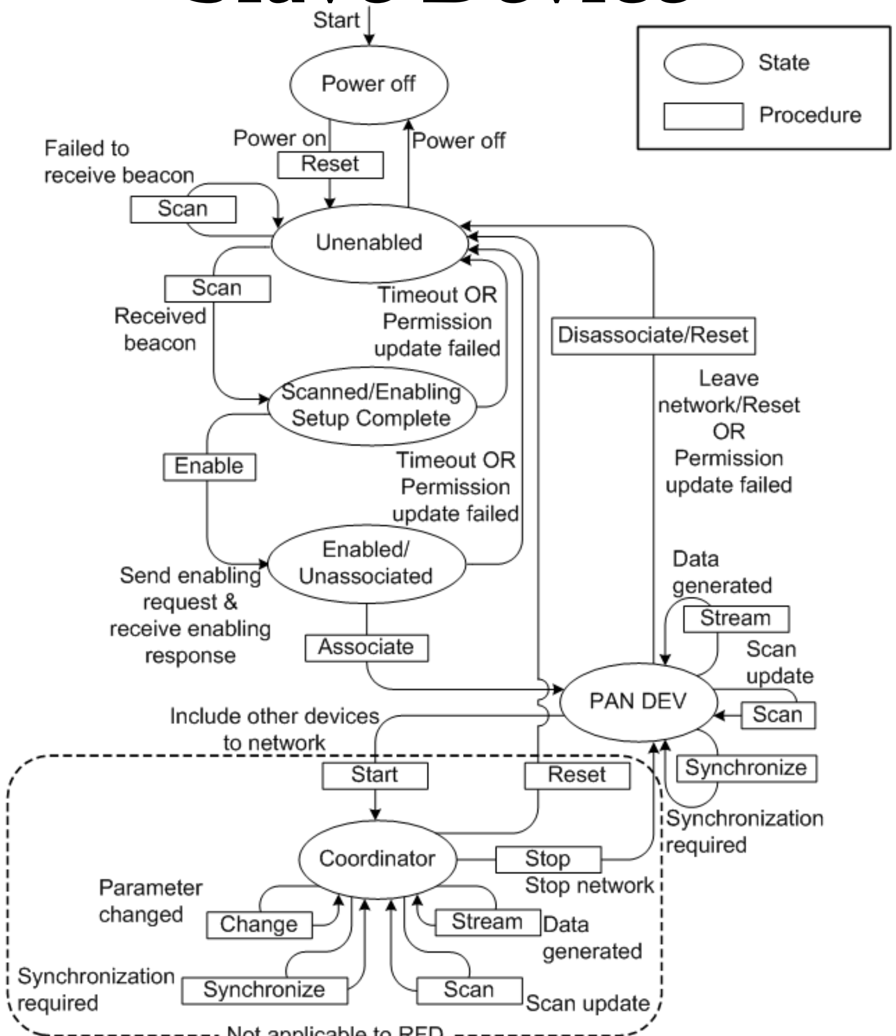
Operational Procedure

- Fixed and Mode independent II devices (*i.e.* 802.15.4m FFD, master device) obtain the list of available TV channels from the GDB through the internet
- Then, the TV channels are mapped to corresponding WPAN channels
- Next, the fixed and Mode II devices transmit the enabling signal in the channel of interest to surrounding devices attempting to join the network
- Upon receiving the enabling signal, the Mode client I devices (*i.e.* 802.15.4m RFD, slave device) are to provide information for verification
- After verification, the fixed and Mode II devices send the WPAN channel list to the Mode I devices
- Besides the list of WPAN channels, the signal may also contain other information such as timing schedule for the occupancy of the channel and nearby locations where the channels are available
- Upon receiving the channel list, Mode I devices are then able to transmit signal in the specific channel(s) of interest
- Additionally, a periodic contact verification signal is required to constantly update the status of enablement
- For both the enabling signal and contact verification signals, the 802.15.4 beacon frame or enhanced beacon frame can be reused with additional IEs
- For the verification signaling handshake, the 802.15.4 command frames can be reused with additional IEs

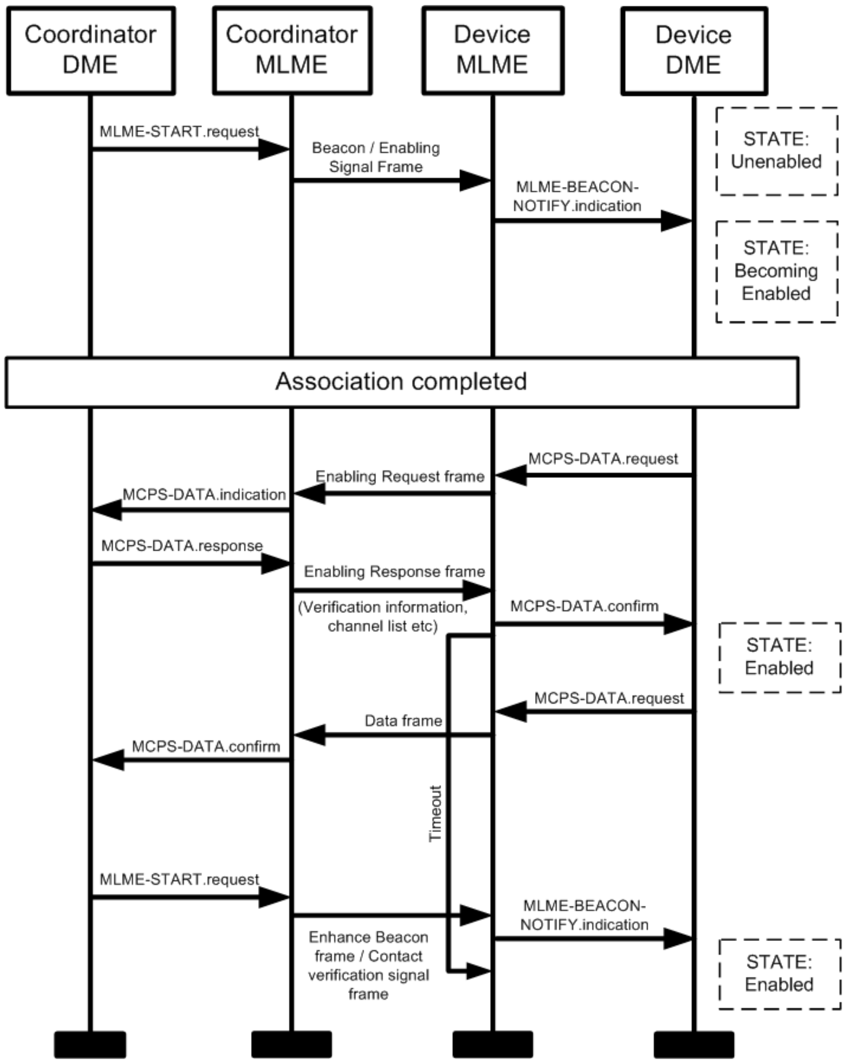
Detailed State Transition Diagram ~ Master Device ~



Detailed State Transition Diagram ~ Slave Device ~



Message Sequence Chart



Frame Format

- Enabling signal frame
  - Reuse IEEE 802.15.4 beacon frame format
  - Reuse the name of the frame with additional IE
  - Include information on regulation and operating channel
- Enabling Request and Response Frame
  - Reuse IEEE 802.15.4 command frame format
  - Reuse the name of the frame with additional IE
  - Include information on verification information, list of vacant WPAN channels, timing schedule for the vacancy, information on vacancy for the channels in nearby locations
- Contact Verification Signal frame
  - Reuse IEEE 802.15.4e enhanced beacon frame format
  - Reuse the name of the frame with additional IE
  - Update on enablement status

Frame Format
~ IE for Enabling signal ~

Bits			Octets
0	1-8	9-15	
Type = 0	Element ID	IE Content Length	IE Content

Octets
1
Inband Enabling Signal

Frame Format
~ IE for Enabling Request and Response~

Bits			Octets
0	1-8	9-15	
Type = 0	Element ID	IE Content Length	IE Content

Octets				
1	1	variable	variable	variable
Channel Query Info	Device Class	Device Identification	Device Location	White Space Info

Frame Format
~ IE for Contact Verification Signal ~

Bits			Octets
0	1-8	9-15	
Type = 0	Element ID	IE Content Length	IE Content

Octets
1
Contact Verification Signal

Service Primitives

- Primitives between DME and MLME of initiator and responder devices on Enabling Signal and Contact Verification Signal frames
  - MLME-START.request
  - MLME-START.indication
  - MLME-ENABLING.request
  - MLME-ENALBLING.response
  - MLME-ENALBING.indication
  - MLME-ENALBING.confirm
  - MLME-CVS.request
  - MLME-CVS.response
  - MLME-CVS.indication

Dynamic Band Switching

Summary

- This document proposes a Dynamic Band Switching (DBS) protocol to facilitate frequency band switching for IEEE 802.15.4 low rate WPAN systems
- What was concluded in our presentation in 2012 May Atlanta meeting, doc.12/222r0:
  - Capability to switch between different regulatory bands, particularly TVWS and other conventional IEEE 802.15.4 bands is beneficial
- This document presents the details of the DBS protocol
  - Required protocol
  - Addition of IE
  - Modification of service primitives

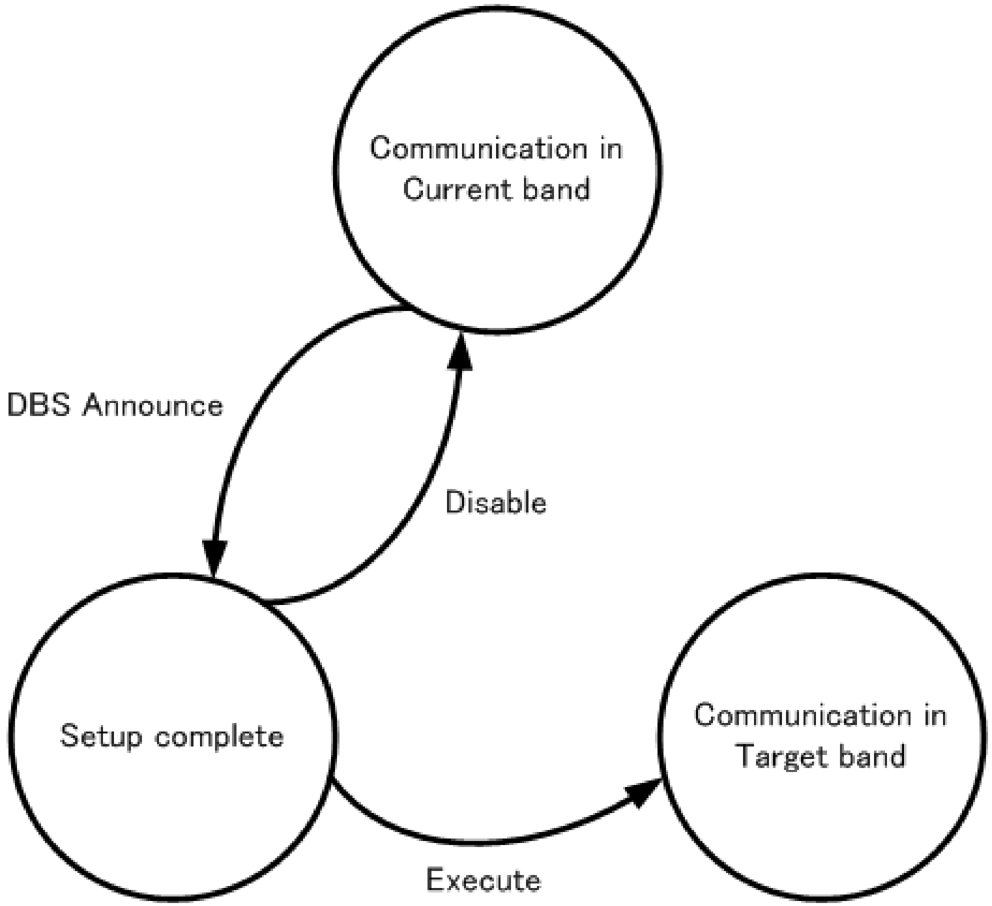
Outline

- Introduction
- State Transition Diagram
- State Description
- Operational Procedure
- Message Sequence Chart
- Frame Format
- Service Primitives

Introduction

- Dynamic band switching (DBS) is a protocol facilitating switching between operating frequency bands
- There are many regulatory-domain specific frequency bands applicable only in certain locations
- Currently existing frequency bands that could be included into the DBS mechanism
  - TVWS frequency bands
  - SUN frequency band specified in IEEE 802.15.4g
  - Other IEEE 802.15.4 conventional frequency bands

State Transition Diagram



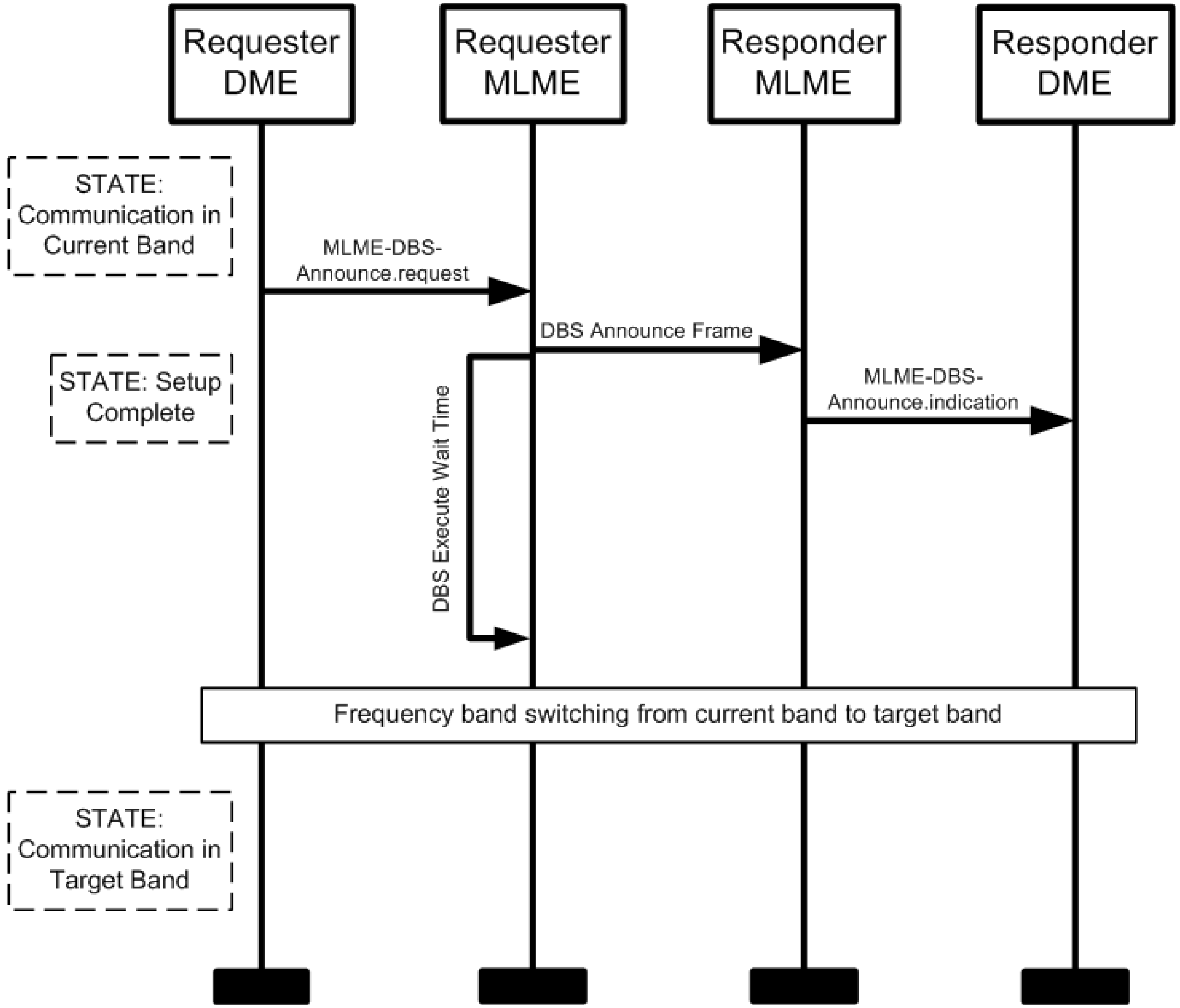
State Description

- Communication in Current Band:
  - Data communication in current (old) frequency band
  - Initiator (normally the coordinator) announces the intention to switch frequency band
  - Enhanced beacon with DBS IE is used to initiate state change
    - DBS IE consists of the time to commencement of band switching
- Setup Completed:
  - Running Timer for band switching
  - If initiator decides to disable the band switching, Enhanced beacon with DBS IE is sent
- Communication in Targeted Band:
  - Data communication in target (new) frequency band

Operational Procedure

- To start DBS, the capability of frequency bands and channels are exchanged between devices in the network
  - In the case where the enhanced beacon with DBS IE is broadcasted, there will be no capability inquiry and response between devices
- The requester sends out the enhanced beacon with DBS IE containing all information needed to perform band switching, including the time for all the devices to commence the band switching
- When the Execute time scheduled by the requester arrives, the operating band of both the requester and responder will be switched to the new band parameters
- During the period of Execute time waiting, if the requester decides to cancel DBS, Enhanced beacon with DBS IE can be used to cancel the operation

Message Sequence Chart



Frame Format
~ DBS IE ~

Bits			Octets
0	1-8	9-15	
Type = 0	Element ID	IE Content Length	IE Content

Octets	
2	Variable
DBS Execute time	New Channel Page

Frame Format ~ DBS IE ~

- To exchange DBS capability
  - Set New Channel Page to the band and channel of interest
  - Set Execute Time to all one
- To announce the DBS intention
  - Set New Channel Page to the targeted band and channel
  - Set Execute Time to the intended time to commence switching
- To cancel the DBS intention
  - Set New Channel Page to the current (old) band and channel
  - Set Execute Time to all zero

Service Primitives

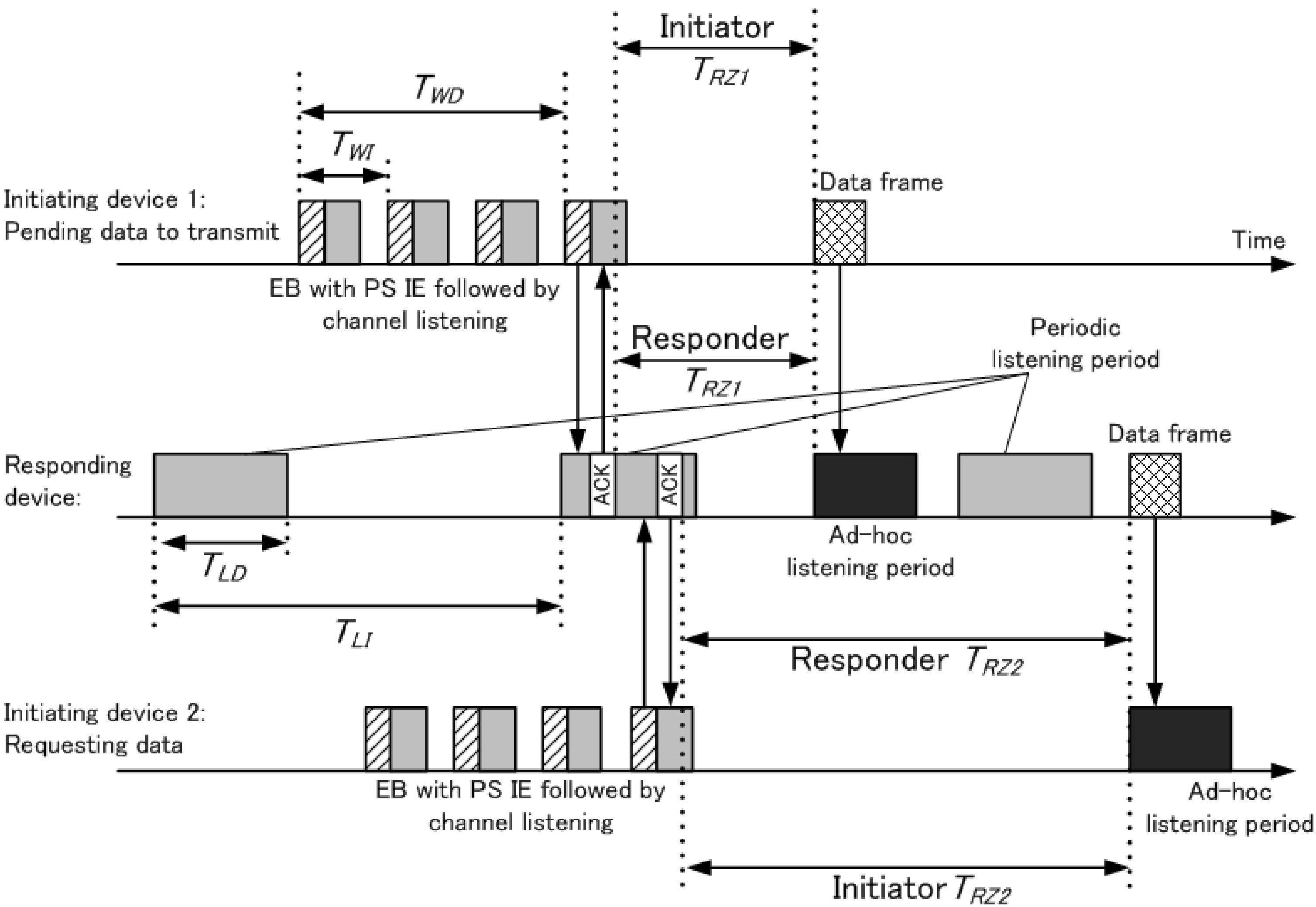
- Primitives between DME and MLME for enhanced beacon with a DBS IE
  - MLME-BEACON.request
  - MLME-BEACON.confirm
- New parameters to be added to the DBS IE
  - DBS Execute Time

Power Saving Mechanism

Summary

- This document proposes a power saving mechanism for IEEE 802.15.4 low rate WPAN systems
- What was concluded in our presentation in 2012 May Atlanta meeting, doc.12/222r0:
  - For most LR-WPAN applications, power saving mechanism to enable long battery lifespan of devices is important
- This document presents the details of the power saving mechanism
  - Required protocol
  - Addition of IE
  - Modification of service primitives

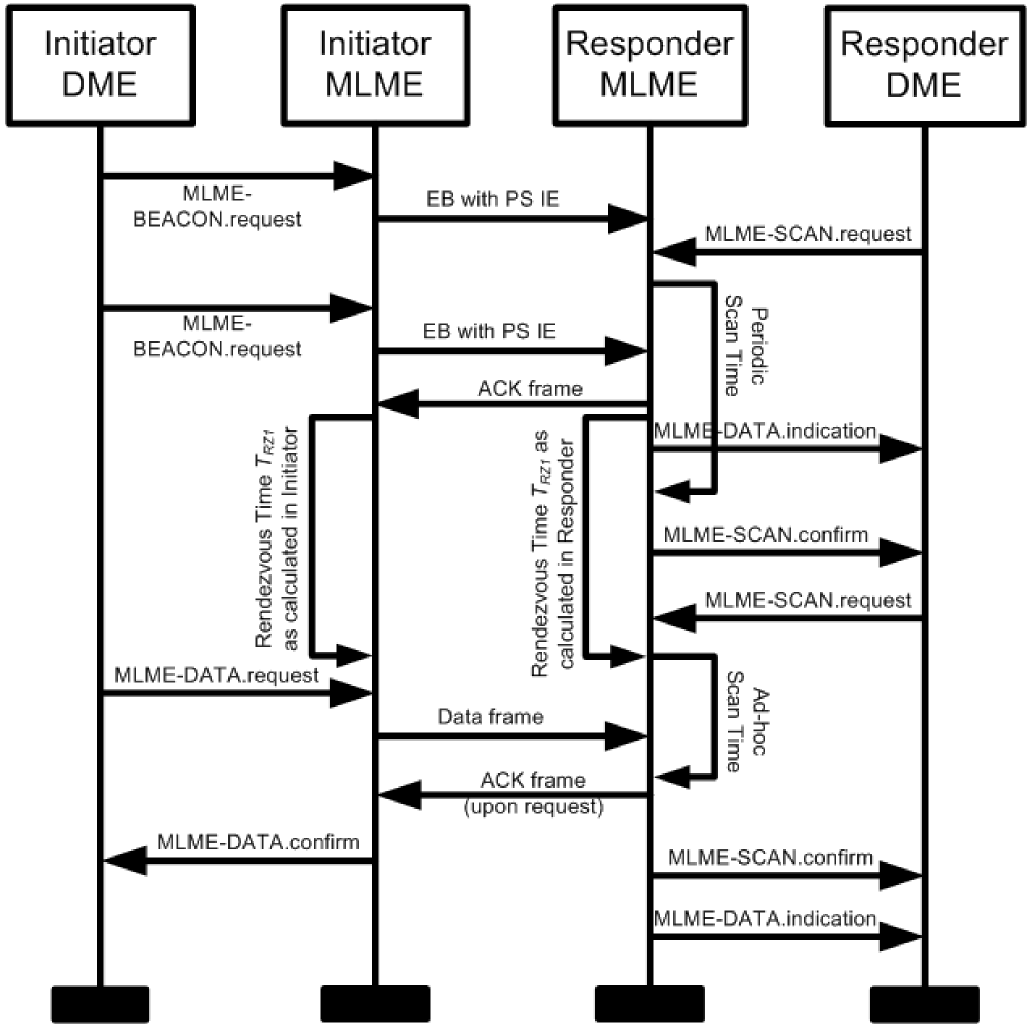
Illustration of Procedure



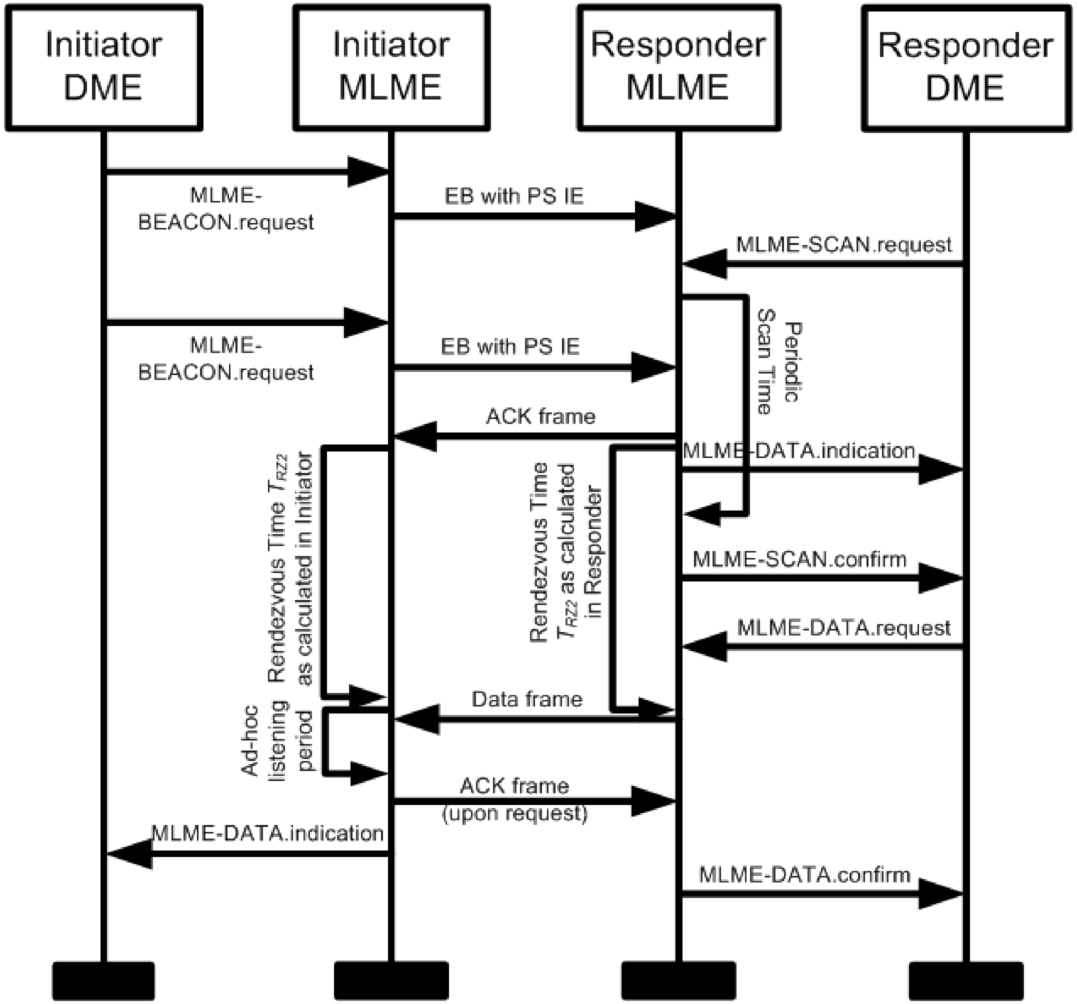
Operational Procedure

- The responding device switches on the periodic listening periods T_{LI} apart each with duration T_{LD}
  - The responding device may announce its T_{LI} and T_{LD}
- The initiating device transmits multiple enhanced beacon frames with PS IE (followed by channel listening), T_{WI} apart for maximum total duration T_{WD} (or upon receiving an ACK, whichever occurs first)
  - It is recommended that $T_{WI} <= T_{LD}$ and $T_{LI} <= T_{WD}$
  - Upon receiving ACK from the responding device, transmission of enhanced beacon frames with PS IE will be stopped
- The PS IE contains information on:
  - Whether the initiating device is transmitting pending data (case 1) or requesting for data (case 2)
  - Timing information for rendezvous
- Upon receiving an enhanced beacon frames with PS IE, the responding device
  - Case 1: Switches on an ad-hoc listening period to receive the data from the initiating device at rendezvous time (the ad-hoc listening period can be set as the subsequent periodic listening period)
  - Case 2: Transmit the data requested by initiating device at rendezvous time
- Rendezvous time can be set by initiator and updated by responder

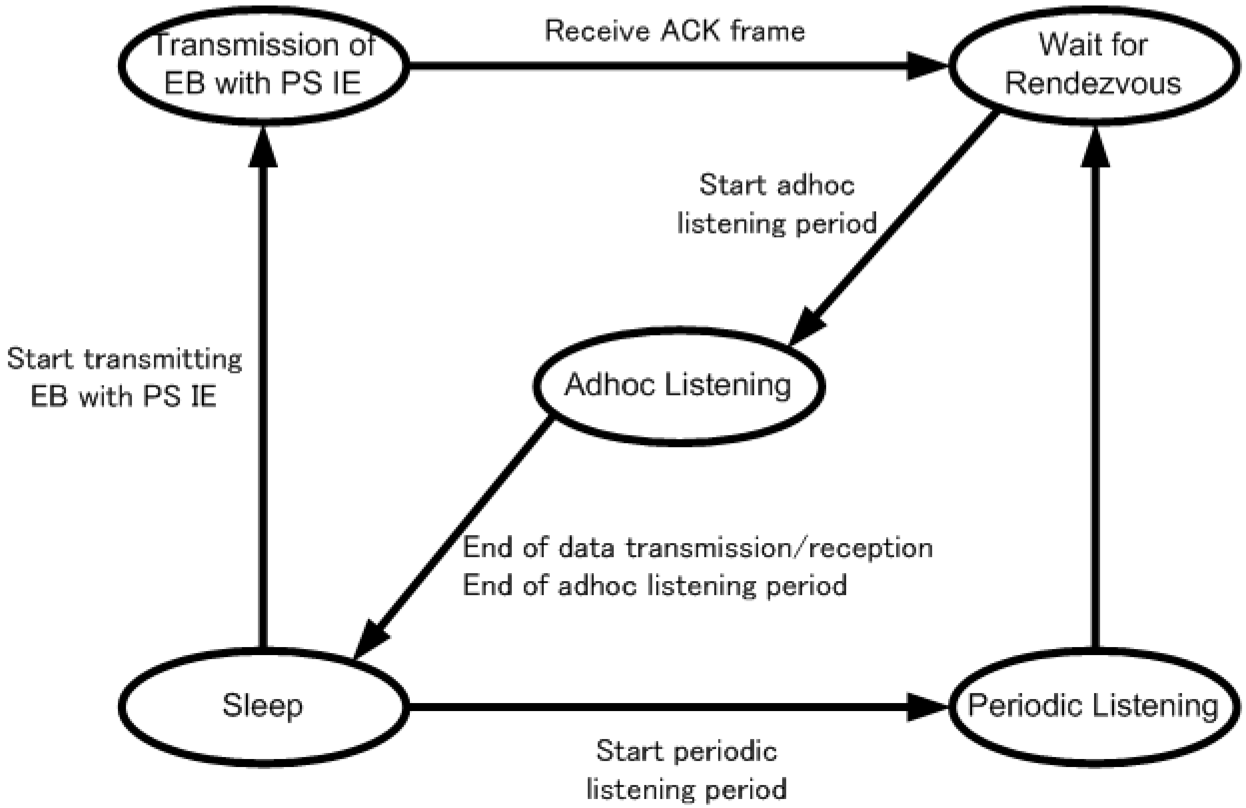
MSC for Case 1
~ Initiator with Pending Data~



MSC for Case 2 ~ Initiator with Data Request ~



State Transition Diagram



Frame Format ~PS IE~

Bits			Octets				
0	1-8	9-15	1	2	2	2	1
Type = 0	Element ID	IE Content Length	PS Control	Periodic Listening Interval	Periodic Listening Duration	Rendezvous Time	Data Size

PS Control:

Bits	Description
0	Pending data to transmit
1	Requesting data
2	Announce T_{LI} and T_{LD}
3-255	Reserved

All three fields use the same bit allocation pattern

Bits	Description
0	0
1	1ms
…	…
65535	65535ms

Data Size:

Bits	Description
0	0
1	TBD
…	…
255	TBD

Service Primitives

- Primitives between DME and MLME for enhanced beacon with a PS IE
  - MLME-BEACON.request
  - MLME-BEACON.confirm
- Primitives between DME and MLME of initiator and responder devices for periodic and ad-hoc scan
  - MLME-SCAN.request
  - MLME-SCAN.indication
- New parameters to be added to the DBS IE
  - PS control
  - Periodic listening period
  - Periodic listening interval
  - Rendezvous time
  - Data size

Direct Device-to-device Data Transfer

Summary

- We propose four modes for direct device-to-device data transfer in IEEE 802.15.4 beacon-enabled PAN
- Neighbor discovery mechanism is also provided
- Devices of the same coordinator are enabled to transfer data directly with the proposal
- Main operation flow chart, procedures as well as message sequence charts are presented

Outline

- Motivation
- Main changes to current 802.15.4 standard
- Neighbor discovery mechanism and message sequence chart
- Mechanism of Probing-mode direct data transfer
- Mechanism of Polling-mode direct data transfer
- Mechanism of Broadcast-mode direct data transfer
- Mechanism of Multicast-mode direct data transfer

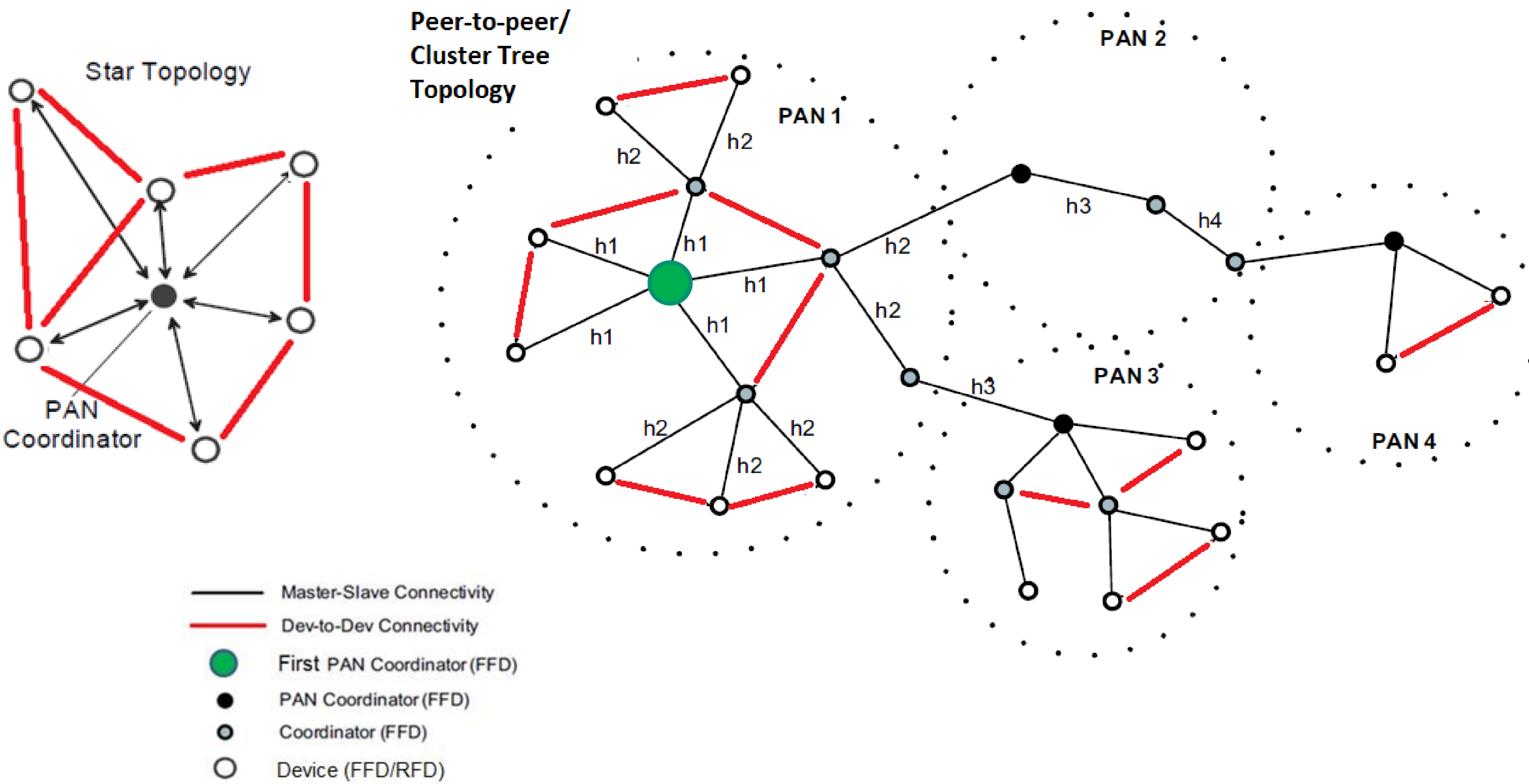
Motivation (1/2)

- 802.15.4m has wide applications such as SUN, ITS, and M2M, etc. (Ref. 15-11-0684-12-004m)
- Peer-to-peer communications are supposed to support 802.15.4m applications
- Although the current 802.15.4 beacon-enabled PAN does not exclude peer-to-peer connections, it has no detailed specifications, such as messages and control/data transmission processes
- In another hand, peer-to-peer communication with full connectivity in 802.15.4 beacon-enabled PAN would be very complex
- As result, only communication between coordinator and device is practically supported in current 802.15.4 beacon-enabled PAN

Motivation (2/2)

- We target to provide enhanced network connectivity with device-to-device data transfer in 802.15.4 beacon-enabled PAN, with limited modifications of the existing standard
- Direct device data transfer allows direct data transmission between devices with the same coordinator, if they are in radio range each other, without relay of their coordinator
- It is limited peer-to-peer communications, however, it increases network connectivity and may meet application requirements of 802.15.4m
- Moreover, it saves energy, as well as bandwidth, and enables shorter time delay, since no coordinator relay involved

Main Changes to Current 802.15.4 (1/2)

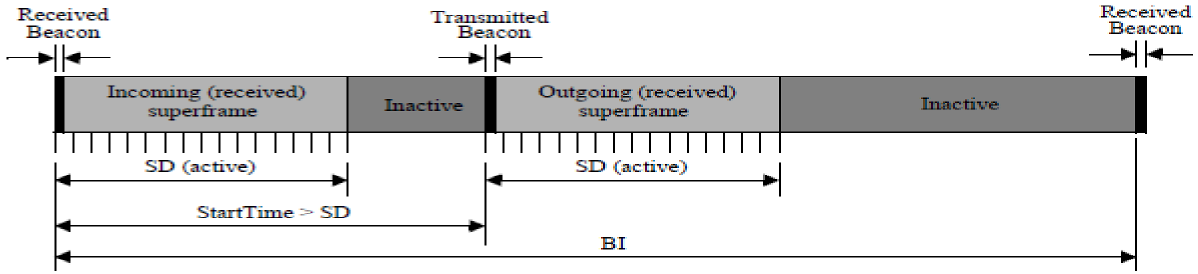


Main Changes to Current 802.15.4 (2/2)

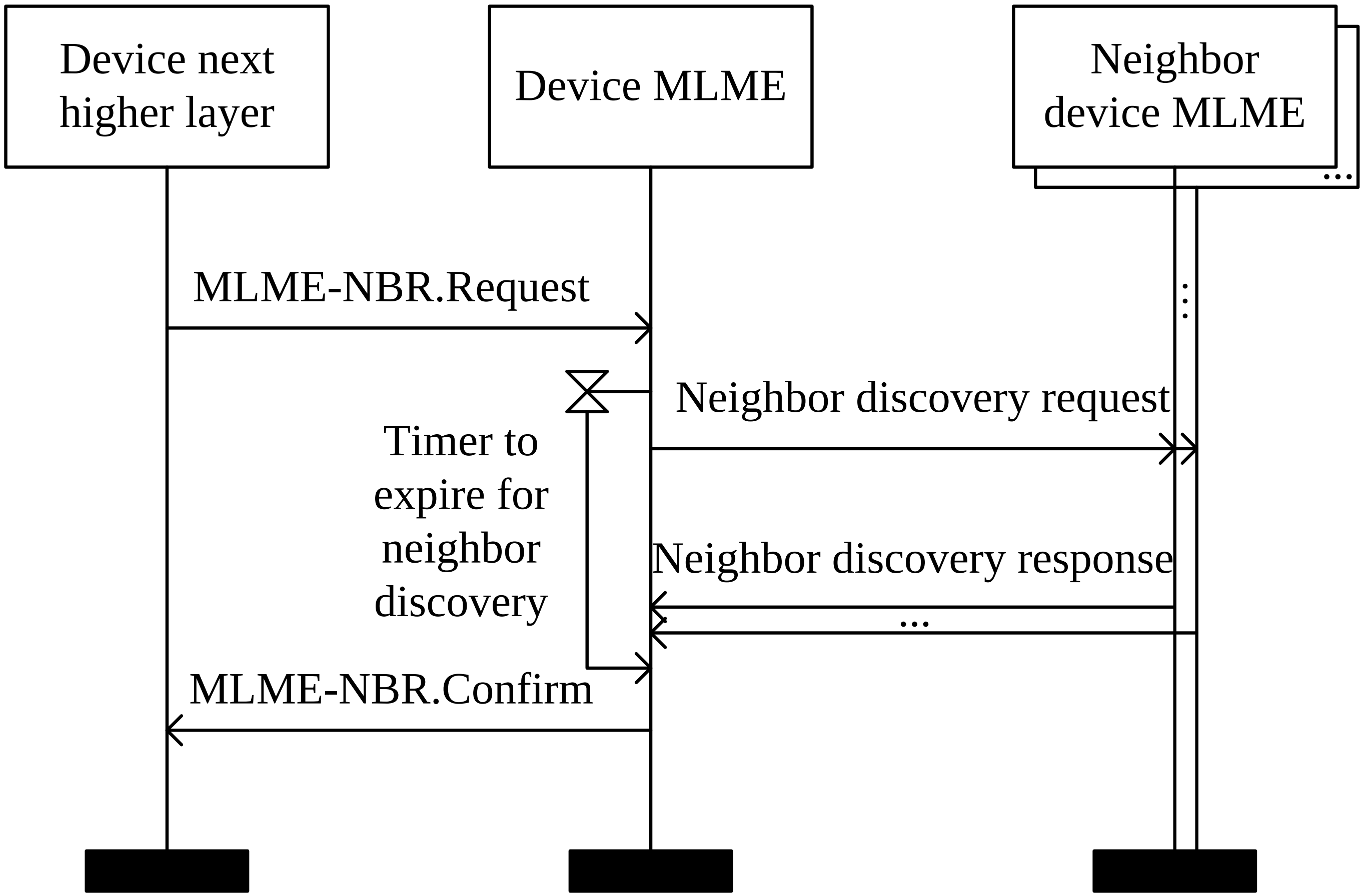
- New device functions
  - Neighbor discovery
  - Probing device for transmitting data
  - Polling device for data reception
  - Broadcast and multicast data
- New commands
  - Neighbor discovery request
  - Neighbor discovery response
  - Probe command
- New Primitives
  - MLME-NBR.Request
  - MLME-NBR.Confirm
- Frames to be modified
  - Beacon frame
  - Data request command frame
  - Acknowledge frame
  - Data frame
- Existing primitives to be modified
  - MLME-POLL.Request
  - MLME-POLL.Confirm
  - MCPS-DATA.Request
  - MCPS-DATA.Confirm
  - MCPS-DATA.Indication

Neighbor Discovery

- What's a neighbor device?
  - In this standard, a neighbor device is a peer device that associates with the same coordinator in a beacon-enabled PAN
- Why a device need to discover neighbor device?
  - To enable direct device-to-device data transfer
- When can a device carry out neighbor discovery?
  - A device may carry out neighbor discovery after association with its coordinator, at appropriate time when receives the MLME-NBR.Request primitive from the next higher layer.
  - On beacon-enabled PAN, a coordinator shall carry out neighbor discovery in the active portion of its incoming superframe.



Message Sequence Chart for Neighbor Discovery



Message Sequence Chart for Neighbor Discovery (cont.)

- // requestor action – sending request //
  - Upon receiving MLME-NBR.Request primitive from next higher layer, at appropriate time a device broadcasts Neighbor Discovery Request command and starts a timer that will expire after [TBD].

- // neighbor device action – responding to request //
  - If a recipient device of the Neighbor Discovery Request command associated with the same coordinator as the requester, it sends Neighbor Discovery Response command to the requester device.

Message Sequence Chart for Neighbor Discovery (cont.)

- // requester action – adding neighbor //
  - When receives a Neighbor Discovery Response command before expiration of the timer, the requester adds the sender to neighbor list if it is not included. The requester device ignores Neighbor Discovery Response command received after expiration of the timer.

- // requester action – reporting to higher layer //
  - After the timer expires, the requester MAC issues MLME-NBR.Confirm primitive to next higher layer.

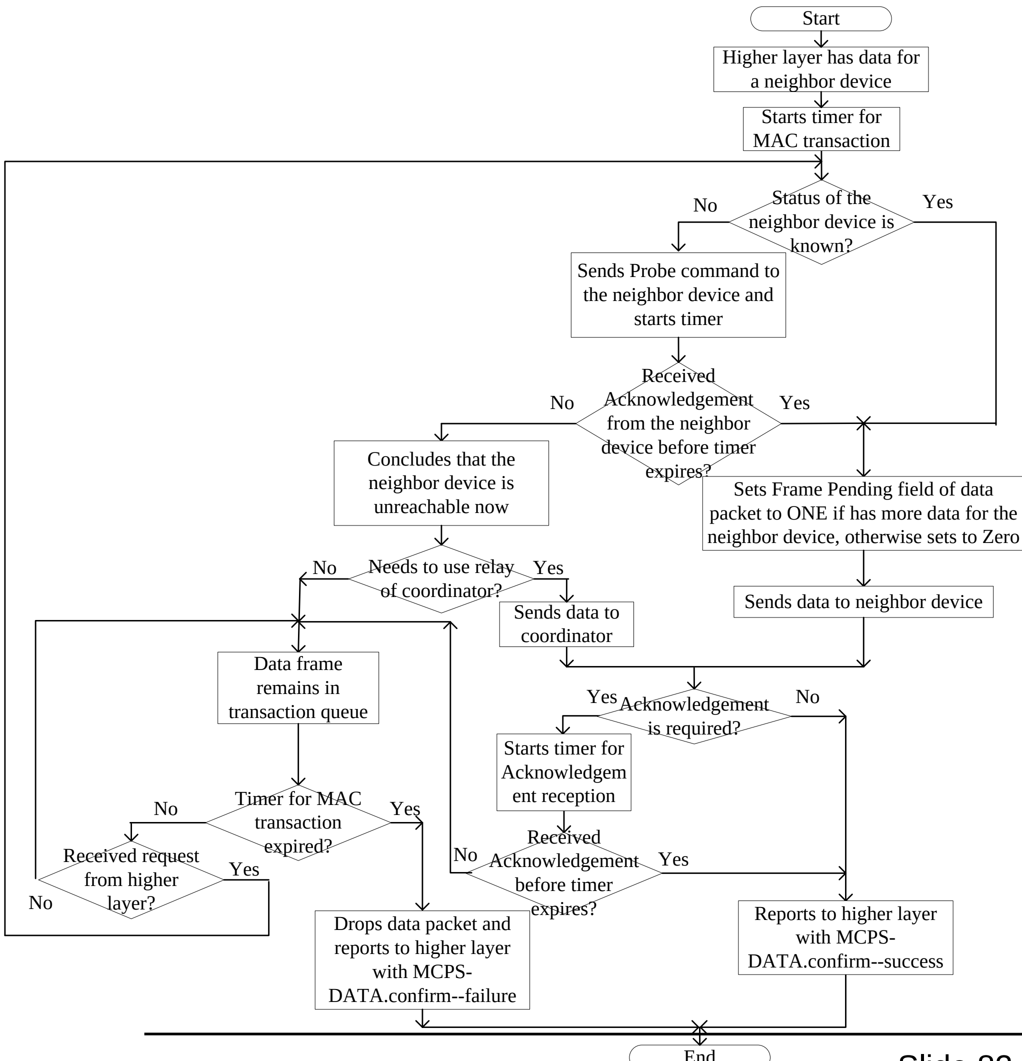
Mechanism of Direct Device-to-device Data Transfer

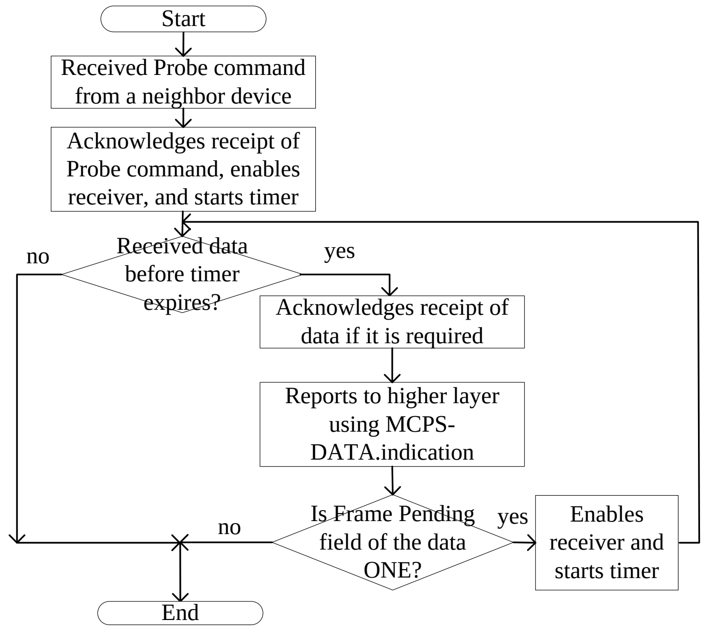
- Four modes of direct data transfer are proposed:
  1. Probing Mode – hi, are you there? I have data for you!
  2. Polling Mode – hi, do you have data for me?
  3. Broadcast Mode – to broadcast data to all neighbor devices
  4. Multicast Mode – to send data to a list of neighbor devices

Comparison to Legacy Data Transfer Methods of Beacon-enabled PAN

Data transfer between coordinator and device		Direct device-to-device data transfer			
Coordinator to Device	Device to Coordinator	Probing mode	Polling Mode	Broadcast Mode	Multicast Mode
Indicating data pending in beacon; sends data to device when request	Device sends to coordinator when synchronize	Source device probes status of destination device before transmitting	Device polls neighbor device for data	Device simply broadcasts data to neighbor devices directly	Device simply multicasts data to a list of neighbor devices directly

Probing Mode





Operation flow chart of device being probed

Operation flow chart of probing device

Probing Mode (cont.)

- // if status of neighbor is known, it is unecessary to probe //
  - In Probe-mode direct data transfer, if a device has data for a neighbor device and it is known that the receiver status of the neighbor device is "on", the device sends data to the destination device at appropriate time.
- // if neighbor status is unknown, it needs to probe status //
  - If the receiver status of the neighbor device is unknown, it sends Probe command to the destination device and starts timer with duration of [TBD -- *macAckWaitDuration*].
- // in case no ACK received, the neighbor is unreachable //
  - If it receives no acknowledgement of the Probe command from the neighbor destination device before expiration of the timer, the destination device is concluded unreachable at this moment.

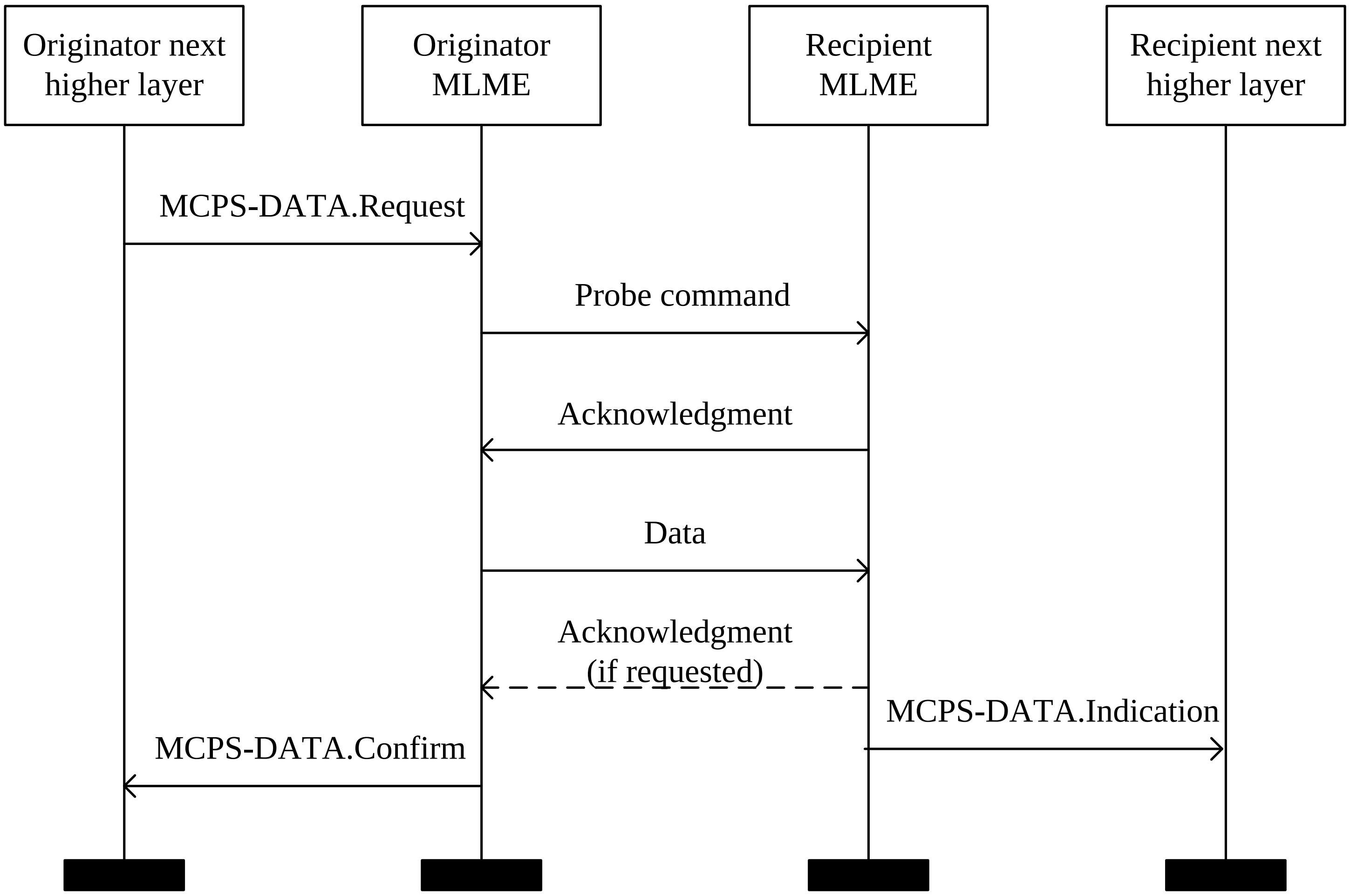
Probing Mode (cont.)

- // when receives ACK, the neighbor is "on" //
  - If before expiration of the timer, it receives acknowledgement of the Probe command from the neighbor destination device, it sends the data to the neighbor device at appropriate time.
- // to remind more data pending //
  - Before sending data to the destination neighbor device, if the device has more data to the destination neighbor device, it sets the Frame Pending field of the data packet to ONE, otherwise it sets the Frame Pending field of the data packet to ZERO.
- // probe message needs being acknowledged //
  - On receiving a Probe command, a destination device shall send acknowledgement and enable its receiver for at most [TBD -- *macMaxFrameTotalWaitTime*] to receive data from the source device.

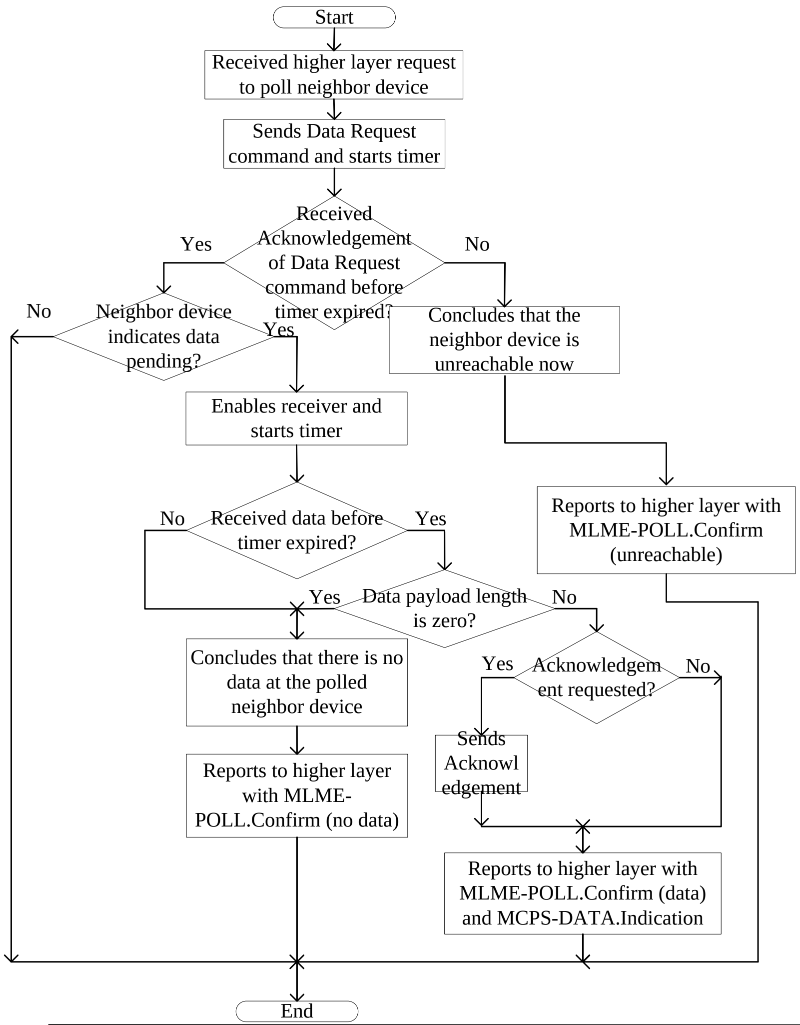
Probing Mode (cont.)

- // neighbor device receives data and may acknowledge //
  - If it receives data before expiration of the timer, it acknowledges receipt of the data if it is required. If the Frame Pending field of the data is ONE, it continues to enable its receiver for at most [TBD -- *macMaxFrameTotalWaitTime*].
- // in case destination device is unreachable, two options//
  - If the destination device is detected unreachable, there are two options for the source device: (a) the data can be sent to its coordinator and then the coordinator sends the data to the destination device; (b) the data frame remains in transaction queue until another request from higher layer or *macTransactionPersistenceTime* is reached.
- // data transaction will be discard in case
  - If *macTransactionPersistenceTime* is reached, the transaction information will be discarded, and the MAC sublayer will issue a failure confirmation to the next higher layer.

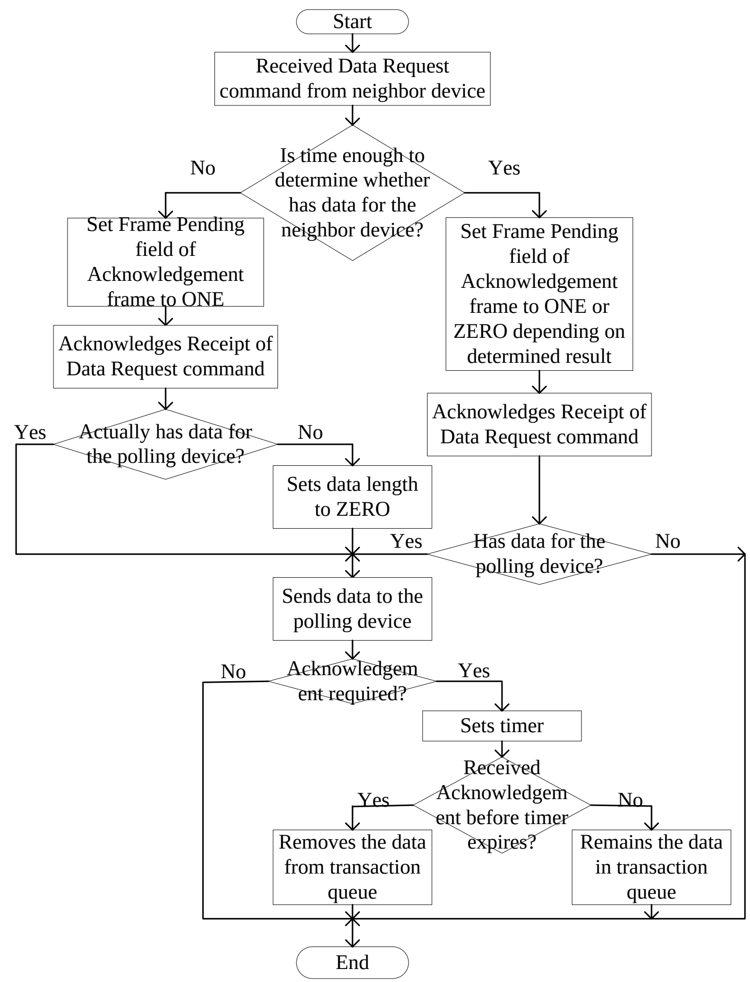
Message sequence of Probe-mode direct data transfer



Polling Mode



Operation flow chart of polling device



Operation flow chart of device being polled

Polling Mode (cont.)

- // polling-mode data transfer is passive //
  - In Polling-mode direct data transfer, a device keeps data in transaction queue until the data is successfully transmitted to the destination neighbor device or it has to be removed due to resource overflow.
- // polling device sends data request command //
  - With Polling-mode direct data transfer, when a device's MAC sublayer receives MLME-POLL.request primitive from next higher layer, it sends Data Request command to a target neighbor device at appropriate time and starts a timer with duration of [TBD -- *macAckWaitDuration*].
- //polled device acknowledges data request command //
  - On receiving a Data Request command, a device shall send acknowledgement to confirm successful reception of the command and indicate whether it has data pending for the polling neighbor.

Polling Mode (cont.)

- // polled device marks data indication //
  - If before sending the acknowledgement of Data Request command, the polled device is able to determine that it has data pending for the polling device, it sets the Frame Pending field of the acknowledgement to ONE. If it is able to determine that it has no data pending for the polling device, it sets the Frame Pending field of the acknowledgement to ZERO. If it has no enough time to determine whether it has data pending for the polling device, it sets the Frame Pending field to ONE.
- // in case no ACK received at polling device //
  - If before expiration of the timer, the polling device receives no acknowledgement of the Data Request command, it concludes that the neighbor device is not reachable at this moment. The polling device MAC sublayer shall issue a failure confirmation to next higher layer.

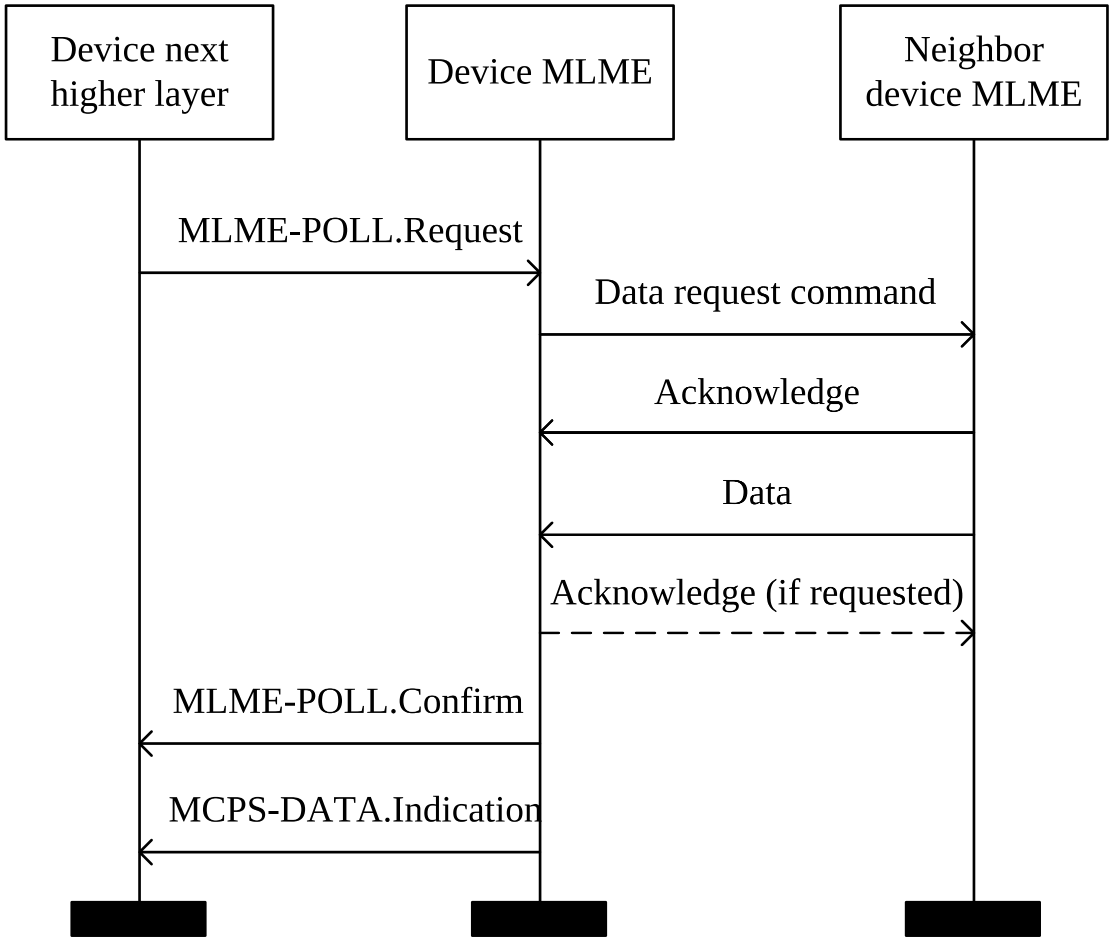
Polling Mode (cont.)

- // in case frame pending is ZERO //
  - If before expiration of the timer, the polling device receives acknowledgement with the Frame Pending field set to zero, it concludes that there is no data pending at the neighbor device.
- // in case frame pending indication is ONE //
  - If before expiration of the timer, the polling device receives acknowledgement with the Frame Pending field set to one, it shall enable it receiver for at most [TBD] to receive the corresponding data from the neighbor device.

Polling Mode (cont.)

- // data receiving at polling device //
  - If the polling device does not receive a data frame from the neighbor device within [TBD] or if the polling device receives a data frame from the neighbor device with a zero length payload, it shall conclude that there are no data pending at the neighbor device. If the polling device does receive a data frame from the neighbor device, it shall send an acknowledgment frame, if requested, thus confirming receipt of the data frame.
- // in case more data pending //
  - If the Frame Pending field of the data frame received is one, then the neighbor device has more data pending. In this case it may extract the data by sending a new Data Request command to the neighbor device.

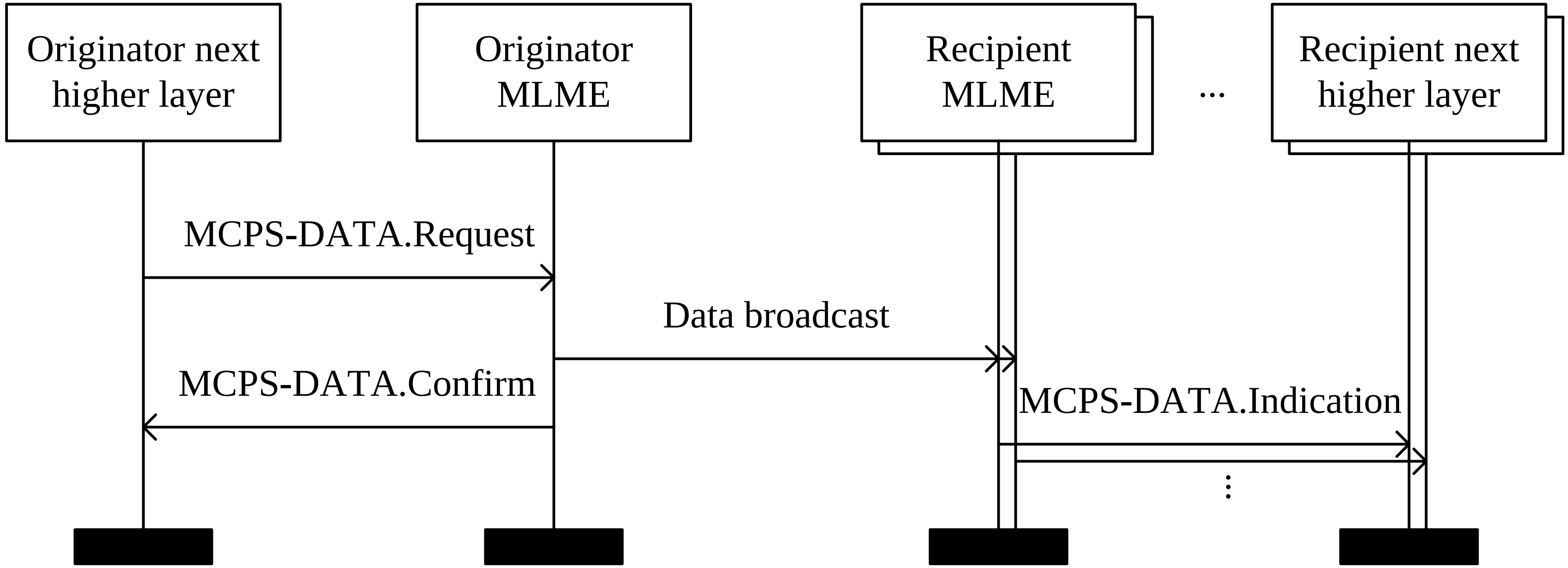
Message Sequence Chart of Polling-Mode Direct Data Transfer



Broadcast Mode

- // data is broadcasted directly when higher layer request //
  - In Broadcast-mode direct data transfer, upon receiving higher layer MCPS-DATA.Request primitive for broadcasting a data frame, a device broadcasts the data frame at appropriate time, [TBD -- by using CSMA/CA algorithm]. The AR field of the data frame shall be set to indicate no acknowledgement requested.

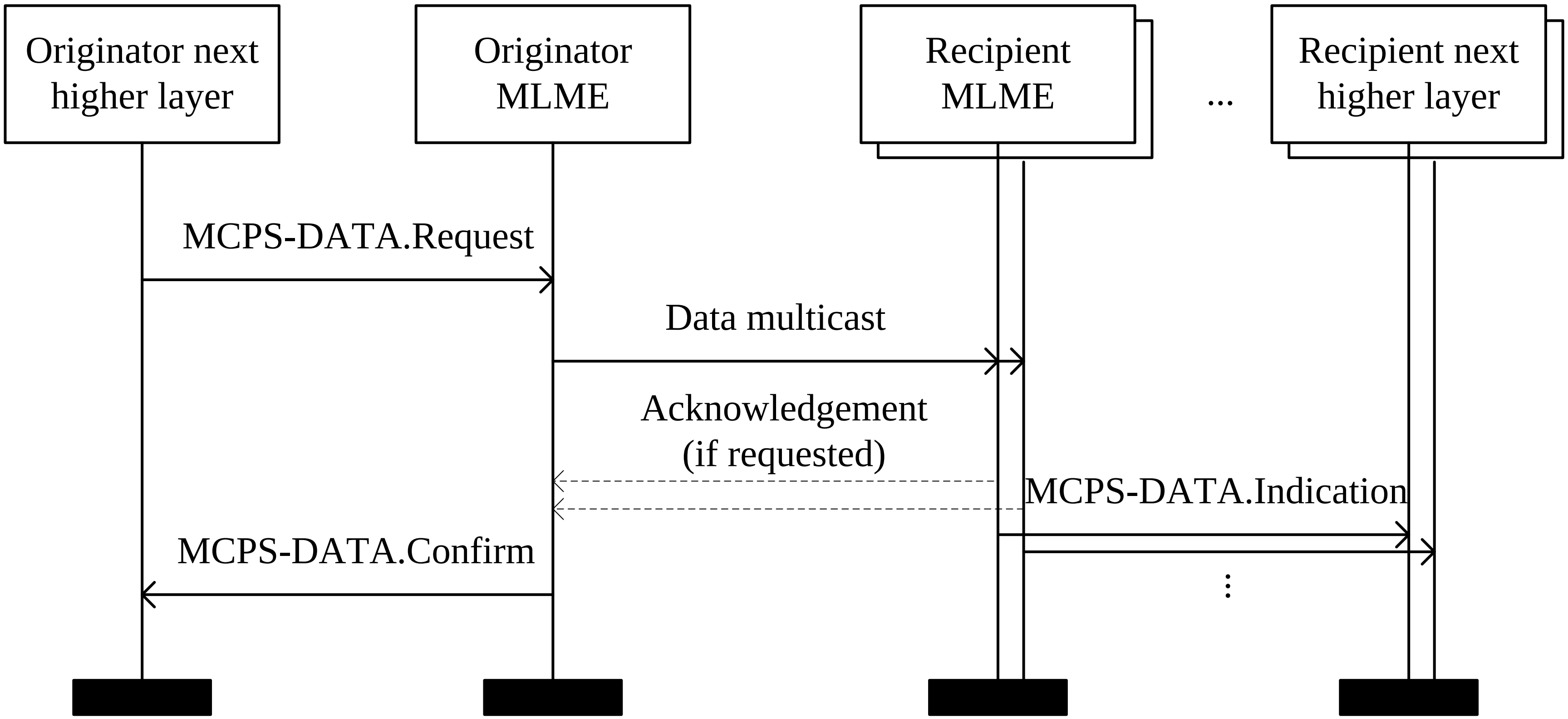
Message Sequence Chart of Broadcast-Mode Direct Data Transfer



Multicast Mode

- // data is sent out directly when higher layer request //
  - A device multicast a data frame to a subset of its neighbor devices upon receiving higher layer MCPS-DATA.Request primitive with type of Multicast. A multicast data frame may request acknowledgement.
- // data receiver needs to subscribe multicast group //
  - A device may subscribe a multicast group by enabling reception of data frames destined for corresponding multicast address. The format of multicast address is [TBD].

Message Sequence Chart of Multicast-Mode Direct Data Transfer



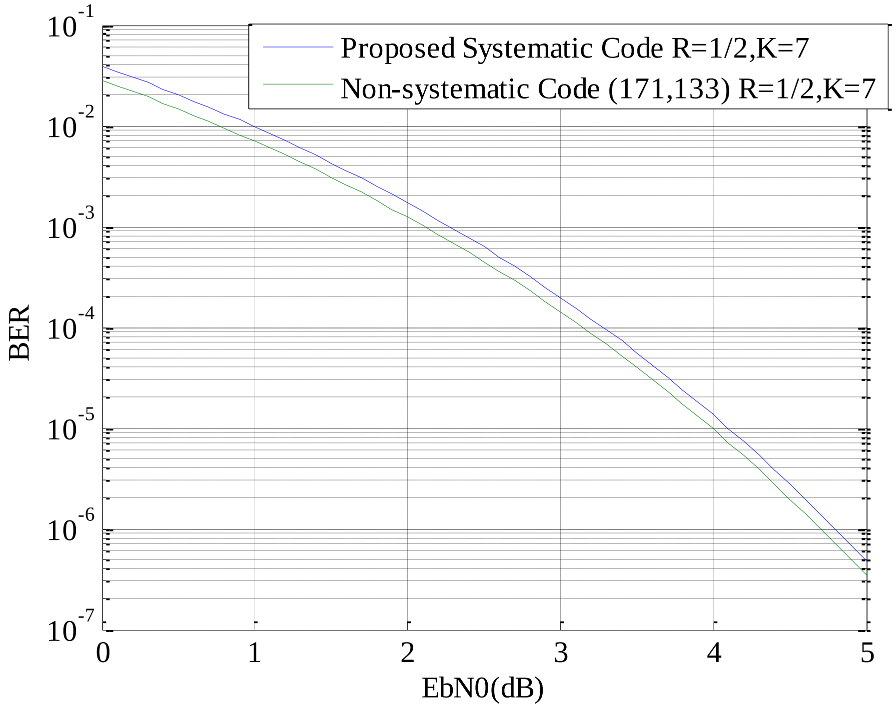
Co-existence among TG4m MAC modifications

- TG4m-MAC should achieve co-existence among not only previous modifications but also further expansions as follow:
  1. TVWS Multi-Channel Utilization (TMCU)
     – Enhancement on GTS allocation and management function
  2. Spectrum Management
     – Definition of Sensing function
  3. Ranging
     – Definition of Ranging function, or enhancement on Beacon IE

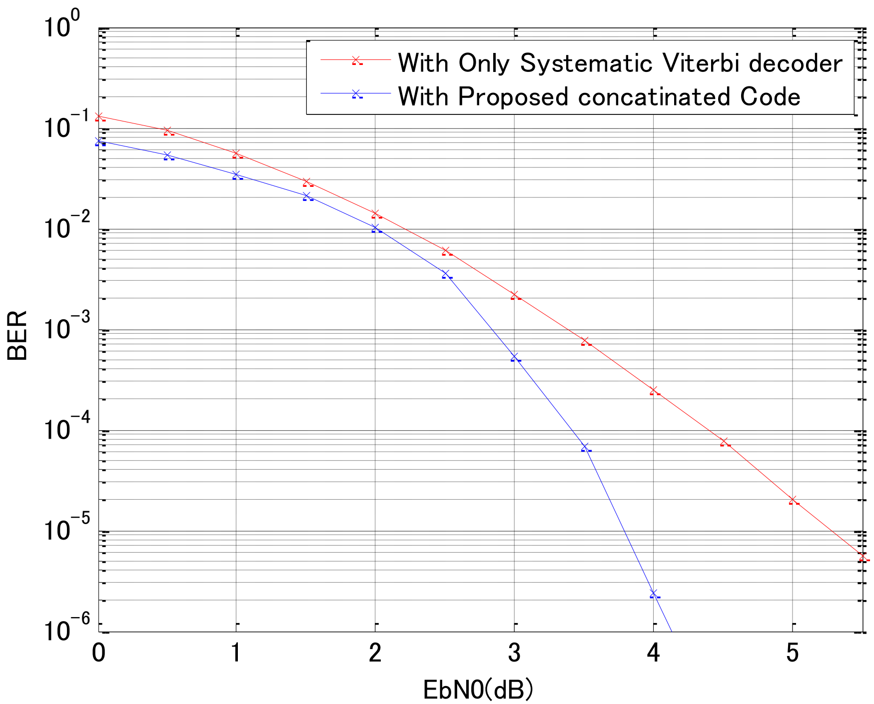
APPENDIX

Appendix: BER Performance of proposed FEC

- Recursive systematic coder with Viterbi decoder has comparable performance with non-systematic coder (133,171) in coding rate of 1/2
- The proposed concatenated code outperforms single systematic coder with further coding gain of 1.5 dB at BER=10^{-6}



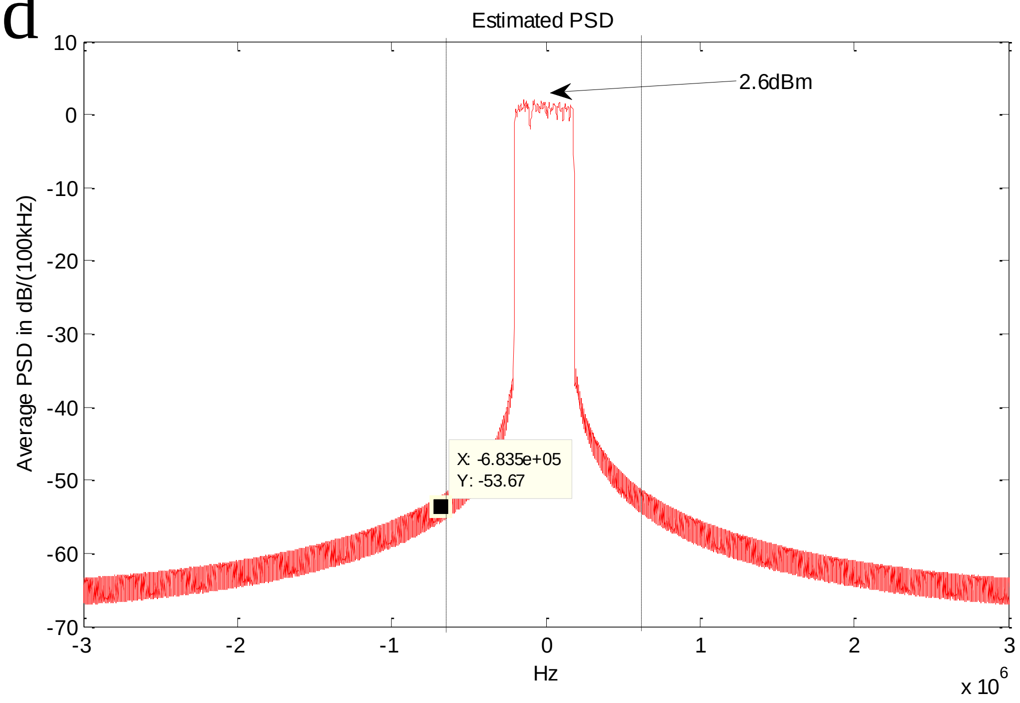
Comparison in theoretical performance of systematic and non-systematic convolutional coder /Viterbi decoder (R=1/2)



Comparison in systematic convolutional code and concatenated code (traceback length:64, soft bit: 3bit)

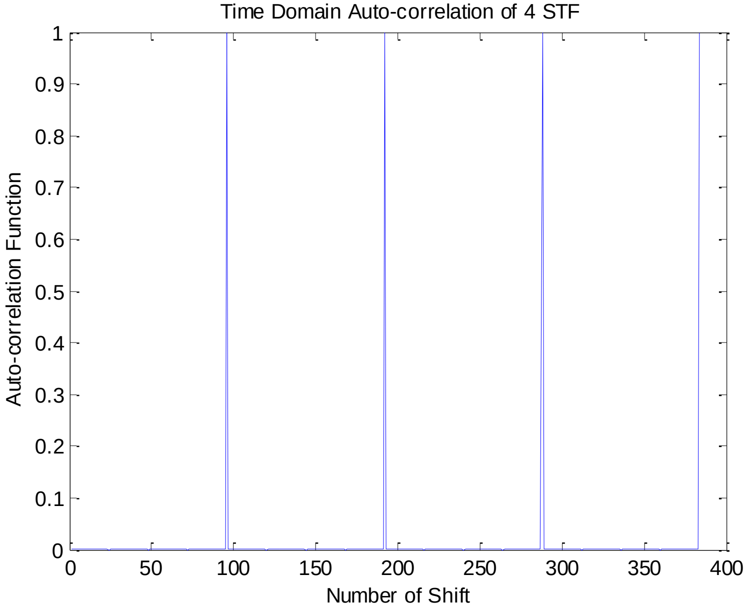
Appendix: Validation: PSD of the proposed OFDM PHY Modes #1 and #2

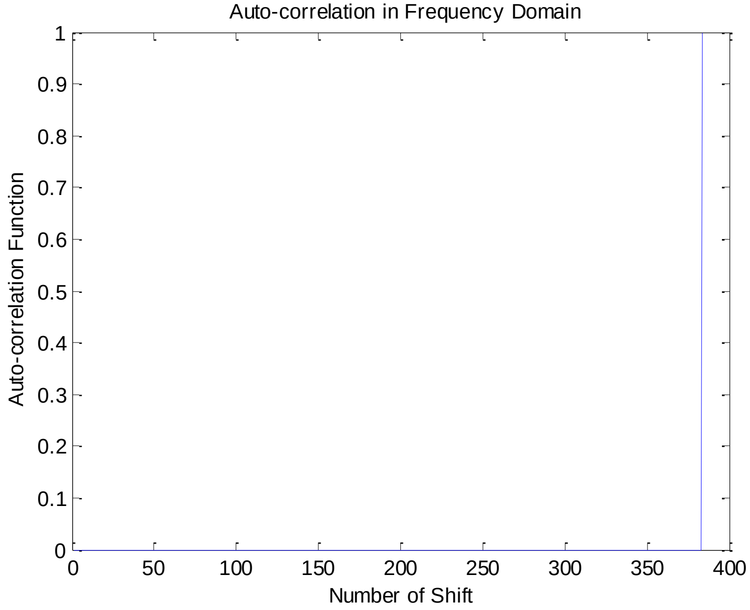
- the revised regulatory limits of portable devices case (i.e., PSD limit (100kHz) of 2.6dBm and adjacent channel limit (100kHz) of -52.8dBm) Satisfied



Appendix: Preamble of OFDM Modes #1 and #2 -Auto-correlation of STFs-

- STF

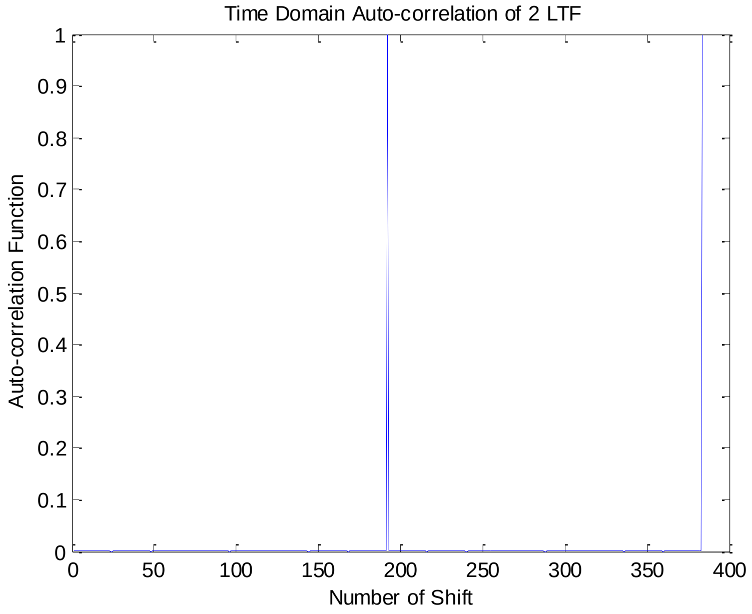


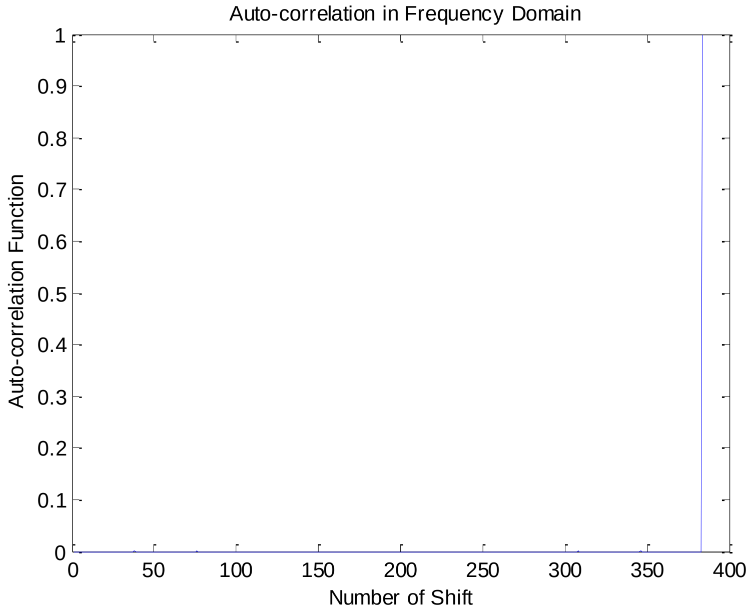


Ideal auto-correlation properties are observed in both time and frequency domains

Appendix: Preamble of OFDM Modes #1 and #2 -Auto-correlation of LTFs-

- LTF



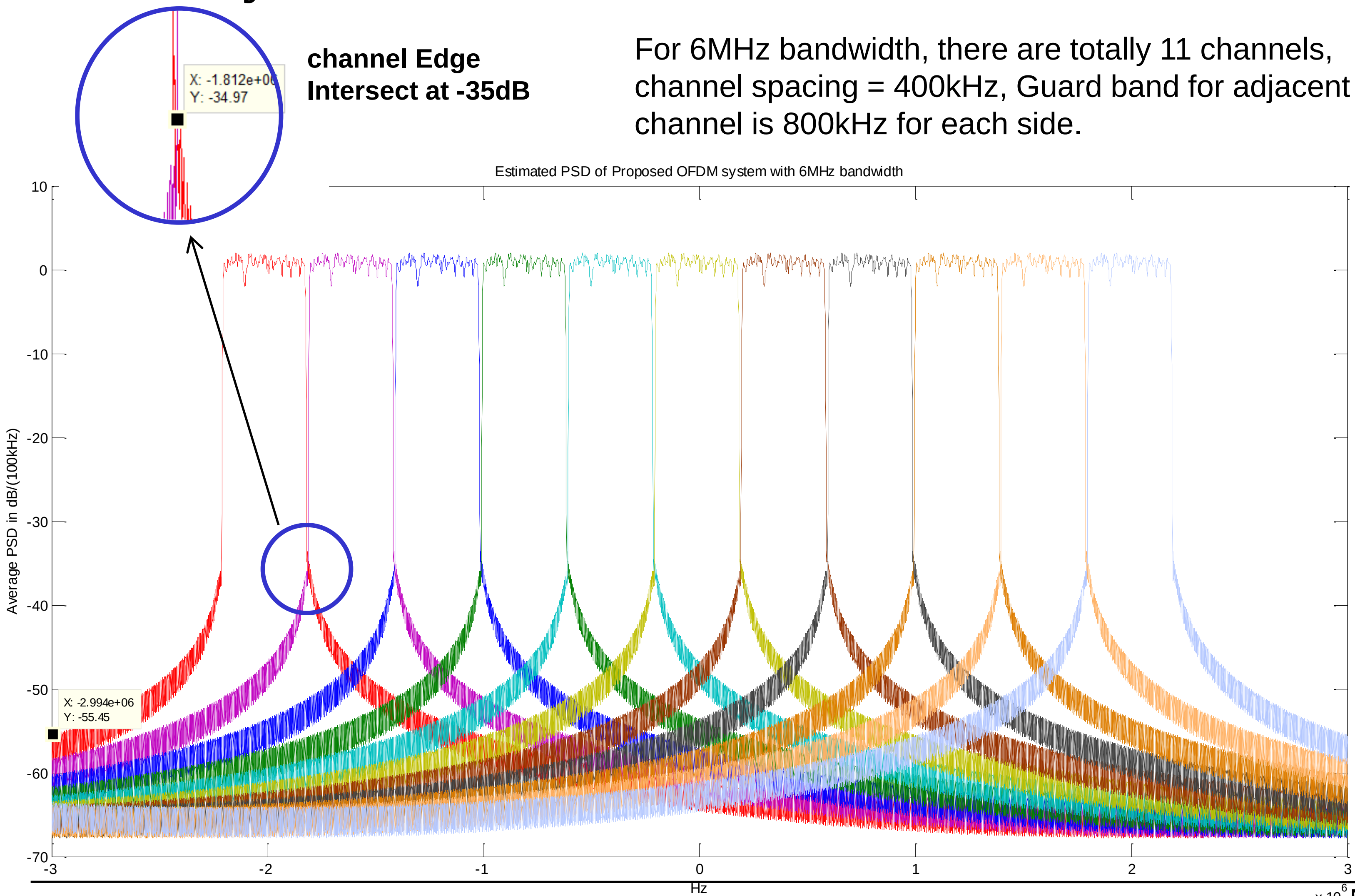


Ideal auto-correlation properties are observed in both time and frequency domains

Appendix: Validation of Estimated PSD of Proposed OFDM System with 11 Channels for 6MHz Bandwidth

For 6MHz bandwidth, there are totally 11 channels, channel spacing = 400kHz, Guard band for adjacent channel is 800kHz for each side.

channel Edge Intersect at -35dB



Appendix: Validation of Estimated PSD of Proposed OFDM System with 16 Channels for 8MHz Bandwidth

For 8MHz bandwidth, there are totally 16 channels, channel spacing = 400kHz, Guard band for adjacent channel is 800kHz for each side.