IEEE P802.15
Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)	
Title	**Cluster Tree Network**	
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Re:	[01135r0P802-15_TG4-MOTOROLA-MAC-Proposal-Overview.ppt]	
Abstract	[This document describes in some detail the operation of the Cluster Tree network proposed by Motorola for the TG4 standard, including network initiation, maintenance, message routing, and device association and dissociation.]	
Purpose	[To be considered during the proposal selection process.]	
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Cluster Tree Protocol (ver. 0.6)

Rev. 0: 04/12/01
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Rev. 0.6: 04/19/01
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Introduction

Many applications for wireless communication networks, such as wireless sensors, industrial control and monitoring, intelligent agriculture, asset and inventory tracking, and security, would benefit from a communication protocol that produced an ad hoc, self-organizing network (i.e., one of random topology in which the network organization and maintenance occurred without human intervention) that enabled each node in the network to be exceptionally inexpensive and have excellent battery life in all possible connection states.

The Cluster Tree Protocol is a protocol of the logical link and network layers for a wireless ad-hoc network designed to meet these requirements. The protocol uses link-state packets to form either a single cluster network, or a potentially larger cluster tree network. The network is basically self-organized, and supports network redundancy to attain a degree of fault resistance and self-repair.

Nodes select a cluster head and form a cluster according to the self-organized manner. In the cluster formation process the cluster head assigns a unique node ID to each member node.

Self-developed clusters connect each other using the Designated Device. The Designated Device is a special node that has high computing ability and large memory space; in most applications it is also the gateway between the network and the Internet. The Designated Device assigns a unique cluster ID to each cluster.

Address Scheme

Each node is assigned 16 bits logical address that consist of a cluster ID (CID) and a node ID (NID).

Cluster ID

The Designated Device assigns a unique 8 bit cluster ID to the cluster. CID 255 means all clusters and is used for broadcast message.

Table 1 Cluster ID

Binary	Decimal	CID Function
00000000	0	Designated Device (DD)
00000001	1	
|	|	Regular Cluster
11111101	253	
11111110	254	Temporary Cluster ID
11111111	255	Broadcast

Node ID

The cluster head assigns a unique 8 bit node ID to its member nodes. The cluster head uses NID 0. NID 255 is for broadcast and 254 for temporary use.

Table 2 Node ID

Binary	Decimal	NID Function
00000000	0	Cluster Head (CH)
00000001	1	
|	|	Member node
11111101	253	
11111110	254	Temporary node ID
11111111	255	Broadcast

Frame Structure

This chapter introduces the different types of packets that are used for communication within and between clusters.

Frame Type

The 6-bit frame type field is defined. The first two bits define the category of the function and the next four bits indicate the detail functions.

Table 3 Frame Type

Frame Type (bit 1, bit 2)	(bit 3, 4, 5, 6)	Frame Function
Intra Cluster Management Frame 00	0000	HELLO
	0001	CONNECTION REQUEST
	0010	CONNECTION RESPONSE
	0011	NODE ID REQUEST
	0100	NODE ID RESPONSE
	0101	DISCONNECTION REQUEST
	0110	DISCONNECTION RESPONSE
	0111	LINK-STATE REPORT
	1000	TOPOLOGY UPDATE
	1001 - 1111	Reserved
Inter Cluster Management Frame 01	0000	NETWORK CONNECTION REQUEST
	0001	NETWORK CONNECTION RESPONSE
	0010	CLUSTER ID REQUEST
	0011	CLUSTER ID RESPONSE
	0100	NETWORK DISCONNECTION REQUEST
	0101	NETWORK DISCONNECTION RESPONSE
	0110	NETWORK LINK-STATE REPORT
	0111	NETWORK TOPOLOGY UPDATE
	1000 - 1111	Reserved
Control Frame 10	0000	REQUEST TO SEND (RTS)
	0001	CLEAR TO SEND (CTS)
	0010	ACKNOWLEDGEMENT (ACK) for Intra Cluster
	0011	ACKNOWLEDGEMENT (ACK) for Inter Cluster
	0100 - 1111	Reserved
Data Frame 11	0000	INTRA CLUSTER DATA
	0001	INTRA CLUSTER DATA with ACK
	0010	INTER CLUSTER DATA
	0011	INTER CLUSTER DATA with ACK
	0100 - 1111	Reserved

Management Frames

Intra Cluster Management Frames

HELLO

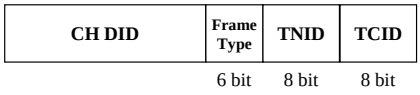


Figure 1 HELLO message

- CH DID (Cluster Head Deice ID): A part of cluster head MAC address. This field is used to determine whether the transmitting node belongs to the same nodecluster.
- TNID (Transmitting Node ID): The node ID of source/intermediate node that sends the packet.
- TCID (Transmitting Cluster ID): This field is the cluster ID of transmitter. Before assignment of CID, the cluster head use temporary CID 254.

CONNECTION REQUEST

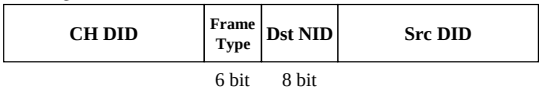


Figure 2 CONNECTION REQUEST message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address that the new node wants to join.
- Dst NID (Destination Node ID): The node ID that the new node requests a connection.
- Src DID (Transmitting Device ID): A part of the source node MAC.

CONNECTION RESPONSE

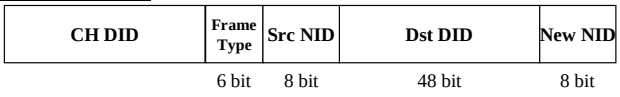


Figure 3 CONNECTION RESPONSE message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- Src NID (Source Node ID): The node ID that is requested the connection by the new node.
- Dst DID (Destination Device ID): The copy of Src DID field of CONNECTION REQUEST message. The MAC address of the newly joined node.
- New NID (New Node ID): The new node ID that is assigned to the requester node. When the requested node rejects the request, it put 254 in this field.

NODE ID REQUEST

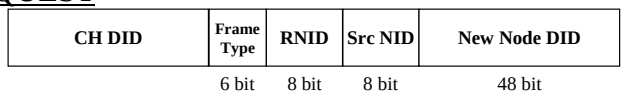


Figure 4 CLUSTER ID REQUEST message

- CH DID (Cluster Head Device ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Src NID (Source Node ID): The node ID that is requesting the connection for the new node.
- New Node DID (New Node Device ID): The copy of Src DID field of the CONNECTION REQUEST message

NODE ID RESPONSE

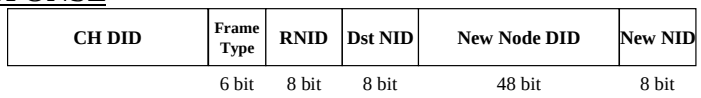


Figure 5 CLUSTER ID RESPONSE message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Dst NID (Destination Node ID): The node ID that is requesting the connection for the new node.
- New Node DID (New Node Device ID): The copy of New Node DID field of the CLUSTER ID REQUEST message
- New NID (New Node ID): The node ID that is assigned to the new node. When the cluster head rejects the request, it put 254 in this field.

DISCONNECTION REQUEST

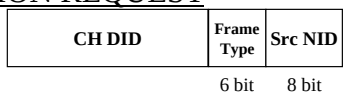


Figure 6 DISCONNECTION REQUEST message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- Src NID (Source Node ID): The node ID of requesting node.

DISCONNECTION RESPONSE

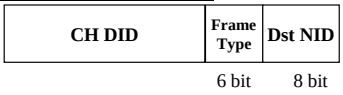


Figure 7 DISCONNECTION RESPONSE message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- Dst NID (Destination Node ID): The node ID of requesting node.

LINK-STATE REPORT

CH DID	Frame Type	RNID	Src NID	Length 1	Length 2	NID #1	NID #2	…	NID #n	CID #1	…	CID #m
	6 bit	8 bit	8 bit	8 bit	8 bit	8 bit	8 bit		8 bit	8 bit		8 bit

Figure 8 LINK-STATE REPORT message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Src NID (Source Node ID): The node ID that originally sends this message.
- Length 1: The number of NID field
- Length 2: The number of CID field
- NID #n (Node ID #n): The neighbor node ID.
- CID #m (Cluster ID #m): The neighbor cluster ID.

TOPOLOGY UPDATE

CH DID	Frame Type	Length 1	Length 2	NID #1	Parent NID	…	NID #n	Parent NID	CID #1	Border NID	…	CID #m	Border NID
	6 bit	8 bit	8 bit	8 bit	8 bit		8 bit	8 bit	8 bit	8 bit		8 bit	8 bit

Figure 9 TOPOLOGY UPDATE

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- Length 1: The number of NID field
- Length 2: The number of CID field
- NID #n (Node ID #n): The member node ID.
- Parent NID (Parent Node ID): The parent node ID for the member node #n named in previous field.
- CID #m (Cluster ID #m): The neighbor cluster ID.
- Border NID (Border Node ID): The border node ID for the cluster #m named in previous field.

Inter Cluster Management Frames

NETWORK CONNECTION REQUEST

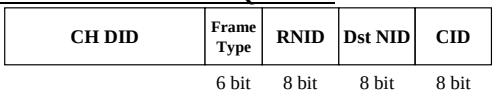


Figure 10 NETWORK CONNECTION REQUEST message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Dst NID (Destination Node ID): The node ID that is asked to be the border node.
- CID (Cluster ID): The cluster ID that the border node should set up a connection

NETWORK CONNECTION RESPONSE

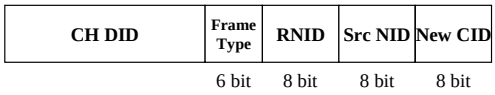


Figure 11 NETWORK CONNECTION RESPONSE message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Src NID (Source Node ID): The node ID of the border node.
- New CID (New Cluster ID): The new cluster ID that is assigned to the cluster head by the Designated Device

CLUSTER ID REQUEST

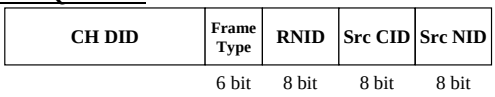


Figure 12 CLUSTER ID REQUEST message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Src CID (Source Cluster ID): The cluster ID of the border node.
- Src NID (Source Node ID): The node ID of the border node.

CLUSTER ID RESPONSE

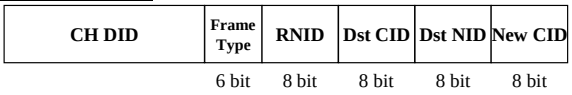


Figure 13 CLUSTER ID RESPONSE message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Dst CID (Destination Cluster ID): The cluster ID of the border node that requested a new CID.
- Dst NID (Destination Node ID): The node ID of the border node that requested a new CID.
- New CID (New Cluster ID): The new cluster ID that is assigned by the Designated Device

NETWORK DISCONNECTION REQUEST

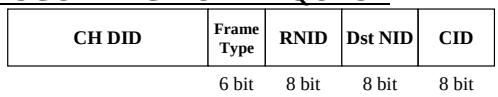


Figure 14 NETWORK DISCONNECTION REQUEST message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Dst NID (Destination Node ID): The node ID of the border node.
- CID (Cluster ID): The cluster ID that the border node should disconnect a connection

NETWORK DISCONNECTION RESPONSE

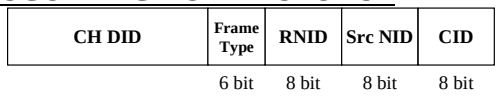


Figure 15 NETWORK DISCONNECTION RESPONSE message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Src NID (Source Node ID): The node ID of the border node.
- CID (Cluster ID): The cluster ID that the border node has disconnected with.

NETWORK LINK-STATE REPORT

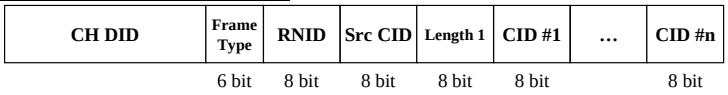


Figure 16 NETWORK LINK-STATE REPORT message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Src CID (Source Cluster ID): The cluster ID of the source node.
- Length 1: The number of fields for CIDs
- CID #n (Cluster ID #n): The neighbor cluster ID

NETWORK TOPOLOGY UPDATE

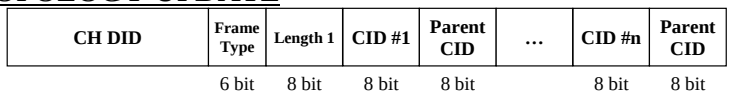


Figure 17 NETWORK TOPOLOGY UPDATE message

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- Length 1: The number of fields for CIDs and their Parent CIDs.
- CID #n (Cluster ID #n): The cluster ID that exists in the network.
- Parent CID (Parent Cluster ID): The parent cluster ID for the cluster #n named in previous field.

Control Frames

RTS

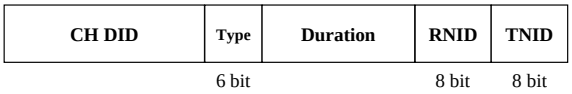


Figure 18 REQUEST TO SEND (RTS)

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- Duration: The value of this field is the amount of time the sending node needs to transmit the data frame, one CTS frame, one ACK frame and three interframe space intervals.
- RNID (Receiving Node ID): The node ID of the requested node.
- TNID (Transmitting Node ID): The node ID of the requesting node.

CTS

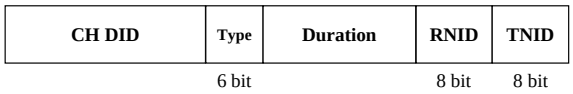


Figure 19 CLEAR TO SEND (CTS)

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- Duration: The value of this field is the duration of previous RTS frame minus the time required to transmit the CTS frame and an interframe space intervals.
- RNID (Receiving Node ID): The node ID of the requesting node.
- TNID (Transmitting Node ID): The node ID of the requested node.

ACK for Intra Cluster Communication

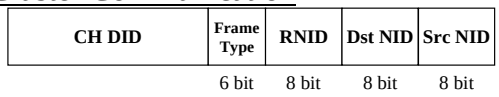


Figure 20 ACKNOWLEDGEMENT (ACK) for Intra Cluster Communication

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Dst NID (Destination Node ID): The node ID of the destination node.
- Src NID (Source Node ID): The node ID of the source node.

ACK for Inter Cluster Communication

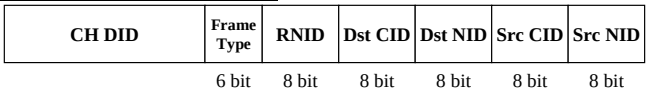


Figure 21 ACKNOWLEDGEMENT (ACK) for Inter Cluster Communication

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Dst CID (Destination Cluster ID): The cluster ID of the destination node.
- Dst NID (Destination Node ID): The node ID of the destination node.
- Src CID (Source Cluster ID): The node ID of the source node.
- Src NID (Source Node ID): The node ID of the source node.

Data Frames

Intra Cluster Data Frame

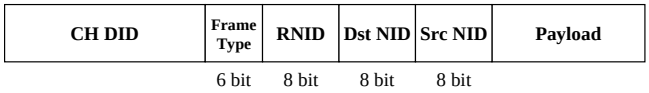


Figure 22 Intra Cluster DATA frame

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Dst NID (Destination Node ID): The node ID of the destination node.
- Src NID (Source Node ID): The node ID of the source node.
- Payload: The Data.

Intra Cluster Data Frame with ACK

The same frame structure as Intra Cluster Data Frame except the Frame Type field.

Inter Cluster Data Frame

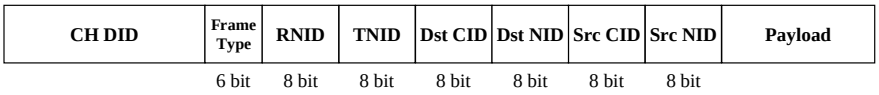


Figure 23 Inter Cluster DATA frame

- CH DID (Cluster Head Deice ID): A part of the cluster head MAC address.
- RNID (Receiving Node ID): The node ID of destination/intermediate node that should receive the packet.
- Dst CID (Destination Cluster ID): The cluster ID of the destination node.
- Dst NID (Destination Node ID): The node ID of the destination node.
- Src CID (Source Cluster ID): The node ID of the source node.
- Src NID (Source Node ID): The node ID of the source node.
- Payload: The Data.

Inter Cluster Data Frame with ACK

The same frame structure as Inter Cluster Data Frame except the Frame Type field.

Single Cluster Network

A cluster head and member nodes form a cluster and the clusters make up the network. This chapter describes single cluster network formation and communication within a cluster. Multi cluster networks are described in the next chapter.

Cluster Formation Process

Cluster Head Selection Process

The Cluster formation process begins with cluster head selection. After a cluster head is selected, the cluster head expands links with other member nodes to form a cluster.

After a node turns on, it listens and searches the HELLO message from other nodes. If it can't get any HELLO messages for certain time, then it turns to a cluster head and sends out a HELLO message to its neighbors. The new cluster head wait responses from neighbors for a while. If it hasn't received any connection requests, it turns back to a regular node and listens again.

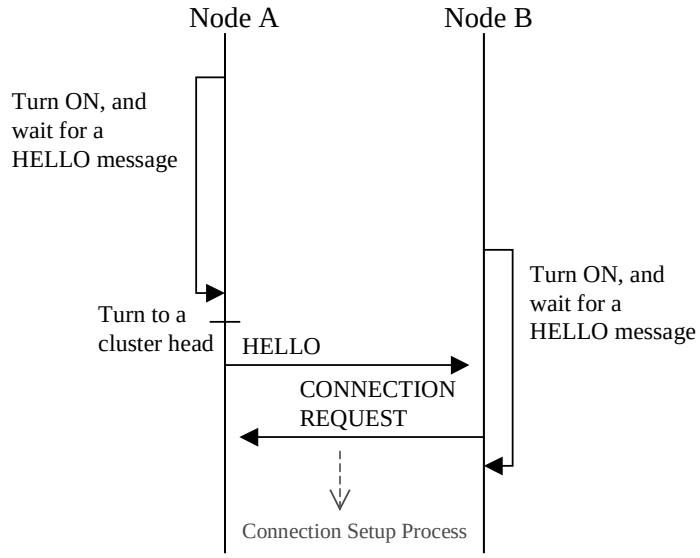


Figure 24 Cluster head selection process

Other methods to select a cluster head might be possible. The cluster head can be selected based on stored/calculated parameters of each node, like transmission range, power capacity, computing ability or location information.

Single Hop Cluster

After a node is selected as a cluster head, it broadcasts a periodic HELLO message that contains a part of the cluster head MAC address and node ID 0 that

indicates the cluster head. The nodes that receive this HELLO message send a CONNECTION REQUEST message to the cluster head. When the cluster head receives the CONNECTION REQUEST, it responds to the node with a CONNECTION RESPONSE message that contains a node ID for the node. The node ID must be unique within a cluster and the cluster head has the responsibility to assign and manage unique node IDs to its member nodes. The node that is assigned a node ID replies with an ACK message to the cluster head. After every message exchange is finished, both nodes set each other as parent or child in their neighbor list. Specifically, the cluster head denotes the newly added node as a child in its neighbor list and the new node denotes the cluster head as a parent. The Link between the cluster head and the member node is established at this moment.

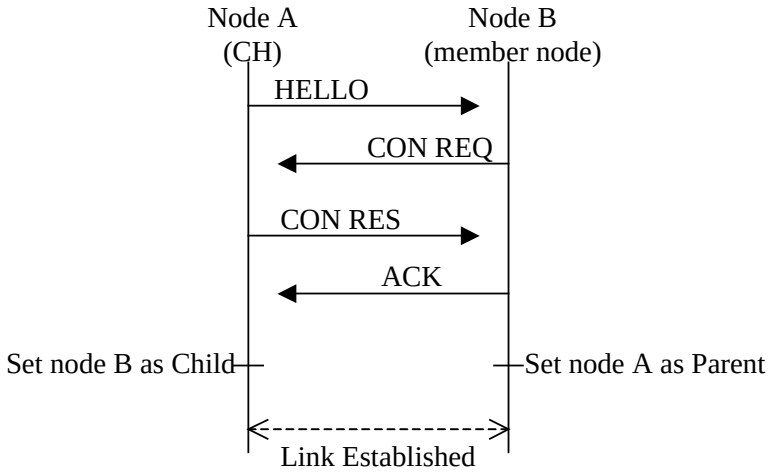


Figure 25 Link setup between CH and member node

If all nodes are located in the range of the cluster head, the topology of connection becomes a star and every member nodes are connected to the cluster head with one hop. The maximum nodes number in a cluster is 254 including the cluster head. The administrator or the manufacturer may limit the node feature to supporting only single hop cluster.

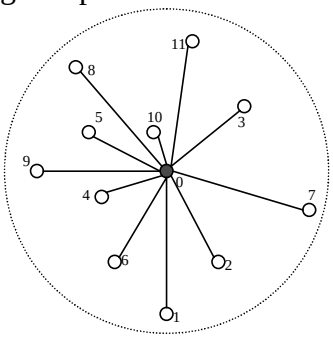


Figure 26 Single hop cluster structure

Multi Hop Cluster

A cluster can expand into a multi hop structure when each node supports multiple connections. Although network delay increases, the coverage within one cluster can increase.

Multi hop cluster setup procedure is described in Figure 27. After node B has established a link with the cluster head, it starts to relay HELLO messages from the cluster head. When node C gets the message from node B, it sends a CONNECTION REQUEST message to node B. Node B requests a new node ID to the cluster head for node C. When node B receives a new node ID from the cluster head, it sends a CONNECTION RESPONSE message to node B. Then node C receives it and answers with an ACK message. After this message exchange, node C sets node B as its parent, node B sets node C as its child, and the cluster head sets node C as node B's child. Then node C starts to relay HELLO messages to announce itself to its neighborhood.

When a node receives several HELLO messages from different nodes, it responds to the earliest HELLO message because it has the strongest possibility of the shortest route to the cluster head. The path to the cluster head might not be ideal at this time. The route to the cluster head will optimize in a later process.

This expansion process can continue until the cluster head runs out of all node IDs. But we can also limit the maximum hop count to reduce maximum network delay.

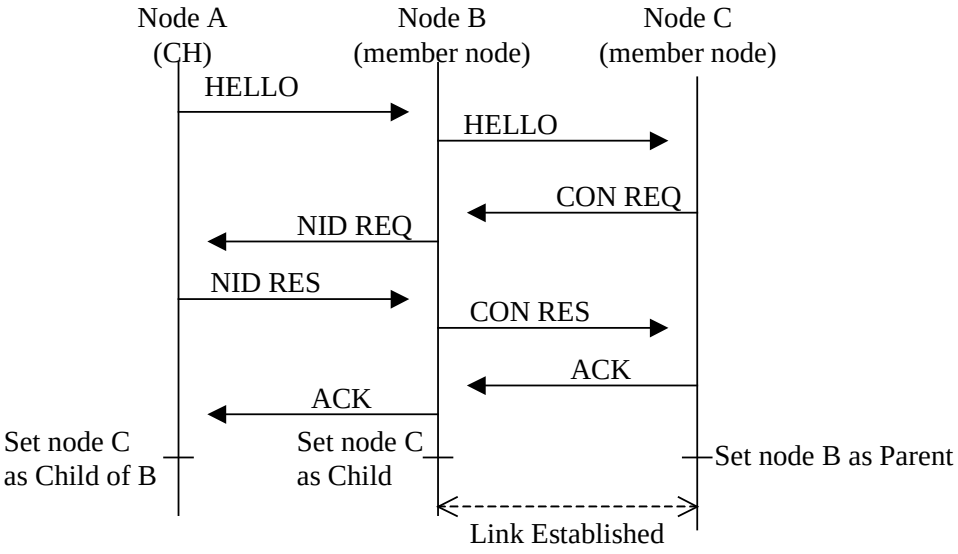


Figure 27 Multi hop cluster setup procedure

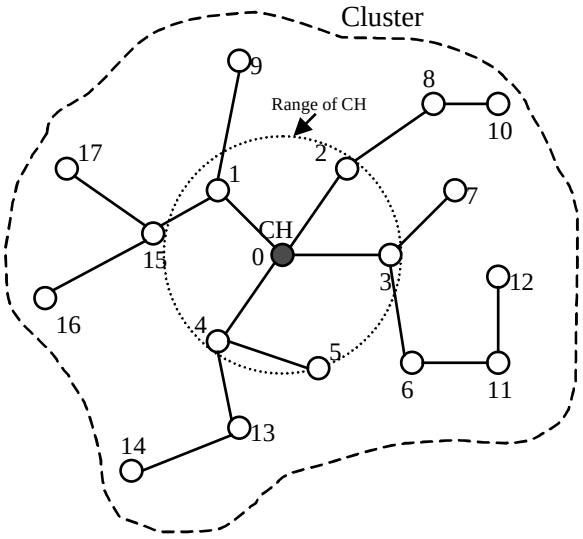


Figure 28 Multi hop cluster structure

Connection Reject

When the cluster head has run out of all node IDs or the cluster has reached some other defined limit, the cluster head should reject connection requests from new nodes. To reject the connection request, the temporary NID, NID 254, is used in the destination NID field of the CONNECTION RESPONSE message or the new NID field of the NODE ID RESPONSE message.

When a requester node receives a NODE ID RESPONSE message with NID 254, it sends a CONNECTION RESPONSE message with NID 254 to the new node.

If a new node has received a CONNECTION RESPONSE with NID 254, it stores the cluster ID and stop sending a CONNECTION REQUEST message to the node belonging to the same cluster for a while.

Network Maintenance

Hello Message And Neighbor List

The cluster head periodically broadcasts HELLO messages to its member nodes. When these member nodes receive the HELLO message from the cluster head, they also send HELLO messages to announce themselves to their neighbors. Every node records their neighbor nodes in their neighbor list. The entry of the neighbor list is updated by the periodic HELLO message. If a node entry doesn't update until certain timeout limit, it should be eliminated.

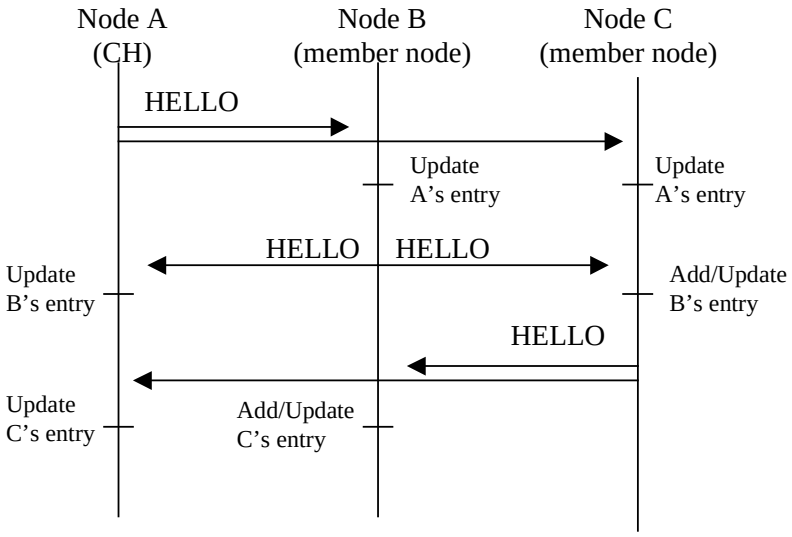


Figure 29 Hello message and neighbor list update

The member nodes can talk directly with the neighbor nodes. If a node want to communicate with a node outside of its range, it asks the cluster head or the parent node to relay the message to the destination.

A node may receive a HELLO message from a node that belongs to different cluster. In that case, the node adds the cluster ID (CID) of the transmitting node in the neighbor list.

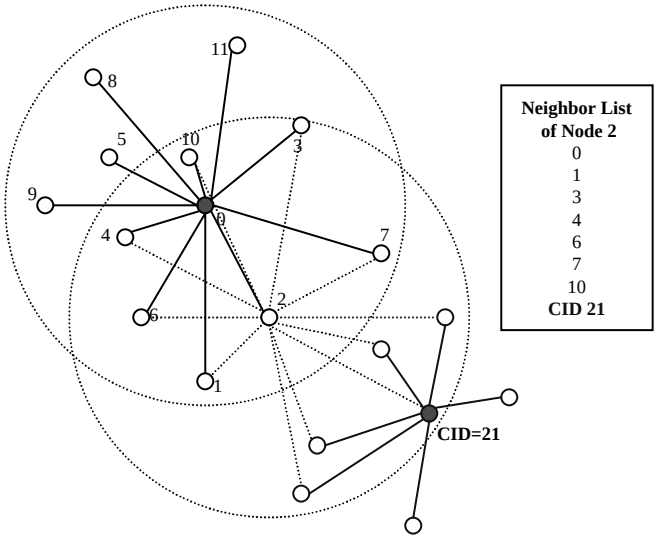
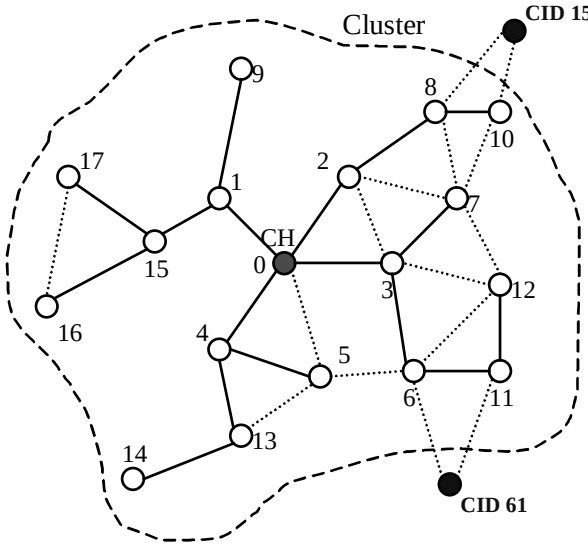


Figure 30 Neighbor list of a node in cluster border

Link-State Report

Every node has to report its link state to the cluster head. A member node periodically sends a LINK-STATE REPORT message that contain its neighbors node ID list to the cluster head. *The frequency of Link-State Report message will be determined by application requirements and stability.*



Sender	LINK-STATE REPORT
Node 1	0, 9, 15
Node 2	0, 3, 7, 8
Node 3	0, 2, 6, 7, 12
Node 4	0, 5, 13
Node 5	0, 4, 6, 13
Node 6	3, 5, 11, 12, *CID61*
Node 7	2, 3, 8, 10, 12
Node 8	2, 7, 10 , *CID158*
Node 9	1
Node 10	7, 8 , *CID158*
Node 11	6, 12 , *CID61*
Node 12	3, 6, 7, 11
Node 13	4, 5, 14
Node 14	13
Node 15	1, 16, 17
Node 16	15, 17
Node 17	15, 16

Figure 31 Link-State Reports

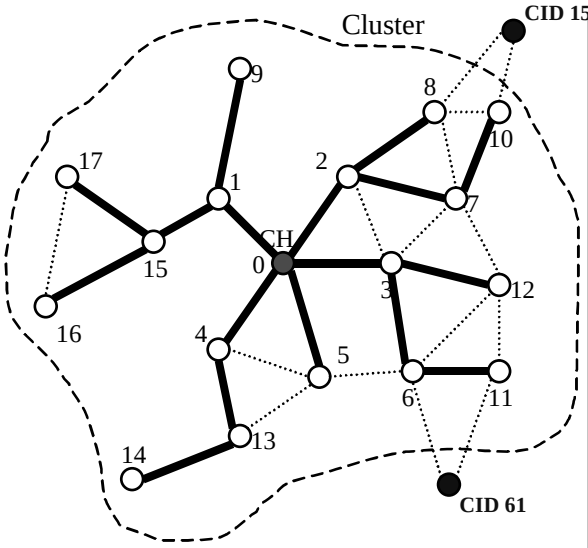
Topology Update

Based on the LINK-STATE REPORT message the cluster head periodically calculates the shortest path between itself and member nodes and informs it to the members by TOPOLOGY UPDATE message.

The route selection rule is simple. The cluster head should choose the route with the smallest hop count. If there are several routes with the same hop count, the cluster head should choose the route that has the smallest node ID as the parent node or some similar arbitration rule.

If a member node receives the TOPOLOGY UPDATE message that the different parent node is linked to the node, it changes the parent node as indicated in the message. And it also records its child nodes and the nodes below it in the tree at this time. The nodes within a cluster basically communicate with other node through the parent node except the case where they communicate with their neighbor nodes directly.

The cycle of the Topology Update depends on the Link-State Report cycle.



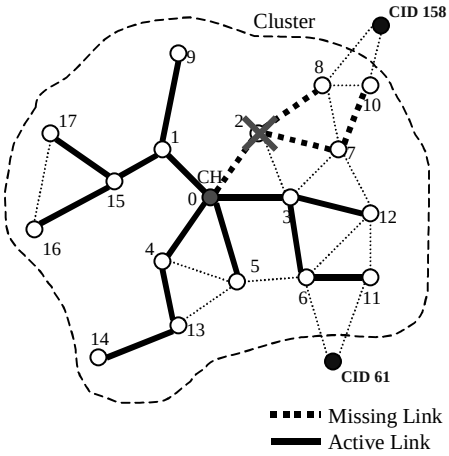
TOPOLOGY UPDATE

Node	Parent Node
Node 1	0
Node 2	0
Node 3	0
Node 4	0
Node 5	0
Node 6	3
Node 7	2
Node 8	2
Node 9	1
Node 10	7
Node 11	6
Node 12	3
Node 13	4
Node 14	13
Node 15	1
Node 16	15
Node 17	15
CID 61	6
CID 158	8

Figure 32 Topology Update

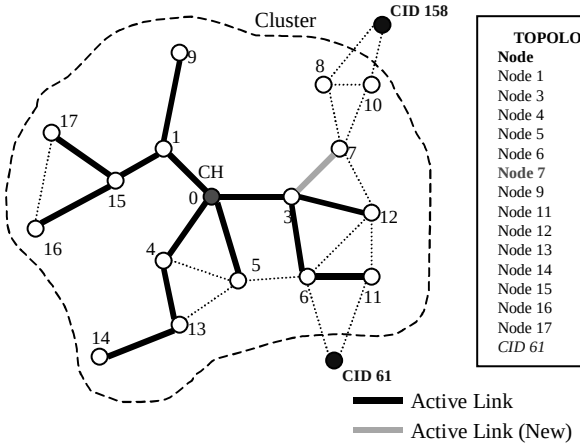
Network Redundancy

If a member node has trouble and becomes unable to communicate, the tree route of the cluster would be reconfigured. Look at Figure 34. In this cluster, the node 2 has trouble and stop communication (Figure 34-i). Since the node 2, 7, 8 and 10 cannot send the LINK-STATE REPORT, the cluster head calculate a new route from other link-state information. By the first TOPOLOGY UPDATE message, the node 7 setup a new connection with the node 3 (Figure 34-ii). In the next cycle of TOPOLOGY REPORT and UPDATE, the node 8 and 10 are instructed to connect to node 7 (Figure 34-iii).



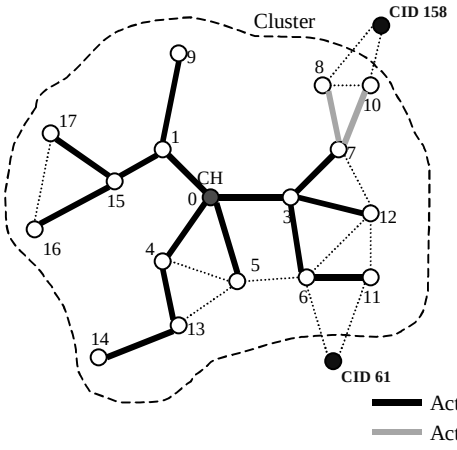
Sender	LINK-STATE REPORT
Node 1	0, 9, 15
~~Node 2~~	~~0, 3, 7, 8~~
Node 3	0, ~~2,~~ 6, 7, 12
Node 4	0, 5, 13
Node 5	0, 4, 6, 13
Node 6	3, 5, 11, 12 , *CID61*
~~Node 7~~	~~2, 3, 8, 10, 12~~
~~Node 8~~	~~2, 7, 10 , *CID158*~~
Node 9	1
~~Node 10~~	~~7, 8 , *CID158*~~
Node 11	6, 12 , *CID61*
Node 12	3, 6, 7, 11
Node 13	4, 5, 14
Node 14	13
Node 15	1, 16, 17
Node 16	15, 17
Node 17	15, 16

(i) Node trouble



TOPOLOGY UPDATE	
Node	**Parent Node**
Node 1	0
Node 3	0
Node 4	0
Node 5	0
Node 6	3
Node 7	3
Node 9	1
Node 11	6
Node 12	3
Node 13	4
Node 14	13
Node 15	1
Node 16	15
Node 17	15
CID 61	6

(ii) Link recovery 1



Sender	LINK-STATE REPORT
Node 1	0, 9, 15
Node 3	0, 6, 7, 12
Node 4	0, 5, 13
Node 5	0, 4, 6, 13
Node 6	3, 5, 11, 12 , *CID61*
Node 7	3, 8, 10, 12
Node 9	1
Node 11	6, 12 , *CID61*
Node 12	3, 6, 7, 11
Node 13	4, 5, 14
Node 14	13
Node 15	1, 16, 17
Node 16	15, 17
Node 17	15, 16

TOPOLOGY UPDATE	
Node	**Parent Node**
Node 1	0
Node 3	0
Node 4	0
Node 5	0
Node 6	3
Node 7	3
Node 8	7
Node 9	1
Node 10	7
Node 11	6
Node 12	3
Node 13	4
Node 14	13
Node 15	1
Node 16	15
Node 17	15
CID 61	6

(iii) Link recovery 2

Figure 33 Network redundancy

When the cluster head has trouble, the distribution of HELLO message is stopped and all member nodes know that they have lost the cluster head. The member nodes lose their node ID and connections with the parent/children nodes. The cluster would be reconfigured in the same way as the cluster formation process.

Intra Cluster Communication

RTS/CTS

There are two options in Multiple Access Control. One is CSMA/CA and the other is pure ALOHA. The RTS (Request To Send)/CTS (Clear To Send) messages are only for the CSMA/CA option.

When a node wants to send a packet to other node, it sends RTS at first and then waits for CTS. After receiving RTS, the receiving node sends a CTS frame to acknowledge the right for the sending node to send data frame. This procedure reduces the chance of collision by hidden nodes.

A node receiving an error-free frame can send an ACK frame to the sending node to acknowledge the successful reception of the frame.

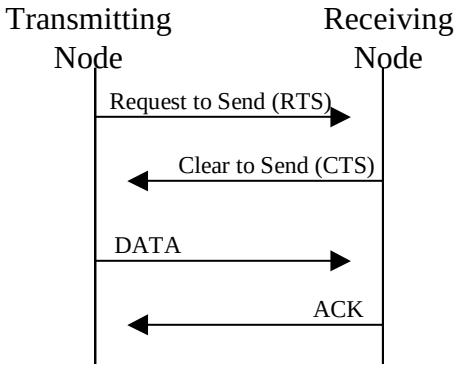


Figure 35 RTS/CTS

Unicast message

When a node wants to send a packet to other node, it sets its node ID in source NID field, destination node ID in destination NID field. If a node isn't sending to one of its neighbors, and if the destination node is below the source in the tree, the source node sets its child node ID in the receiving NID field and asks its child node to forward to the destination. If the source isn't sending to one of its neighbors, and if the destination node isn't below the source branch, the source must sets its parent node ID in the receiving NID field and send the packet to its parent. Each intermediate node should relay the packet toward the destination node as it updates receiving and transmitting NID fields.

The packet is routed along the tree topology except the last one hop. If the destination node is below the sender node in the tree structure, the packet is forwarded along the branch to the destination. Otherwise the packet goes up along the tree structure and looks for the destination. If the intermediate node has the destination node in its neighbor list, the packet is routed apart from the tree route.

When a node receives a unicast message, the receiving node should respond to the transmitting node with an ACK message.

The detail of packet forwarding process is described in Figure 36.

Broadcast message

The broadcast message within a cluster is always sent by the cluster head and forwarded by all member nodes. The receiving node shouldn't respond to the broadcast message with ACK message.

A member node should forward the broadcast message that is sent by its parent to avoid forwarding the same packet more than once.

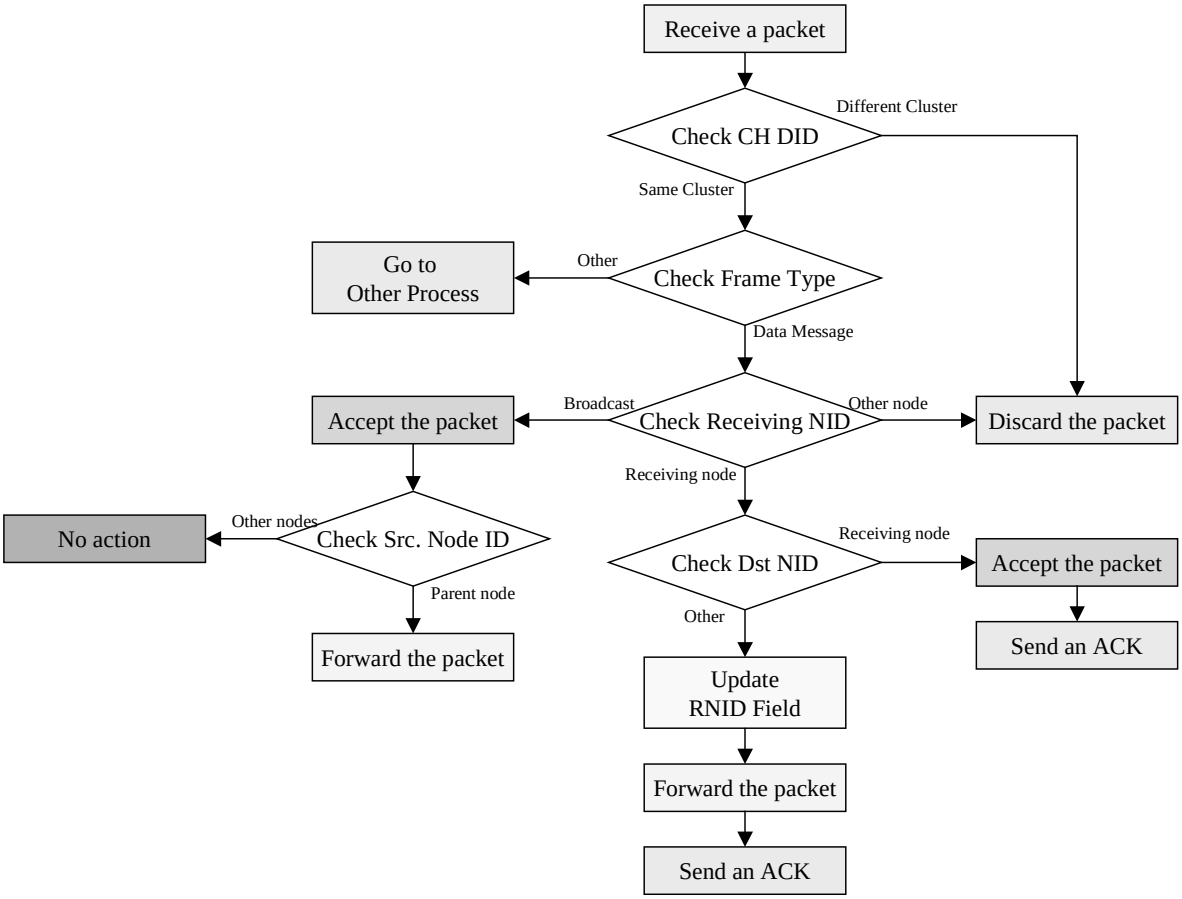


Figure 36 Data Packet Forwarding Flow

Packet Fragmentation

If the packet size will be long, packet fragmentation rule should be specified.

Inter Cluster Network

This chapter describes multi cluster network formation and communication between clusters.

Designated Device

To form a network a Designated Device is needed in the network.

The Designated Device assumes an important role in the network. It has the responsibility to assign a unique cluster ID to each cluster head. This cluster ID combined with the node ID that the cluster head assigns to each node within a cluster forms a logical address and is used to route packets. Another role of the Designated Device is to calculate the shortest route from the cluster to Designated Device and inform it to all nodes within the network.

Network Formation Process

Cluster ID Assignment

Each node is unique due to the combination of the cluster ID (CID) and the node ID (NID). The NID is assigned by each cluster head (CH) and the Designated Device (DD) assigns a unique 8bit CID to each cluster in early stage of multi cluster network formation.

When the DD joins the network, it acts as the cluster head of cluster 0 and starts to send HELLO message to the neighborhood. If a CH has received this message, it sends a CONNECTION REQUEST message and joins the cluster 0. After that, the CH requests a CID to the DD. In this case, the CH is a border node that has two logical addresses. One is for a member node of the cluster 0 and the other is for a cluster head. When the CH gets a new CID, it informs to its member nodes by the HELLO message.

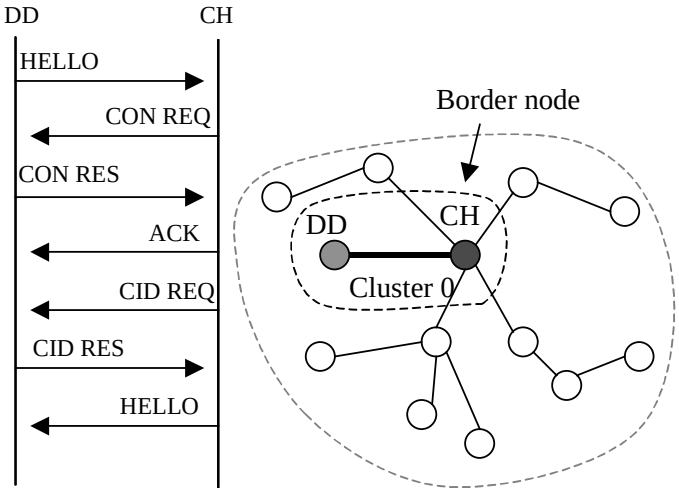


Figure 37 CID assignment 1

If a member node has received the HELLO message from the DD, it adds CID 0 in its neighbor list and reports to its CH. The reported CH selects the member node as a border node to its parent cluster and sends a NETWORK CONNECTION REQUEST message to the member node to set up a connection with the DD. The border node requests a connection and joins the cluster 0 as its member node. Then it sends a CID REQUEST message to the DD. After the CID RESPONSE message arrival, the border node sends NETWORK CONNECTION RESPONSE message that contains a new CID to the CH. When the CH gets a new CID, it informs to its member nodes by the HELLO message.

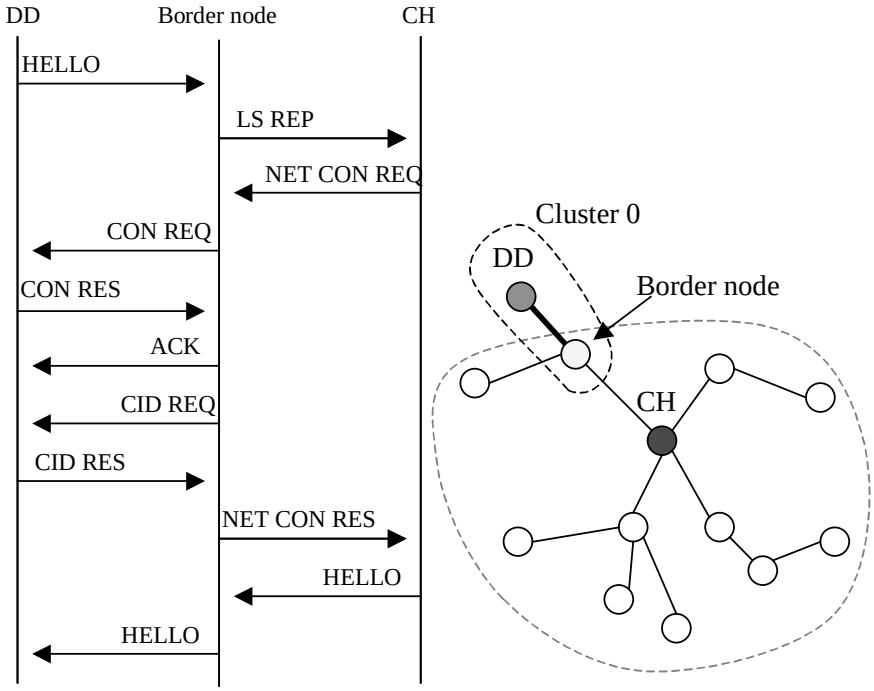


Figure 38 CID assignment 2

The clusters not bordering cluster 0 use intermediate clusters to get a CID. Two cases can be thought as the same as above. One is the CH becomes the border node to its parent cluster. The other one is the CH names a member node as the border to its parent cluster. In both case, the process is triggered by the HELLO message that contain a CID from 1 to 253 instead of the HELLO from the DD.

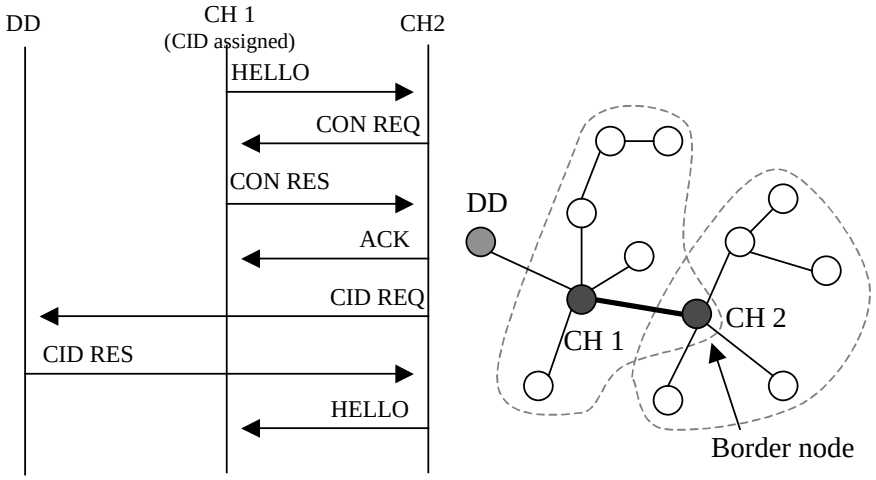


Figure 39 CID assignment 3

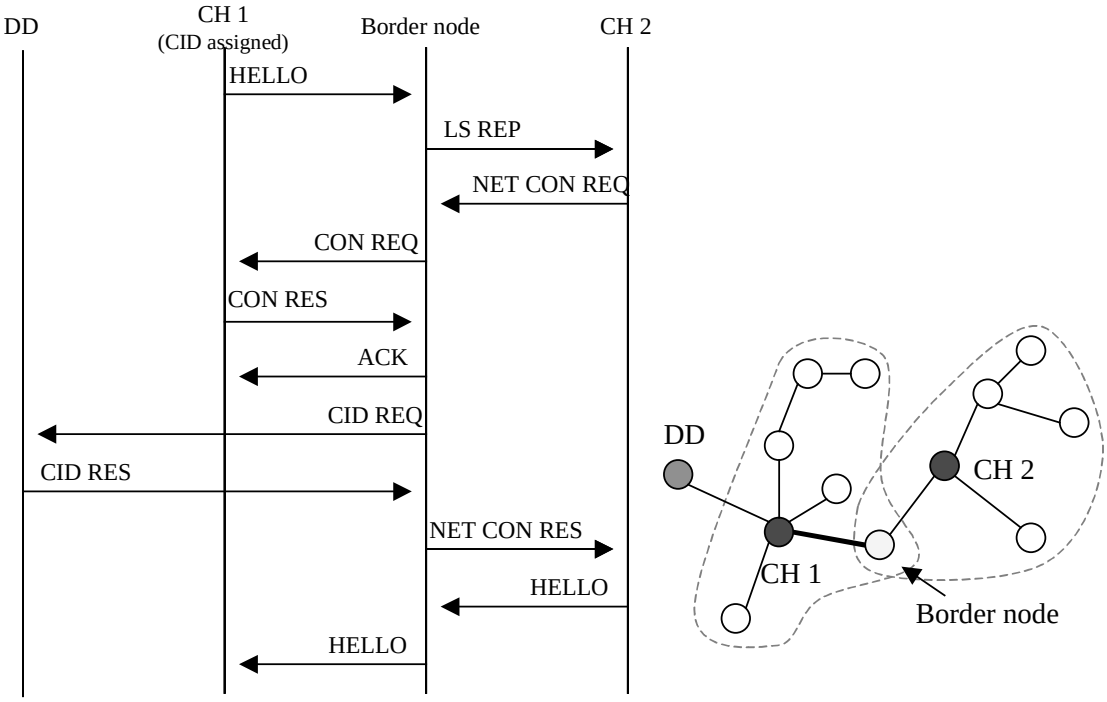


Figure 40CID assignment 4

Each member node of the cluster has to record its parent cluster, child/lower clusters and the border node IDs associated with both the parent and child clusters. The DD should store the whole tree structure of the clusters.

Network Maintenance

Although the clusters form an initial tree topology in the CID assignment procedure, it may not be the optimized tree structure and the tree structure may change due to the failure of nodes. The clusters use the cluster link-state information to calculate the optimized route and periodically update their topology for the network redundancy.

Network Link-State Report

Every cluster has to report its link-state information to the DD. The cluster head periodically sends a NETWORK LINK-STATE REPORT message that contains its neighbor cluster CID list to the DD.

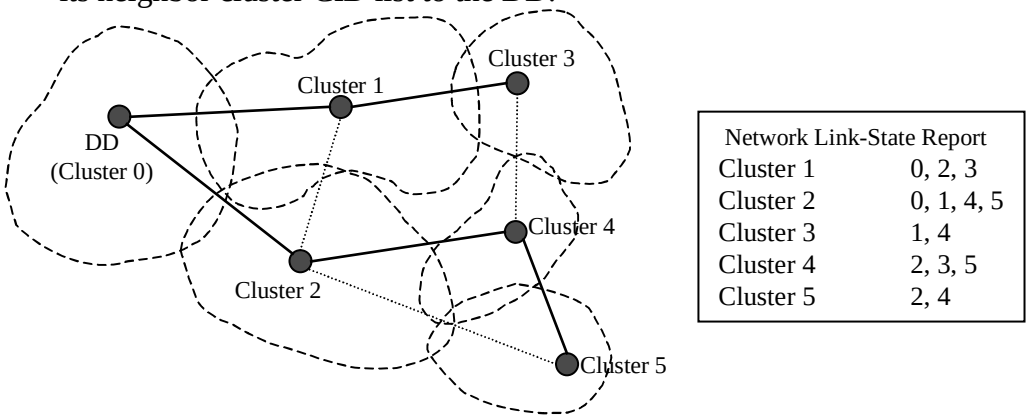


Figure 41 Network Link-State Report

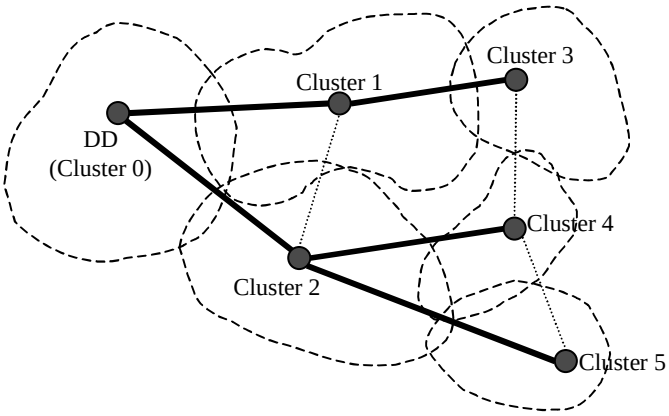
Network Topology Update

Based on the NETWORK LINK-STATE REPORT message, the DD periodically calculates the optimized tree route and sends a NETWORK TOPOLOGY UPDATE message to inform up-to-date route from the DD to the clusters.

The route calculation is simple. The DD should choose the route with the smallest hop count. If there are several routes with the same hop count, the DD should choose the cluster that has the smallest CID as the parent cluster, or some other functional rule for arbitrating ties.

If a cluster head receives the NETWORK TOPOLOGY UPDATE message and determines that a different parent cluster is linked to the cluster, it changes the parent cluster as indicated in the message. All nodes within the cluster should

memorize its parent cluster, child/lower clusters and the border nodes' NID at this time.



Network Topology Update

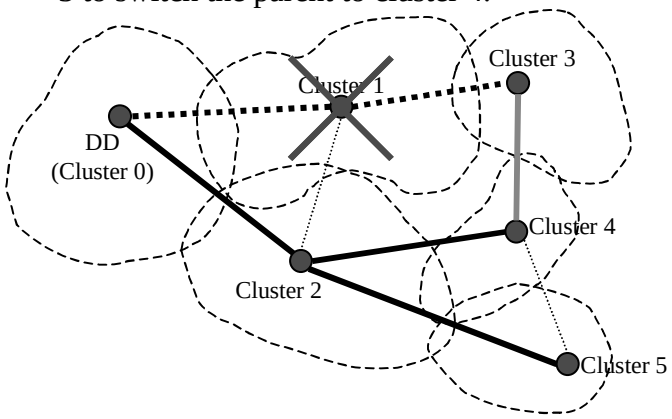
Cluster	Parent Cluster
Cluster 1	0
Cluster 2	0
Cluster 3	1
Cluster 4	2
Cluster 5	2

Figure 42 Network Topology Update

Redundancy

When a failure has occurred in the network, the cluster may have to find an alternative route to the DD. This feature is achieved by using the messages explained above.

Look at Figure 43. Since trouble occurred in cluster 1, the NETWORK LINK-STATE REPORT messages from cluster 1 and 3 didn't arrive at the DD. The DD broadcasts a new NETWORK TOPLOGY UPDATE message and indicates cluster 3 to switch the parent to cluster 4.



Network Link-State Report

~~Cluster 1~~	~~0, 2, 3~~
Cluster 2	0, ~~1~~, 4, 5
~~Cluster 3~~	~~1, 4~~
Cluster 4	2, 3, 5
Cluster 5	2, 4

Network Topology Update

Cluster	Parent Cluster
~~Cluster 1~~	~~0~~
Cluster 2	0
Cluster 3	~~1~~ 4
Cluster 4	2
Cluster 5	2

Figure 43 Network Redundancy

Backup Designated Device

A backup Designated Device (BDD) can be prepared to prevent network down time due to the DD's trouble. One example is that a BDD is connected to the DD by wired or wireless network and periodically duplicate the list of cluster ID and network link-state information from the DD. The BDD takes over the DD role as soon as it detects the DD's failure.

Other solutions may be possible to realize the BDD.

Inter Cluster Communication

Inter cluster communication is realized by routing. The border nodes act as routers that connect clusters and relay packets between clusters.

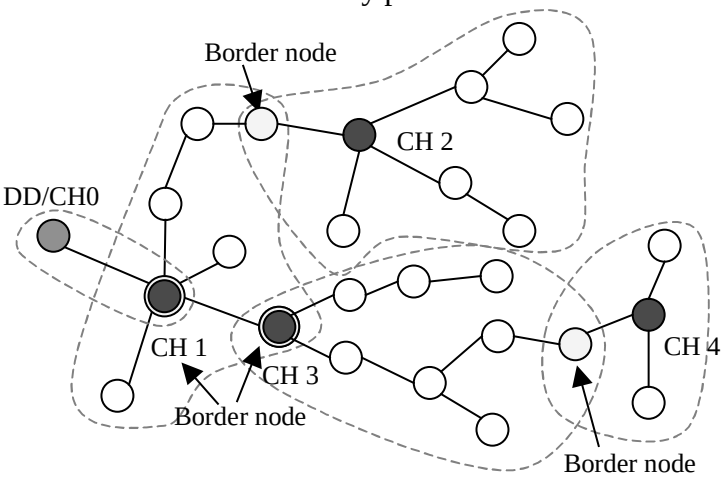


Figure 44 A multi cluster network and the border nodes

Unicast

Since every node knows its parent cluster, child/lower cluster and the border node ID, they can decide where they should send/forward the packet. When a border node receives a packet, it examines the destination address, then forwards to the next border node in the adjacent cluster or to the destination node within the cluster.

Broadcast

Only the DD can send a message to all nodes within its network. The message is forwarded along the tree route of clusters. The border node should forward the broadcast packet from the parent cluster to the child cluster.