EE 662

WIRELESS SENSOR NETWORKS

Midterm Project

Multi hop-Multichannel Network Design

- Arunima Koneripur Prasad (818459337)
- Iswarya S Gabbita (818457998)
- Nithin Kumar Narayana Swamy (818535426)
- Saddam Ali (818523687)

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1. INTRODUCTION

A. PRINCIPLES

The multi-hop multichannel ad-hoc network in consideration consists of spatially distributed nodes that act as sensors to monitor physical and environmental conditions. It is a self-organizing and self-healing network that performs dynamic routing. There are certain criteria responsible for the ad-hoc network to be successful, as follows:

Network Scan- Scan in different frequencies to detect existing networks.

Channel Allocation- Effective channel allocation such that no two overlapping and adjacent networks operate on the same channel.

Guaranteed Time slot allocation- Efficient allocation and management technique to ensure data transmission.

Synchronization- All nodes are synchronized as to effectively send and receive messages.

The network mapping follows a cluster tree architecture, with the gateway being the root node and the sensing nodes follow a parent-child hierarchy under the root node.

The cluster-tree topology is a special case of a mesh network where there is a single routing path between any pair of nodes and there is a distributed synchronization mechanism (operates in the beacon-enabled mode). The network is rooted off a gateway node which has an IP address and acts as a cluster head for the first network. The address of the gateway node is 1:254. All clusters have a cluster head with an address of Network ID: 254.

While the GUID (Globally Unique ID) is statically assigned during manufacturing time, the nodes are assigned an ID composed of Network ID: Node ID. All nodes belonging to the same cluster share the same Network ID.

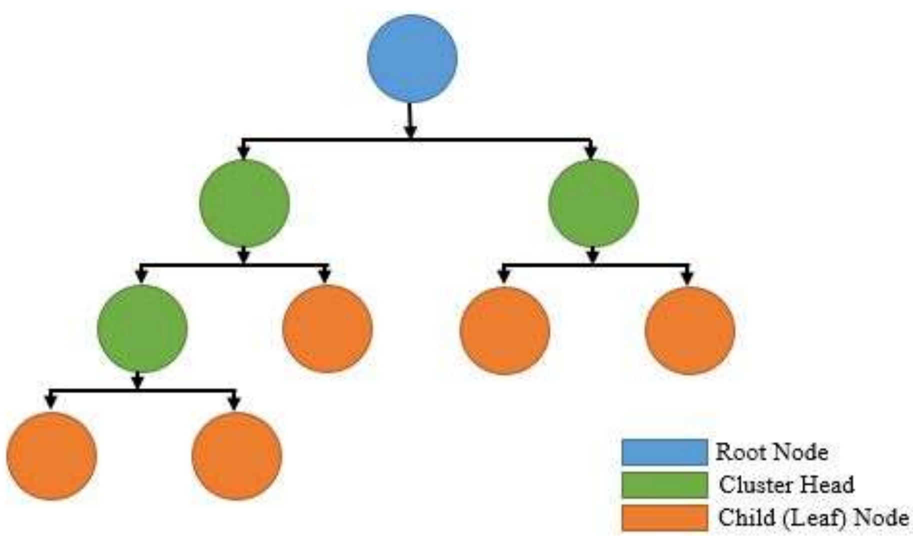


Figure 1*: *Network Hierarchy

B. NODE TYPES

The network nodes have been divided into the following types according to their nature:

1. Associated Nodes - These are the nodes that are associated with a certain cluster on the current network and have a network address.
2. Non-Associated Nodes - These are the nodes that are not associated with a cluster within the current network. They do not have a network address.
3. Gateway - It is the root node. All network communication happens through the gateway. All the nodes report to the gateway for address and frequency assignment.
4. Cluster Head - It is the head of a sub network (cluster). A node can become a cluster head when a new node approaches it. A node is measured by a fitness value (based on age, reliability, battery and such parameters) to measure its ability to become a cluster head.
5. Orphan - It is an existing node in the network which doesn't have a parent node either because the node has moved or the parent node has failed.

The network nodes have been divided into the following types according to their functionality:

1. Root Node (Gateway)
   A Gateway node acts as a relay between two neighboring network clusters. Any node covered by two or more network cells accessible by two or more different Cluster Heads is a candidate to be chosen as a Gateway. A Gateway acts as a relay node between two cells enabling communication between two Cluster Heads. Thus the Gateway nodes enable the overlay mesh network.
2. Cluster Head
   A Cluster Head is the manager for a cluster of nodes and networks spanned off from its member nodes. The Cluster Head acts as a router node between its cluster of networks/ nodes and its parent node. By definition, any node, with child nodes, in the hierarchical cluster tree structured network is a router.
3. Leaf Node
   A Leaf Node is a regular network node where all data is originated or terminated. Only Root Node and Cluster Heads participate in the management of the distributed dynamic address assignment process. A Gateway is assigned an address like any other ordinary network node.

C. NODE ARCHITECTURE

An example of a two-tier multi-hop multi-channel network is shown below in Figure 2. The whole network is governed by the Gateway (Root) node while each individual cluster is controlled by its own Cluster Head (CH). Each sub network (cluster) operates on a different (frequency) channel.

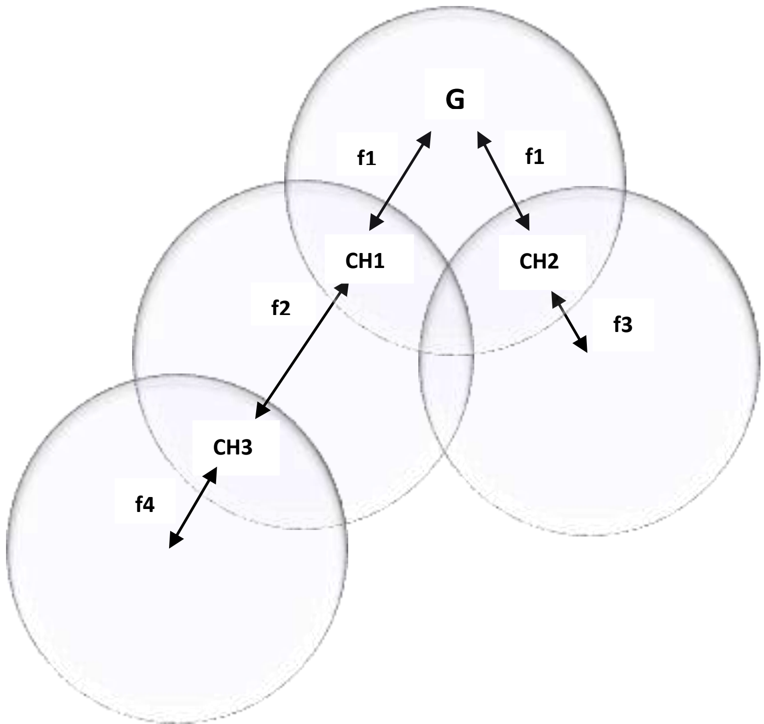


Figure 2: *Network Architecture*

The cluster heads CH1 and CH2 are the child coordinators of the Gateway node G. Whenever the gateway has to communicate with these nodes, they operate on frequency f1.Alternatively, when the cluster heads have to communicate with their children C1 and C2, they switch to their respective frequencies of f2 and f3.These frequencies are allotted by the gateway during the sub-network creation.

D. MAC PROTOCOL

The network has been designed to implement a combination of CSMA/CA and TDMA which ensures collision free data delivery and efficient routing. We make use of beacons that are periodically sent out, to ensure network wide synchronization and guaranteed time slots to nodes on a rotation policy for data delivery. A beacon also acts as a heartbeat informing nodes if they are still connected to the network. The design can also be extended to suit QoS parameters.

In our scheme, a beacon is broadcasted periodically over the network. It not only contains information about the network but also indicates the beginning of a frame. A beacon signal is used to synchronize the nodes in the network. The advantage of this synchronization method is that all nodes within in a cluster wake up and enter sleep mode at the same time. The time interval between two consecutive network beacons is called as a Beacon Interval (BI) and it includes:

Contention Access Period (CAP) – Child nodes can communicate to their cluster heads at one frequency using CSMA/CA with random back off

Contention Free Period (CFP) - Special nodes can reserve slots to provide guaranteed communication. This period is optional and is activated by the Gateway when needed. All the cluster heads are assigned guaranteed slots so that they can communicate with their parent in every successive frame.

Inactive period- All or some nodes are put to sleep during the inactive period to reduce power consumption.

The CAP and the CFP are the active periods during which transmission and reception occurs. The active period, called the Super frame duration (SD) is divided into 16 equally sized time slots during which transmissions are allowed.

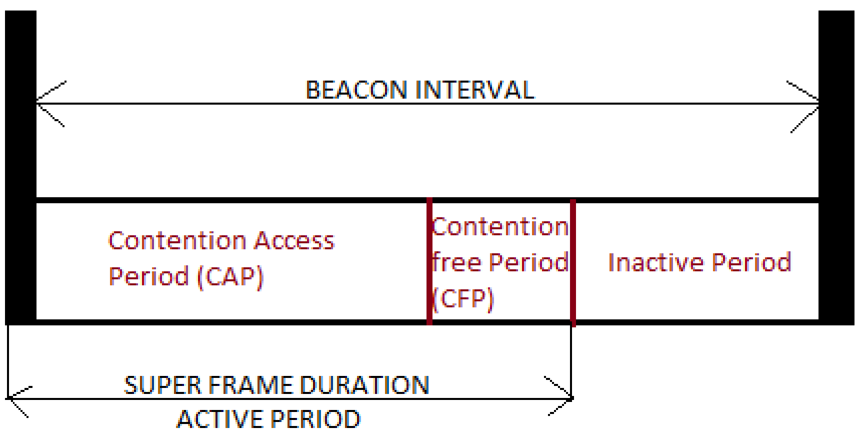


***Figure 3*:** *Super frame Structure*

E. MULTICHANNEL V/S SINGLE CHANNEL SELECTION

The use of a single channel for communication naturally leaves all the other channels free thereby decreasing the overall channel capacity. Although multiple orthogonal communication channels are available on most sensor networks, applications use only one channel for communication. This is a major source of bandwidth inefficiency. The use of a single channel causes decreased bandwidth utilization as the rest of the bandwidth goes unused.

Therefore, to perform better bandwidth utilization more than one channel could be used for wireless communication. Such a network that utilizes multiple channels for communication forms a multichannel ad-hoc network. Multichannel network gives the advantage of creating networks that operate standalone but still perform routing creating overlapping networks on different channels thus reducing interference from adjacent networks and thereby increasing the scalability of the network.

F. PACKET FORMATS

1. Probe (Association Request)

GUID	Packet Type	Source Address	Next Hop	Destination Address

This packet is sent either by the non- associated node or the orphan node to a neighboring node (associated node) to request to join the network and for a node address within the network.

2. Association Response (Invitation)

Reliability	No. of Children	Power level	No. of Hops to Gateway	Battery Level	Offered Address	GUID	Packet Type	Source Address	Next Hop	Destination Address

In response to the association request packet sent by the non-associated node, the associated node sends an invitation packet to inform the new node of its decision to accept it within its network. This packet is required as not all nodes that receive the association request packet would have the capability to accept new nodes. It sends some of its fitness parameters for the new node to decide if it still wants to join its network.

3. Association Acknowledgement (Invitation Acknowledgement)

Battery Level	Node Type	GUID	Packet Type	Source Address	Next Hop	Destination Address

The association acknowledgement packet is sent by the new node to the associated node whose network it is ready to join in response to the Association response (Invitation) packet.

4. Net ID + Frequency Request

Frequencies available nearby	Current operating frequency	GUID	Packet Type	Source Address	Next Hop	Destination Address

This packet is sent if the associated node that receives the association request (probe) is not a cluster head and doesn't have an existing network of its own. The associated node then sends the NetID + Frequency Request packet to the gateway (Root Node) to allot a network and frequency for itself to begin a new cluster.

5. Net ID + Frequency Response

Offered Frequency	Offered Net ID	GUID	Packet Type	Source Address	Next Hop	Destination Address

Gateway generates the above packet in response to the request packet from an associated node to form a cluster head. It checks its tables and allots a network ID and a channel frequency based on frequency reuse parameters.

6. Node Address Allocation

Allocated Frequency	Allocated Address	GUID	Packet Type	Source Address	Destination Address

Node address is allocated by the associated node/cluster head to the non-associated node/orphan after it is accepted to its network. While the cluster head sends this packet immediately after the Invitation Acknowledgement, the associated node sends this packet after it is assigned a network address by the gateway.

7. Child Notification Message

Allocated Frequency	Net ID's of Child Networks	GUID	Packet Type	Source Address	Destination Address

This message is sent by the orphan node to the new parent (cluster head) after it is accepted to the new network. It is to inform the cluster head of all its child nodes so that the routing tables are updated.

8. Hello Message (Heartbeat Message)

GUID	Packet Type	Source Address	Destination Address

Hello messages are periodic messages sent by the leaf nodes as a part of the network maintenance to inform the cluster heads if they are still alive. It is important for the parent nodes to know of the status of the child nodes for efficient routing and to make dynamic updates in the tables for efficient routing.

9. Data Packet

QoS Parameters	DATA	GUID	Packet Type	Source Address	Next Hop	Destination Address

This packet is designed for data transmission from the source node to the destination. The Quality of Service parameters include priority, type of data and so on.

2. NETWORK DISCOVERY & ADDRESS ALLOCATION

Network Discovery:

When a new node wants to join a network, the node waits for certain duration on each channel for a beacon. This scan will need the device to be present on each channel for a minimum duration greater than the super frame duration in order to successfully receive a beacon if any associated nodes/cluster heads are present (passive scan).

In our scheme, a new node initializes by performing a passive scan to determine an existing channel. It scans all the available channels for network beacons after which it selects one of the parent nodes, if multiple are found, and then sends a join request. If the scan was not successful in locating a parent node, it performs an energy detection scan (that makes use of the physical layer to find the peak to peak amplitude value in a particular channel). An ED scan determines the best channel with maximum network activity and sends an association (probe) request on that channel excepting a response.

Address Allocation:

In this implementation we use the 802.15.4 standard technique of dynamic address allocation. The 16 bit short address is separated into two 8 bit addresses given as “**XX:YY”** where XX is the Network address and YY is a particular node address in XX network,

The network addresses begin at 01:YY for the first network and the root node address being 01:FE. All cluster heads are assigned a node address as XX:FE . This helps in distinguishing a leaf node from a cluster head.

The Root node assigns network addresses to all its child nodes whenever they request to create their own network. The cluster head assigns all the child node addresses within its cluster. Thus there can be a maximum of 256 cluster in a network with each cluster can have a maximum of 254 child nodes.

SEQUENCE DIAGRAM FOR ADDRESS ALLOCATION

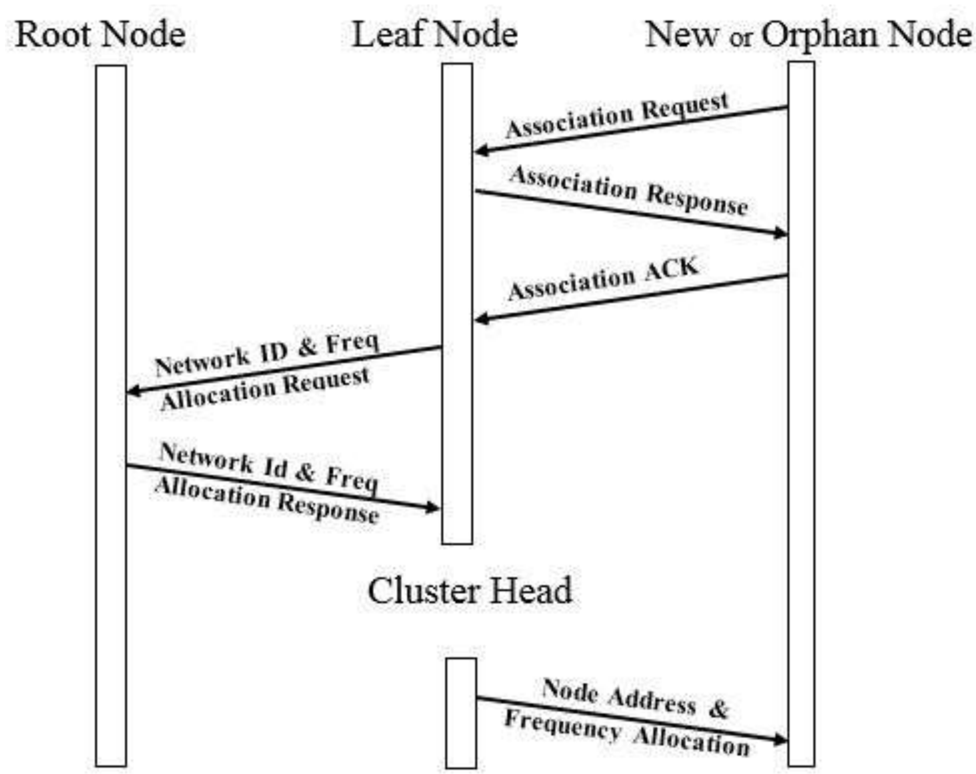


Figure 4: *Address Allocation Overview between new node and leaf node*

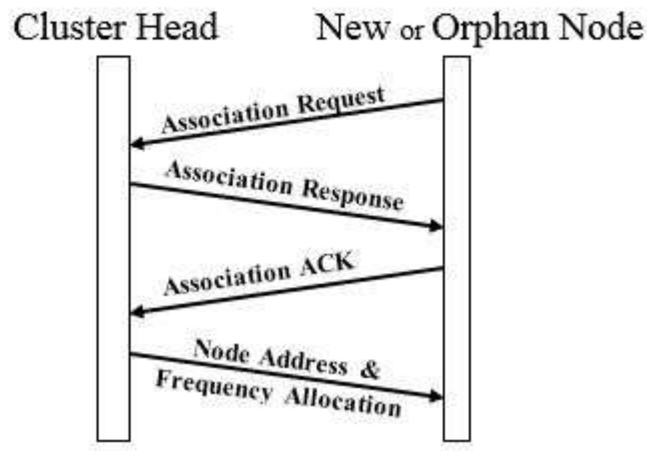


Figure 5: *Address Allocation between new node and cluster head*

A. PROBING

When a new node is trying to join a network, it probes the nodes on the neighboring channel for being accepted into the network. The sequence of operations are as follows:

PACKETS INVOLVED- [Probe (Association Request)] Packet

I. Sequence Diagram

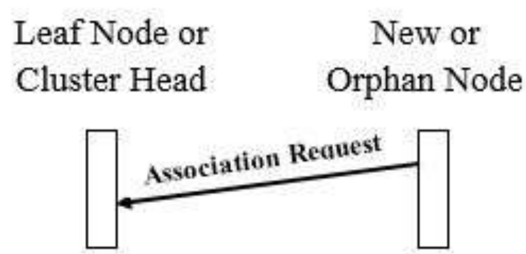
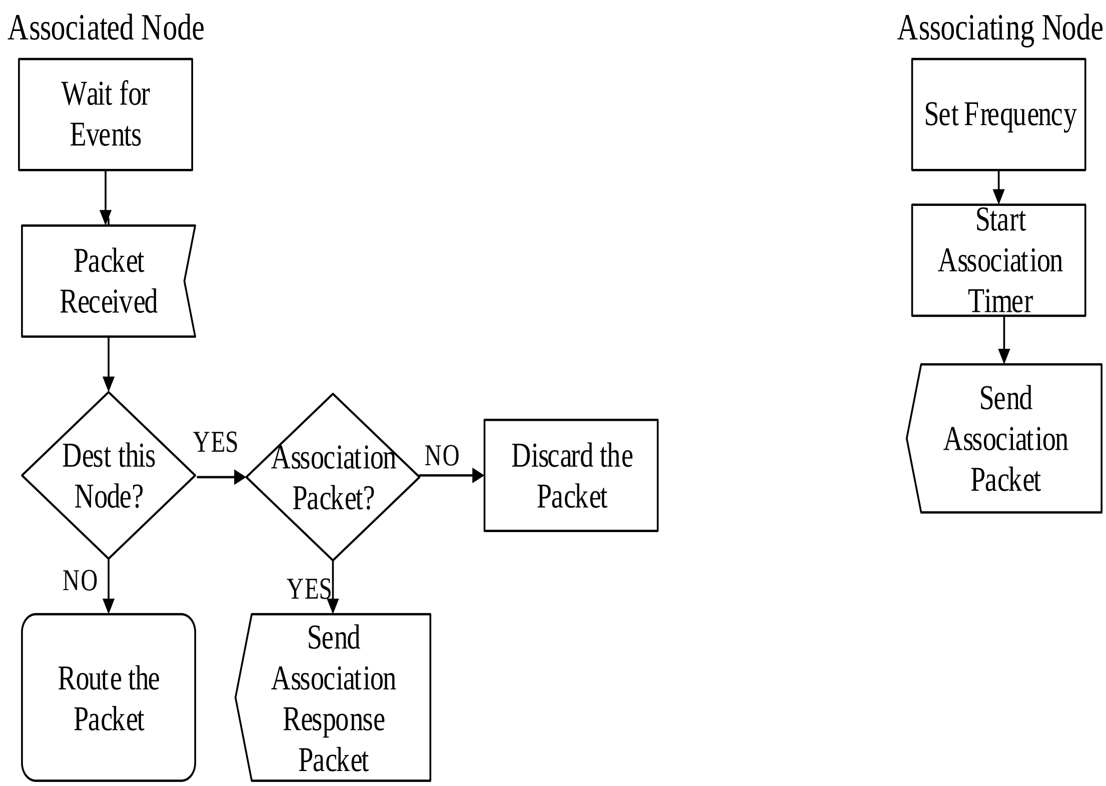


Figure 6: *Sequence Diagram for Probing*

II. Activity Diagram



<u>Figure 7</u>: *Activity Diagram for Probing*

B. NODE ADDRESS ALLOCATION

PACKETS INVOLVED- [Probe (Association Request)], [Invitation (Association Response)], [Invitation Ack (Association Ack)], [Node Address Allocation] Packets

I. Sequence Diagram

CASE 1 – When the new node approaches a Leaf Node (non-Cluster Head)

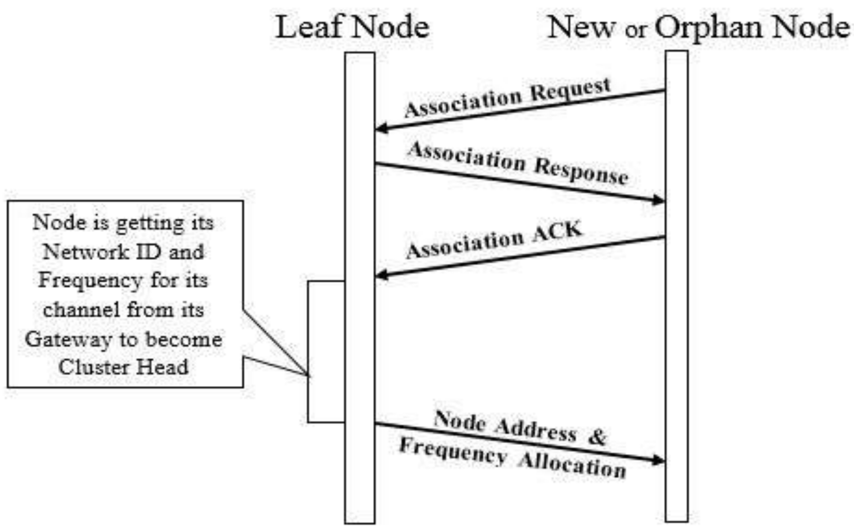


Figure 8: *Sequence Diagram for Node Address Allocation (Case 1)*

CASE 2- When the new node approaches a Cluster Head.

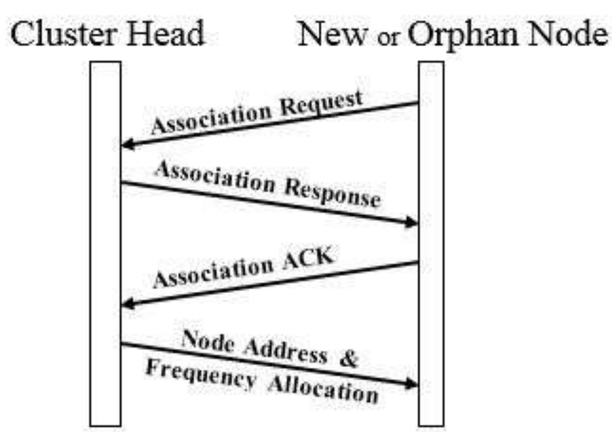
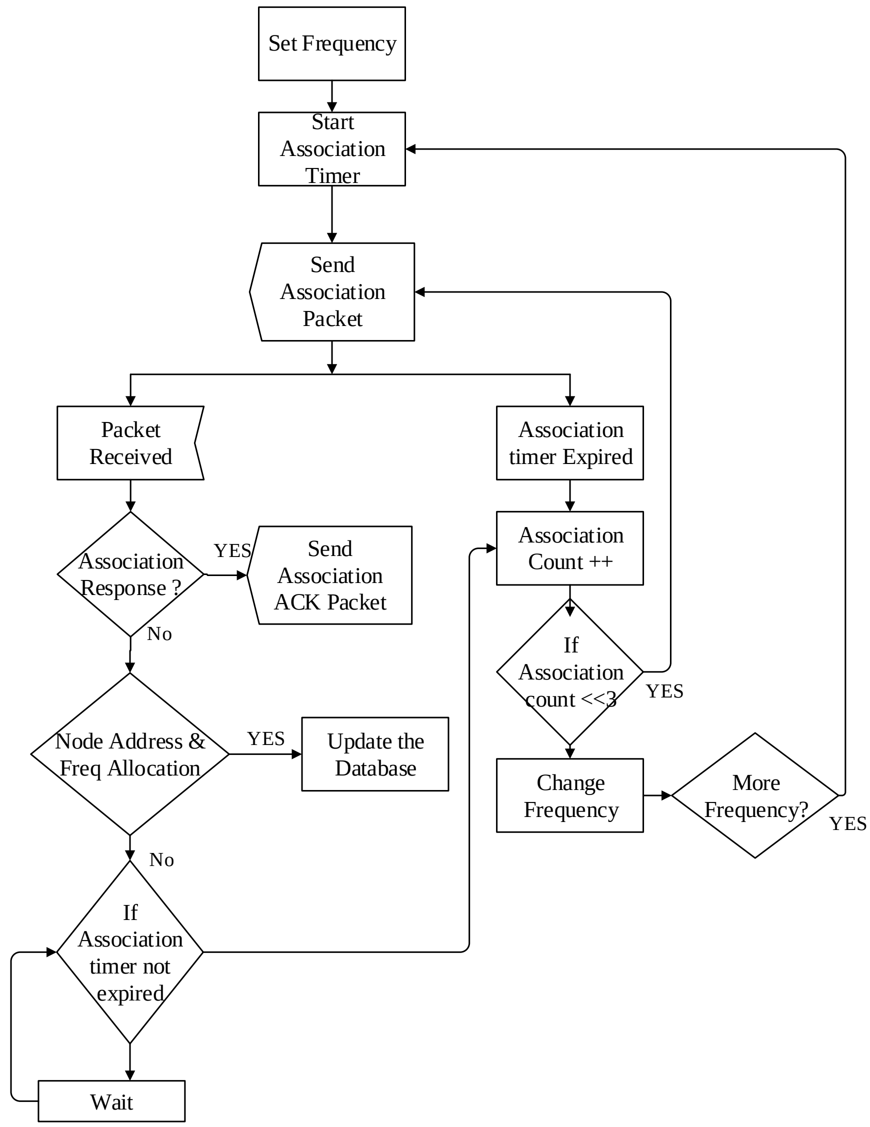


Figure 9: *Sequence Diagram for Node Address Allocation (Case 2)*

II. Activity Diagram

a) New Node or Orphan Node Activity



<u>Figure 10</u>: *Activity Diagram for New Node/Orphan Node*

b) Leaf Node or Cluster Head Activity

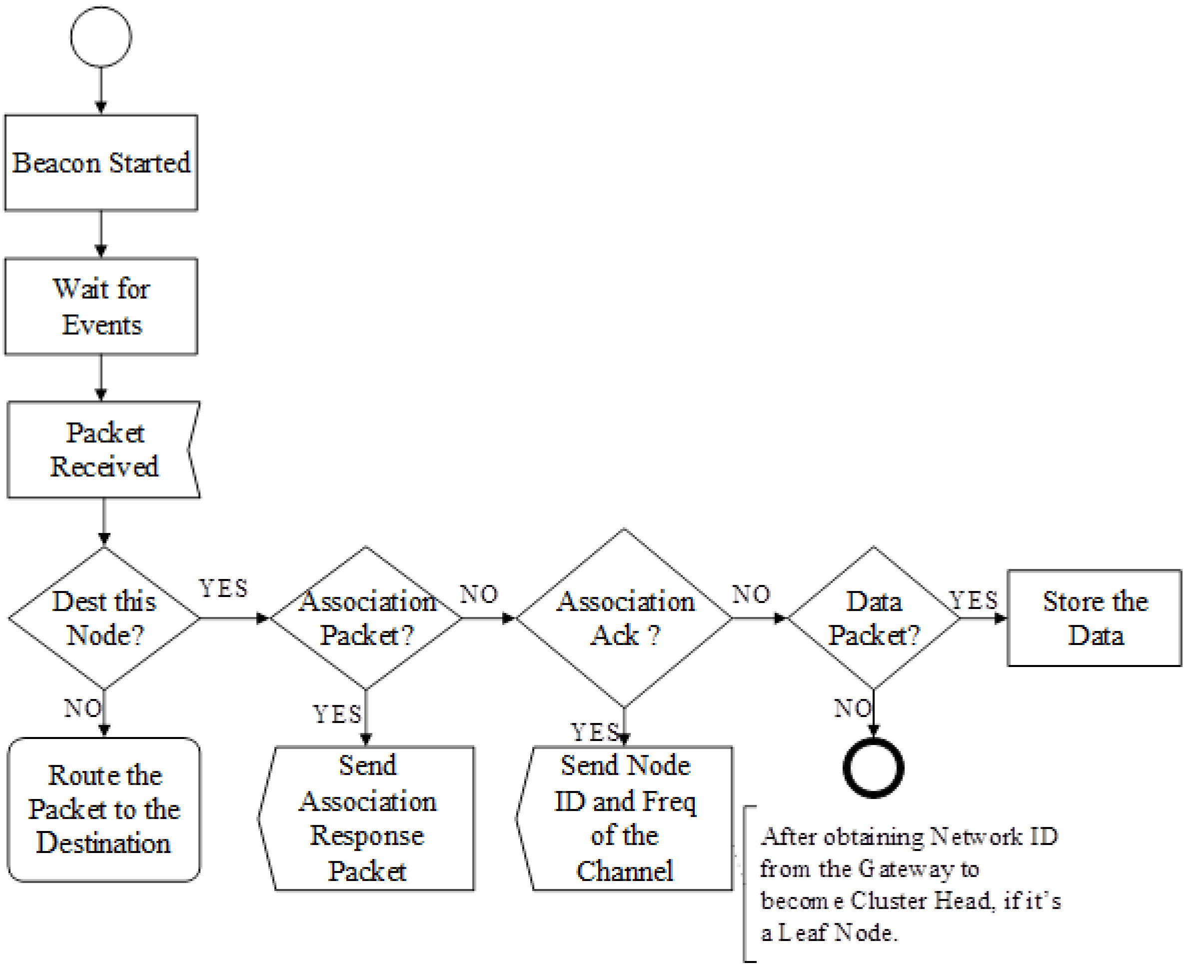


***Figure 11**: Activity Diagram for Leaf Node/ Cluster Head*

C. NETWORK ADDRESS ALLOCATION

PACKETS INVOLVED- [Net ID + frequency Request], [Net ID + Frequency Response] Packets

I. Sequence Diagram

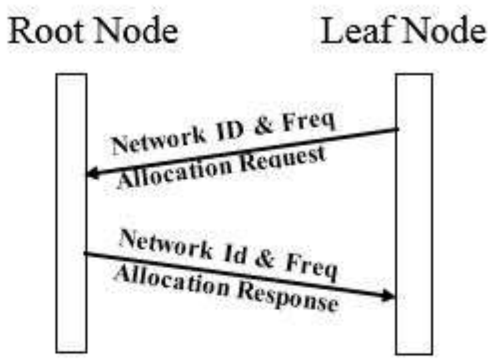


Figure 12: *Sequence Diagram between Root Node and Leaf Node*

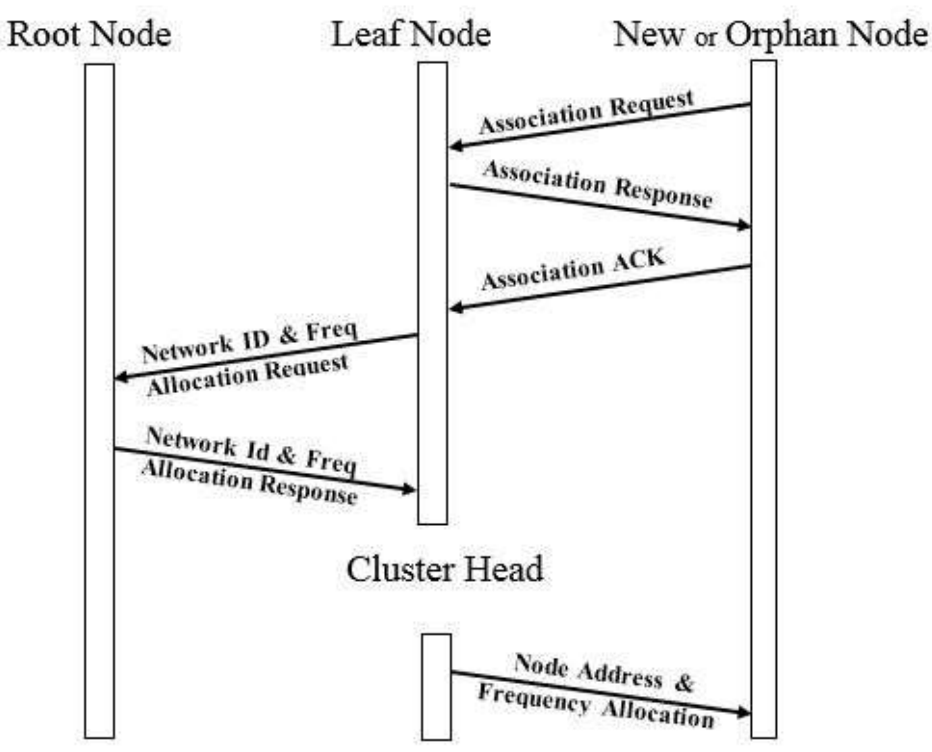


Figure 13: *Sequence Diagram Overview for Network Address Allocation*

II. Activity Diagram

a) Leaf Node

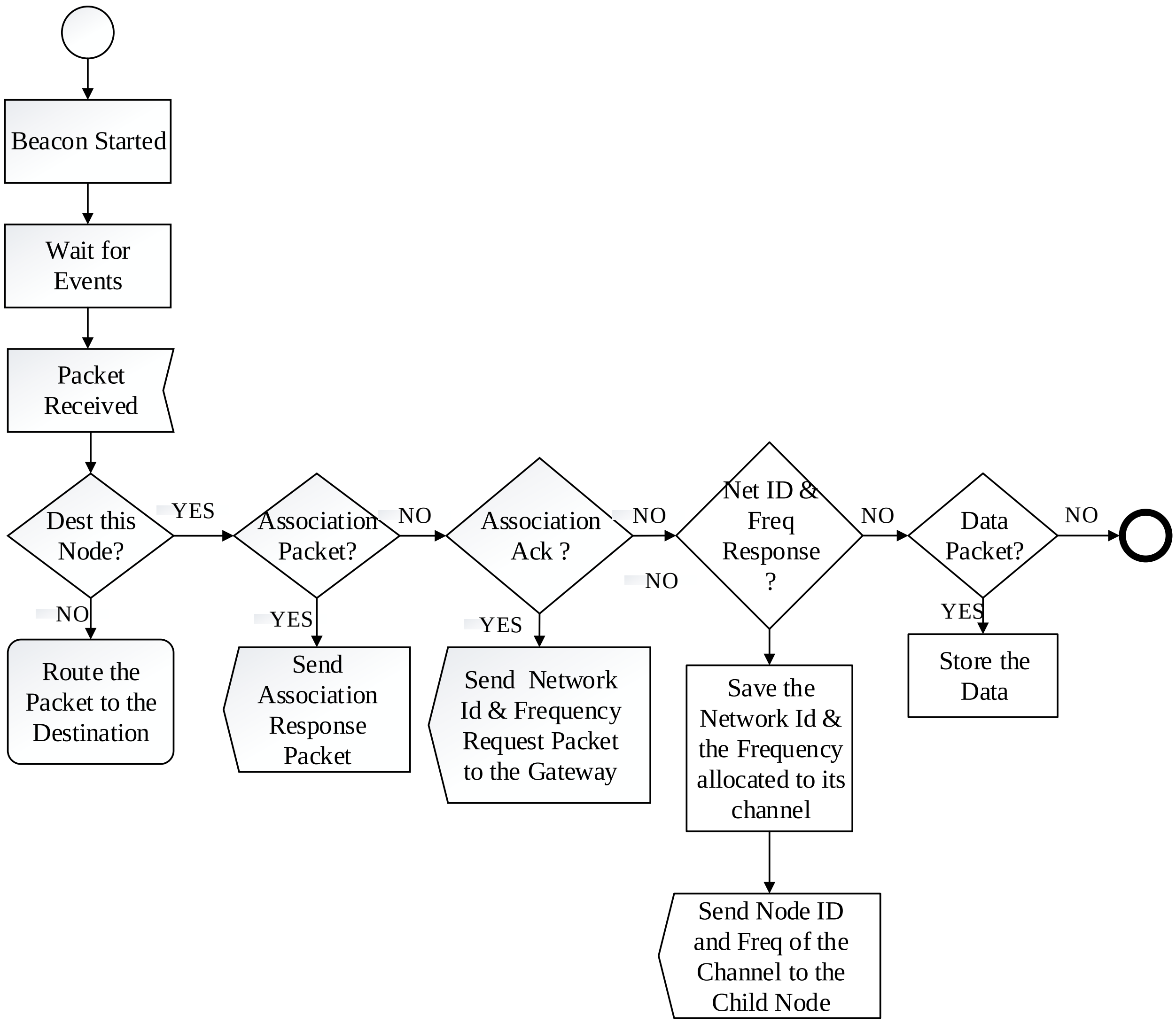


Figure 14: *Activity Diagram for Leaf Node during Network Allocation*

b) Root Node

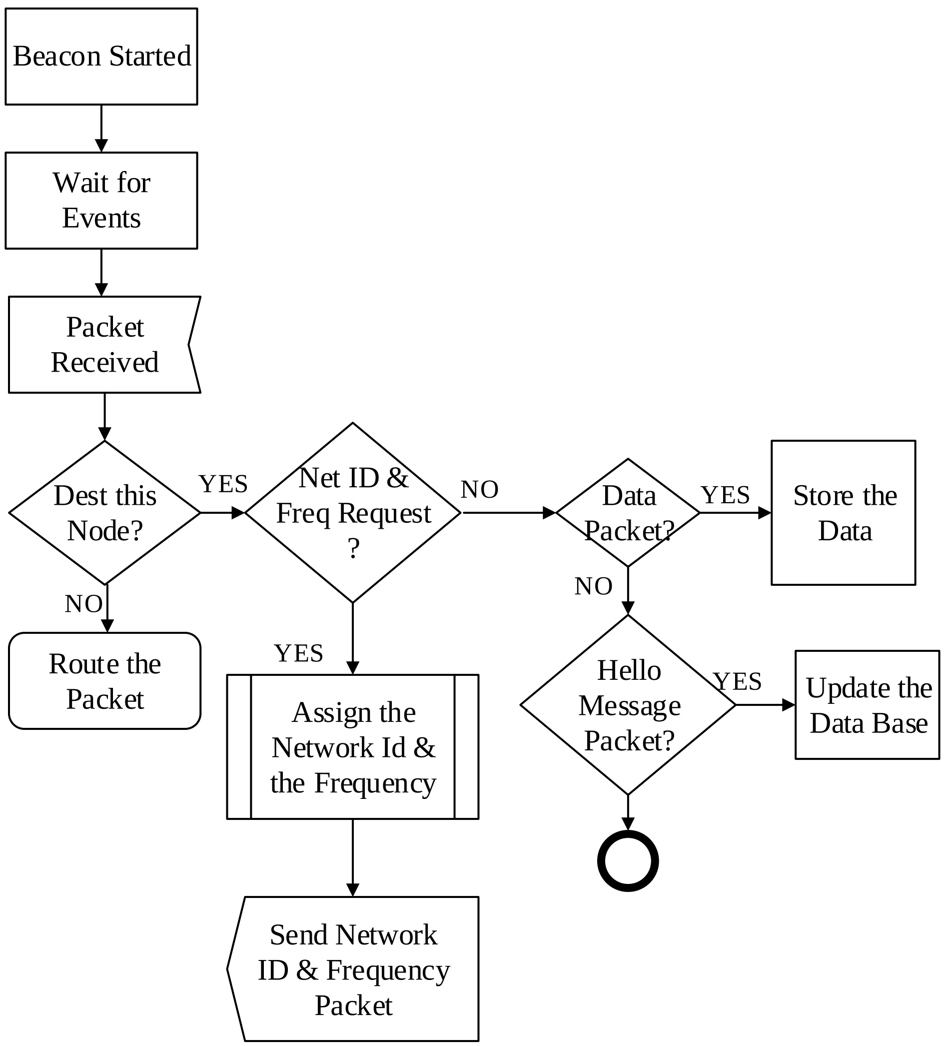


***Figure 15**: Activity Diagram for Root Node during Network Allocation*

D. ADDRESS RECOVERY

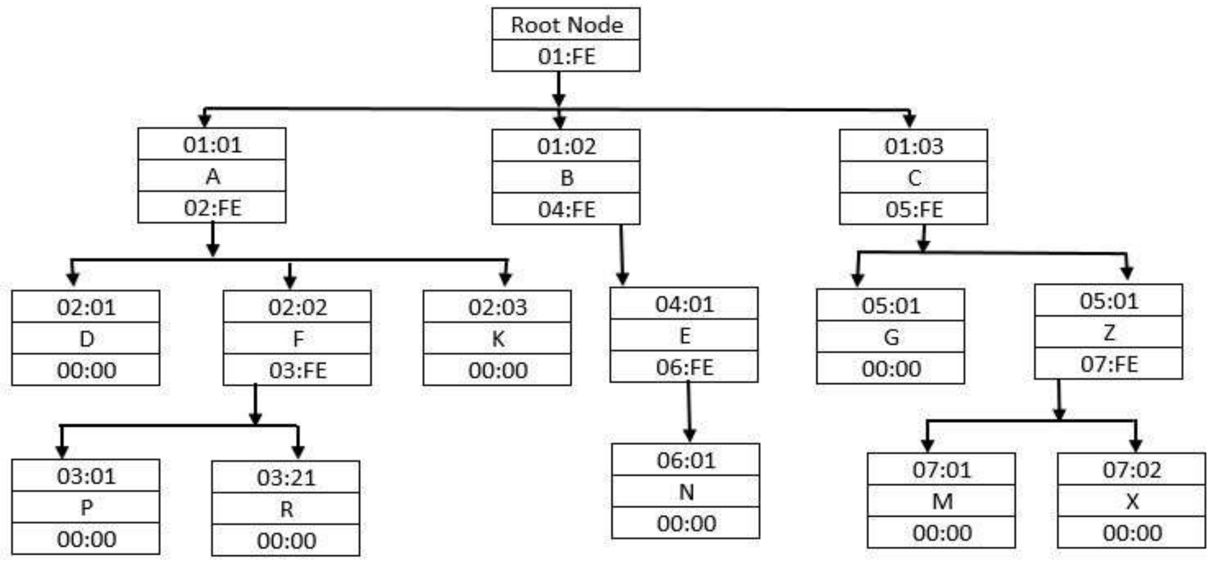


Figure 16: *Network Node Instance*

PACKETS INVOLDED – [Hello Message (Heartbeat Message)] packet

The periodic hello messages (heartbeats /invitation messages) transmitted by the Leaf Nodes allows the Cluster Head to detect if a Leaf Node has left the network or failed. Regardless of the cause, the Cluster Head removes the Leaf Node from its address allocation table claiming the address assigned to failing/moving node. To accommodate temporary failures or packet losses, a Cluster Head waits until it misses a certain number of heartbeats from a node before reclaiming the address. However, routing to this node is immediately seized until the node heartbeat returns to normal.

E. ROUTING

Each network node is supposed to maintain a neighbor table and each cluster head is supposed to maintain two tables that is a network table (containing information on routes to access other networks) and a children table (containing information about his children). The routing protocol will proceed as follows:

Each node after receiving a packet discovers /checks its neighbors from its neighbor table.

1. If destination is a neighbor, then Next hop=Destination.
2. If parent of destination is in neighbor, then Next hop= Parent of destination.

3. If neighbor of destination is your neighbor, then Next hop= Neighbor of destination.
4. If none of above is applicable, then Next hop= Your parent.

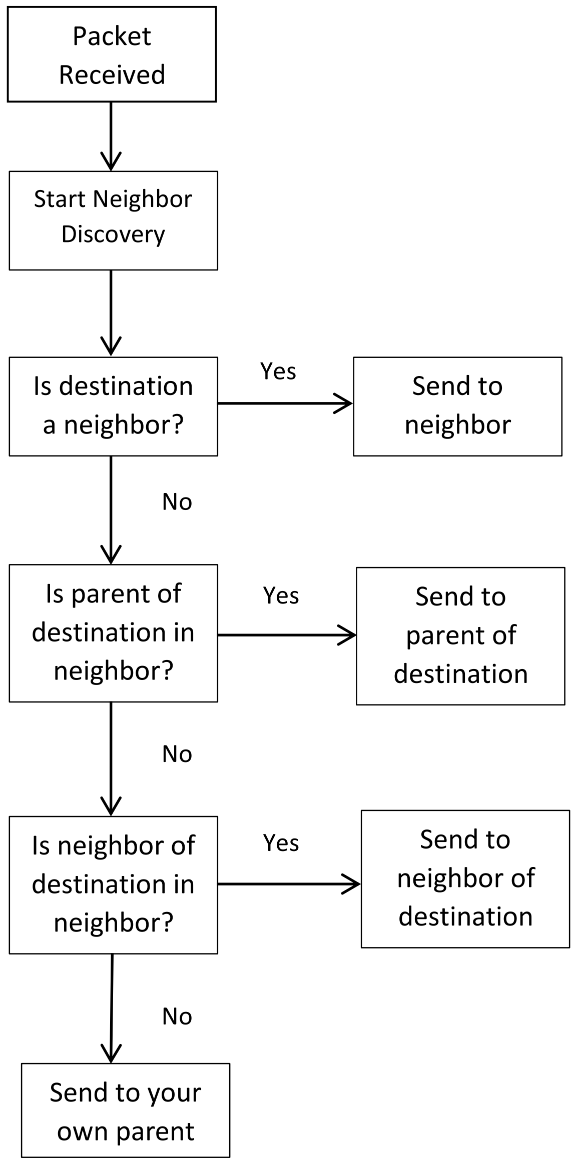


***Figure 17**: Routing Decision*

F. NODE AND LINK FAILURES

PACKETS INVOLVED- [Child Notification Message] packet

The address allocation protocol implemented here assumes that nodes at any level can fail or move physically from one network domain to another. If a Cluster head fails or moves, it will be disconnected from the network and all its children will become orphans. All orphaned nodes will go back to the initial state and seek another parent node to connect to the network. They will all be assigned new node IDs in the network they join. When a Cluster head moves from one network to another, it takes all its children with it and thus the failure of any node in the system, whether it is a Leaf node or a Cluster head, is managed locally.

G. MULTICHANNEL NETWORK OPERATION

The cluster heads plays a major role in multi-channel network operation. They operate at a certain allotted frequency within their network while communicating with the child nodes and switch to a different frequency while communicating with the gateway. The multi-channel switching is made possible with the help of synchronization. Distributed synchronization is employed within each cluster to synchronize the child nodes with the parent. Thus with additional power, a router operates in multiple channels switching between its own parent and child nodes.

H. SWITCHING BETWEEN MULTI CHANNEL AND SINGLE CHANNEL OPERATION

The decision of using a single channel or multiple channels is based on number of factors like number of nodes in a cluster and availability of dedicated interfaces for each channel (for multichannel scenario). Since we are considering IEEE 802.15.4 nodes in our design therefore each node is able to communicate on all 16 channels of this standard. Based on the number of associated nodes to him a cluster head may switch to multichannel operation because if there are too many nodes contending for a single channel in a cluster then a cluster head may not be able to communicate to his own parent. So in order to handle these types of scenarios we are considering multichannel operation in our design and a super frame structure with combination of CSMA/CA and TDMA. In Contention Access Period child nodes can communicate to their cluster heads at one frequency using CSMA/CA and in Contention Free Period the Cluster heads communicate to their parents at some other frequency using slotted TDMA operation. Hence we can achieve an overall improved network capacity by using a multichannel scenario.