

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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Source: Sangjae Lee, Jaehwan Kim, Sangsung Choi (ETRI), Jae-Beom Kim, Young-Bae Ko (Ajou Univ.), and Soo-Young Chang (SYCA)

Company: ETRI, Ajou Univ., and SYCA

Address: 161 Gajeong-dong, Yuseong-gu, Daejeon, KOREA

Voice: +82-42-860-1572, **FAX:** +82-42-860-5218, **E-Mail:** leestrike@etri.re.kr

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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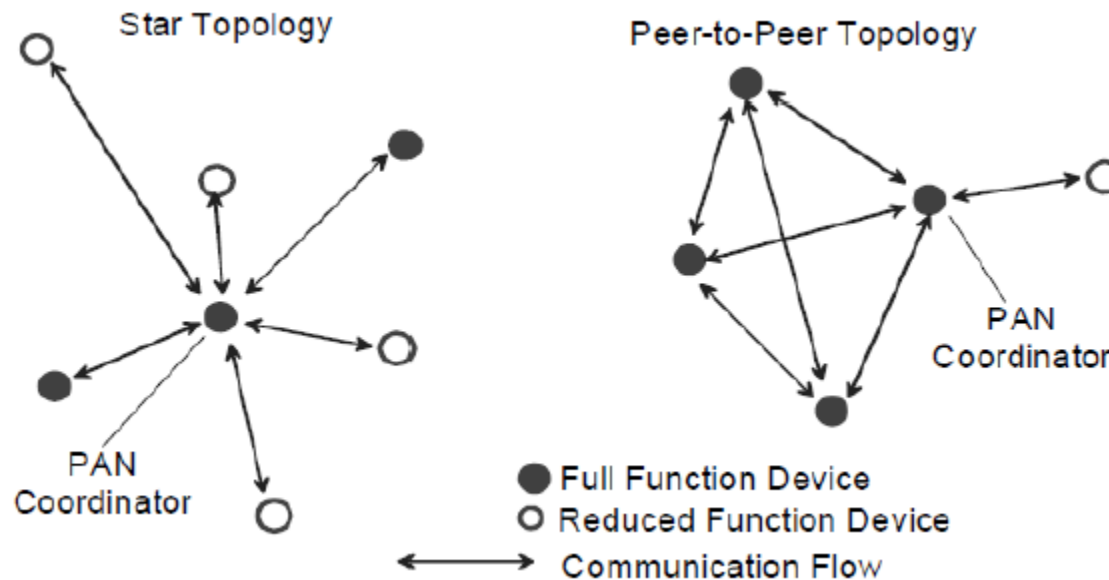
Requirements of IEEE 802.15.10 Layer 2 Routing

- 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

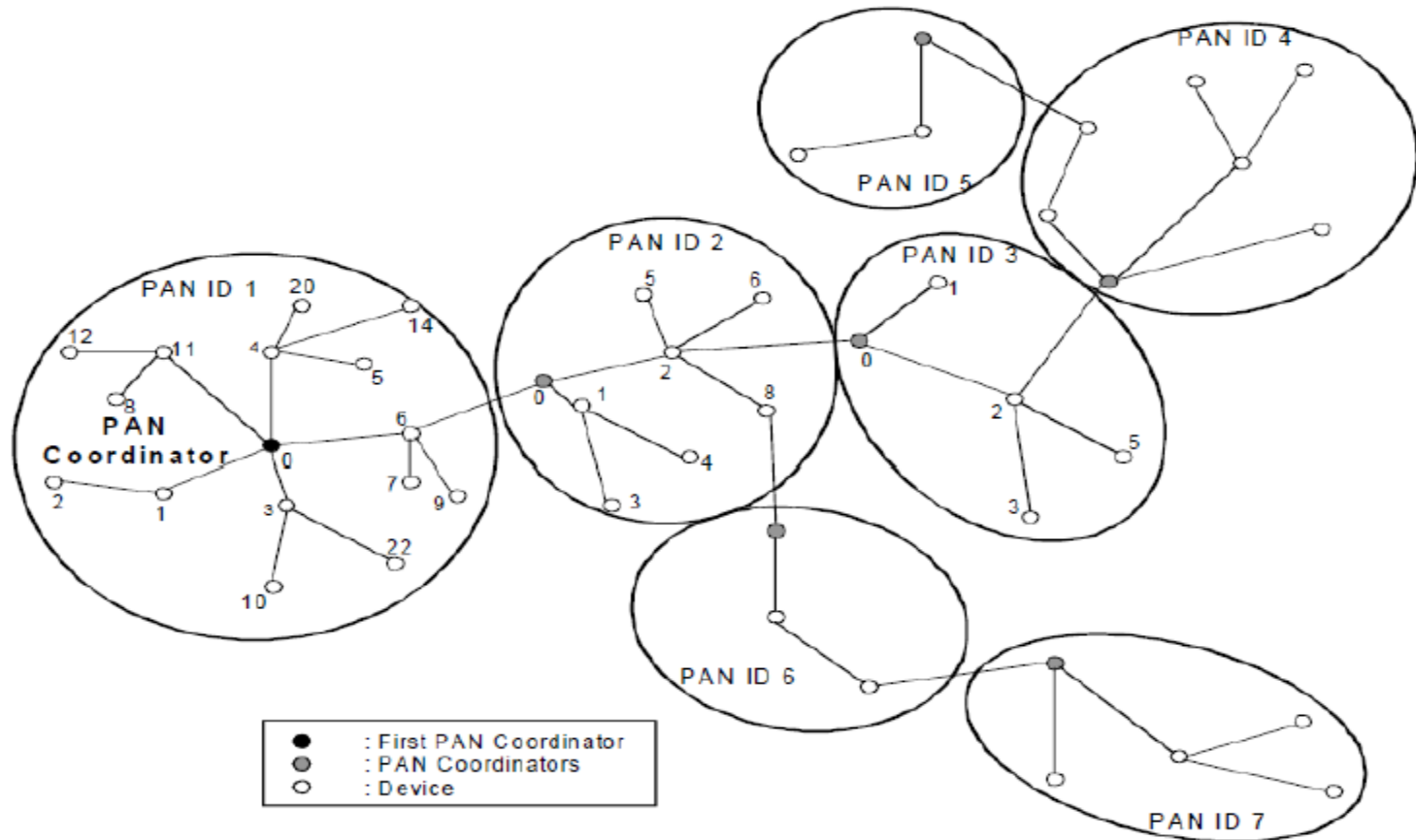
Topologies of IEEE 802.15.4 (1/2)

- Star and peer-to-peer topologies



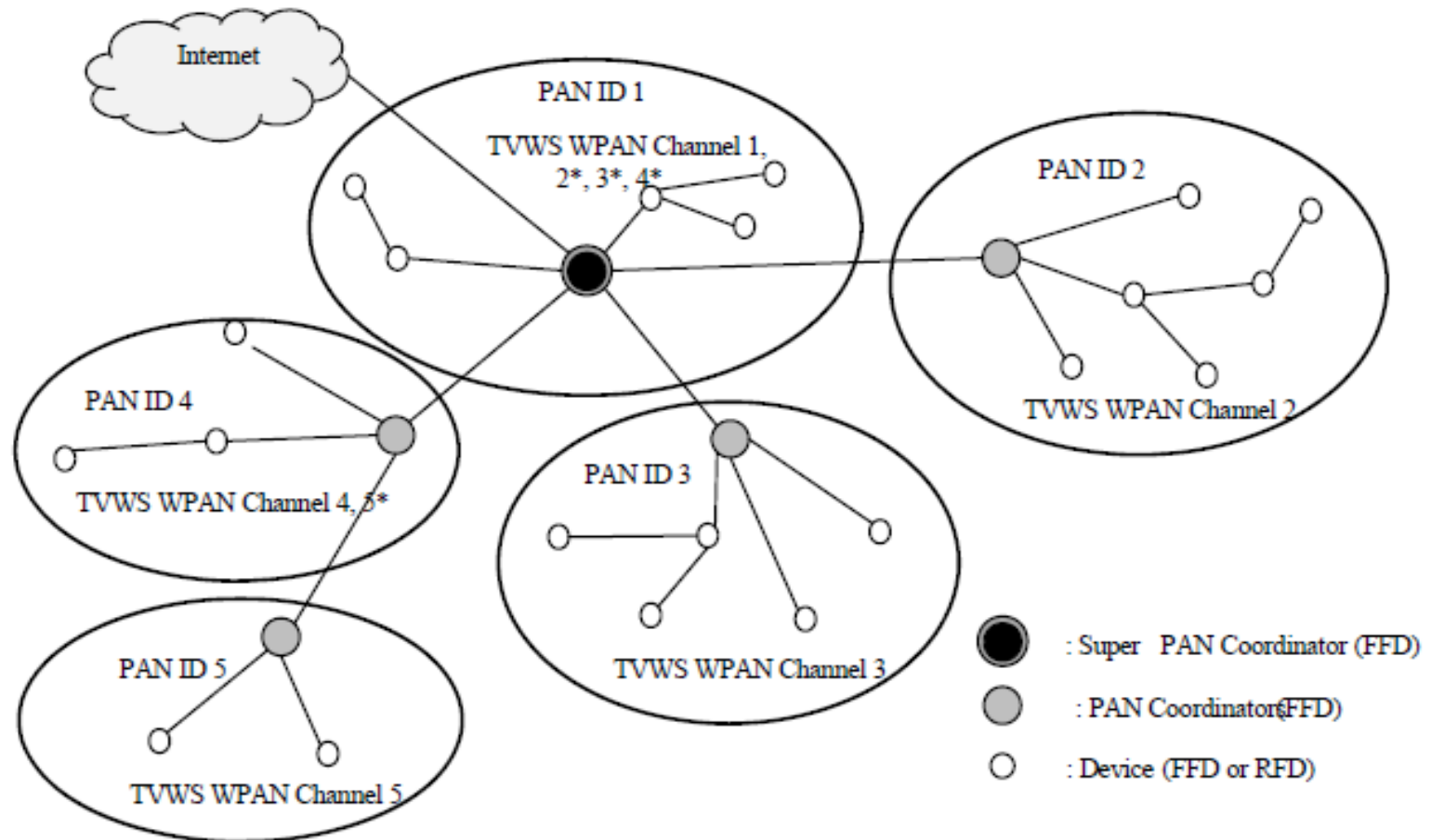
Topologies of IEEE 802.15.4 (2/2)

- Cluster tree network



Topology of IEEE 802.15.4m

- Cluster tree network with 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 | | |

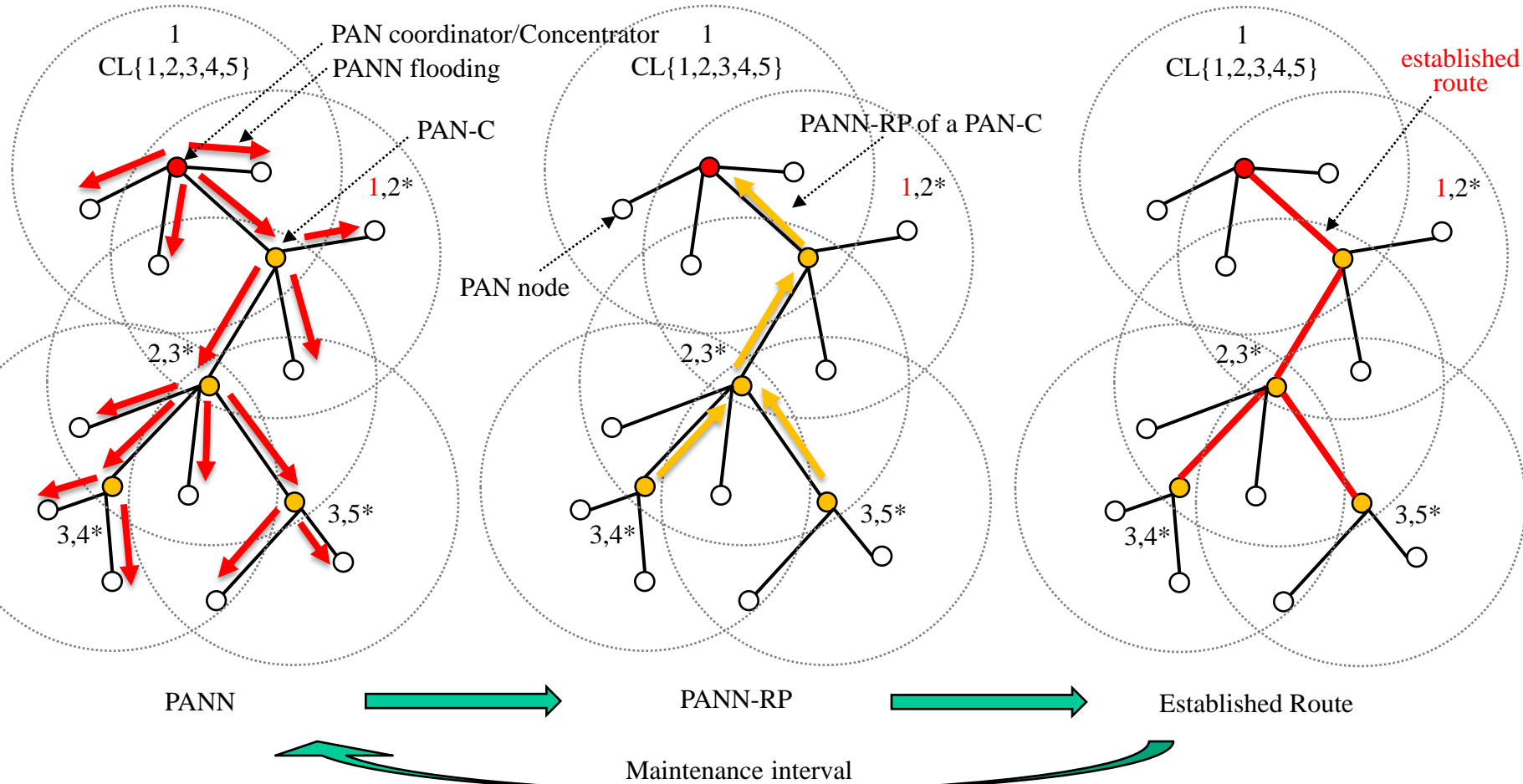
Proactive control messages

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. |

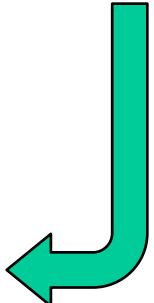
Inactive Overhead Aware Link Metric

- 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. |

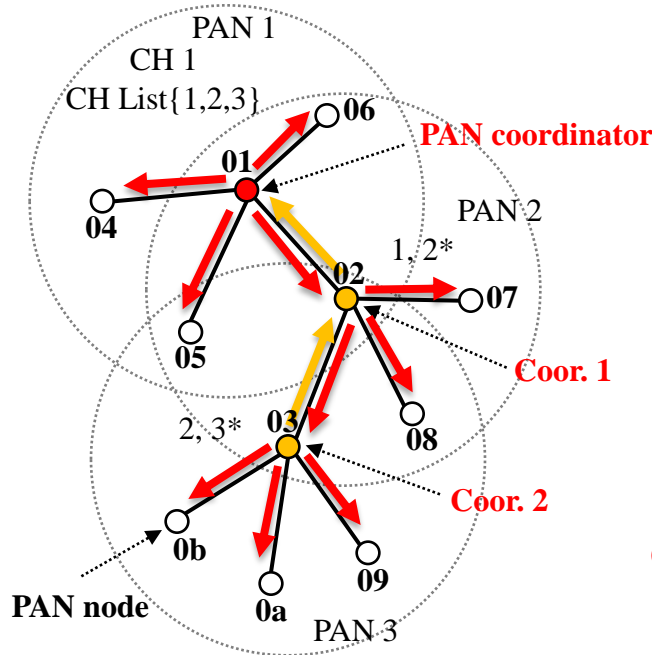
Routing Table

- 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 | |

Status field: 127

| | |
|-----------------|--------|
| Big | little |
| 0 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

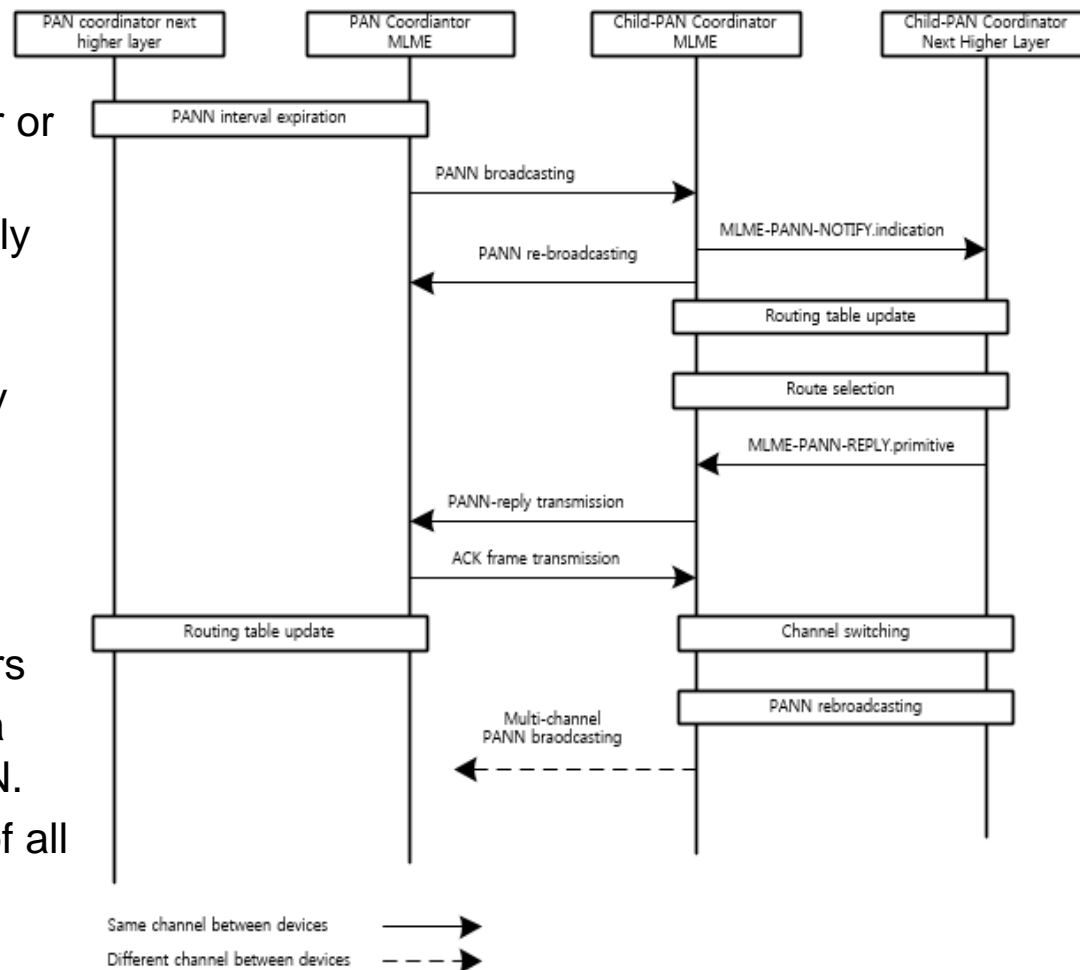
| | | | | | | | |
|-------------------------|---|---|---|---|-------------------------|---|-----|
| 00:00:00:00:00:00:00:01 | 1 | 1 | 1 | t | 00:00:00:00:00:00:00:01 | 1 | 127 |
| 00:00:00:00:00:00:00:09 | 3 | 2 | 1 | t | 00:00:00:00:00:00:00:03 | 3 | 79 |
| 00:00:00:00:00:00:00:0a | 3 | 2 | 1 | t | 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 | 2 | t | 00:00:00:00:00:00:00:02 | 2 | 127 |
|-------------------------|---|---|---|---|-------------------------|---|-----|

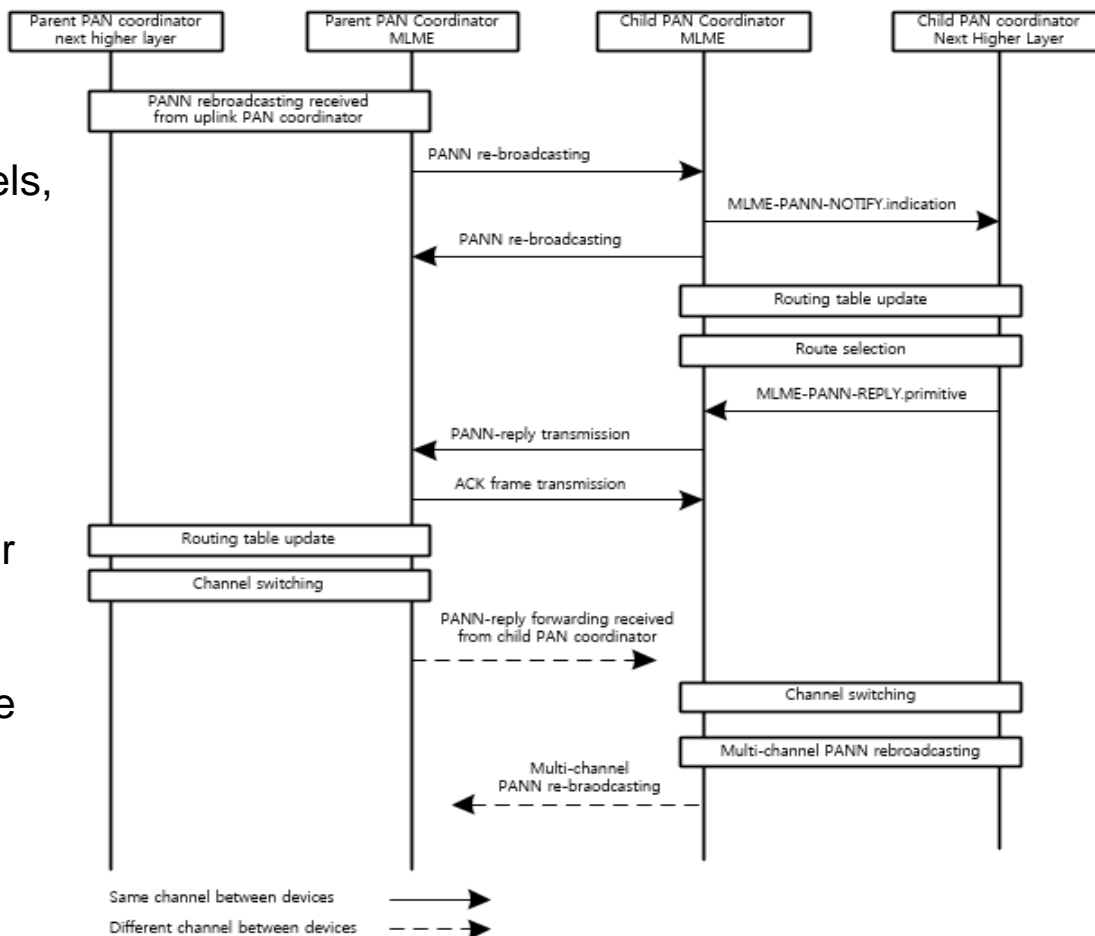
Message Sequence between PAN Coordinator and Child Coordinator

- 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.

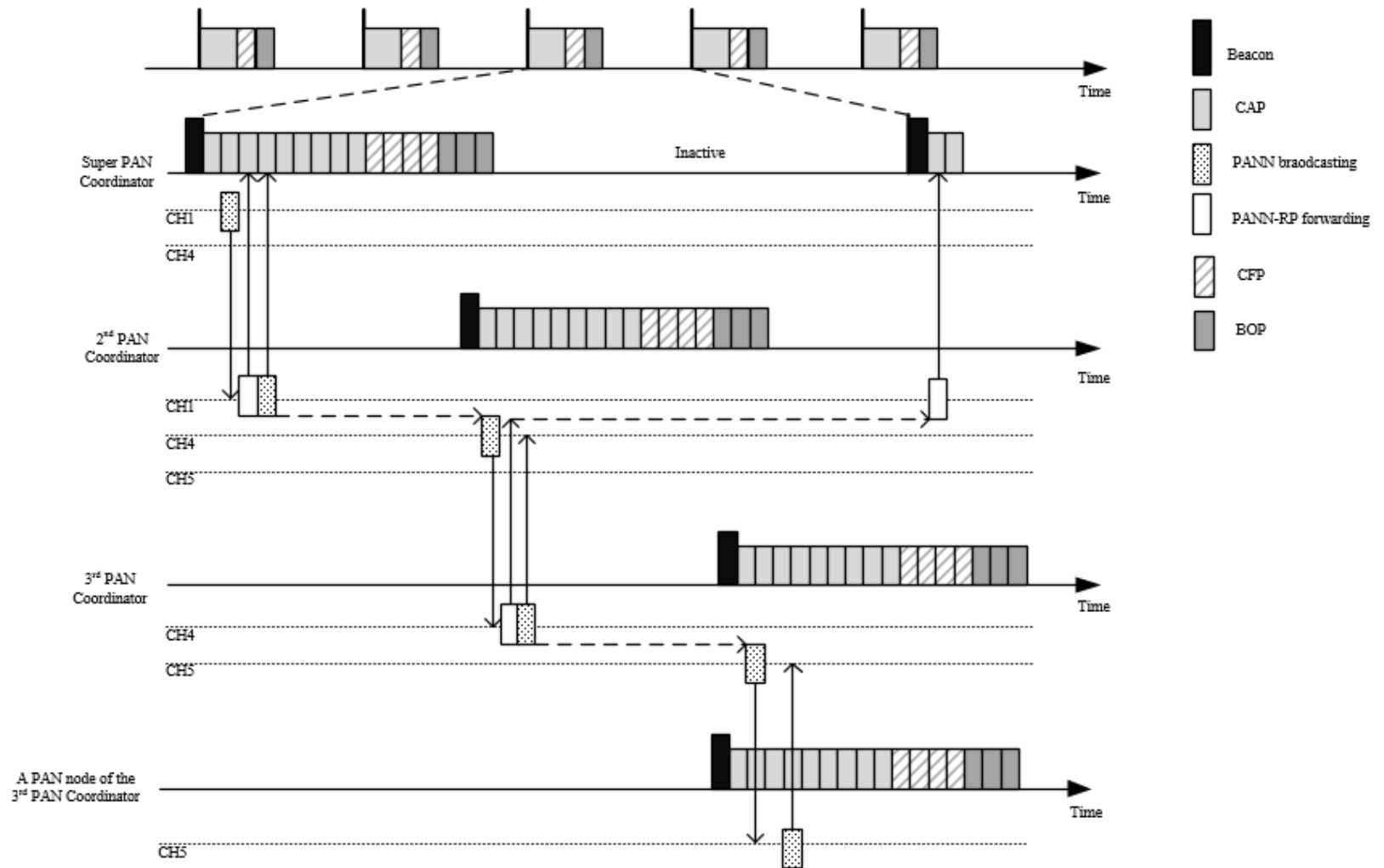


Message Sequence between Parent Coordinator and Child Coordinator

- 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.



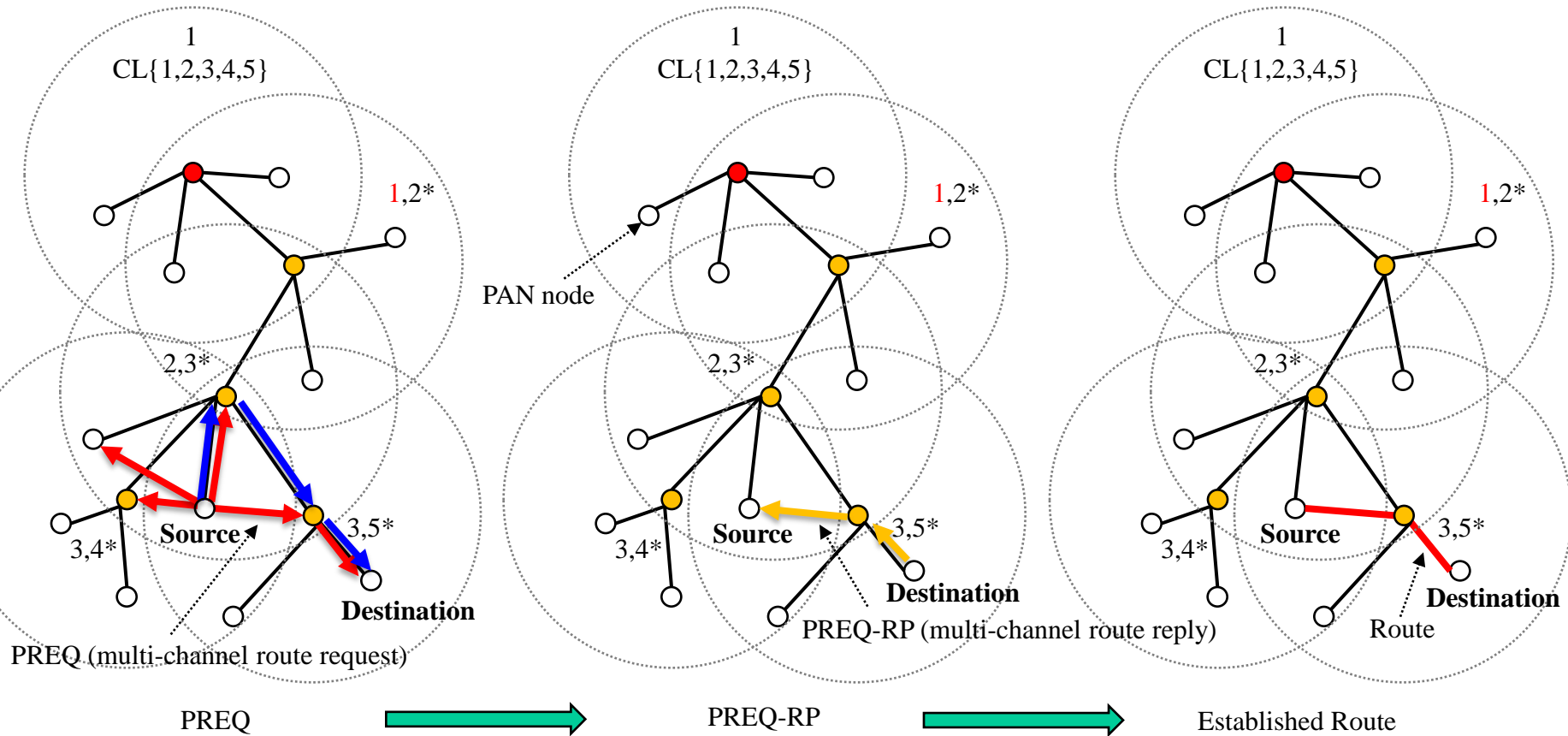
Proactive Route Discovery in TMCTP



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

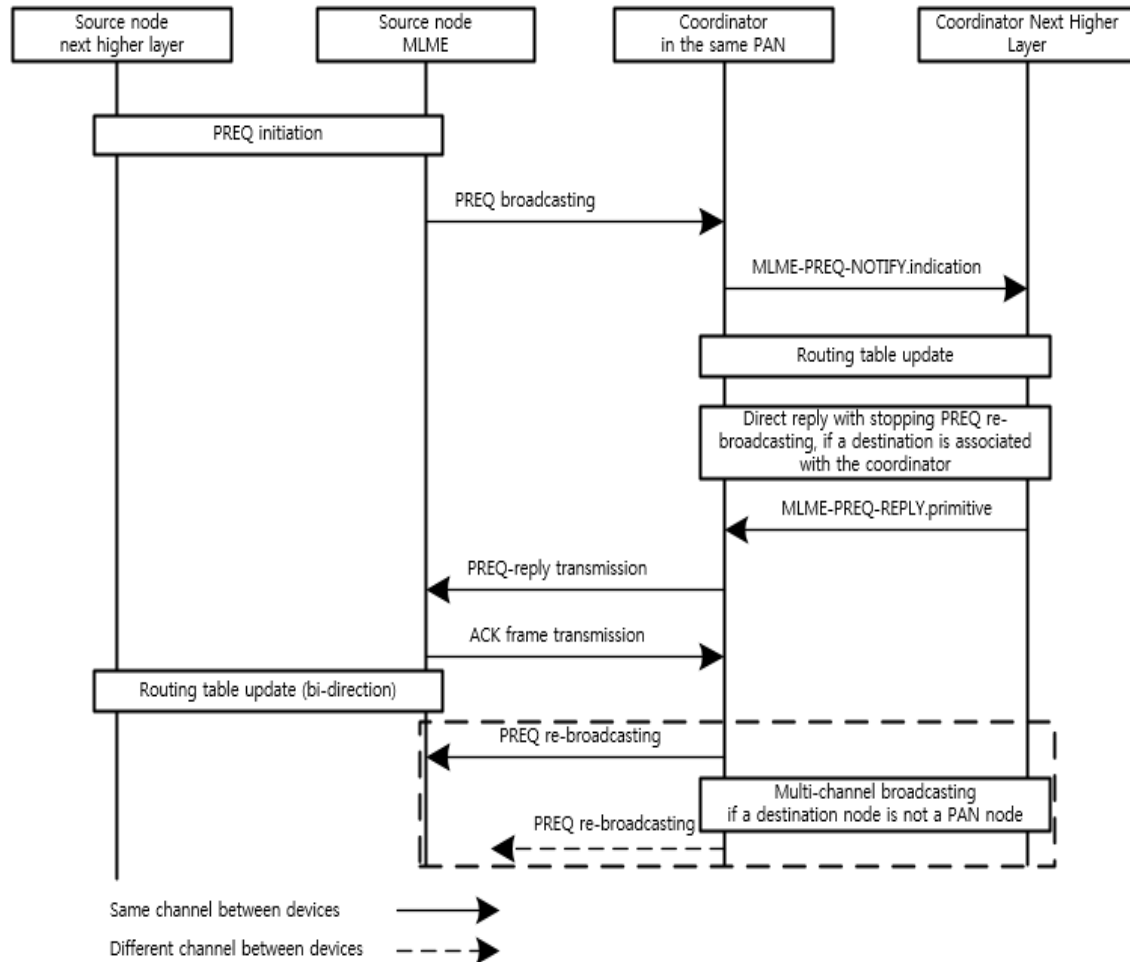
- In the MAC header, source and destination addresses of PREQ become destination and source addresses of PREQ-RP.
- The PREQ-RP is transmitted to the source node using backward path which is constructed by PREQ message.

| | | | | |
|-----------------|--------------------------|------------------------------|--------------------------|--------------|
| 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. |

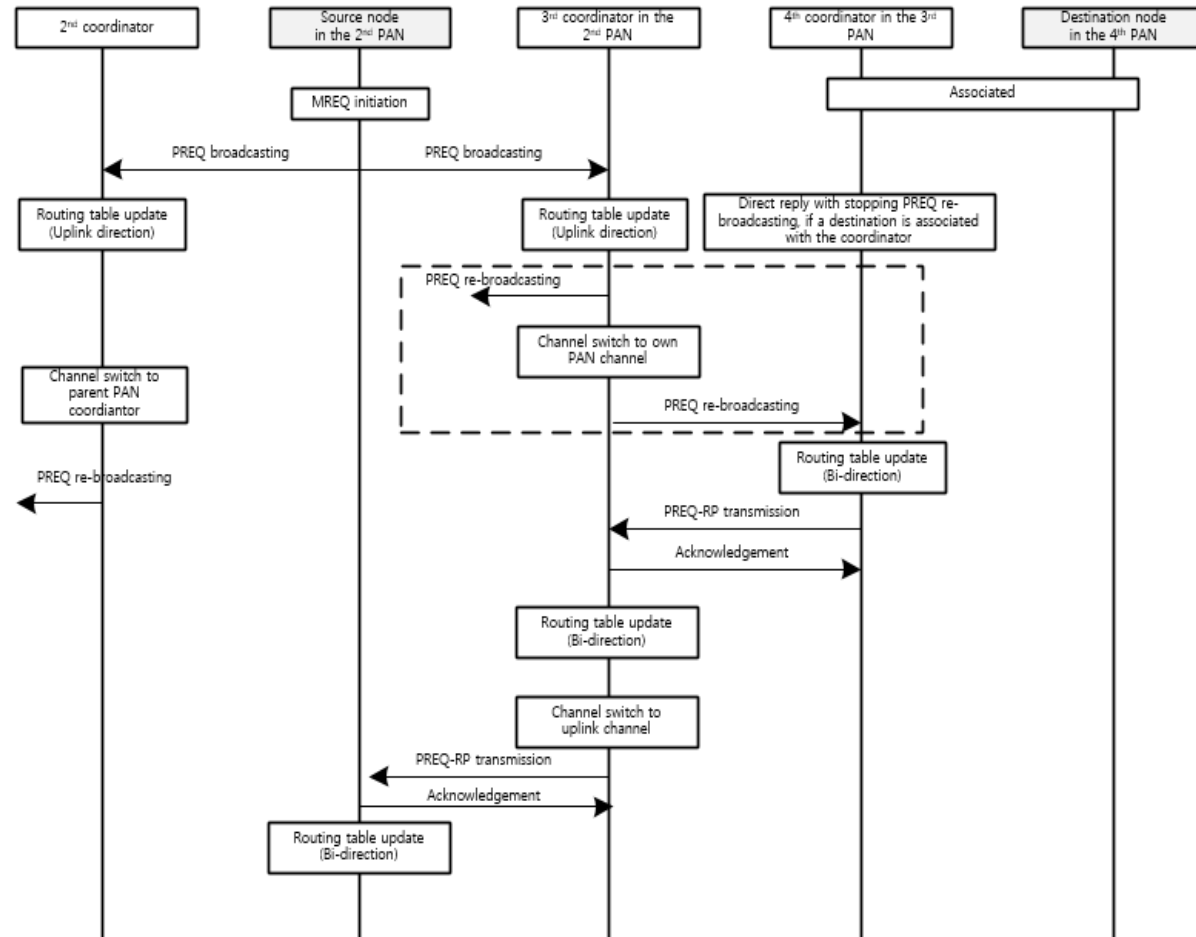
Message Sequence Using PREQ and Direct Reply

- 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.

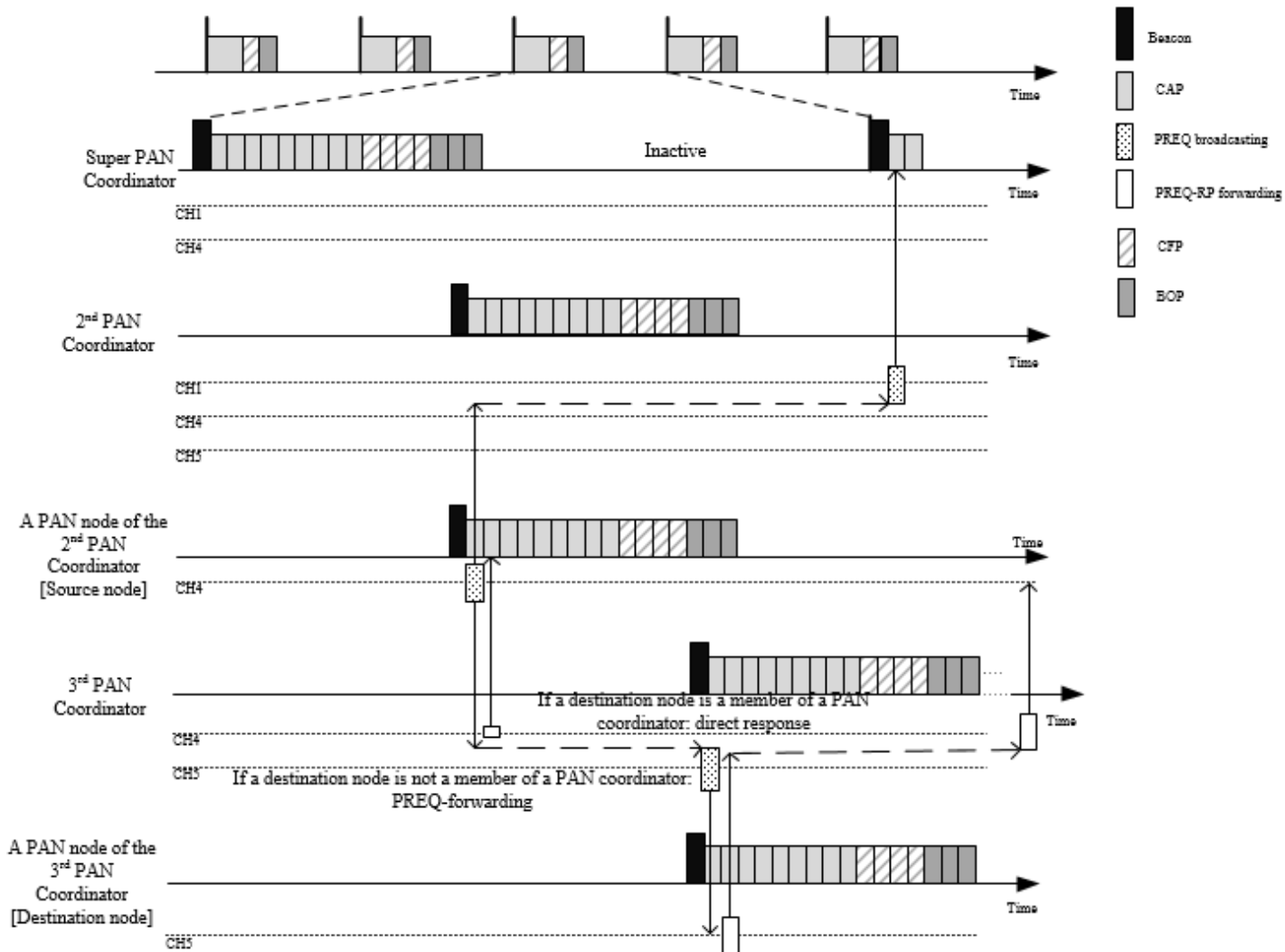


Message Sequence Using PREQ Broadcasting

- 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



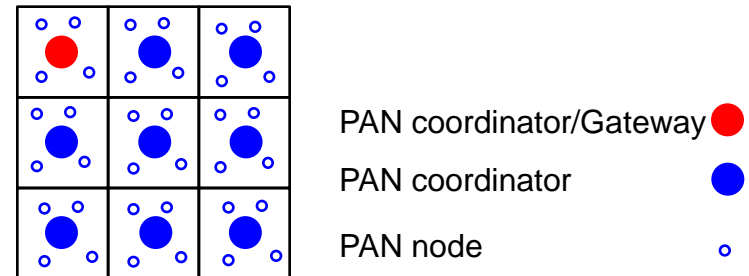
Simulation Environment (1/2)

- 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 |

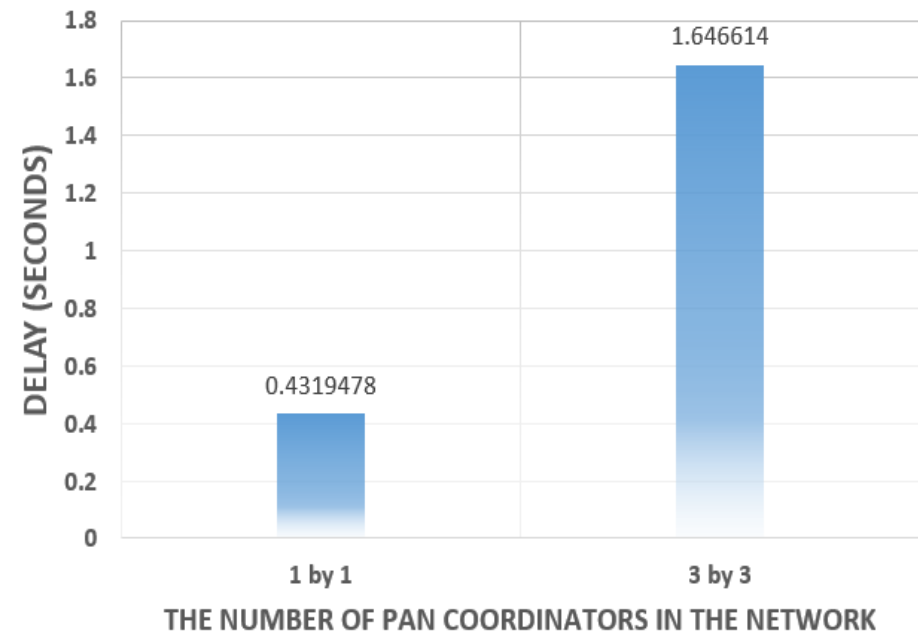
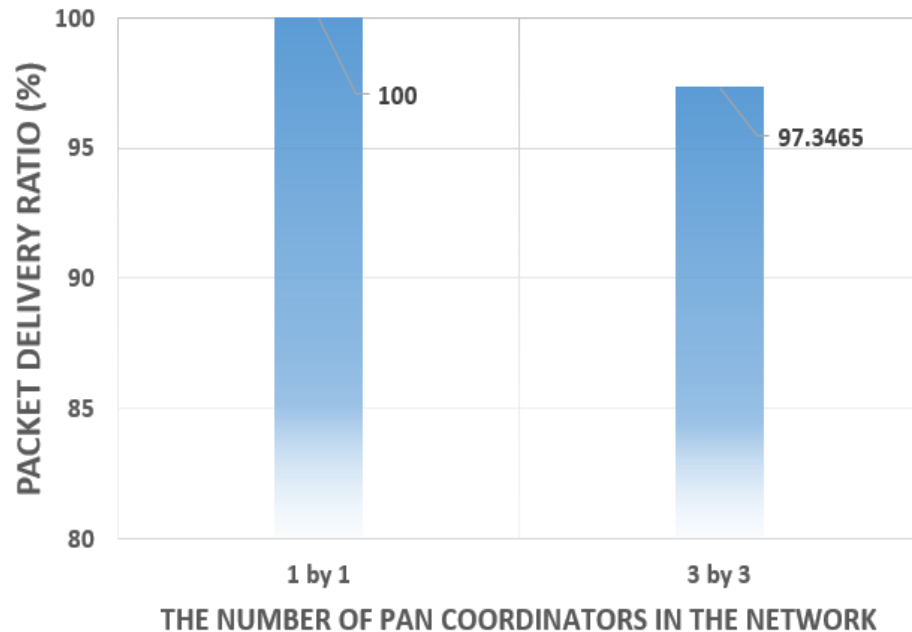
Simulation Environment (2/2)

- 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