Chapter 4

Routing for Secondary user in Cognitive Radio Network

This chapter provides history of routing to cognitive routing. Firstly it reviews hardwired routing a kind of switching to dynamic routing for telecommunication network starting with dynamic alternate routing (DAR) to ATM (Asynchronous Transfer Mode) routing. Secondly it presents routing in data network or packet switching. Thirdly it reviews routing for wireless multi hop network with special reference to MANET and WMN (Wireless Mesh Network). Consequently it reviews suitability of MANET and WMN routing protocol to Cognitive routing. Finally presents Cognitive routing protocol developed by author.

4.1 INTRODUCTION:

For routing between SU’s a CRT based routing protocol is necessary to coordinate the SU’s through data routing, data recovery in case of forced radio switch, congestion control and link establishment. While research in cognitive routing is still in it’s infancy. Cognitive routing can be realized in MANET and WMN routing in general and MRLQSR (Multi radio Link Quality source Routing) and AODV (Ad-hoc On-demand Distance Vector routing) in specific.
4.1 CHAPTER GOALS

This chapter discusses routing technology leveraged from circuit switching to cognitive routing to establish a foundation for further research on network layer protocols for Cognitive Radio networks. It is foreseen that several characteristics of routing protocols used in MANET and WMN have similar effect in Cognitive Radio networks. The chapter address following research questions in context to routing protocols for CR networks.

1. What features of MANET and WMN routing, as well as their merits and demerits that could be inherited by the routing system of CR network.

2. What are the additional functionalities that WMN and MANET routing protocols must offer to qualify as routing system for CR network?

3. What are the additional requirements for multi channel routing?

4. Which mode of routing would employ for Cognitive Radio Network Routing?

4.3 OVERVIEW OF SELECTED ROUTING PROTOCOLS

4.3.1 Telecommunication networks

Circuit switching is the oldest technology that ruled the communication networks for many decades. Originally it was designed for communication networks which carries voice communication and consisted of establishing physical circuits from sources to destinations
of phone calls. Each of these hardwired circuits was reserved and dedicated for the users at both ends for the whole duration of the call.

4.3.1.1 Routing in telephone networks

In early days, the telephone network relied on static, preconfigured and computed offline routes. The routing patterns depended upon network topology and provisioning of traffic demand, but they remained independent of the state of the network or time of day. To minimize the impact of eventual route failure or network overcharge, the switches had provision of multiple routes to each destination. Some times manual intervention were necessary to reconfigure the set of paths if necessary. The static routing has advantage of complete control over the route selected and considerably reduces switching computation requirement. Adaptability of system is slow to unpredictable in event of changing state. Also they required frequent human intervention and a substantial amount of switch memory to store the configured multiple routes per destination. Resulting in introduction of dynamic routing protocols, which can to mitigate the inefficiency of former protocols.

Expansion of switching was hindered by the limited processing capacity of switches and economic implications of wrong route decision, which can have severe economic implications. Introductions of stored program control switch with processing capabilities speedup progress of routing and switching. Dynamic switch can increase capacity of telecom network by 30% in compare to static routing,
Dynamic Alternate Routing (DAR), is a dynamic routing approach which has a adaptive call routing strategy that stochastically select alternate route when direct route is not possible. The alternate route is determined by using local information about the loading of outgoing trunks to determine feasibility of selected route. DAR has advantage over circuit switching is its speed response due to distributed operations. For sake of simplicity, the protocol does not process a path for a call on the basis of the overall network traffic. This type of strategy was implemented in *Network state dependent* protocols, which are a subset of dynamic routing strategies. They interpolate traffic congestion and try to establish connections in a way that minimizes the probability of future call blocking. *Dynamic Nonhierarchival Routing (DNHR)* is an example of such a protocol. It uses extensive off-line calculation to select, for a particular time of the day, a set of alternative routes for every pair of core switches. DNHR responds slowly to the traffic fluctuations because routing patterns are constructed for a period of time on the basis of user’s information. *Dynamically Controlled Routing (DCR)* is a centralized protocol that selects routes based on analysis of network by core switches. However this protocol is very susceptible to failure of the control processor because it maintains routing tables [B. HURLEY et al 1987]. The evolution of telephone as data networks led to the development of Asynchronous Transfer Mode (ATM) technology that uses different routing protocols.
4.3.1.2 Routing in ATM networks

Initially, the telephone networks were pure analog systems capable of carrying only voice data over mechanically interconnected wires. The advantages of digital transmission motivated, introduction of digital transmission on phone networks. In the mid 1980s the telephone industry observed an increased market demand for other services e.g. videoconferencing, Internet access, data transfer etc. Telephone companies thus decided to build an integrated voice/data network that they called Integrated Services Digital Network (ISDN) [R. AARON AND R. WYNDURM, 1986]. Soon, the transfer rate defined in the standard turned out to be inadequate to assure the success of ISDN and thus CCITT issued an improved version called the B-ISDN where the B stands for "broadband". By the end of the 1980s, Asynchronous Transfer Mode (ATM) [A. E. JOEL, ed., 1983] was developed as a promising technology to carry both synchronous voice and asynchronous data service and it was recommended for B-ISDN. ATM represents the transition from digital circuits to the packet / cell based telecommunications networks. It combines benefits of circuit switching (e.g. constant transmission delay and guaranteed capacity) with those of packet switching (e.g. flexibility). Routing consists of establishing a so-called virtual channel between source and destination at the beginning of the connection and guiding packets (called cells) over it. There are two main routing protocols in ATM networks, Private Network-Node Interface (PNNI) and Interim Interswitch Signalling Protocol (IISP). IISP provides a static routing solution and
is based on manually configured routing tables. Smaller ATM based systems are simple to deploy and they can also use proprietary implementations of PNNI. However, for large networks it is prone to errors and time-consuming to configure. In contrast to IISP, PNNI supports QoS and crank back. It provides two significant services: network topology call establishment and discovery. It is a hierarchical, dynamic link-state, source routing protocol. So upon receiving the call request a source router references the PNNI routing table to determine a path to the intended destination that is capable to support the QoS requirements specified by the caller. The connection message is then forwarded to the destination along the potential path and if sufficient resources are available on every intermediate node, the transmission can start. Otherwise the crank back or back off occurs and a new path has to be computed. If it does not satisfy the request requirements, the connection is refused. Numerous telecom companies have deployed ATM networks. However, it has failed to gain wide use as a LAN technology and its great complexity has hampered its full deployment as the single integrating network technology in the way that its inventors originally intended.

4.3.2 Data networks
Packet switching technology was designed in the 1960s as a means for providing cost-effective and efficient data communication between high-speed computers and remote users. In a packet-switched network packets are routed between nodes over links shared with other traffic.
Primarily advances in computer technology have driven the evolution of this type of network. Historically, three concurrent efforts contributed to the rapid development of packet switching technology:

- **ARPANET**, a network created in 1969 by Advanced Research Projects Agency (ARPA) for the US Defense Department and initially interconnecting four computers. During the 1970s, the ARPANET grew, connecting research institutes and laboratories throughout USA and Europe. In 1990 the ARPANET was retired and various higher speed networks had already replaced its functions.

- Computer time-sharing companies, eager to expand their computing resources, developed their own propriety packet-switched networks (*e.g.* TYMNET) to provide remote user access to their distributed machines network. Most such networks migrated to IP technology and are now considered obsolete.

- Computer manufacturers designed integrated systems for data communication (*e.g.* IBM’s SNA) to add functionality to their computers and peripherals. Although many such networks are still in operation, they are also being replaced by IP technology. The purpose of a network influenced the specific design of its routing strategy. The routing algorithms used in these networks all turn out to be variants of shortest path algorithms that route packets from source to destination over a path of least cost (*e.g.* minimum delay). Nowadays, in general most data networks employ some type of shortest-path strategy to
generate and select routes according to the network and user state. Thus we describe two most popular least cost algorithms (distance vector and link-state), which are the basis for the routing procedures in many networks.

### 4.3.2.1 Distance-vector routing

ARPANET developed the first packet routing called Distance Vector (DV) technique. The protocol also known as Bellman Ford algorithm due to it’s creator name. The Protocol relies on fact that each node has its identity with router and router also identify and recognize each other. It has to maintain a list of hop or time distance as tuple (destination, cost) called DV. The cost is a additive function of a current estimate of link cost or hop count on the shortest path to the destination. DV are shared among router in periodic interval. A receiver of that packet, determines whether it is possible to reach any destination with a smaller cost by sending packets through the sender. It can do so by comparing its current route cost to the destination with the sum of the cost to reach the neighbor and its neighbor’s cost to communicate with the same destination. The DV strategy was implemented in many routing protocols. One of the most common examples is the Routing Information Protocol (RIP) [C. L. HEDRICK, 1988]. It was initially deployed with Xerox Network Services by Xerox. RIP is most commonly used as a routing protocol on intranets. The main advantage of the DV protocol is its simplicity and small overhead. This permits distributed and asynchronous
operation and requires only locally available costs to compute and select routes. However, the Bellman-Ford algorithm causes problems when the network architecture is unstable. It suffers then from a count-to-infinity problem [M. STEENSTRUP, ed., 1995] and does not prevent routing loops. Thus another class of protocols (called link-state) for data networks was developed.

4.3.2.2 Link-state routing

Link-state (LS) routing was developed by John Mc-Quillan [J. M. MCQUILLAN, et al 1988] for the ARPANET in 1978 as a solution to the instability of DV protocols in cases of changing network connectivity. Later this type of strategy was proposed for use in an ISO Intermediate System to Intermediate System (IS-IS) routing protocol [J. MOY 1988]. The LS algorithm was also adapted by the Internet Engineering Task Force in the Open Shortest Path First (OSPF) protocol for use in the Internet. Both protocols, IS-IS and OSPF, are broadly utilized for intra autonomous system routing. In a LS protocol a router periodically broadcasts its local view of the network as link states, in terms of the properties of the links connecting it to neighboring nodes. Then every router updates its dynamic map of the network which is essentially a database describing the current interconnections and their network’s components. Routers compute routes for the traffic use the databases generated by exchanging route packets. This contrasts with the DV strategy in which every router shares its routing table with neighbors and this
information serves to construct local routing paths. The prime advantage of LS routing is that it reacts quickly to the network changes. It also requires a smaller overhead than the DV algorithm as in the earlier protocol nodes only broadcast information about links with their immediate neighbors in compare to the DV protocol routers share entire routing tables. The main disadvantage of LS is that it requires more storage and computational than the DV protocol. Both routing classes, DV and LS, are broadly used for routing in a single autonomous system. However for communication between autonomous systems so-called Inter-domain algorithms were developed.

4.3.2.3 Inter-domain routing

The need for distinct algorithms to route packets between heterogeneous networks comprising multiple organizations emerged with the growth of the Internet. After being initially a research project it became in the late 1980s a worldwide communication infrastructure for diverse organizations with heterogeneous goals and objectives. Thus, interconnecting these users requires extensive cooperation among networks. Three protocols chiefly contributed to the evolution of inter-network routing, each based on the DV paradigm. The three protocols are the Exterior Gateway Protocol (EGP), the Border Gateway Protocol (BGP) and the Inter-Domain Routing Protocol (IDRP).

The first inter-domain routing protocol EGP was introduced in the Internet world. It was designed in 1982 [E. C. ROSEN, 1982] and was
deployed to deal with routing between ARPANET and sites attached to it. The concept of a domain was first time introduced by EGP, which has a globally unique identifier. The protocol operations consist of three main tasks: neighbor acquisition, neighbor reachability and exchange of routing information. The former objective is achieved by a simple two-way handshake. Then to maintain the information about connectivity with neighbors, nodes periodically send HELLO or keep alive messages and expect responses from adjacent routers. Finally, the routing information is shared between neighbors via a message, the metric (whose definition is left to the designers of the autonomous system [E. C. ROSEN, 1982], and network-layer address of an appropriate nexthop. EGP was sufficient for the initial needs of the Internet but when the network NLRI, (Network-Layer Reachability Information) is a list of IP network numbers architecture became more complex, its suitability deteriorated and hence became obsolete. It was replaced in the late 1980s by BGP (Border Gateway Protocol) which addressed all the shortcomings of EGP.

The current version of **BGP** (v4) is the core routing protocol of the internet. It allows an arbitrary interconnection of network topologies between autonomous systems in contrast to EGP which was intended to operate only within a strictly hierarchical inter-domain topology. Nodes exchange similar routing information as in EGP. Additionally, routers add to the packet the list of domains that the routing information has traversed so far. This mechanism prevents routing
loops and is the reason for calling BGP as a path vector protocol. Scalability is a key requirement for the inter-domain routing and therefore BGP has mechanism that allows reduction of the volume of the information that needs to be handled by routers. Routers assume that the network is hierarchical and therefore they can aggregate close destinations in NLRI summary. BGP adopts a policy-based routing mechanism where each domain applies local rules to select a route and to decide whether to propagate this route to neighboring domains. Although there has been a continuous improvement of BGP, it has some shortcomings. The number of domains is limited to 65536 that is insufficient for very large Internets. Besides, BGP provides a single path to a destination and therefore it excludes the ability to support multiple routes with different performance characteristics.

IDRP was developed to accommodate the growth in the number of networks and users. It shares many features with BGP (path-vector routing, aggregation of NLRI, variable address lengths) and some of them are improved. A significant effort was undertaken to increase the scalability of IDRP in heterogeneous, multiprotocol Internets. As a result IDRP allows up to 2160 domains, in comparison to 216 the maximum of domains allowed by BGP. IDRP was a major divergence from the BGP development track, the de-facto standard of the Internet, and was not adopted by industry. One primary reason for this was that IDRP was incompatible with the BGP development track, which was operational, mature, and commercially supported by major IP router
vendors with running code in the Internet. In addition, the IETF considered the complications of IDRP QoS routing enhancements less attractive relative to the simpler BGP paradigm.

4.3.3 WIRELESS MULTIHOP NETWORKS

The research on wireless packet networks was initiated in the 1970s with the first successful network based on packet radio, developed at the University of Hawaii in 1971 called ALOHANET. This system enabled computer sites at seven different campuses spread out over four islands to communicate with a central computer via radio transmission. Although it assumed a simple star topology of the network, many solutions and principles incorporated in its routing protocol are still in use today. Then DARPA invested significant resources during the 1970s and 1980s to develop networks using packet radios for military applications. Over time, packet radio networks found commercial applications in supporting wide area wireless data services (e.g. email, file transfer, web browsing) in the 1990s. The development of data wireless networks led to the classification of those into Wireless Networks (WMNs) and Mobile Ad-hoc Network (MANET). They are designed for different applications and deployment objectives and thus use different routing protocols. However, both these types of networks share many properties with (CRN) and have substantially influenced the development of CRNs routing protocols.
4.3.3.1 Mobile Ad-hoc Networks routing

MANET originated from the DARPA Packet Radio Network [J. JUBIN AND J. D. TORNOW, 1987] developed in the 1970s. In 1983 DARPA established a successor to the packet-radio program that Internet Engineering Task Force is the body that develops and promotes Internet standards it called Survivable Adaptive Networks (SURAN) [M. STEENSTRUP, ed, 1995]. Mobile devices that can dynamically move and reorganize themselves and communicate over wireless links form MANET. Because of the importance of routing protocols in dynamic multi-hop networks, a lot of mobile ad hoc network routing protocols have been proposed in the past. The development of routing protocols for MANET was boosted by the formation of the IETF MANET working group and publication of its charter in 1997 with the objective of developing a solution framework for routing in an ad hoc network. We can distinguish three main groups of routing protocols for MANET:

- **Proactive, table-driven routing protocols**:
  - Optimized Link State Routing Protocol (OLSR)\(^1\)
    - Fisheye State Routing (FSR)\(^2\)


– Destination Sequence Distance Vector (DSDV)\(^3\)

**Reactive, source initiated, on-demand routing protocols:**


– Ad hoc On-demand Distance Vector Routing (AODV) [C. PERKINS, 1997]

– Temporally Ordered Routing Algorithm (TORA) [V. D. PARK AND M. S. CORSON, 1997]

**Hybrid routing protocols:**

– Zone Routing Protocol (ZRP) [Z. HAAS, 1997]

**Optimized Link State Routing Protocol (OLSR)** is a very popular proactive, Link State routing approach for wireless Ad hoc networks designed at INRIA and standardized at IETF. The main goal of OLSR is to minimize the protocol overhead by reducing the number of retransmitted link state packets. Each node selects a subset of its neighbors (called multipoint relays (MPR)) in such a way that all 2-\(^3\)C. PERKINS AND P. BHAGWAT, 1994, *Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers*, in ACM SIGCOMM’94 Conference on Communications Architectures, Protocols and Applications, 1994, pp. 234–244
hop neighbors can receive broadcast messages, even if only MPRs nodes retransmit the packets. Every node computes the MPR set independently, solely based on the received local topology received. Additionally, the OLSR reduces the overhead due to fact that nodes need to share only the link state information to all MPR selectors for the computation of shortest paths. Every node periodically broadcasts its link state information by topology control messages. The frequency of topology control messages is proportional to the topology change in the network has been detected. The OLSR routing table that contains entries for all reachable destinations in the mesh network is computed with a classical shortest path algorithm (e.g. Dijkstra algorithm). The initial OLSR protocol does not relay on the link quality for the route selection algorithm. This assumes that links are bimodal (either working when packets from a given node can be heard or failed if not), which is not necessarily the case in wireless networks and may result in a high packet loss and retries. Later implementations of OLSR (e.g. Radio Aware-OLSR (section 4.3.3.2)) solve that problem by using radio-aware metrics in forwarding path with MPR based calculations. Another disadvantage of OLSR is that OLSR floods the link state database unreliably and may cause transient loops if the link state database becomes inconsistent because of the packet loss.

**Fisheye State Routing (FSR)** It is a proactive protocol, based on the Link State paradigm with reduced overhead caused by the update of network topology information. The idea behind the protocol is based
on the fish eye lens that catches the pixels near the focus with high detail, and the detail decreases with distance from the focal point. Similarly, FSR maintains accurate distance and path quality information about neighboring nodes, and progressively reduces detail as the distance increases. This is achieved by varying the periodicity of the Link State messages with the scope of the destination. The nodes closer to the source of Link State packet receive topology information more frequently than faraway nodes. This is done by incrementing TTL of messages for each flood until the maximum value before it continues with the initial, small value. FSR exhibits very good scalability because it does not strive to keep all nodes in the network on the same knowledge level about link states. Although FSR limits the network topology information shared among nodes, the packets are routed correctly because the route information becomes more and more accurate as the packet gets closer to the destination. The main disadvantages carries by FSR are its large processing overhead and routing table storage complexity.

**Destination Sequence Distance Vector** (DSDV), developed in 1994 is a table-driven routing protocol based on the Bellman-Ford algorithm. The main contribution of the algorithm is to prevent the routing loop problem. Every node maintains a routing table in which all-possible destinations within the network and the numbers of hops to each destination are also recorded. Each entry is marked with a sequence number assigned by the destination node. Sequence numbers are used
to distinguish stale routes from fresh ones and to avoid the formation of route loops. Routing tables are constructed similarly as in Bellman Ford algorithm. To reduce protocol overhead, these routing updates can employ two possible types of packets. The first is known as a full dump. Full dump packet carries all available routing information and can require multiple NPDUs. During periods of occasional movement, these packets are transmitted infrequently. Smaller incremental packets are used to relay only that information which has changed since the last full dump. DSDV is not suitable for hi dynamic networks due to fact that faster network topology change and hence higher packet discard rate in context to TTL, which tells the network router whether or not the packet has been in the network too long and should be discarded. network changes, a new sequence number is necessary before the network re-converges, which can take a significant period of time.

**Dynamic Source Routing** (DSR): It is one of the pioneering routing solutions for MANET, based on reactive paradigm that utilizes a source routing algorithm. DSR consists of two major phases: route maintenance and route discovery. When a source node wants to send a packet, it consults its routing cache. If the required route is available, the node inserts it into the header of the packet. Else, it broadcasts the route discovery packet. Receiving that packet, a node checks its route cache. If the node does not have routing information for the requested destination, it forwards the packet with its own address appended to
the route record field of the header. When the request reaches the
destination or an intermediate node has routing information to the
destination, a route reply packet is sent. It comprises addresses of
nodes that have been traversed by the request packet eventually
concatenated with the route from the intermediate node’s cache. A
route error packet is sent when a node discovers link failure. Then all
the nodes remove from the cache all routes containing the broken link.

DSR, as a reactive protocol, eliminates the overhead due to the
periodical flooding of the network with route updates. This approach
however increases the connection setup delay and its performance
degraded rapidly in a mobile environment. Also DSR requires
considerable routing overhead because every data packet contains
complete routing information.

**Ad hoc On-demand Distance Vector routing** (AODV) is a most used,
reactive routing protocol for MANET that has been standardized by
IETF. AODV uses many solutions implemented in DSDV. The main
difference between these protocols relies in the route calculation task
which is performed only when necessary in case of AODV. When a
source node wants to send a message to some destination node and
does not already have a valid route to that destination, it broadcasts a
route request (RREQ) packet to its neighbors, which then forward the
request to their neighbors, and so on, until either the destination or an
intermediate node with a route to the destination is reached. Then a
route reply (RREP) packet is created and forwarded back to the
source. The RREP follows the reverse path of the respective RREQ as AODV only supports the use of symmetric links. Upon receiving the RREP packet, every intermediate node updates its next-hop routing table entry for the corresponding destination node. When a node discovers a link failure, it broadcasts a route error (RERR) message to its neighbors, which then forward the message to nodes whose routing tables may be affected by this change. Then, the route discovery procedure may be re-initiated if the route is needed. The disadvantage of AODV is that multiple RREP packets generated in response to a single RREQ packet can cause a heavy control overhead.

**Temporally Ordered Routing Algorithm** (TORA) is a highly adaptive, reactive, distributed routing algorithm based on the concept of link reversal. The key idea of TORA is to limit the propagation of routing control messages to a very small set of nodes near the occurrence of a network topological change. The operation of the protocol is composed of three main functions: route creation, maintenance and erasure. During the route creation and maintenance phases, TORA assigns to every node a “height” metric in order to construct a Directed Acyclic Graph (DAG) rooted at the destination. The destination of the message has a value of height 0 and values assigned for remaining nodes are proportional to the distance from the destination. Then, like water flowing, a packet goes from upstream to downstream according to the height difference between nodes. In the event of a link failure, when a node loses its last downstream link, it
generates a new reference level which results in the propagation of that reference level by neighboring nodes and in consequence the reversion of links directions reflecting the new reference level. The erasing operation of outdated entries from routing tables in TORA consists of flooding CLR packets and dropping invalid routes. TORA may suffer from oscillations especially in situations when multiple nodes detect link failures. However those oscillations are temporary and are followed by a route convergence. TORA requires clock synchronization of nodes that may be an energy demanding operation especially in large networks.

**Zone Routing Protocol** (ZRP) is a hybrid routing protocol that implements an algorithm which divides the network into overlapping zones and then uses a proactive routing within the zones and reactive routing between them. Zones are selected according to the hop distance between mobile nodes. Most existing proactive routing approaches can be used for intra-zone routing. For inter-zone routing the Inter-zone Routing Protocol (IERP) is used which is very similar to DSR. The hybrid routing approach decreases the route setup delay of reactive routing schemes and reduces the control overhead of proactive routing protocols. ZRP causes large overlapping of routing zones and thus it generally suffers from bigger overhead than other

**Table 4.1 Comparison of various Wireless Routing Protocol**

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Type</th>
<th>Overhead</th>
<th>Agility</th>
<th>Scalability</th>
<th>Suitability for CRN</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLSR</td>
<td>Proactive</td>
<td>Low</td>
<td>No</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>DSDV</td>
<td>Proactive</td>
<td>High</td>
<td>V. low</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>DSR</td>
<td>Proactive</td>
<td>High</td>
<td>2-phase</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>AODV</td>
<td>Reactive</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>TORA</td>
<td>Reactive</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Yes</td>
</tr>
<tr>
<td>ZRP</td>
<td>Hybrid</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Yes</td>
</tr>
</tbody>
</table>


4.3.3.2 Wireless Mesh Networks

The Wireless Mesh Networks (WMNs) was developed due to expansion of the Internet in the 1990s. WMNs were developed to extend a connection to Internet for wireless devices. The network is formed of static wireless relay nodes providing a distributed infrastructure for mobile client nodes over a partial static mesh topology. The main difference between a MANET and a WMN lies in the mobility of nodes and network topology. MANETs are characterized by the lack of static infrastructure and a highly dynamic topology whereas WMNs use
multi hop wireless relaying over a relatively static partial mesh topology for its communication. In 2004 the 802.11s Task Group (responsible for standardization of mesh networking in Wireless Local Area Network (WLAN)) was created to address the issue of lack of interoperability between equipment from different vendors and also to further the ability and ubiquity of mesh networking. Over the years WMNs have seen three generations of technology of which the second and the third were defined by the 802.11s Task Group (the first generation corresponds to the early WMNs systems). Each of them incorporated iterative improvements and allowed for greater scalability with higher network throughput and reduced latency. These generations are described below:

• In the first generation the radio mesh uses one radio channel both to service clients and to provide the mesh backhaul. This architecture is very inefficient due to users competition for the bandwidth and mesh nodes have to listen frequently to the channel prior to every transmission.

• The second generation of WMNs uses separate radio channels for servicing the clients and for mesh infrastructure. Most currently available products use this architecture and it considerably improves network performance in comparison to the first generation WMNs.

• The third generation of WMNs, also uses different channels for service and infrastructure, in this these channels are managed
dynamically so that there is no interference between occupied links. This solution provides improved performance as it preserves bandwidth and reduces latency over multiple mesh hops. Some MANET routing protocols are in use due to the similarities between architectures of MANET and WMN. However, many routing protocols have been designed specifically for WMNs based on the unique properties of WMNs (multihop, wireless, mesh architecture with fixed nodes, reliable with high throughput links, self-healing and self-configurable network). Existing WMNs routing protocols can be classified as being position-based or topology-based. Furthermore, the topology-based algorithms are divided into three categories: proactive, reactive and hybrid (see section 4.3.3.1). This classification with corresponding examples is shown below:

- location-based protocols, *e.g.* Greedy Perimeter Stateless Routing (GPSR) [B. KARP AND H. T. KUNG, 2000]

- topology-based protocols

  - Proactive, table-driven routing protocols, *e.g.* Radio Aware Optimized Link State Routing (RA-OLSR)

  - Reactive, source initiated, on-demand routing protocols, *e.g.* Multi radio Link Quality Source Routing (MRLQSR)

[R. DRAVES et al, 2004]
– Hybrid routing protocols, *e.g.* Hybrid wireless mesh protocol (HWMP)

**Greedy Perimeter Stateless Routing** (GPSR) is one of the first and foremost position based routing protocols for wireless mesh networks. It exploits the correspondence between geographic position and connectivity in a wireless network, by using the positions of nodes to make packet-forwarding decisions. GPSR combines greedy forwarding with face routing as a fallback (after bypassing the disconnected region the greedy forwarding resumes). The main advantage of GPSR is that forwarding decisions are made using local information and there is no need to maintain routing tables for all nodes. However, GPSR requires that nodes know their locations that may be difficult to obtain, especially in large networks.

**Radio Aware Optimized Link State Routing** (RA-OLSR) is a proactive, link state and optimal routing protocol of the IEEE 802.11s standard. It is an adaptation of the OLSR protocol (section 4.3.3.1) to the WMN environment incorporating some features of the FSR paradigm (section 4.3.3.1). Packets are forwarded along the shortest path according to an arbitrary, radio-aware metric (*e.g.* an airtime metric) instead of using a hop-count metric as in OLSR. A hello message consists of metric link cost information along with topology control message to reduce overhead of control message. To reduce the related control overhead, RA-OLSR uses the concept of MPRs (similarly to OLSR) and optionally controls with reduced message
exchange on basis of Fisheye scopes (see section 4.3.3.1). Each mesh node maintains a local association base (LAB) that contains all legacy client stations associated with this mesh node. It broadcasts local association base advertisement (LABA) messages periodically, in order to distribute the association information in the mesh network. Each receiver of LABA messages stores this information in the global association base (GAB). Both of LAB and GAB is used in the construction of the routing table and provides routes to legacy client stations associated with mesh nodes. To reduce overhead, it is possible to broadcast only the checksum of the blocks of the LAB in case of a mismatch between a received checksum and the checksum in the GAB of the node. New route establishing system comes into action. In face routing the network graph is logically segmented into so-called faces, where the considered links do not cross each other. Packets can proceed out of a local minimum by being forwarded around these faces toward the destination. An airtime metric reflects the amount of channel resources consumed for transmitting a frame over a particular link. requests an update of the corresponding block of the LAB of the originating node. RA-OLSR inherits the stability of a link-state routing protocol and has the advantage of having routes immediately available when needed due to its proactive nature.

**Multi radio Link Quality Source Routing (MRLQSR)** is a DSR (section 4.3.3.1) based, reactive protocol developed by Microsoft for static community third generation WMNs. The main contribution
of MRLQSR is the use of a new routing metric called weighted cumulative expected transmission time (WCETT) that takes into account channel diversity, link quality, and minimum hop count. It can achieve a good trade-off between throughput and delay because it considers channels with good quality and channel diversity at the same time. Neighbor discovery, link weight information propagation and path finding processes are same in MRLQSR and the DSR protocol. MRLQSR identifies all nodes in the WMN and assigns weights (according to the WCETT metric) to all possible links. The main advantage of MRLQSR is the improved throughput performance compared with the throughput achieved by other multi radio routing metrics (e.g. it was found that WCETT outperforms the ETX11 routing metric by about 80%). This throughput advantage is because MRLQSR considers a trade-off between end-to-end delay and the path throughput for candidate paths. One of main disadvantages is that the use of multiple radios on a single node may consume substantial power and hence the routing metric should effectively look into energy efficient routes when used in mobile WMNs.

Hybrid wireless mesh protocol (HWMP) is the default routing protocol of IEEE 802.11 and its compliant networks. The HWMP is based on AODV and its extension of the reactive routing protocol (section 4.3.3.1), called radiometric AODV (RMAODV), to layer 2 and to radio-aware metrics. HWMP combines ad hoc and spanning tree-

---

5 www.ieee.org/802.11
based routing features that incorporate proactive and reactive methods in the following way:

• The former method is applied if a node in the WMN is optionally configured as a root node and then other nodes proactively maintain routes to the root using topology discovery primitives and distance vector methodology identical to the RM-AODV protocol. When a node wants to send a packet, and has no route to the destination, it may send a frame to the root. Then it looks up the routing and bridging tables to see if the packet is intended for a node within the mesh or outside. It forwards the messages appropriately back to the mesh or its uplink. If it finds the entry inside the mesh, it sends the frame to the destination parent mesh node, which in turn will initiate an on-demand, optimal route discovery between the destination-source pair for all subsequent frames sent between them.

• The latter approach uses an RREQ and a route reply RREP mechanism (borrowed from AODV (see section 4.3.3.1)) to establish routes between two mesh nodes. The main difference from AODV is that HWMP works at layer-2 and uses MAC addresses. Apart from this adaptation, it uses the following mechanisms of the original AODV protocol: route discovery, sequencing, route maintenance, route acknowledgment and route errors.

The main advantage of HWMP is the scalability, due to its hybrid nature, it combines the flexibility of on-demand route discovery with
the option of efficient proactive routing to a mesh node. Another benefit of HWMP is its reduced protocol overhead. The protocol reduces flooding by sending a single RREQ for multiple destinations simultaneously. It also enables proactive maintenance of routes to popular destinations (e.g. the root node) and to do that each active source node sends a periodic RREQ message (maintenance RREQ) for those destination(s).

<table>
<thead>
<tr>
<th>Table 4.2 Comparison of various Wireless Mesh Network Routing Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Protocol</strong></td>
</tr>
<tr>
<td>RA-OLSR</td>
</tr>
<tr>
<td>MRLQSR</td>
</tr>
<tr>
<td>GPSR</td>
</tr>
<tr>
<td>HWMP</td>
</tr>
</tbody>
</table>

**4.4 MULTI EDGE WEIGHTED GRAPH ROUTING FOR CRN**

**4.4.1 Background**

Some solutions based on multi-layered graph, which uses multiple layers of graph represents dynamic channel or communicating PHY
4. Routing for Secondary user in Cognitive radio Network

environment. In multi layered graph model, each channel or frequency band in operation are represented by a layer of a graph, i.e if there is 3 channel operational then the graph shall have 3 layers. Each layer in a graph containing nodes representing users and edges joining any two nodes if they are in the transmission range [Pradeep Kyasanur, Nitin H. Vaidya, 2005] for a particular channel. Communication among the nodes for a particular channel. Communication among the nodes across layer is possible through inter layer links. Using multi layer model a routing strategy can be devised to find a near optimal solution. The multi layer graph model is a bit complex in nature and it wouldn’t work with tradition routing protocol like AODV [C. E. Perkins et al.], DSDV [C. E. Perkins and P. Bhagwat, 1994], DSR [D. B. Johnson, 2003] etc. that assume planner structure graphs. Some routing protocol based on cross layer information and their statistical inferences are also suggested for cognitive radio. But all these protocols have problems of either suboptimal results or delayed decision not suitable for agile behavior of cognitive radio. Therefore a new multi edge planar graph model for routing in cognitive radio is proposed. Such model is simpler and more accurate in routing decision where multiple radio with dynamic channel allocation in case of cognitive radio.

4.4.2 Multi Edge Weighted Graph Routing

As the name implies, this graph model, unlike the traditional graph models used in routing, has multiple edges between a pair of nodes. This added feature of the graph accounts for the modeling of extra
characteristics of Cognitive, Radio such as available channel set, possible routes to other nodes through various channels and neighbor set of each channel. Unlike in layered graph model where layers represent different channels, multi-edged graph model takes advantage of extra edges to represent the channels and weights of these edges to represent the channel’s characteristics. Due to this characteristic of multi-edged graph model, a layered structure is obviated and is reduced to a planar structure. It can be argued that the layer complexity is shifted to edge complexity in the multi-edge planar graph model. But it will be demonstrated later in this chapter that edge complexity of the new model is much lower than layered graph model.

### 4.4.2.1 Cost function

The device based on cognitive radio has the capability to sense the environment and react on it for optimal communication using features of agility. These features can be used to find better routers from communicating nodes in terms of interference, liveliness, and bandwidth utilization. A routing cost function incorporating measurements of current network status in terms of interference suffered by overlaid networks was proposed in [L. De Nardis and M.-G. Di Benedetto, 2006] This can be done by adding weight to communicating links or edges in representing graph of the network. The cost function is a mechanism of generating weight or logical distance between edges in the graph. A routing cost function incorporates measurement of external world like traffic in network,
bandwidth available, interference suffered by the overloaded network. The cost function includes selected six vital parameter of cognitive radio like SINR, Bandwidth, Power, Reliability of channel. Cost function is calculated as multi weight average of the parameter given by

\[
\sum_{i=0}^{n} X_i P_i \\
\sum_{i=0}^{n} X_i
\]

**Algorithm 1**: Construction of Multi Edge Graph

Add a vertices (communicator) \( V_i \) to the graph \( G \) for each in CRN (cognitive radio Network).

1. Add an edge (connector) between \( V_i \) and \( V_j \). If they are potential neighbors through channel \( C_i \) for all \( V_i, V_j \in V \) and \( C_i \in C \)

2. Assign weight for each edge between \( V_i \) and \( V_j \) using Weight Assignment Algorithms

**Algorithm 2**: Weight Assignment

1. Assign distance \( D \) in terms of time as the weight for the edge connecting vertices

   ( device) \( V_i \) and \( V_j \) for all \( V_i, V_j \in V \)

2. Add cost function to the weight for all edge connecting Vertices \( V_i \) and \( V_j \)

   for all \( V_i, V_j \in V \)
4.4.2.3 SIMULATION RESULT AND ANALYSIS

A queuenet based discrete simulation environment written using Omnet++ simulation environment is used to simulate weighted multi-edge graph. The multi-edge graph model is tested using AODV protocol. Various parameter of simulation areas

<table>
<thead>
<tr>
<th>Table 4.3 Multi edge Routing Simulation setup</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Topology</td>
</tr>
<tr>
<td>No. of Node</td>
</tr>
<tr>
<td>Channel Selection</td>
</tr>
<tr>
<td>Probability of available channel</td>
</tr>
<tr>
<td>Maximum no. of channel</td>
</tr>
<tr>
<td>Modes</td>
</tr>
<tr>
<td>Switched channel</td>
</tr>
<tr>
<td>Static channel</td>
</tr>
</tbody>
</table>

The simulation results shown in figure 4.1 and 4.2 are resultant of extensive simulation (more than 100 times) on omnet++ simulation using quenenet and MiXiM for multi edge graph and routing protocol simulation. The simulation are carried on two aspects, for analyzing successful routes with reference to number of nodes and analyzing successful routes with reference to available channel. It can easily shown that the variation of percentage of successful routes with number of nodes in the networks in which switching the interface
between the channels is allowed and not allowed respectively are not in ratio. It is observed that there is a success rate around 91% with switching. If switch is not allowed constraint on communicating with two different channels simultaneously arises which limits no. of node communicating in an instance. This fact is evidently visible in the results shown in fig 4.1. It is also observed that as the number of node increase, the success rate decrease. This is due to fact probability of common channel for routing is inversely proportional to number of node.

![Figure 4.1 Successful routes with reference to number of nodes](image)
In Fig. 4.2 percentage of successful routes is plotted against the maximum number of channels. From the graph it is evident that success rate of routes is proportional to number of channel available and can go up to full success in case of channel switch is allowed. This due to this fact that number of channel available increase probability of getting at least one channel for establishment of route between nodes. Apart from that slight increase in percentage of route success is also observed in static case to high availability of non-interfering common channel for route establishment. The real world value lies between static and switching value due to mixed interface in various devices used in real world application.
4.4.3 Future Prospects and Conclusion

We proposed the algorithm and simulation result of multi edge weighted graph routing (MEGRP). The algorithm is a novel approach of routing, which guarantee an optimal route in very small time frame. The routing has feature of high adaptability, a required for cognitive radio. Apart from this the protocol also ensure no loop route which might happen in multi edge graph by assigning cost function to each edge, hence labeling each edge. The multi edge graph lessens complexity in routing by using scalar matrix operations on edge in
compare to vector matrix operations on multipath graph. Apart from this number of edges in graph is greatly reduced from multi level graph. The algorithm can be enhanced by providing statistical information to the cross layer system, which can assist route decision making or can advice route decision. The algorithm with support of bio inspired routing algorithm can be enhanced, which can support better route guarantee and faster adaptability, a must for cognitive radio. We hope that this protocol will be useful for the said system.

4.5 BIO INSPIRED CROSS LAYER AWARE NETWORK PROTOCOL FOR COGNITIVE RADIO NETWORK

4.5.1 The Motivation:

S. Haykins\(^6\) defined Cognitive radio as an intelligent wireless communication system that is aware of and learn from it’s environment and adapts its internal states by making corresponding changes in certain operating parameters. In similar track many research had been done in reconfigurablity in parameters from definition of radio parameter, physical layer protocol change, modulation technique adaptation, MAC layer adaptation and in some place Network layer adaptation. Little research had been reported on cross layer aware protocols in wireless communication. It can be shown that significantly improved protocol for MAC layer an be

designed by adapting the cross layer aware system. The enhancement in performance is due to awareness and adaptation of PHY parameters. It can be shown that significant improvement in routing protocol by using cross layer aware protocol design in network layer protocols. Noticeable improvement are also reported over KR-MAC (Knowledge based Reasoning MAC and CLA-AMAC. Routing in multi-hop heterogeneous wireless network using non adaptive routing system is not adequate because it selects minimum Hop count path, which have significantly less capacity than the best paths that exist in the Network.

Table 4.4 Comparison on various Approaches of Cognitive Routing

<table>
<thead>
<tr>
<th>Approach</th>
<th>Route Life</th>
<th>Adaptability</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bio-Inspired</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Multi-Graph</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Multi-Edge</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Multi Protocol</td>
<td>Low/Fast refresh</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Bio inspired algorithm are mainly based on hybrid (both reactive and proactive) multipath algorithm, AntHocNet 7 is one of the most respected bio inspired routing algorithm in MANET. In AntHocNet [Caro, F. Bucatella, and L. M. Gambardella,2005] a routing table consists of a destination, the next possible hop to it, and a special data

7 A ANT colonization optimization based Routing protocol
structure based on odors released by ant called pheromone. A pheromone is a value that indicates the estimated goodness of a path between a source and a destination. In this way, pheromone data structures in different nodes indicate multiple paths between two nodes in the network, and are stochastically spread over it (in each node they select the next hop with a probability proportional to its pheromone value). Once paths are set up and the data start to flow, the source node starts to send proactive forward ants to the destination. This is a maintenance phase where each proactive forward ant follows the pheromone values in the same ways as the data, but has a small probability at each node of being broadcast. This technique serves as follows. If the forward ANT reaches the destination without a single broadcast, it means that the current path is working and optimal, and it provides an efficient way of data transferring. On the other hand, if the ant gets broadcast at any point, it leaves the currently known pheromone trails as knowledge base and it explores new paths. A threshold of value two (2) is used to avoid proactive forward ants being broadcast to the whole network, allowing the search for improvements or variations to be concentrated around the current paths. In the case of a link failure, a node may use an alternative path based on the pheromone values. However, if the failed link was the only one in each pheromone table, the node sends out a route repair ant that travels to the involved destination like a reactive forward ant would do. Simulation experiments have shown that AntHocNet\(^8\) can

\(^8\)Caro, F. Bucatella, and L. M. Gambardella, 2005
outperform AODV and other routing algorithm in terms of delivery ratio and average delay [Caro, F. Bucatella, and L. M. Gambardella, 2005].

The layered architecture simplifies development of different components by keeping each layer isolated from the others. Originated from the wired networks world, the concept of transparency is what makes OSI; TCP/IP and IEEE 802 models allow rapid and universal development and improvements. Nevertheless, it has become evident that the traditional layered approach that separates routing, flow control, scheduling, and power control is suboptimal in the realm of wireless and agile networks. This can be attributed to the complex and unpredictable nature of the wireless medium. Thus, the need for adaptation in network protocols remains high. In order to tackle the problems faced in wireless agile networks, a cross layer design [M. Ibnkahla, ed., 2009] is desired to optimize across multiple layers of the protocol stack. The basic idea of cross layering is to make information produced or collected by a protocol available to the whole protocol stack, so as to enable optimization and improve network performance. Until now researchers have proposed several approaches that use cross layering in order to improve and optimize different network mechanisms. In most of the cases, the cross-layer design takes place between the media access control (MAC) and the physical (PHY) layers. However, there is a number of recent examples that illustrate the benefits of having other layers jointly designed, such as network-
data link layer (DLL), or even application-network. For instance, in order to bypass the resource constraints, Shah and Rabaey [R. C. Shah and J. Rabaey, 2002] have proposed an energy-aware routing protocol that uses a set of suboptimal paths occasionally to increase the lifetime of the network. The idea is that paths are chosen by means of a probability and knowledgebase that depends on how low the energy consumption of each path is. The energy consumption is a result of signal strengths, a piece of knowledge that can be found at the MAC layer of the stack. Hence, cross layering helped to access the information and use it to the network layer (routing layer) to make analogous decisions. Another example, this time in link-aware routing was proposed by Lee and Gerla [S. J. Lee and M. Gerla, 2000]. This protocol makes use of channel state information (CSI) [I. Perez-Neira and M. R. Campalans, 2009] and cross-layer integration to route traffic along higher-capacity paths by consistently selecting channels with favorable conditions. This supports the idea that a node with multiple next-hop alternatives can measure the channel state on the links, and then forward a packet based on the link quality and other metrics. Cross-layer has also been a great help in designing cost aware routing approaches. [Suhonen et al, 2006] have proposed a protocol that uses cost metrics to create gradients from a source to a destination node. The cost metrics consist of energy, node load, delay, and link reliability information that provide traffic differentiation by allowing choice among delay, reliability, and energy.
4.13 Steps to Solve a Problem Using ACO

From the currently known ACO applications, we can identify some guidelines of how to study new problems by ACO. These guidelines can be summarized by the following six-design tasks weighted graph that is travelled by the ants to build solutions.

- Appropriately define the meaning of the pheromone trails, i.e., the type of decision they bias. This is a crucial step in the implementation of an ACO algorithm. A good definition of the pheromone trails is not a trivial task and it typically requires insight into the problem being solved.

- Appropriately define the heuristic preference to each decision that an ant has to take while constructing a solution, i.e., define the heuristic information associated to each component or transition. Notice that heuristic information is crucial for good performance if local search algorithms are not available or cannot be applied.

- If possible, implement an efficient local search algorithm for the problem under consideration, because the results of many ACO applications to NP-hard combinatorial optimization problems show that the best performance is achieved when coupling ACO with local optimizers [Dorigo and Di Caro, 1999] [Dorigo and Stützle, 2003].

- Choose a specific ACO algorithm and apply it to the problem being solved, taking the previous aspects into consideration.
Tune the parameters of the ACO algorithm. A good starting point for parameter tuning is to use parameter settings that were found to be good when applying the ACO algorithm to similar problems or to a variety of other problems. An alternative to time-consuming personal involvement in the tuning task is to use automatic procedures for parameter tuning.

**Generic Ant Algorithm**

Step 1: Initialization

- Initialize the pheromone trail

Step 2:Iteration

- For each Ant Repeat
  - Solution construction using the current pheromone trail
  - Evaluate the solutions constructed
  - Update the pheromone trail
- Until stopping criteria

**2.5.2 The Protocol**

This is an extension of cross layer aware protocol develop by author. In this information about channel state, observed link state and hop by hop reasoned and observed information are utilized by network layer protocol in general and routing algorithm in specific. Exactly Signal to interference and noise ratio(SINR), received power(RP), delay observed by reactive ant, pheromone value, knowledge based interpolation are passed on to routing algorithm for decisions for source routing between source and destination. The protocol improves
over another cross layer protocol by employing ANT colonization approach for optimization and knowledge based reasoning for decision support. Apart from decision in proactive routing it can also adapt as per reconfigurability of PHY or flexibility provided by agile radio. The protocol is based on source routing with additional information and decision parameters from PHY and MAC Layer. The protocol has very simple two-fold approach. First fold use to discover the route, which is as.

1. A small packet known as ANT is sent to discover new route.
2. ANT places small amount of data containing PHY and MAC observed information on to every node it traverse. It is just like ANT leaving pheromone in the route.
3. If ANT found destination route without broadcast. It can be thought as optimal route.
Fig 4.3 Flow Chart Bio Inspired Cross Layer Aware Routing

1. Network arrangement in form of graph
2. Identification of all edge in graph with weight in form of SINR and RP
3. Construction of initial route with AODV or similar algorithm
4. Generation of artificial Ant
5. Ant Agents evaluation of best possible solution
6. Terminating condition
   - YES: Update Route table
   - NO: Assign the new route and binary cast ant
8. Update the solution set based on the goodness of the solution and generate a new Route list
9. Stop
4. If ANT stuck at any node it broadcast with threshold 2, which guarantee non-flooding of network and producing sub optimal alternate route.

The protocol is based on source routing with additional information and decision parameters from PHY and MAC Layer. The protocol has very simple two-fold approach. First fold use to discover the route, which is as.

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3. If ANT found destination route without broadcast. It can be thought as optimal route.
4. If ANT stuck at any node it broadcast with threshold 2 which guarantee non flooding of network and producing sub optimal alternate route.

In second step the pheromone placed at each node is used by reasoning engine for short-term prediction on link state and route condition in hop by hop basis. Which is use to adapt optimize various communication.
Figure 4.4 Reachability analysis of Protocol’s Petri Net
parameter based on AgileMAC protocol developed in the present work

4.5.2 Simulation results

Analysis of Petri Net diagram of BC-LAN shows that all the transition of the protocol are alive which represents that the protocol can survive in given circumstances. The analysis also shows weak reversible property of the protocol which indicates that protocol can be used in tandem and audit trails can be done. The protocol is bounded in nature represents that data will travel in secure manner and it is following admissible conditions. Apart from this Time Petri Net Simulation of Protocol faster route decision by the protocol and reachability to every transition in timely fashions.
Figure 4.5 Time Petri Net Simulation of Protocol.
The proposed cross-layer protocol has been implemented in the OMNET++ 4.0 network simulator. The simulations have been carried out for various topologies, scenarios with different kinds of traffic, and routing protocols. The following performance metrics have been used:

(i) Total packets received,
(ii) average throughput (Mbps),
(iii) lifetime LND (seconds),
(iv) FND: first active node died (seconds),
(v) lifetime RCVD (seconds),
(vi) average aggregate delay (seconds),

The average throughput \( \text{Thr} = \frac{\text{Total number Packets received in Simulation Time}}{\text{Simulation Time}} \) and average sending bit rate \( \text{Sbit} = \frac{\text{Total number Packets sent}}{\text{Simulation Time}} \)

Table 4.5 Basic simulation setup For Routing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of active nodes</td>
<td>25, 50 (default)</td>
</tr>
<tr>
<td>Simulations area</td>
<td>( \leq 1000 \times 1000 \text{m} )</td>
</tr>
<tr>
<td>Topology</td>
<td>Random</td>
</tr>
<tr>
<td>PHY/MAC</td>
<td>DSSS, IEEE 802.11b</td>
</tr>
<tr>
<td>SINR thr. (dB)</td>
<td>22.05</td>
</tr>
<tr>
<td>Type of network</td>
<td>homo/hetero-geneous</td>
</tr>
<tr>
<td>Initial energy (J) variable</td>
<td>0.5, . . , 5, 20</td>
</tr>
<tr>
<td>PtMAX – 250m</td>
<td>0.200888W</td>
</tr>
</tbody>
</table>
The first node died metric is defined as the instant in time when the active (a node transmitting/receiving) first node died. We have defined the network lifetime as the time duration from the beginning of the simulation until the instant when the active (a node transmitting/receiving) last node died, that is, there is no live transmitter-receiver pair left in the network. The Lifetime RCVD is specified as the instant in time when the last packet is received.
Table 4.6: Typical values of path loss exponent and shadowing deviation for Routing.

<table>
<thead>
<tr>
<th>Environment</th>
<th>$\rho$ (dB)</th>
<th>$\sigma$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor Free space</td>
<td>2.4</td>
<td>4 to 12</td>
</tr>
<tr>
<td>Outdoor Shadowed Urban</td>
<td>2.7 to 5.6</td>
<td>4 to 12</td>
</tr>
<tr>
<td>Indoor Line-of-sight</td>
<td>1.6 to 1.8</td>
<td>3 to 6</td>
</tr>
<tr>
<td>Indoor Obstructed</td>
<td>4 to 6</td>
<td>6.8</td>
</tr>
</tbody>
</table>

We study the performance of the routing algorithms in different regimes. The performance metrics for the stationary and turtle mobility scenario in various offered load regimes are plotted and discussed as follows.
Consider the fixed mobility scenario in Fig. 4.6. As the offered load increase the average throughput increase, for DSR scheme congestion begins to buildup at packet rate of 40-packets/sec. The throughput falls slightly when packet rate is further increase. Since rate adaptation is used in BCLAN schemes, the network capacity is much higher and congestion is non-observant. The BCLAN offered 45%
more throughput enhancement compared to the DSR scheme. The result for turtle mobility can be observed in Figure 4.7.

![Throughput Vs rate(packet) turtle mobility](image)

**Figure. 4.7 DSR Vs BCLAN turtle mobility**

### 4.5.4 Conclusion

In this author advocate a new design concept in routing protocol based on bio inspired computing with prediction capability of reasoning engine. We argue that by exploiting information from MAC and PHY layer, significant performance enhancement of a routing protocol could be achieved. The proposed protocol BCLAN protocol produces 45% better result than the DSR algorithm. The can be used for broadband services like VoD, VoIP.