

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

Submission Title: Proposal of the Hybrid L2 Routing for IEEE 802.15.10

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Re:

Abstract: A proposal for the IEEE 802.15 TG10 Recommended Practice to propose L2 Routing to be applied for IEEE 802.15.4 - especially cluster-Tree and TVWS multi-channel Tree PAN topologies.

Purpose: Response to the IEEE802.15 TG10 call for final proposal

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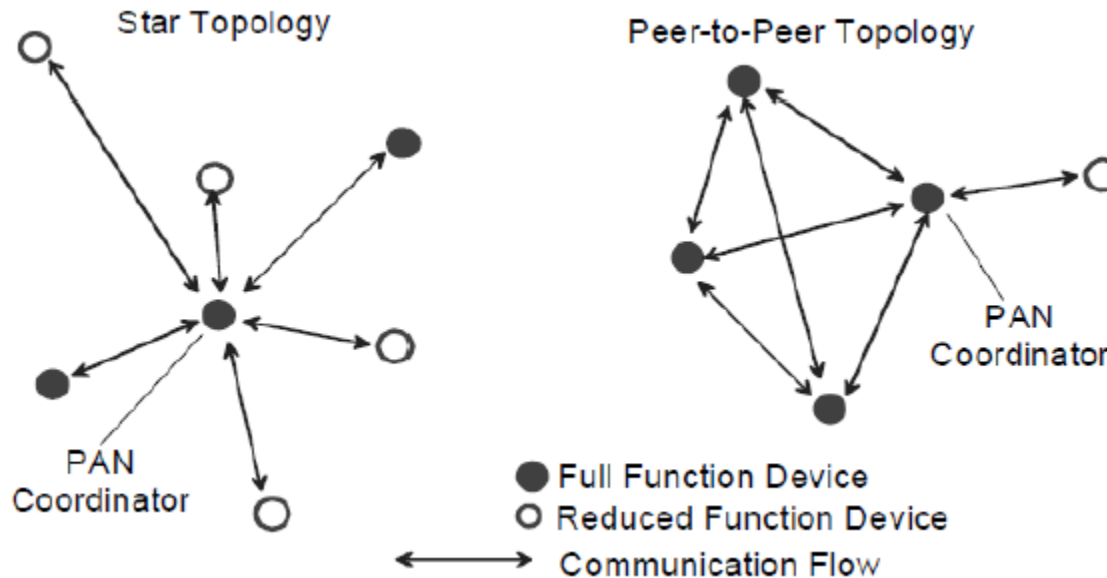
Requirements of IEEE 802.15.10 Layer 2 Routing

- General requirements
 - Compatible with IEEE 802.15 family protocols
 - Multi-hop relay, self-healing, self-configuration, and self-optimization
 - Support for commercial automation, control services and similar applications

- Functional requirements
 - Route establishment
 - Dynamic route discovery and reconfiguration
 - Discovery and addition of new nodes
 - Breaking of established routes
 - Loss and recurrence of routes
 - Real time gathering of link status
 - Allowing for single hop appearance at the network layer (by not breaking standard L3 mechanisms)
 - Support of broadcast, multicast, and many-to-one

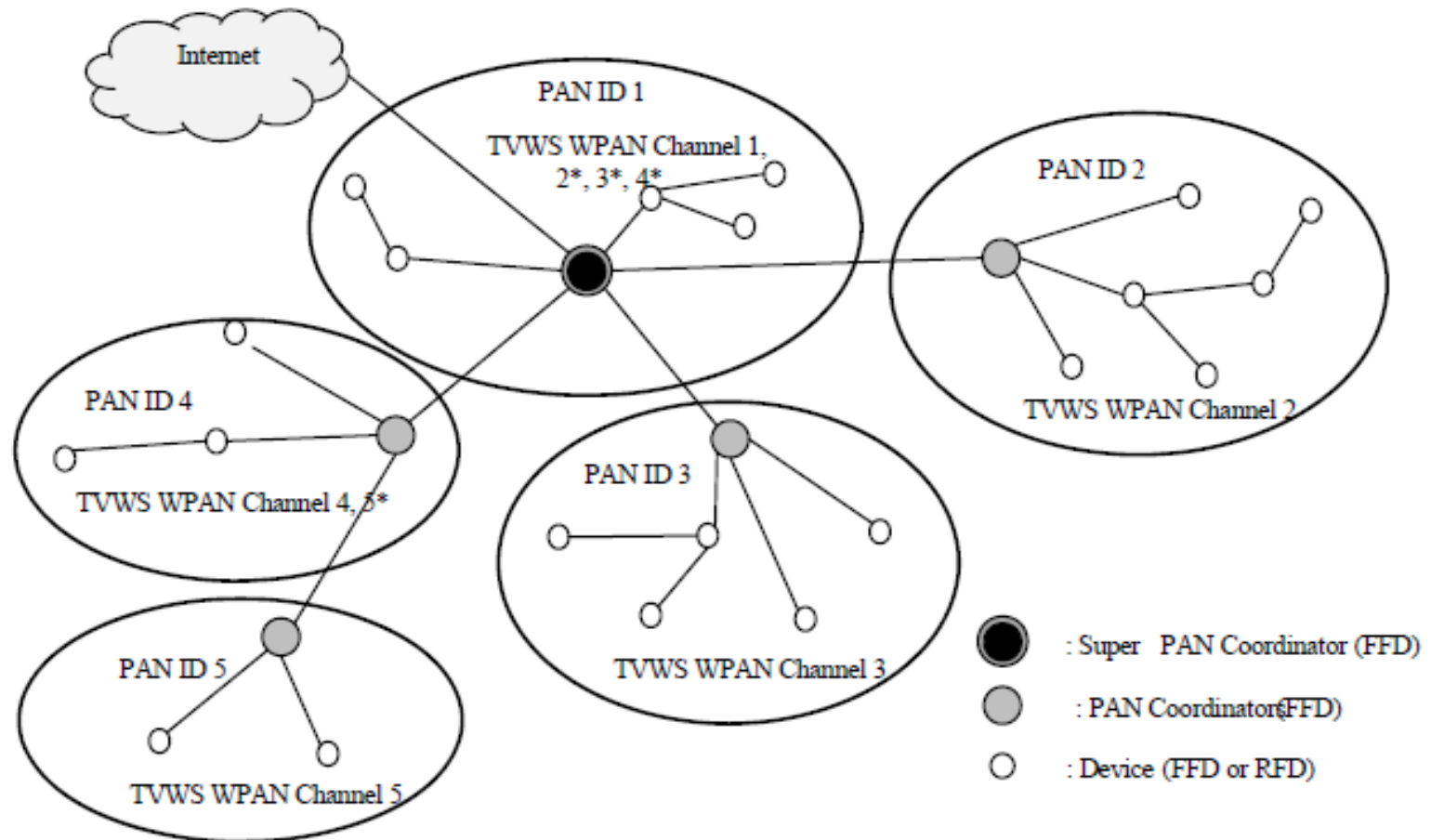
Topologies of IEEE 802.15.4 (1/2)

- Star and peer-to-peer topologies



Topology of IEEE 802.15.4m

- TVWS Multi-channel Cluster Tree PANs (TMCTP)



Hybrid Layer 2 Routing

- Proactive routing
 - Enabling routes between a PAN coordinator and coordinators.
 - Making all devices know routes heading from and to PAN coordinator.
 - PAN coordinator announcement (PANN) and PAN coordinator announcement reply (PANN-RP) control messages.

- Reactive routing
 - Enabling routes between PAN nodes each of which exists in same or different PANs.
 - P2P route request (PREQ) and P2P route reply (PREQ-RP) control messages.

Addition of Control Messages

- New control messages
 - added in existing IEEE 802.15.4 command frame by using additional command frame identifiers.

Original MAC command frame format

Octet:2	1	variable	0/5/6/10/14	1	Variable	2
Frame Control	Sequence Number	Addressing Field	Auxiliary Security Header	Command Frame Identifier	Command Payload	FCS
MHR				MAC payload		MFR

Command frame identifier	Command name	RFD	
		Tx	Rx
0x01-0x09	Same as IEEE 802.15.4 2011 std.		
0x0a	PAN coordinator announcement		
0x0b	PAN coordinator announcement reply		
0x0c	P2P route request	X	X
0x0d	P2P route reply	X	X
0x0e-0xff	Reserved		

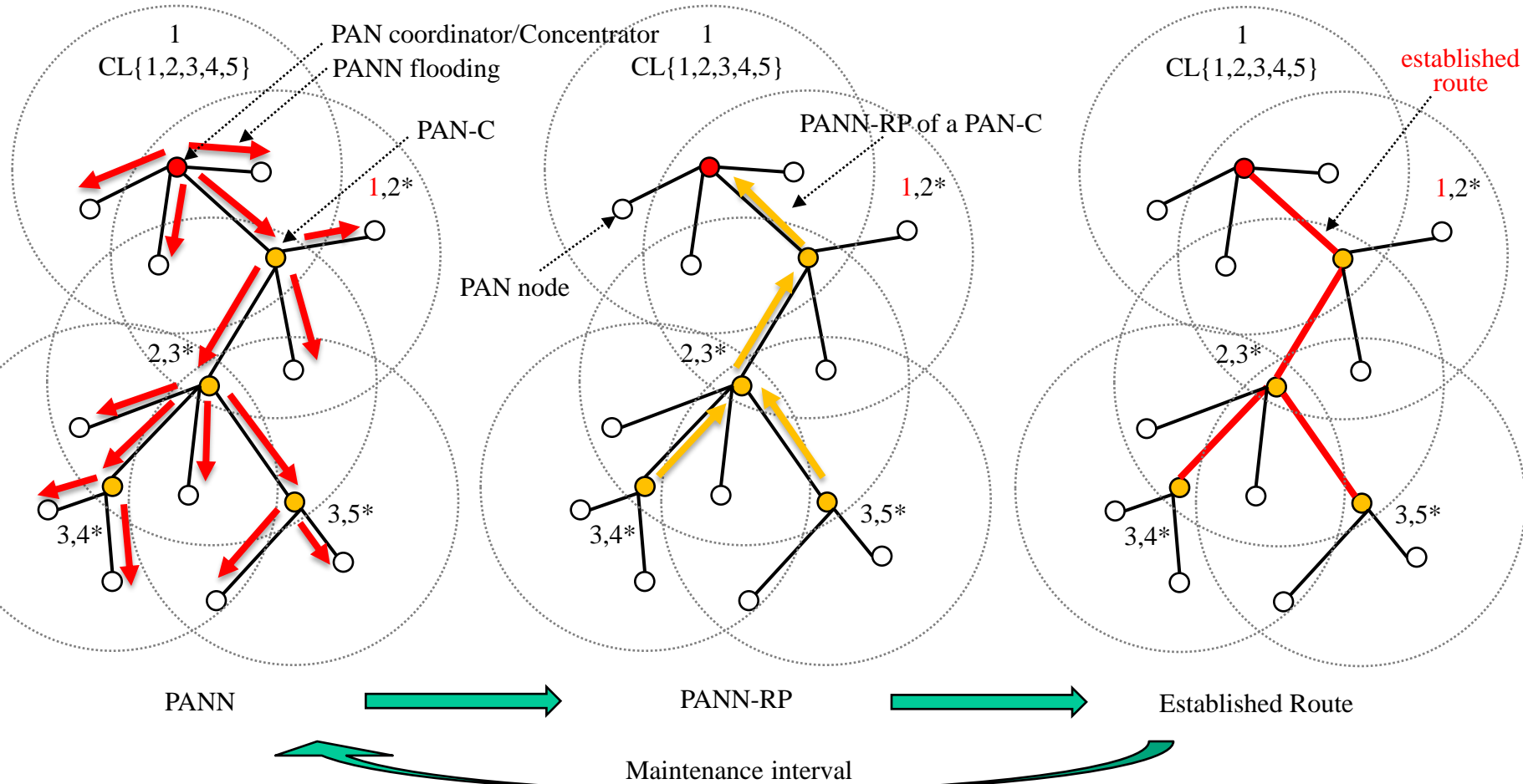
Proactive control messages

Reactive control messages

Proactive Routing

- PAN coordinator Announcement (PANN) message
 - PANN is a single or multichannel broadcast message, which is broadcasted through the entire assigned channels of the network.
 - The PAN coordinator first starts sending a PANN message to the network.
 - Coordinators receiving the PANN message from the PAN coordinator re-broadcast it through all channels assigned to them.
- PAN coordinator Announcement Reply (PANN-RP) message
 - PANN-RP is a single channel unicast message, which is transmitted to the selected PANN sender node.
 - Coordinator that received a PANN message sends PANN-RP including information on PAN nodes associated with it to the PAN coordinator.

An Example of Proactive Routing in TMCTP



PAN-C: PAN coordinator

Frame Format of PANN

- When a coordinator receives several PANN messages from neighbors, it can decide the most effective route using hop counts or another routing metric.

Octet: Variable	1	8	1	1	1	4	4	4	1
MHR field	Command Frame Identifier	Extended address of the transmitter	Allocated channel number	HOP Count	TTL	PANN sequence number	Interval	Metric	L2R capability

- Using L2R capability field, the PAN coordinator can inform all devices of whether supporting 802.15.4 or TMCTP.

SPC information bit mask	Description
0x01	Route establishment enabled.
0x02	The device wish to reset entire route information.
0x04	Route access denied.
0x08	TMCTP enabled (Multi-channel operation).
0x10	Reserved.
0x20	Reserved.
0x40	Reserved.
0x80	Reserved.

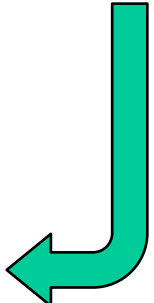
Inactive Overhead Aware Link Metric

- A link cost is calculated using channel access overhead, inactive duration overhead and link error rate of the link.
- Using gap between BO and SO, PAN coordinators can select a route that has smaller inactive duration.

Octet: Variable	1	8	1	1	1	4	4	4	1
MHR field	Command Frame Identifier	Transmitter Extended address	Allocated channel number	HOP Count	TTL	PANN sequence number	Interval	Metric	L2R capability

$$\text{LinkCost} = \left[o + \frac{b_t}{r} \right] \left[2 - \frac{S_o}{B_o} \right] \frac{1}{1 - e_f}$$

Channel access overhead
Inactive duration overhead
Link error rate



Frame Format of PANN-RP

- Using PAN status field, a PAN coordinator can inform whether supporting TMCTP or inter-PAN communication or not.
- The PANN-RP includes extended addresses of the PAN nodes that are associated with it.

Octet: Variable	1	8	1	2	Variable	1
MHR field	Command Frame Identifier	Transmitter Extended address	Allocated channel number	Length	Associated PAN node Extended Addresses	PAN status

PC information bit mask	Description
0x01	TMCTP enabled (Multi-channel operation)
0x02	Reserved.
0x04	Inter-PAN communication enabled
0x08	Route access denied
0x10	Reserved.
0x20	Reserved.
0x40	Reserved.
0x80	Reserved.

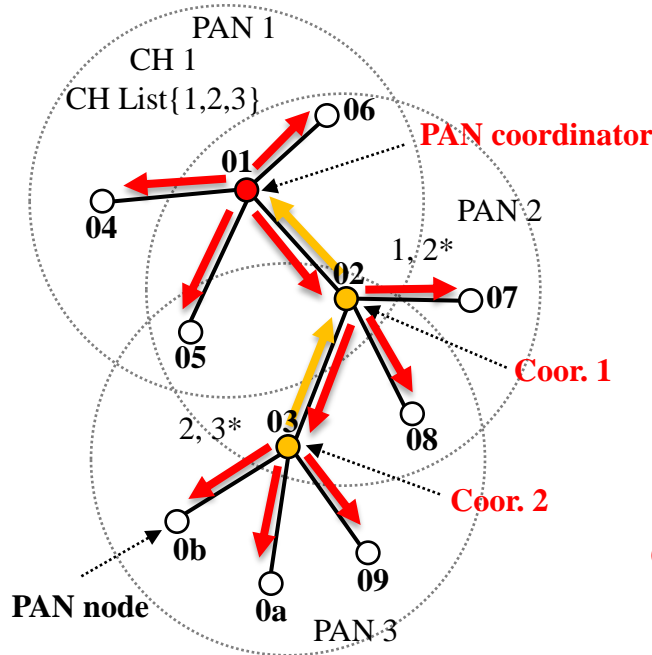
Routing Table

- By exchanging PANN and PANN-RP messages, the PAN coordinator and coordinators update their routing table.
- Using the routing table, the coordinator that receives a data packet forwards the packet, if the coordinator is not the final destination.
- L2R status field represents node type and route information.

Octet:8	8	1	1	2	8	1	1
Dest. Extended Address	Associated PAN ID	HOP Count	L2R sequence number	Route expiration time	Extended Next hop Address	Next hop Allocated channel number	status
.							
.							
.							

status bit mask	Description
0x01	Uplink direction
0x02	Downlink direction
0x04	Route established
0x08	Proactive route
0x10	Gateway enabled node (internet connection)
0x20	SPC enabled
0x40	TMCTP enabled (Multi-channel operation)
0x80	Reserved

An Example of Updating Routing Table



Status field: 79

Big	little
0 1 0 0 1 1 1 1	1 1

Status field: 127

Big	little
0 1 1 1 1 1 1 1	1 1

Octet:8	8	1	1	2	8	1	1
Dest. Extended Address	Associated PAN ID	HOP Count	PANN sequence number	Route expiration time	Extended Next hop Address	Next hop Allocated channel number	status

PAN coordinator routing table

00:00:00:00:00:00:00:03	2	2	1	t	00:00:00:00:00:00:00:02	2	79
00:00:00:00:00:00:00:07	2	2	1	t	00:00:00:00:00:00:00:02	2	79
00:00:00:00:00:00:00:08	2	2	1	t	00:00:00:00:00:00:00:02	2	79
00:00:00:00:00:00:00:09	3	3	1	t	00:00:00:00:00:00:00:02	2	79
00:00:00:00:00:00:00:0a	3	3	1	t	00:00:00:00:00:00:00:02	2	79
00:00:00:00:00:00:00:0b	3	3	1	t	00:00:00:00:00:00:00:02	2	79

Coordinator 1 routing table

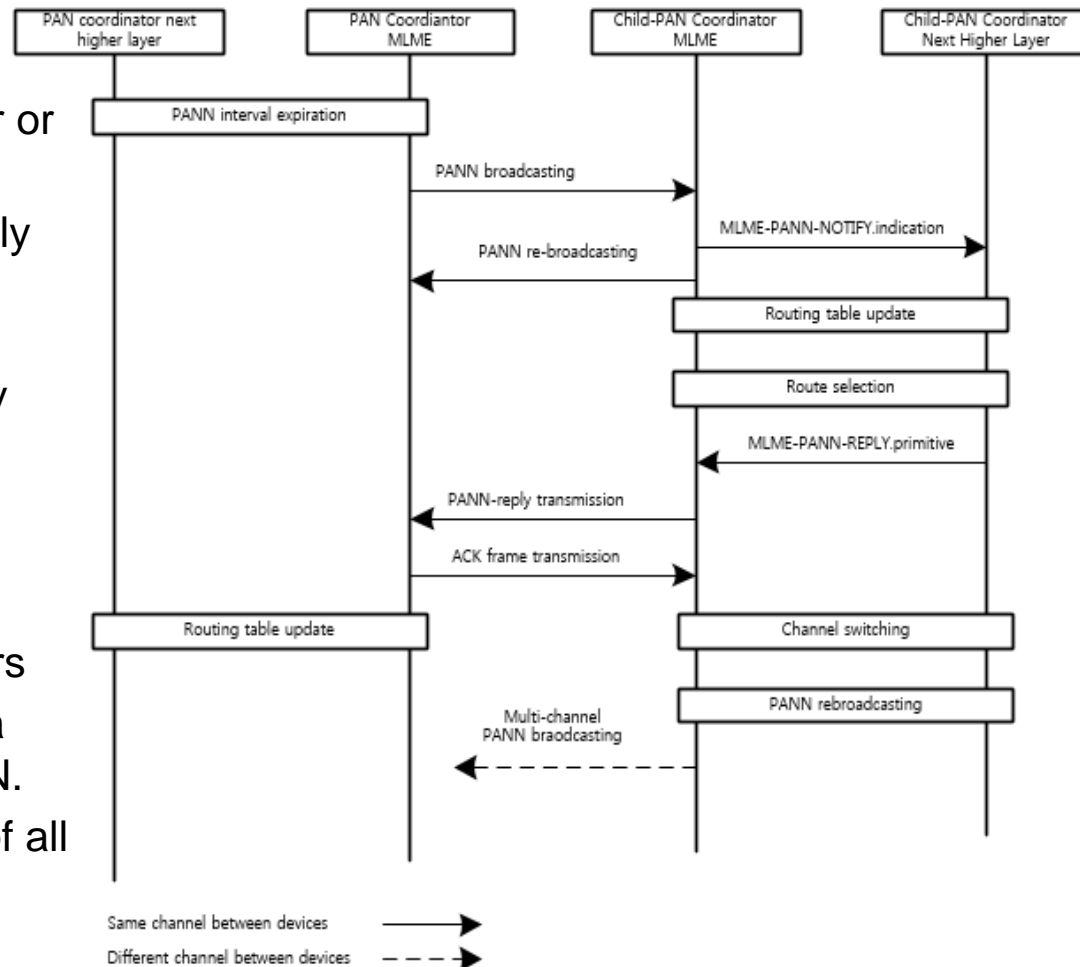
00:00:00:00:00:00:00:01	1	1	1	t	00:00:00:00:00:00:00:01	1	127
00:00:00:00:00:00:00:09	3	2	1	t	00:00:00:00:00:00:00:03	3	79
00:00:00:00:00:00:00:0a	3	2	1	t	00:00:00:00:00:00:00:03	3	79
00:00:00:00:00:00:00:0b	3	2	1	t	00:00:00:00:00:00:00:03	3	79

Coordinator 2 routing table

00:00:00:00:00:00:00:01	1	2	1	t	00:00:00:00:00:00:00:02	2	127
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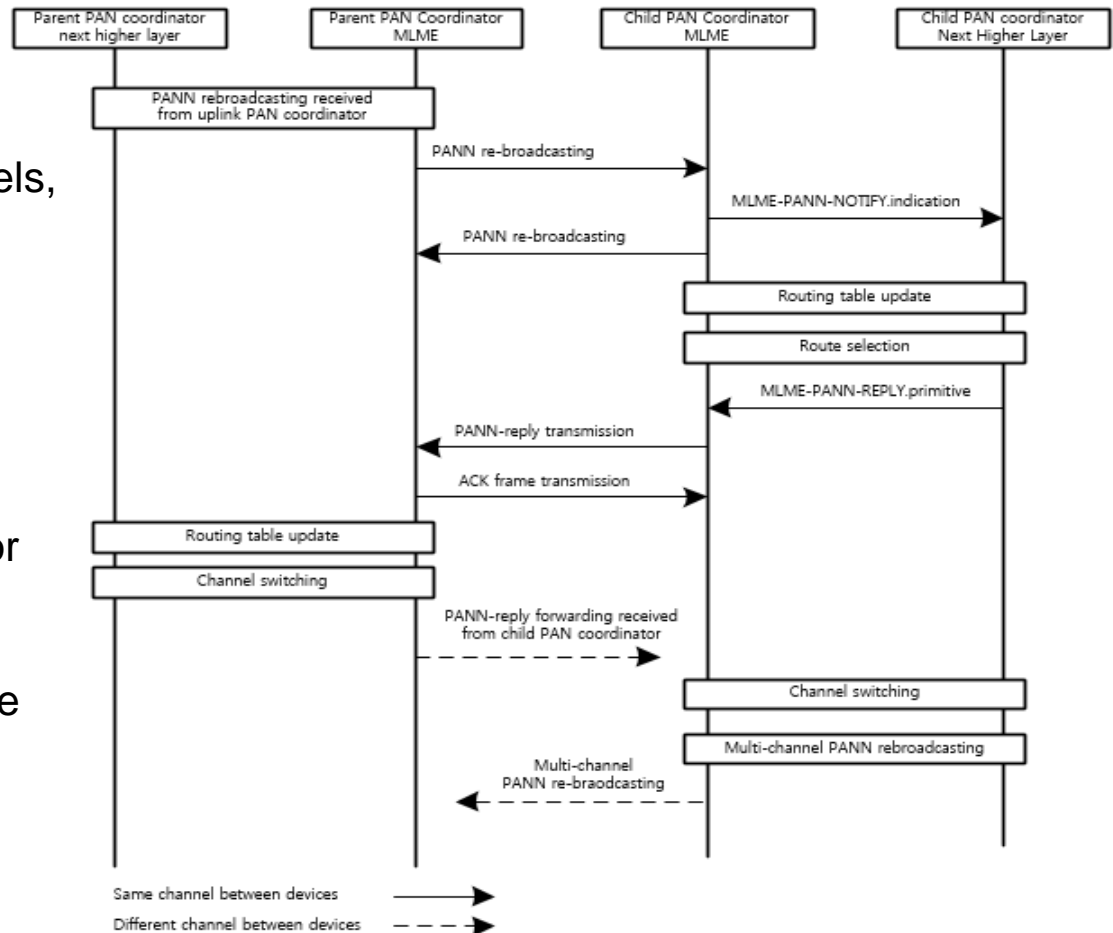
Message Sequence between PAN Coordinator and Child Coordinator

- PANN broadcasting
 - Transmitted by PAN coordinator or gateway
 - PANN is broadcasted periodically with a specific interval.
 - PANN rebroadcasting (or forwarding) is only performed by PAN coordinators.
- PANN-RP transmission
 - Transmitted by child coordinators
 - PANN-RP is transmitted when a child coordinator receives PANN.
 - PANN-RP includes addresses of all PAN nodes in a PAN.

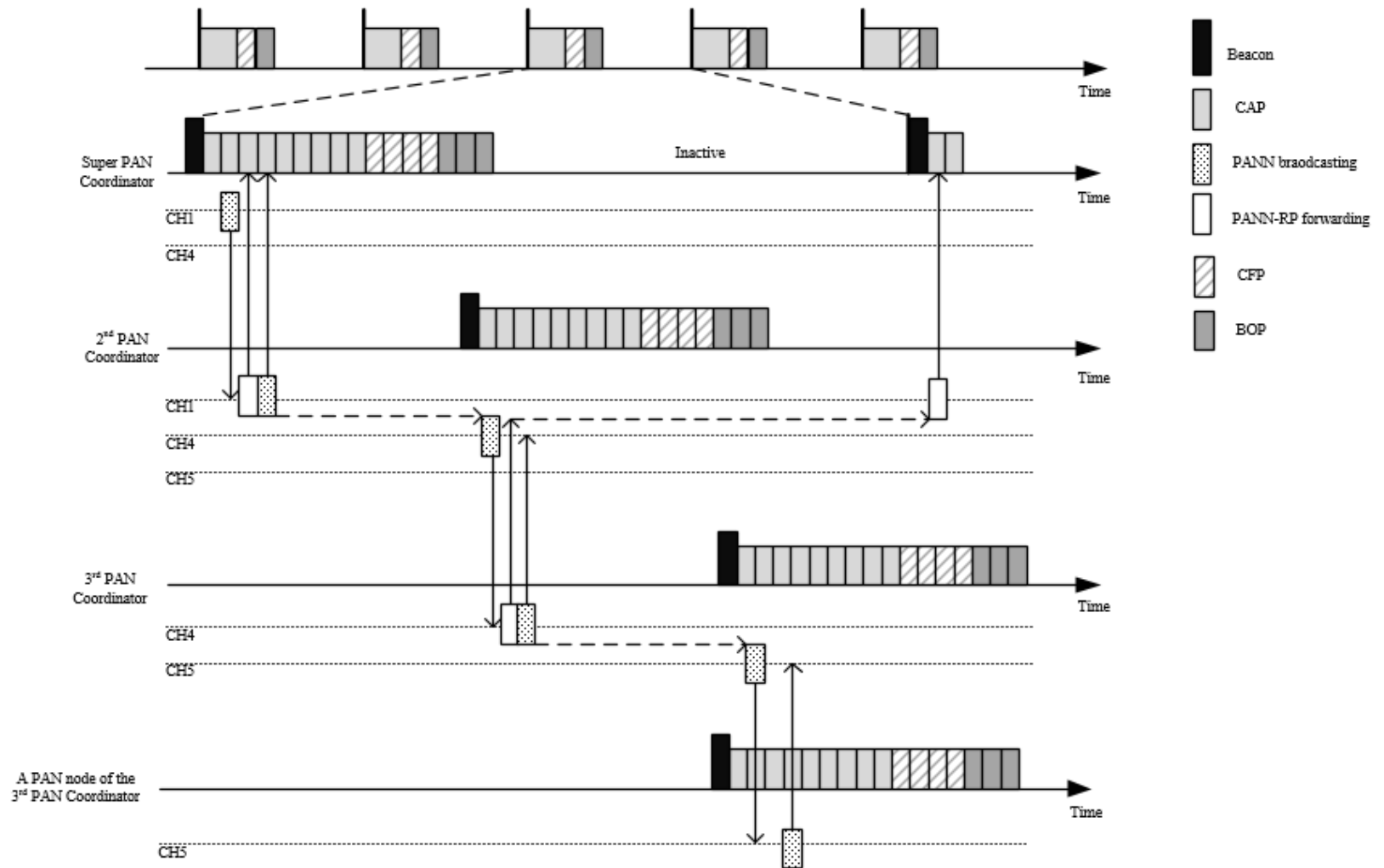


Message Sequence between Parent Coordinator and Child Coordinator

- PANN re-broadcasting
 - The parent coordinator, which has multiple channels, re-broadcasts received PANN message through entire channels.
- PANN-RP transmission
 - When a parent coordinator receives a PANN-RP message from its child coordinator, it forwards the message using uplink channel.



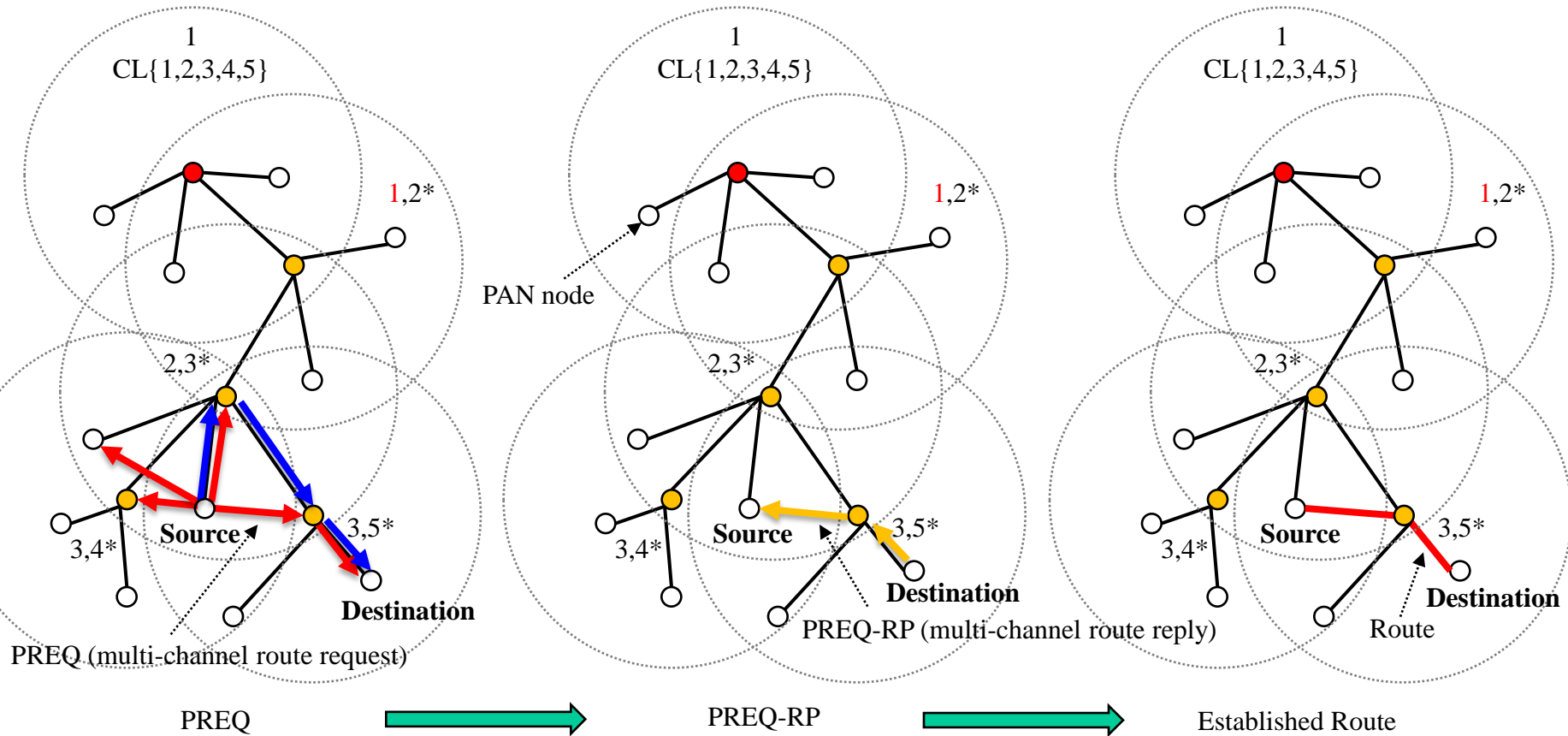
Proactive Route Discovery in TMCTP



Reactive Routing

- P2P route request (PREQ) message
 - A PAN node broadcasts a PREQ to find a route to the destination node when the node does not have any route to the destination
 - The PREQ can be flooded through entire nodes in the network using single or multiple channels.
- P2P route request reply (PREQ-RP) message
 - If a destination node receives a PREQ, it sends a PREQ-RP through the route on which the PREQ is delivered.

An Example of Reactive Routing



Frame Format of PREQ

- Original source and destination addresses are included in the MAC header.
- Transmitter extended address field is the address of the sender of the message. For example, if a node receives a PREQ, it sets this field to its extended address.

Octet: Variable	1	8	1	1	1	4	4	1
MHR field	Command Frame Identifier	Transmitter Extended address	Allocated channel number	HOP Count	TTL	PREQ sequence number	Metric	Request Status

- Request status is utilized to inform the functionalities and properties of the source node.

Request information	Description
0x00	The device wish to make a route through different PAN
0x01	The device wish to receive direct route response
0x02	The device is not associated to any PAN coordinator
0x03	TMCTP enabled (Multi-channel operation)
0x04	The device want to repair the route to PAN coordinator (Gateway)
0x04-0x7f	Reserved.
0x08-0xff	Reserved for MAC primitive enumeration values.

Frame Format of PREQ-RP

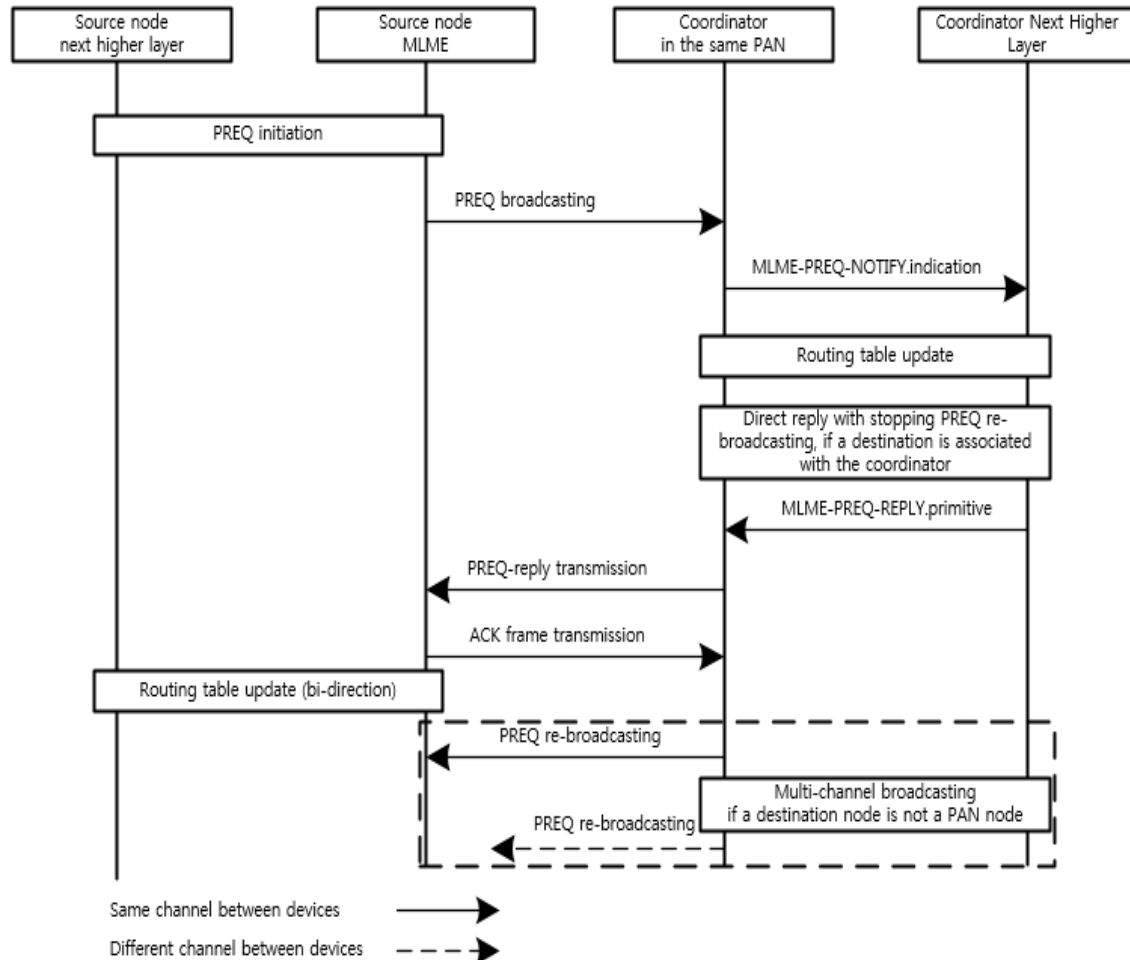
- In the MAC header, source and destination addresses of PREQ become destination and source addresses of PREQ-RP.
- The PREQ-RP is transmitted to the source node using backward path which is constructed by PREQ message.

Octet: Variable	1	8	1	1
MHR field	Command Frame Identifier	Transmitter Extended address	Allocated channel number	Reply Status

Reply information bit mask	Description
0x01	The device is a PAN coordinator.
0x02	Reserved.
0x04	TMCTP enabled (Multi-channel operation)
0x08	Reserved.
0x10	Reserved.
0x20	Reserved.
0x40	Reserved.
0x80	Reserved.

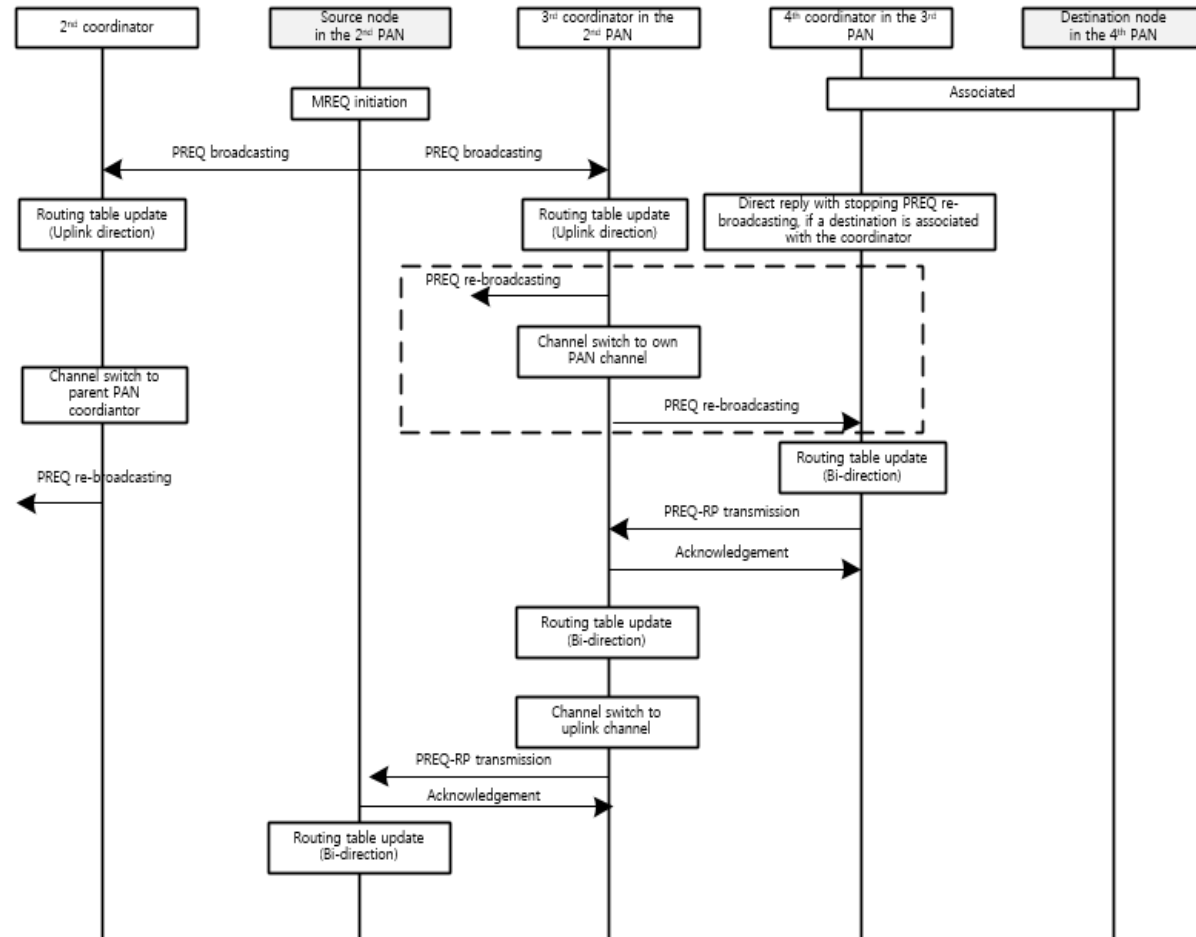
Message Sequence Using PREQ and Direct Reply

- The source node sends a PREQ to find a route to the destination node.
- If a coordinator receives the PREQ, it looks up the destination address of PREQ and checks whether the destination node is associated or not.
- If the coordinator finds the destination node, then it directly transmits the PREQ-RP.

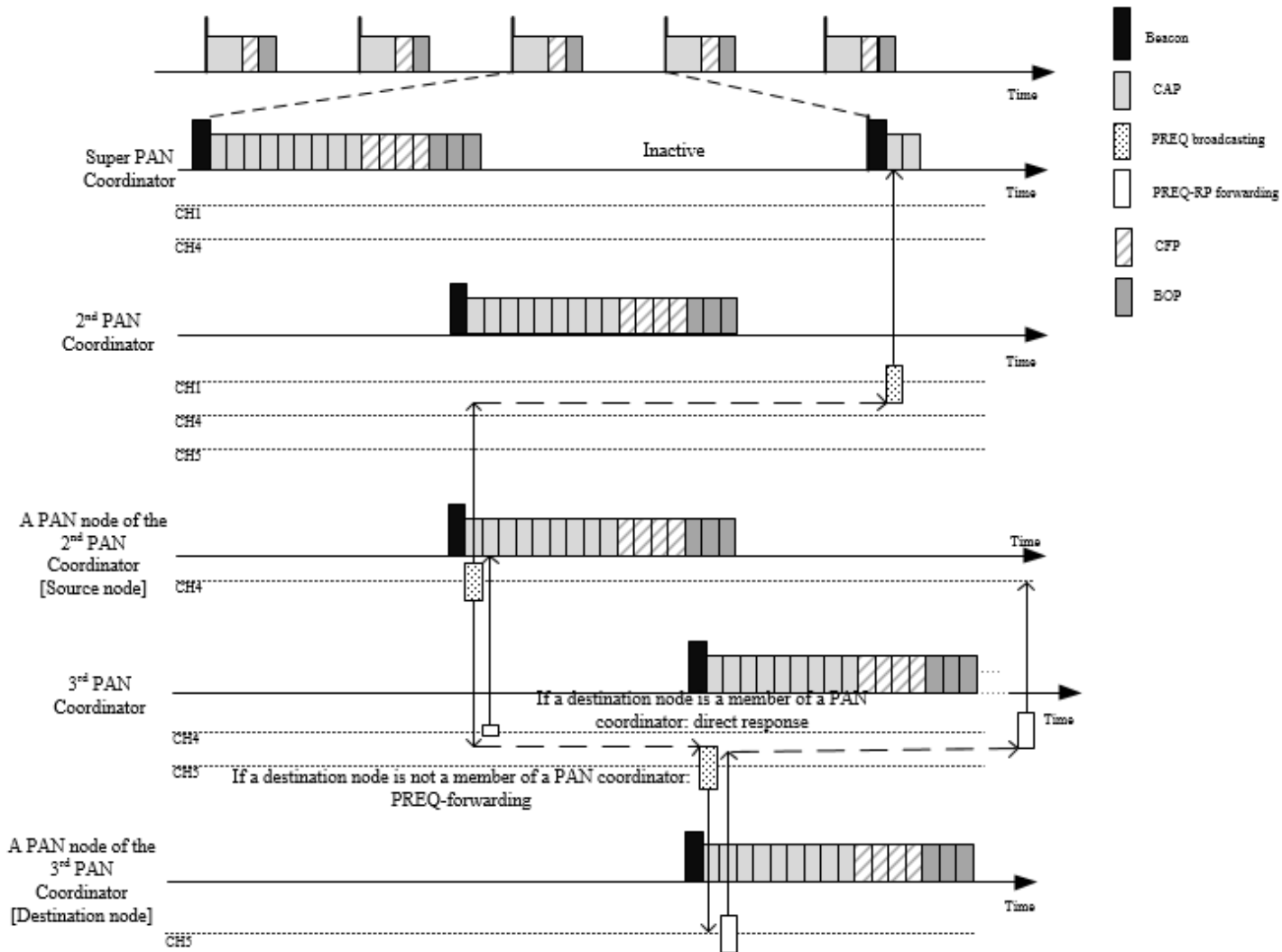


Message Sequence Using PREQ Broadcasting

- If the destination node is not a PAN node, then the coordinator re-broadcasts the received PREQ
- If the coordinator finds the destination node, then it transmits a PREQ-RP to the node which transmitted the PREQ.



Reactive Route Discovery in TMCTP



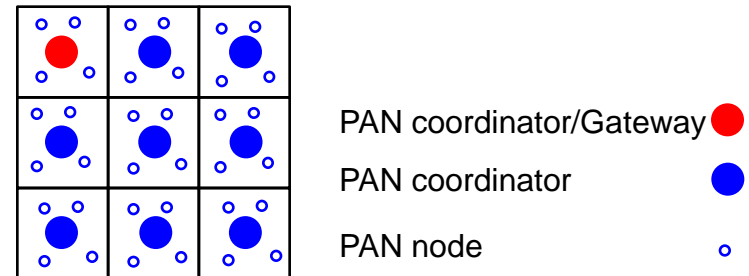
Simulation Environment (1/2)

- MAC/PHY
 - IEEE 802.15.4m TMCTP
 - Slotted CSMA/CA (CAP only)
 - Beacon based synchronization and association response and request
 - Frequency and modulation: 2.4GHz O-QPSK
 - Data rate: 250Kb/s

Type	Value
BO(Beacon Order)	6
SO(Superframe Order)	4
EO (TMCTP Extended Order)	4
Beacon interval	0.983sec
Slot duration	0.0154 s
aBaseSuperframeDuration	960
aNumSuperframeSlots	16
Simulation time	2500 s

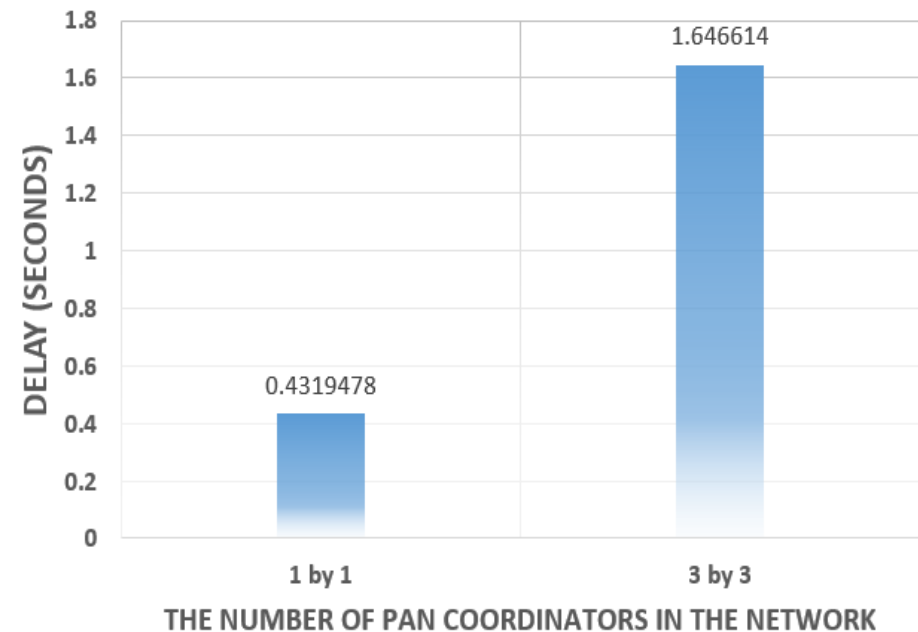
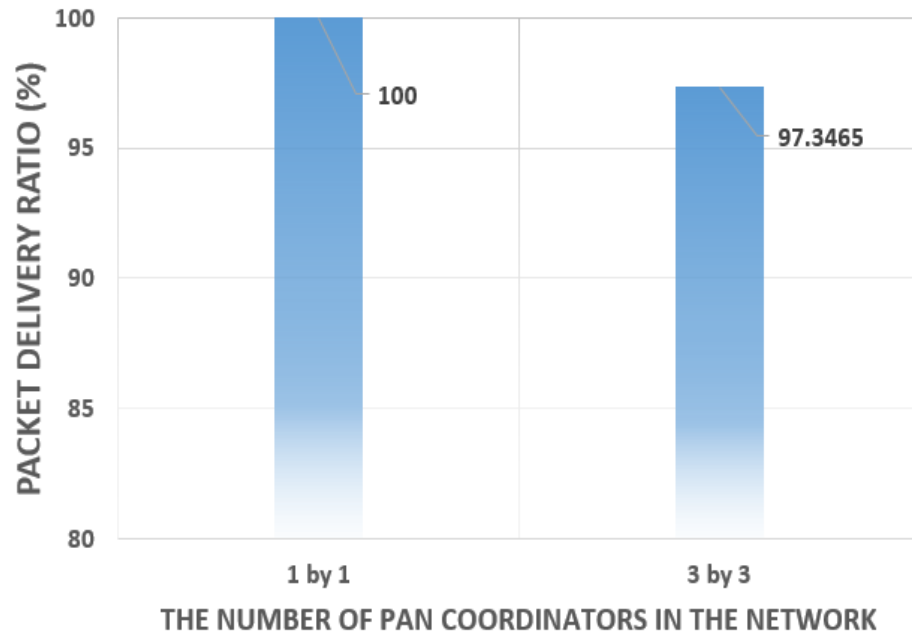
Simulation Environment (2/2)

- Topology
 - 1 Super PAN coordinator
 - 8 PAN coordinators in a network
 - 11 devices in a PAN
 - Total 108 devices
- Data traffic
 - Packet size: 100 bytes
 - Interval: 15 sec
 - Source nodes: PCs and PAN devices
 - Destination node: PAN coordinator



Performance Evaluation Results

- When total number of nodes is 108 with proactive routing
 - Successful packet delivery ratio is about 97%.
 - Packet delay is less than 1.65 sec for 3 hop communication.



Q/A