Chapter 4
Two-Layer Cross Architecture

4.1 Introduction

The nodes in mobile ad-hoc networks have different transmission power, bandwidth, battery life, reliability, and data rate. This variant property of the nodes leads to hidden/exposed terminal problem in the MAC layer and routing problem due to link asymmetry. A two-layer cross architecture in between the MAC and Network layer is proposed to minimize the routing problem by taking the advantage of the heterogeneous nature of the nodes. The IEEE 802.11 Distributed Coordination Function DCF) performs poorly due to link asymmetry. The routing layers assume all the links to be bidirectional that leads to the performance degradation when the links become unidirectional due to mobility or power limitations. A cross-layer design that ropes adaptability and optimization between the layers are essential. The cross-layer approach can be referred to as a protocol design based on actively utilizing the dependence between protocol layers to enhance the network performance. This differs from the traditional layered approach where the protocols at the different layers are designed independently [67]. The link layer adapt to power, data rate, and coding to meet the requirements of current channel and network condition. The MAC layer can adapt on underlying link and interference conditions as well as delay constraints and priorities. Improvement of the MAC layer in ad-hoc wireless network is essential to maximize the network efficiency. The MAC protocol dictates how different users share available channel. A cross-layer approach takes into account the nature of wireless medium. As an example, cross-layer multi-channel selection algorithms have been developed which can be used with any routing protocol, even when the protocol was developed for use with a single network interface [68].

In this chapter, the focus is to have cross-layer design that spans in the network and MAC layer. The concept is incorporated in the Dynamic Source Routing (DSR) by making necessary changes. The objective is to have energy efficient routing such that the network lifetime is enhanced. The information available in the MAC layer is to be utilized at the routing layer to find an optimal route that is efficient and reliable. A new metric that explicitly considers local availability called Access Efficiency Factor (AEF) will be utilized. This metric will be used during route discovery mechanism of the DSR protocol. By incorporating the change in the DSR the throughput is increased. There is frequent node mobility that leads to frequent link breakage; hence hop count is a convenient routing metric. The path length affects the performance of an end-to-end flow. The path weight equals the total number of links through the path. Even though hop count is a convenient routing metric it does not consider local availability of bandwidth, transmission rate, link quality, and interference. The most popular and widely used hop count protocol is the DSR protocol. It operates on-demand in order to minimize the overhead by reacting only when route discovery is necessary. The DSR protocol uses source routing in which the the sender learns about the complete hop-by-hop route to the destination. The discovered routes are then stored in a route cache. The packets carry the source route in the packet header.

Hence hop count is not good enough to build a good route from source to destination with acceptable reliability, throughput, and delay [69]. A routing protocol that does not consider interference in the network leads to reduction in global capacity and throughput of the network [70]. It has been stated in [71] that considering different physical layer factors assist the routing protocol to find paths with high transmission rate, high packet delivery rate, and low interference. From the work noted above, the employment of certain features and characteristics of network layers can provide a sufficient routing algorithm that finds routes with satisfactory throughput and delay [72].

4.2 Wireless MAC Protocol

IEEE 802.11 standard defines Media Access Control and Physical layer specifications for WLANs. The wireless MAC specifies two access methods: Distributed Coordination Function (DCF) [73] that uses back-off method for channel access and Point Coordination Function (PCF) that has central controlled through polling. DCF is an access method used in wired and ad-hoc mode. The stations contend to use the medium using CSMA/CA in a distributed manner. In

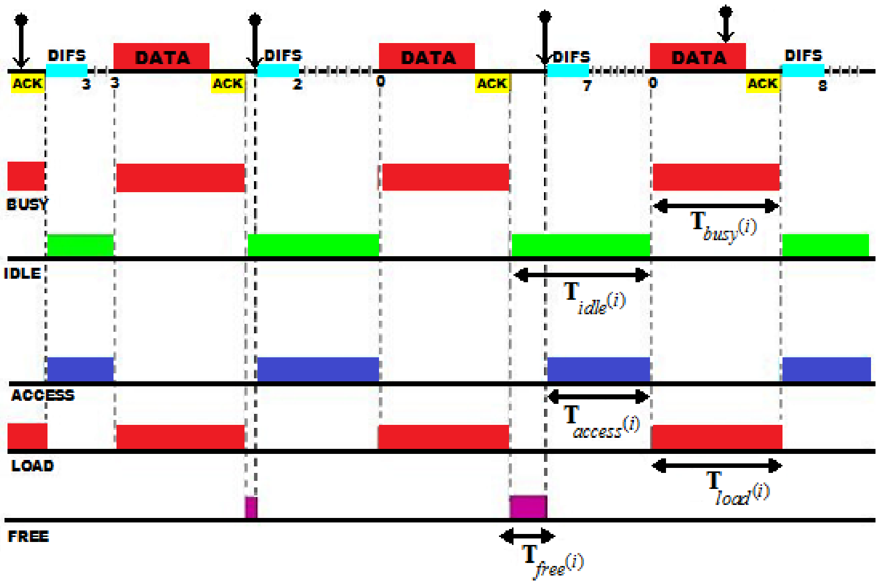

Figure 4.1: Time Intervals in CSMA/CA

DCF, data frames are transmitted by two mechanisms, i.e., the basic access mechanism and the Request-To-Send (RTS) and Clear-To-Send (CTS) mechanism [74]. Any station wishing to transmit first listens to the medium during a DCF Inter-Frame Space (DIFS). If the medium is busy, the station defers its transmission until the medium becomes idle. When the station senses the medium as idle, it additionally waits for a random back-off interval as a part of the collision avoidance mechanism. The random back-off interval is randomly chosen according to the following formula [75][76].

$$Backoff_{int} = N * S_{time} \tag{4.1}$$

where N is a pseudorandom integer from the interval $[0, C_{wdw}]$, C_{wdw} is the contention window; the transmission of packets starts when back-off interval reaches to zero value.

When the medium becomes busy during decreasing the back-off timer, the back-off procedure is paused and restarted once the medium is sensed to be idle for an interval of DIFS. The destination station waits for a short time called Short Inter-Frame Space (SIFS) before sending back an Acknowledgment (ACK) frame to the source node to notify a successful transmission. When the medium is busy, all other stations must wait for the channel to become idle. During the busy period, the waiting stations maintain a random back-off interval counter. These stations start decrementing when the medium is sensed idle. The decrementing of the back-off counter is frozen when the medium is sensed busy and restarted when the medium is free for DIFS time interval. When there are stations competing to transmit, the station with the lowest back-off number gets the channel. After a successful transmission, a new back-off value is selected and the contention window is set to its minimum value (default value of 31 in IEEE 802.11), else C_{wdw} value is doubled up to the maximum value (with a default value of 1023 in IEEE 802.11). Contention window sizes are always 1 less than an integer power of 2 (e.g., 31, 63, 127, 255, 511, and 1023). Collision will occur when more than one station is concurrently attempting to transmit through the medium. The size of the contention window is doubled if the transmission is not acknowledged positively i.e. a new N value will be chosen [77][78][79]. A and B stations

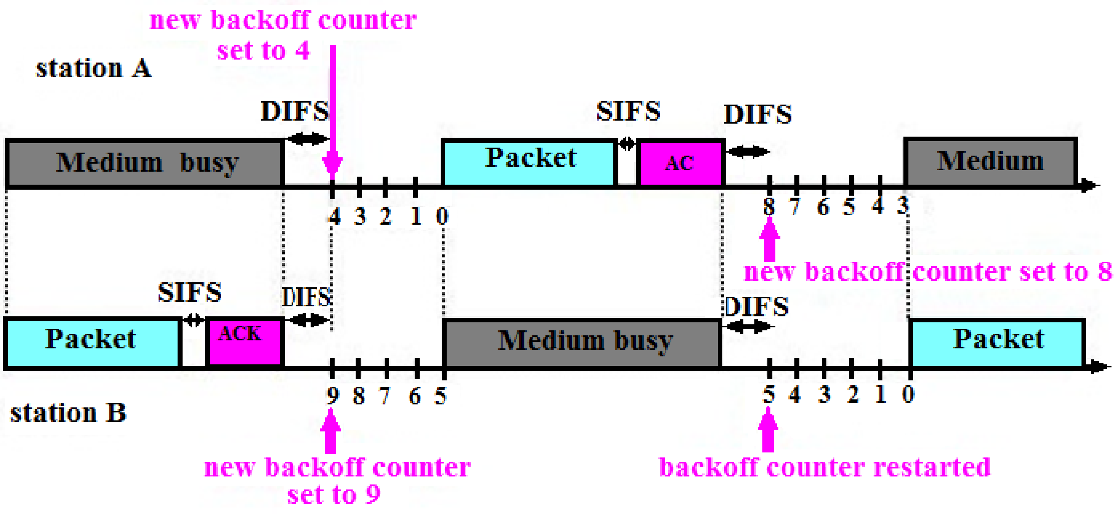

Figure 4.2: DCF Operation

share the same wireless channel. At the end of the packet transmission by station B, stations B and A wait for a DIFS and then choose a randomly generated back-off time. Station B chooses a back-off counter value equal to 9 and A selects 4. The back-off counter of station A reaches the value of zero before station B since it is smaller that 9 and hence wins the medium for its transmission. Once the station A starts transmitting, the station B freezes its back-off timer at value 5. When station A finishes transmitting its packet, it sets its back-off counter for a new value after a DIFS. Station B restarts its back-off counter decrements from where it halted prior to station As transmission and starts transmitting its packet after sensing the channel for a DIFS. The MAC bandwidth framework can be used to describe how the distributed MAC mechanism allocates the bandwidth of the medium among the contending stations. There are three parameters to describe how a station utilizes the bandwidth of the medium, viz., load bandwidth B_{load}, B_{access} and B_{free} [72][80].

4.3 Access Efficiency Factor (AEF)

The AEF is a measure of how efficiently a station utilizes the time on the medium to transmit its load. It is used to avoid local congestion in DSR routing mechanism over hop count parameter hop_{count}. The route with the highest minimum AEF value is selected as the path. The intention is to devise congestion avoidance metric and path selection rules. It can be determined by finding the B_{access} that is related to the average time to get the back-off counter to zero and $B_{transmit}$ that is average time to transmit a frame. Busy time $T^{(i)}_{busy}$corresponds to the transmission of frames and their positive acknowledgments during the i^{th} busy interval.

$$T_{busy} = \sum T^{(i)}_{busy} \tag{4.2}$$

$$B_{busy} = \frac{T_{busy}}{T_{busy} + T_{idle}} \tag{4.3}$$

$$B_{busy} = \sum_k B_{load}(k) \tag{4.4}$$

when the station has no frame to transmit then the idle time is not being used and is considered as free time and can be used when it is required. The idle time interval T_{idle} can be given as

$$T_{idle} = 1 - T_{busy} \tag{4.5}$$

where B_{idle} represents idle bandwidth that is the fraction of time interval when no transmission is taking place. During these idle intervals the station may use it to decrement its back-off counter win transmission opportunities. However, different stations use the idle time differently. Consequently, different stations perceive different capacity in the network depending on the load of the specific station and the load of all competing stations. The idle bandwidth consists of two components, an access bandwidth $B_{access}(k)$ which represents the time required by a station k for accessing the wireless medium and a free bandwidth $B_{free}(k)$ corresponding to the remaining unexploited idle bandwidth. The idle bandwidth can be stated as follows:

$$B_{idle} = \frac{T_{idle}}{T_{idle} + T_{busy}} \tag{4.6}$$

$$B_{acess}(k) + B_{free}(k) = B_{idle} = 1 - B_{busy} \tag{4.7}$$

It is possible to associate the transmitted frame with station k by examining the address fields contained in the MAC header. This can lead to the concept of the load bandwidth $B_{load}(k)$ which represents the fraction of the interval time on the medium consumed by a frame transmission from the station k and can be defined in terms of a bandwidth as follows [21]:

$$B_{load}(k) = \frac{T_{load}(k)}{T_{busy} + T_{idle}} \tag{4.8}$$

$$T_{load}(k) = \sum T^{i}_{load}(k) \tag{4.9}$$

$$AEP = \frac{B_{transmit}}{B_{access}} \tag{4.10}$$

To calculate capacity, all the idle time is used to support the stations load.

$$B_{transmit} + B_{acc} = 1 \tag{4.11}$$

$$B_{transmit} + \frac{B_{transmit}}{AEP} = 1 \tag{4.12}$$

Substituting equation (4.11) in (4.12)

$$B_{transmit}(\frac{AEP + 1}{AEP}) = 1 \tag{4.13}$$

The AEF can be determined from the access efficiency parameter where

$$LetAEF = \frac{AEP}{1 + AEP} \tag{4.14}$$

Equation (4.13) can be written as

$$AEF = B_{transmit} \tag{4.15}$$

AEF is the maximum load for a station in ideal case where there are no other stations participating but if there are more stations participating AEF will depend on AEP.

4.4 Problems of IEEE 802.11 DCF

The IEEE 802.11 DCF is a four-way handshake (RTS-CTS-DATA-ACK) procedure that is based on CSMA/CA mechanism. DCF faces certain challenges in heterogeneous MANETs [81] yet it is widely used in simulations of MANETs. A major suffering is the problem of hidden and exposed terminal problem.

4.4.1 Hidden and Exposed Terminal Problem

If the intended receiver is a low-power node and is in the transmission range of a distant high-power node, its CTS message may not be received by the high-power node. Since the high power node may also not sense the data packet transmission, it may transmit a packet, resulting in a collision at the receiving node this is termed as hidden station problem. If the intended receiver is a high-power node and its CTS message is sent within a large range. All low-power nodes within the large CTS area are blocked by the CTS message. Packets sent by most low-power nodes will not interfere with the reception of the high-power node, yet most low-power nodes are blocked unnecessarily. This is termed as exposed station problem.

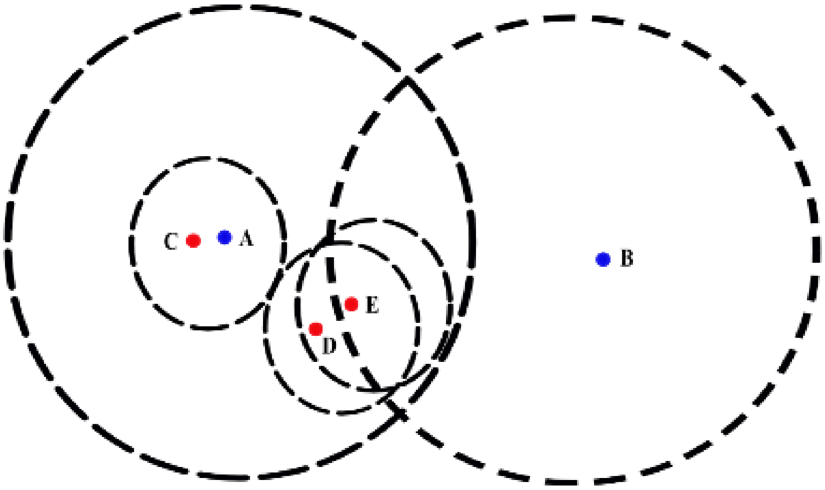

Figure 4.3: Exposed/Hidden Station Problem

In Figure 4.3, high-power node A receives RTS from C and then returns CTS. The CTS blocks all the neighbour nodes including D and E. However, transmission between D and E will not affect.

4.4.2 Unidirectional Links

If the sender node is high powered, then and receiving node is low powered, then the CTS and ACK will not reach the high powered transmitter. The transmitter will retry sending RTS or

DATA until reaching the retransmission threshold. This causes to significant consumption of channel bandwidth and degrades performance of routing layer due to inaccurate link broken message. Furthermore, this problem degrades performance of routing layer protocols since the MAC layer may return an inaccurate link broken message to the routing protocol.

4.5 System Model

The nodes in the ad-hoc networks are varied as they have different transmission power, bandwidth, data rates, etc. For simplicity, the nodes are categorized into two groups: Backbone nodes (B-nodes) having high transmission range, high data rate, and good processing capability, and others are called General nodes (G-node). These nodes are equipped with two interfaces that work with separate frequency bands: channel-1 and channel-2. The transmission range of G-nodes using channel-1 is R_g and do not send via channel-2. B-nodes using channel-1 is R_g and channel-2 is R_b, $R_g = \alpha R_g (\alpha > 1)$. Using this concepts, there are four types of transmission links: B-B, B-G, G-B, G-G and all these links are bidirectional except B-G link.

The proposed network is represented as a weighted graph, made of nodes N and edges L, i.e., $G(N, L)$. N nodes include B-nodes and G-nodes, and L is made up of communication links between the B-nodes and G-nodes. The graph $G(N, L)$ has two subgraphs $G_b(N_b, L_{bb})$ and $G_g(N_g, L_{gg})$. A cost metric function that associates a non-negative cost is given as

$$C : L- > R+ \tag{4.16}$$

Two nodes (i,j) $\in N$, the path from node i to j is represented as $P_{i,j}$ which is an ordered sequence of nodes. The routing problem is finding a minimal cost path P^* in the graph G

$$P^* = minC(p) \quad where \quad p \epsilon P_{i,j} \tag{4.17}$$

The communication rules of the nodes are:

1. G-nodes send packets via channel-1 and receive DATA/ACK via channel-2. It does not use channel-1 for sending packets.
2. B-nodes send packets via channel-2 and return CTS/ACK to G-nodes via channel-1

3. G-G, G-B, and B-B links use IEEE 802.11 DCF as their MAC protocol.

4. B-G links use modified-MAC protocol.

B-G link suffers from hidden station problem and asymmetric link problem. The MAC protocol is modified to alleviate these problems. The neighbouring nodes of type τ within the circle centered at node N
and radius r is denoted as

$$Nei_r^\tau = N_i | Dist(N, N_i) < r \tag{4.18}$$

Definition 1:
Denote $Nei_r^\tau(N)$ as the set of nodes of type τ within the circle centered at node N
and of radius r:

$$Nei_r^\tau(N) = N_i(Dis(N, N_i) < r) \bigwedge (Type(N_i) = \tau) \tag{4.19}$$

where $Dis(N, N_i)$ is the Euclidean Distance between node N and N_i and Type(N_i) is the node type of $Ni(Type(Ni) \in B, G)$. For example, $Nei_{RB}^B(G_i)$ is the set of B-nodes within the circle centered at G_i and of radius R_B.

Definition 2:
The homogeneous degree of a G-node Gi and a B-node Bi is

$$deg(G_i) = |Nei_{RG}^G(G - i)| \tag{4.20}$$

$$deg(Bi) = |Nei_{RB}^B(B_i)| \tag{4.21}$$

respectively. The average homogeneous degree of G-nodes and B-nodes in the network is:

$$\lambda_G = \frac{\sum_{Gi \in N_G} deg(Gi)}{|N_G|} \tag{4.22}$$

$$\lambda_B = \frac{\sum_{Bi \in N_B} deg(Bi)}{|N_B|} \tag{4.23}$$

$$\lambda_B = \beta\lambda_G, then |N_G| / |N_B| = \alpha^2/\beta. \tag{4.24}$$

Since a B-node is more complex and expensive than a G-node, It is assumed that $\beta < 1$ and α^2/β_1 in the network model. Also it is assumed that nodes are distributed as the two-dimensional Poisson distribution [82] (note that this is a common assumption of nodes distribution in MANETs) and the probability that $deg(Gi) = k$ is:

$$Prob(deg(Gi) = k) = \frac{(\lambda_G)^k}{r} k! e^{\lambda_G} \tag{4.25}$$

Similarly,

$$Prob(deg(B_i) = k) = \frac{(\lambda_B)^k}{r} k! e^{\lambda_B} \tag{4.26}$$

4.6 Proposed Cross-Layer Design

The cross-layer design (CLD) in this chapter shows the communication between the MAC and routing layer. In the MAC layer, two modules are proposed where DSR-MAC tackles hidden/-exposed terminal problem and DSR-MAC Routing module handles asymmetric link problem that is a low layer support of DSR-MAC Module.

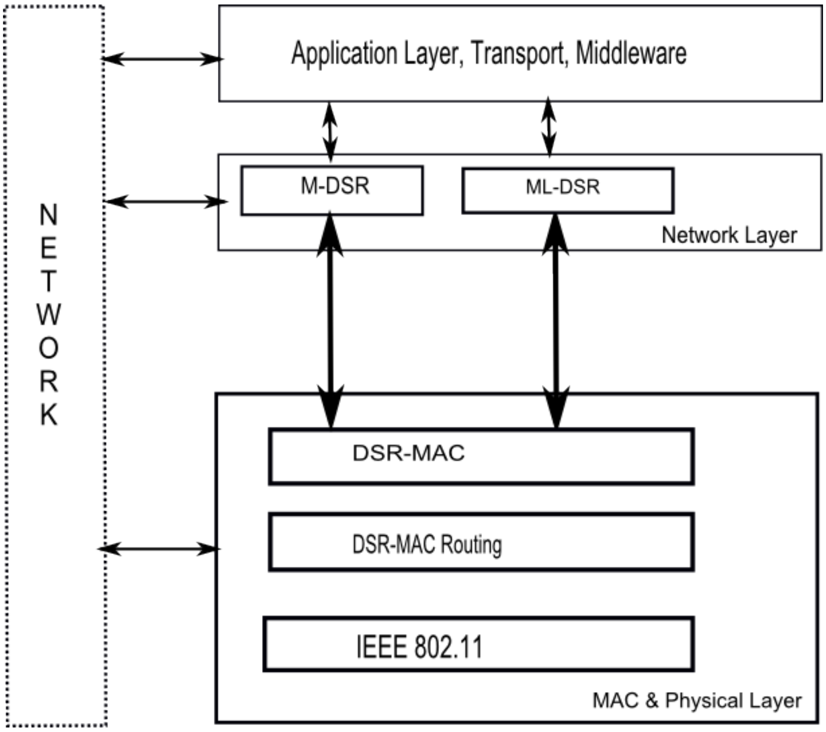

Figure 4.4: Proposed Cross-Layer Model

4.6.1 DSR-MAC

Whenever any high power sender node B_T like to transmit, it sends RTS signal through channel-2 to a low power receiver node G_R. The low powered node G_R sends CTS to B_T through channel-1. G_R later calculates the set of hidden terminal according to

$$H = B_{hidden} | B_{hidden} \in Nei^B_{RB} \bigwedge Dis(B_T, B_{hidden} > R_B) \tag{4.27}$$

Here B_T sends DATA to G_R over channel-2 and G_R returns ACK via channel-1 using DSR-MAC Routing.

4.6.2 DSR-MAC Routing

DSR-MAC routing sends RTS signal to the neighbour nodes. The receiver calculates the shortest path tree using breadth first search in the list of sensitive G-nodes. Shortest path tree is used to send CTS by multicasting to the transmitter and hidden station problem simultaneously.

1. The sender senses the channel if it has been idle for time of DIFS, then it sends RTS to receiver G_i. All the B-nodes in $Nei^B_{R_B}(B_T)$ can receive the RTS. The receiving nodes may be placed in three sensing areas: area-1, area-2, hidden terminal area.
   After receiving the RTS the neighboring nodes find the area to which it belongs. Say a node B-node, B_i in $Nei^B_{R_B}(B_T)$ is in area-1
   If $DIS(B_i, G_R) > R_B$ else if $DIS(B_i, G_R) < R_B$ then it is in area-2.
   If B-node falls under area-1 then the Network Allocation Vector (NAV) is set to 0, to protect transmission from collision with CTS and ACK. But in this model, CTS and ACK are send through channel-1 and RTS through channel-2. So the B-nodes need not wait for four-way handshake and this tackles the *exposed terminal problem.*

2. After receiving RTS, the receiver G_R first calculates the set of all hidden terminals H and then the shortest path to the transmitter according to the sensitive G-nodes obtained from the network layer. The value τ determines the duration B_T needs to wait before sending DATA. After SIFS, G_R uses DSR-MAC routing to multicast CTS to the transmitter and hidden stations.

3. After B_T receives CTS, it waits for Avoid Collision Inter-Frame Sequence (AIFS) before transmitting DATA.

4. The receiver sends back ACK through reverse path that is determined according to Sensitive G-node information available from the network layer.

4.6.3 Modified Location-based DSR Routing (ML-DSR)

The nodes in the network belong to two categories either high capacity or lower capacity, wherein the higher capacity ones can be the cluster heads and others are the cluster members.

4.6.4 Intra-group Node Management

Step 1: B-node flood an RREQ to the neighbouring nodes including its location.
Step 2: Each low power nodes, i.e., G-node receives the RREQ packet from all neighbouring B-nodes in $Nei^{B}_{RB}(G_i)$. The G_i nodes select the B-nodes with the shortest Euclidean distance as the group head $GH(G_i)$. The G-nodes send back Route Reply (RREP) packet that includes G-nodes$'$ location and group head identifier.
Step 3: B-node B_i wait for some time to get the G-nodes information and keeps the information in the group member table.
Step 4: The B-node B_i later broadcasts a one-hop group location information (GLI) packet that includes B_i ID with location and list of its group member nodes' IDs with location.
Step 5: Every neighbour nodes either B-node or G-node can receive the group location information packet from B-nodes in $Nei^{B}_{RB}(N_i)$. The G-node whose location can be traced from the group location information packet is called sensitive G-nodes. Each G-node broadcasts a group location information packet to the group heads at intervals T_{intra}. Let $SG(N_i)$ be the set of sensitive G-nodes of N_i then

$$SG(N_i) = G_j | GH(G_j) \epsilon Nei^{B}_{RB}(Ni) \tag{4.28}$$

4.6.5 Intra-group Information Updation Method

To make every node know about the topology of its sensitive nodes information, it is important to make the updating. T_{inta} denotes the interval of updating the sensitive node locations, if T_{inta} is too small then there is heavy communication overhead but it must be small enough to reflect the topology changes. Whenever a group location information packet is received by G-nodes, it calculates the Euclidean distance between itself and the B-nodes, and checks if there is a need to select a new cluster head or not. For a G-node G_i if $Nei^B_{RB}(G_i) = 0$ then G_i is not a member node of any group. The probability that a G-node do not belong to any group member is

$$Prob(|Nei^B_{RB}(G_i)| = 0) = e^{\lambda_B} \tag{4.29}$$

The average distance between a G-node G_i and $GH(G_i)$ is D_{min} That can be represented as

$$D_{min} = \int_0^{RB} \frac{2\lambda_B r^2}{RB^2} e^{\frac{-\lambda_B r^2}{RB^2}} dr \tag{4.30}$$

D_{min} decreases as λ_B increases which indicates that the average distance between a G-node and its group-head is very short. So, T_{intra} value is set as frequent as the interval of Hello beacon in location based routing.

The network made of B-node is small network and the link between B-nodes is symmetric link. The intergroup information update method is done as follows: Every group head broadcast group information packet to other group heads when the accumulated moving distance between the position of latest group information packet generated and current location exceeds a threshold value D_{Thresh}. Due to the distance effect of each flooding range, the nearby nodes are frequently updated than the nodes further away.

4.6.6 Modified DSR

Modified DSR (M-DSR) is a multipath routing protocol that maintains several paths from the sender and receiver, and selects the path with minimal cost. M-DSR is flow-based that considers both the sender and receiver for routing packets, it is done so such that the routing can manage with the high time difference in the network topology and link quality. Most important feature of flow-based routing is that to start any new transfer session; a route discovery procedure must be carried out based on the current network status. Every new path selected for routing must have minimal delivery delay.

If sender node S wants to communicate with destination node D, S starts Route Discovery Procedure by sending Route Request (RREQ). The neighbouring nodes keep forwarding until the destination node is reached. Once D is reached, Route Reply (RREP) is sent back to S, whereby the node installs a path identified as (S, D). The source node S then transfers DATA using the associated path. An intermediate node may receive more than one answer related to (S,D) flow, this node needs to send the first received answer to minimize the route finding time. A consequent answer is sent to S only if yields an improvement on the cost metric and the other routes are stored in the routing table. Once S gets the answer of the first route, it starts sending over that route and evaluates the cost metric of each successive reply. If the incoming reply is better than the route it used, then S starts using a new route. Route maintenance is done once S detects link failure, in such case the current route will be deleted and the best back-up route is selected by sending a short control packet [83][84]. The route will be deleted if the control packet does not reach the destination and the other routes in the routing table will be tested. If all the back-up routes do not function, then route error packet is sent to the sender. A new route discovery procedure will follow up. The following notations are introduced as follows:

- $V(i) \subseteq N$ denotes the set of neighbours of node *I* that are directly connected to *i*;
- $Ti, j \in R^{+}$ denotes the cost of moving from node *i* to node $j \in V(i)$;
- $J^{h}(i) \in R^{+}$ denotes the nominal cost to move from node *i* to destination node D, after the hth reception of an RREP message;
- p(*i*) is the path traveled by the RREP forwarded by node *i*.

4.6.7 Forward Communication

The route discovery starts when the sender S floods RREQ packet until the destination D gets it. Any node other than D is the intermediate node *i*, it does the forward step in Algorithm 1 for the RREQ message with the highest sequence number and discards the rest. The Forward RREQ is used to inform the destination D for a communication request. To limit the forward step propagation, when node *i* receives an RREP packet for the same flow (S,D) with the same sequence number, any RREQ with the same sequence number will be discarded[85].

Route maintenance process is done when there is link failure. MANETs are dynamic in nature, initiation of new route discovery on path failure, leads to reduction of throughput and excessive usage of network resources. One of the approach to minimize the route discovery rate is by storing multiple paths of the same S-D and to replace the best path currently used with

Algorithm 1

```
*Forward Step*
if $anyneighbournode(i) = destinationnode(D)$ then
then initiate the Backward Step procedure
else
Broadcast the RREQ control packet again
end if
Backward step
The destination node (D) unicasts RREP control packet to all the reachable nodes $j \in V(D)$
with $J(D) = 0$ and $p(D) = D$. Say any reachable node *i* from D, receiving an RREP
containing J1 and p1 from a node $l \in V(i)$, initiates algorithm 2.
```

Algorithm 2

```
*Backward step*
if $h = 1$ then
$J^h(i) \leftarrow Ti, l + J(l)$
Else
$J^h(i) \leftarrow minTi, l + J(l), J^{h1}(i)$
end if
if $J^h(i) \neq J^{h1}(i)$ or $h = 1$ then
$H + 1(i) \leftarrow l$
if $i \neq S$ then
send (unicast) to all $j \in V(i)$ $p(l)$ an RREP with $J^h(i)$ and$p(i) = i, p(l)$
end if
end if
```

the next path in the ranking. There are four algorithms for the Route maintenance procedure. The reliability test of the backup routes is carried out by Route Backup Test procedure. The other procedures like RTEST Management, RTEST Ack Management, and RERR Management handles the management and propagation of the relative messages. This algorithm is used when node *i* detects link failure between (S,D).

The intermediate node j that receives RERR packet executes the Route Backup Test, the node i stores the MAC address of the node from where it received the last packet for the flow. The information of the proceeding node is continuously updated so it is assumed that the RERR packet will reach the sender node even if there is any link failure from (S, D). When the destination node D sends the RREP control packet to its neighbouring nodes, the Backup step procedure will be initiated. The cost to reach the destination node ”metric” in the RREP packet is set to 0 by node D.

Algorithm 3

```
Route Backup Test
Begin Discard e1(i)
for $k = 2$ to $|E(i)|$ do
Unicast RTEST with $f(i) = i$ to $H_k^+(i)$
if the RTEST Ack is reached within time then perform
$T < NewTestDelay$
Break
Else
Eliminate ek(i)
end if
end for
if $i \neq S$ then
Unicast RERR to $H(i)$
else
go to Forward Step
end if
RTEST management
The transitional node j that RTEST containing the path f (i), performs the RTEST management procedure.
```

Algorithm 4

```
RTEST Management
if $j \neq D$ then
send (unicast) RTEST with $f(j) = f(i), j$ to $H_1^+(j)$
else
send (unicast) RTEST Ack with $r(i) = f(i)$ to last element of f (i)
end if
RTEST Ack management
Intermediate node j, receiving an RTEST Ack containing the path r(i),
performs the Algorithm 5.
```

Algorithm 5

```
*RTEST Ack Management*
if $j \neq r(i)$ where r(i) is the first element then
Eliminate j from r(i)
Unicast the RTEST Ack having r(i) to the last
```

The neighbouring node i of D, updates the metric field and sends the modified RREP to the other neigbouring nodes excluding the node D. The neighbouring node i has the knowledge of the mean waiting time W_i of its queue, hence it can compute the cost to reach destination node D. $R_{i,j}$ denotes the mean time needed to send the packets to D. The transitional nodes that hears the RREP does the same procedure as that of node i, until the RREP gets back to the source S and later the data transmission begins to take place.

4.7 Routing Metric

The average hop crossing time T is the sum of the average waiting time W and average transmission time R, that can be formulated as

$$T = W + R \tag{4.31}$$

where $T \triangleq E[T]$, $W \triangleq E[W]$, $R \triangleq E[R]$

4.7.1 Average Queue Waiting Time (W)

Littles law states that $Q = \lambda W$ where Q is the anticipated users of the queue and λ is the average traffic incoming rate in the queue and W is the average waiting time. W [83] [84] can be calculated by observing the queue evolution time

$$W(t) = \frac{\sum_{K=1}^{\alpha(t)} W^k}{\alpha(t)} = \frac{\int_0^t Q(\tau)d\tau}{\alpha(\tau)} \tag{4.32}$$

where W^k is the waiting time of the k^{th} packet in the queue, $\alpha(t)$ is the number of queued packet. It is essential to consider buffer overflow by reporting the probability of packet loss.

4.7.2 Average Transmission Time (R)

The average transmission time depends on the path error rate of the link. That is the probability of not receiving the packet correctly. Packet Error Rate (PER) of a link is measured by sending periodic Hello message. Every node that receives the "Hello"message determines the SINR to calculate the PER. So, $PER = F(SINR)$ and F is a function that depends on the coding, transmission energy, modulation, etc. The transmission time of a packet is the time taken to pass on the packet multiple times unless it is obtained completely.

$$R = X\frac{L}{B} \tag{4.33}$$

where X is variable having geometric distribution and it is the number of packet retransmissions and it is modified by the parameter $p = 1 - PER$, L is the packet length of the physical layer, B is the rate of transmission, while L and B are deterministic and the expected value of R is

$$R = E[X\frac{L}{B}] = E[X]\frac{L}{B} = \frac{1}{p}\frac{L}{B} = \frac{1}{1 - PER}\frac{L}{B} \tag{4.34}$$

Now, R decreases if PER decreases tending to the normal transmission time L/B for $PER \to 0$.

For the nodes *i* and *j*, link(*i*,*j*) between them is given by

$$T_{i,j} = W_i + R_{i,j} = \frac{\int_0^t Q_i(t)dt}{\alpha I(t)} + \frac{1}{1 - PER_{i,j}}\frac{L}{B} \tag{4.35}$$

where W_i stands for node i average waiting time, $R_{i,j}$ denotes the time taken for sending/receiving packets on the link (*i*,*j*) and $PER_{i,j}$ is the PER associated to the link (*i*,*j*);

The proposed method provides a better estimate of network crossing time due to the reasons:
(i) The waiting time for the packet in each queue of the node.
(ii) The analytical calculation of the PER is based on SINR of the channel.

The cross-layer design [84] takes into account the power consumption indirectly in terms of W_i and $R_{i,j}$. When ever the waiting time is less in the queue, then lesser energy is needed to send/receive the queued packets. Higheg level of energy is required for transmission when the link quality is poor. The other energy expenditure parameters must be considered like additive penalty that is inversely proportional to the node's residual energy. Link metric directly affects the following:

- **Channel quality:** PER is a good measure for link quality of the channels.
- **Congestion:** The average waiting time permits to penalize congested nodes.
- **Mobility:** It is possible to avoid selecting links based on average PER.

4.8 Implementation

To get the mobile node position and energy of the nodes, the mobilenode.h is included in dsr.h #include<mobilenode.h >

In the simple-wireless.tcl the initial energy values are declared as

```
double      posx;
double      posy;
double      posz
double      iEnergy;
int         node_speed;
MobileNode  *iNode;
```

```
set val(rp)                DSR            ;routing protocol
set val(energymodel)       EnergyModel    ; Energy Model
set val(initialenergy)     100            ; initial energy

$ns_ node-config           -energyModel     $val(energymodel)
                           -initialEnergy   $val(initialenergy)
                           -rxPower         35.28e-3
                           -txPower         31.32e-3
                           -idlePower       712e-6
                           -sleepPower      144e-9
```

Inside the dsr.cc file the variables are initialized within the class DSR: public Agent { } as

```
posx              = 0.0;
posy              = 0.0;
```

```
posz                = 0.0;
node_speed          = 0;
MobileNode          *iNode;
```

The required functions inside mobilenode.h are accessed in DSR::forward() function.

```
void dsr :: forward(dsr_rt_entry *rt,Packet*p,double delay) {
iNode = (mobileNode*)(Node::get_node_by_address(index));
(MobileNode*)iNode)->getLoc(&posx,&posy,&posz);
printf(”Position_of:%d,X=%f,Y=%f,Z=%f,index,posx,posy,posz);

iNode=(MobileNode*)(Node::get_node_by_address(index));
((MobileNode*)iNode)->getVelo(&posx,&posy,&posz);
printf(”Velocity_of:%d,X=%f,Y=%f,Z=%f,index,posx,posy,posz);

iNode = (mobileNode*)(Node::get_node_by_address(index));
node_speed = (MobileNode*)iNode)->speed();
printf(”Position_of:%d,speed=%d,index,node_speed);}
```

4.9 Performance Evaluation

The simulation was carried out in NS 2.34, where a network was considered having constant bit rate application, UDP protocol for the transport layer, IP protocol at the network layer, and IEEE 802.11g as the radio technology for MAC layer. The speed, congestion degrees, and quality of channel of the nodes were varied for simulation. The proposed algorithm CLD was compared to AODV and DSR routing protocols.

4.9.1 Channel Quality

A network was set up with 23 fixed nodes with different transmitting power levels 1.60 mW, 0.85 mW and 0.40 mW. The proposed cross-layer design shows that the best routing path was selected with highest channel quality that permits best performance in respect to QoS shown in

Table 4.1. The proposed design shows lowest delivery delays in respect to mean and variance as it has lowest number of retransmissions of four times lesser than AODV and nine times lesser than DSR. The ration between the number of erroneous received packets the total number of packets is the MAC layer loss rate. It was observed that delivery delays were reduced due to low MAC loss rate. The proposed algorithm on a total number of 3,760 data packets depicts lesser by 55 procedure postponed packets per node (1.46%), while AODV and DSR depicts lesser by four procedure deferred packets (0.11%). Additional, 50 packets of proposed algorithm are for periodic signaling to maintain local connectivity. The control packets are of 11-bits at the network layer in order to reduce the network load.such that the so that the overall network load is only slightly increased.

Table 4.1: Performance based on Channel Quality

Performance based on channel quality			
	AODB	DSR	CLD
Mean Delay (m/s)	3.82	2.616	2.126
Standard Deviation	53.450	1.114	0.556
MAC Loss Rate	6.04	7.45	1.30
Re-transmission	76	600	266
Signaling	3.00	3.68	3.29
Periodic Signaling	X	X	50.95

4.9.2 Mobility

The scenario consists of 22 mobile terminals shown in Table 4.2. The nodes are assumed to have mobility speed of 1.0 m/s, 2.5 m/s, and 5.0 m/s. Throughput is the ratio between the number of packets received by the receiver node over the number of broadcasted packets by the sender node. As the speed of the nodes increases, the percentage throughput of DSR decreases. So, DSR is ineffective for nodes with speed higher than 1 m/s in contrast to AODV and CLD. The proposed algorithm has higher delivery rate than AODV with less route discoveries. At speed of 5 m/s, CLD has lowest mean delays that are around 14 times smaller than AODV. The proposed method is able to find paths made of fixed terminals faster than AODV. The throughput of CLD is optimal, has low delays, and signalling load is 10 times lesser than AODV. The proposed algorithm runs only one route discovery process but AODV algorithm runs about 50 times to get the best route that predicts that AODV does not chose the best route.

Table 4.2: Performance based on Mobility

Performance based on Mobility		
	AODB	CLD
Mean Delay (ms)	5.321	2.771
Mean Deviation (ms)	43.456	18.678
Signaling	53.45	5.78
Throughput	95.00	100.00
Route Discovery	52	1
Periodic Signaling	X	202

4.9.3 Congestion

The part of the network zone with heavy queue loads lead to congestion that is to be avoided while routes are selected from the source node to receiver node. CLD method selects routes avoiding the congested zone. The proposed algorithm depicts delivery of 95% correct packets with low delays while AODV at 80% and least in DSR, as shown in Table 4.3.

Table 4.3: Performance based on Congestion

Performance based on Congestion			
	AODB	DSR	CLD
Mean Delay (S)	1.78	12.86	0.078
Mean Deviation (S)	0.218	6.090	0.567
Signaling	6.08	106.90	128.05
Throughput(%)	79.03	9.56	95.34
Periodic Signaling	X	X	39.80

4.10 Conclusion

The proposed algorithm is designed to tackle the networks with different capabilities. It is used to handle the limitations of existing routing protocols. A cross-layer approach was designed to allow the information between MAC and routing layer. The main issues to be addressed by ad-hoc networks are heavy processing loads on nodes, power limitations, mobility, and high variability of nodes. Robust design is essential to maintain the quality of service. The CLD design proposed here takes into account the user mobility, node congestion, and channel quality to permit packet delivery with less delay and high throughput. The extensive simulations of the design show that it performs better than AODV and DSR protocols.