CHAPTER 3

ANALYTICAL MODEL OF LINK CONNECTIVITY AND OVERHEAD CONTROL

3.1 GENERAL

The MANET initially was considered standalone, but now due to high demand for mobility, it is linked with the Internet and is named as hybrid MANET. It is generally accepted that the MANET nodes use IP addresses and the internetworking is straightforward. Unlike the fully hierarchical addressing scheme used in the Internet, the MANET has a completely flat addressing model. In fact, the ad hoc routing protocols like OLSR and AODV do not employ the concept of IP subnet and typically routes traffic within itself. In the ad hoc routing protocol, a node in the MANET may use any IP address, provided it is not duplicated. In fact, ad hoc routing protocols use host-based routes rather than network prefixes.

Unlike the traditional Internet, two neighboring nodes in hybrid MANET do not require addresses belonging to the same IP subnet for communicating directly. The issue of defining interfaces between the MANET and the Internet is not straightforward as the two are very different networks. In the hybrid MANET access to Internet consist of at least one gateway node as shown in Figure 3.1.
Figure 3.1 Gateway connections in hybrid MANET

The gateway runs both IP protocol and the ad hoc routing protocol. The traffic flow in the hybrid MANET, in and out from the Internet is channeled through gateway for external communication. If the mobile node wants to send data outside the MANET, it should discover gateway nodes that are reached through single-hop or multi-hop communication. The process by which a mobile node identifies the node acting as the gateway is called gateway discovery process. This is one of the major operations encountered in hybrid MANET.

The MANET contains a single-hop direct connection or multi-hop indirect connection though intermediate mobile nodes to the gateway. The mobile nodes in the hybrid MANET have multiple gateways with multiple paths to the gateway. The important issue in hybrid MANET is the gateway selection criteria. As Figure 3.2 shows there are multiple gateways rather than one gateway as encountered previously in Figure 3.1. The problem is not only to discover but also to choose a gateway, based on some criterion.
In the MANET, radio links are active as long as mobile nodes stay close to one another. This condition varies with movement of mobile nodes affecting the lifetime of the links. An ideal condition in the MANET is that radio links should be held for a long time to prevent communication from being interrupted by link failure. A route in the MANET includes a sequence of links and a stable route is one that endures for a longer period of time. In the MANET a route is formed with multiple wireless links from intermediate mobile nodes. If any one of these link breaks, the whole route is useless and has to recover the broken link or has to find new route. If, only one link in the sequence fails the route no longer works. The route stability is heavily affected by link instability. Whenever a route fails, consequent route maintenance is triggered and the network throughput decreases. To reduce the overhead of route maintenance, connections are made with stable routes or long-lived routes.

The main goal of this thesis is to provide a routing scheme in hybrid MANET with ACO strategy to discover gateway with stable routes. The proposed new routing algorithm is capable of finding paths within the MANET to the gateway. A probabilistic model of ACO strategy is used to determine the stable path to the gateway. The stable path to gateway is very useful to increase the throughput, and reduce the delay and overhead in hybrid
MANET. The analytical model described here gives maximum data transfer with minimum overhead. The analytical model derives the probability equations for varying conditions of speed and transmission distance.

### 3.2 CONCEPTS IN ANALYTICAL MODELING

The following are the terminology used in analytical modeling:

Mobile Node: A mobile node is a basic element in the MANET. Mobile nodes can be any mobile devices, such as Laptops, PDA and cell phones.

Source Mobile Node: A source mobile node in the MANET is one which sends messages by means of IP packets.

Destination Node: Destination nodes are the target of the source to send messages. The destination nodes within the MANET form the internal communication. The destination nodes called the correspondent nodes within the Internet form the external communication.

Intermediate Node: Intermediate node link paths within the MANET or the gateway at the edge of the MANET. The intermediate node relay messages from source node to destination node.

Direct Node-to-Node Link: Direct node-to-node link is the direct wireless access between two nodes without the intermediate nodes. For example, IEEE 802.11 proposes the wireless access of 250 meters.

Route: A route is a combination of several direct node-to-node links from the source node to the destination node.
Route Length: The route length is the number of direct node-to-node links in the route.

All nodes are mobile and so the topology of the MANET changes often. Thus routes between the source node and the destination node are subject to frequent changes. Once a route is broken, routing mechanism is activated to search a new route. All data from the source node to the destination node have to wait until a new route is built. The time taken from the birth of a route to its death is called as Life Span which is an important factor. The life span of a route depends on various parameters, such as speed of mobile nodes, route length, direct node-to-node wireless accessible range and the mobility pattern.

3.3 LINK CONNECTIVITY MODEL

The performance of hybrid MANET is highly sensitive to changes in node-to-node connections. Link stability in the hybrid MANET gives a stable path to the gateway but is very difficult to analyze mathematically. This section explains a mathematical tractable model for the hybrid MANET in which the mobile nodes are in motion with constant velocity and derives a precise relation between mobility and connection stability. The connection stability of the multi-hop communication in the hybrid MANET with some underlying properties is proposed to give link duration as an excellent mobility metric to give maximum probability of successful data transfer.

3.3.1 Fundamental Consideration in Link Connectivity

A framework for analyzing the dynamics of communication links in a hybrid multi-hop MANET is given by an analytical expression. This represents the probability of successful transmission to characterize link
behavior. The probability of successful transmission is used in estimating a stable path to gateway in dynamic hybrid MANET. The following are few assumptions with arguments:

1. A mobile node in the hybrid MANET has a bidirectional communication link with other nodes that are within a distance of $R$ meters. The link breaks, if the distance between the nodes becomes greater than $R$.

2. A mobile node in the hybrid MANET moves with a constant velocity which is uniformly distributed between $a$ meters / second and $b$ meters / second.

3. The direction of mobile nodes with a constant velocity is uniformly distributed between $0$ and $2\pi$.

4. The speed, direction of motion and location of mobile nodes are mutually independent.

5. The initial location of mobile nodes in the network are modeled by a two-dimensional Poisson Process with intensity ($\sigma$), in a network region (D) with an area (A), with a probability D containing k nodes is given by equation (3.1).

$$\text{Prob} ( \text{k nodes in D} ) = \frac{(\sigma A)^k e^{-\sigma A}}{k!} \quad (3.1)$$

Using the equation (3.1), it is easy to see that the expected number of nodes in (D) is equal to $\sigma A$. Thus, $\sigma$ represents the average density of nodes in the network.
The first assumption given above implies that the Signal to Interference Ratio (SIR) remains higher, up to a certain distance \( R \) from the transmitter, enabling a nearly perfect estimation of the transmitted signal. However, SIR drops beyond this distance, rapidly increasing the Bit Error Rate (BER) to unacceptable levels. Such rapid deterioration of performance is typical of channels encoded with powerful error control codes. Though the shadowing and multipath fading experienced by the received signal may asymmetrically take the actual transmission zone, a fair approximation of all the nodes in the network utilizes the same transmission power.

The second assumption gives a model of a mobile environment where nodes are moving around with different velocities that are uniformly distributed between two limits. This high mobility model is chosen as it is challenging for network communication and, thus, can facilitate finding out worst-case bounds on the link properties for general scenario. It is noted that the degree of mobility in a given application is taken into account by appropriately choosing the two parameters, \( a \) m/s and \( b \) m/s.

The second to fifth assumptions characterize the aggregate behavior of nodes in a large hybrid MANET. Due to the large number of independent mobile nodes operating in an ad hoc fashion, correlation between mobile nodes is assumed to be insignificant. Although some mobile nodes share similar objectives and move together, a large population of autonomous nodes is also available in the network for the composite effect modeled by a random process.

The fifth assumption indicates the distribution of nodes in the network at the start. As a consequence, at any later point of time, Bartlett’s Theorem is followed to give the velocities of nodes which are mutually independent. Poisson process model is random, and reflects the randomness
of the aggregate behavior of nodes. This assumption is frequently used in the model of the distribution of nodes in the hybrid MANET.

In the large scale hybrid MANET many mobile nodes operate without any fixed infrastructure and are recently dampened with their reduced capacity as the density of nodes per unit area \( (\lambda) \) becomes large. The Interferences and contention for medium access are the cause of this fundamental limitation. The transmission range of the hybrid MANET is limited by power constraints, frequency reuse and channel effects. The store-and forward packet routing is required over multi-hop wireless paths in the hybrid MANET. The communication end-points are mobile nodes in the hybrid MANET moving freely and independently giving challenges in routing. The connectivity of the mobile nodes is not a problem, if \( (\lambda \rightarrow \infty) \) and the distance is function of \( \lambda \) \( (r(\lambda)) \), where nodes connects and decreases at a rate slower than \( \sqrt{\log \lambda / \lambda} \).

The gateway nodes form one end of the interface and IP network forms other end of the interface in the hybrid MANET and overcomes this limitation. This hybrid MANET model might prevail practically within a few years for wireless access in most highly populated areas such as city centers, airports and railway stations.

### 3.3.2 Mobility distribution in Link Connectivity

In the hybrid MANET a random mobility model is formed where a continuous-time stochastic process is characterized by the movement of mobile nodes in a two-dimensional space. In the random mobility model each mobile node movement consists of a sequence of random length intervals called mobility epochs during which a mobile node moves in a constant
direction at a constant speed. The speed $V^i_n$ and direction $\theta^i_n$ of each node varies randomly from epoch to epoch. So during epoch $i$ of duration $T^i_n$ node $n$ move a distance of $V^i_n T^i_n$ in a straight line at an angle of $\theta^i_n$. The number of epochs during an interval of length $t$ is the discrete random process $N(t)$.

The mobility profile of a given node $n$ moves according to a random mobility model which is specified based on three parameters: $\lambda_n$, $\mu_n$ and $\sigma^2_n$. The following list defines these parameters for node $n$, and describes the assumptions made in developing this model:

- The epoch lengths, $T^i_n$, are exponentially distributed with mean $1/\lambda_n$.
- The speed, $V^i_n$, during each epoch is a distributed random variable with mean $\mu_n$ and variance $\sigma^2_n$, and remains constant only for the duration of the epoch.
- The direction, $\theta^i_n$, of the mobile during each epoch is uniformly distributed ($0, 2\pi$), and remains constant only for the duration of the epoch.
- Speed, direction and epoch length are uncorrelated.
- Node mobility is uncorrelated and link failures are independent.

These assumptions reflect a network environment with a large number of autonomous mobile nodes, resulting in aggregate node movement which is modeled as the random mobility. The correlation of movement among the mobile nodes is assumed to be small in the model, where each
node moves as an independent process. In order to characterize the availability of a link between two nodes over a constant velocity, the distribution of the mobility of one node with respect to the other must be determined. To characterize this distribution, it is first necessary to derive the mobility distribution of a single node in isolation. The single node distribution is extended to derive the joint mobility distribution which accounts for the mobility of one node with respect to the other. Using this joint mobility distribution, the link availability distribution is derived. The link availability metric is known for each link along a path between two mobile nodes. Assuming that links fail independently, the path availability is easily determined as the product of the individual link availability metrics.

The mobile nodes in the hybrid MANET are randomly placed on an infinitely large boundless plane with a finite node density ($\rho$). The mobile nodes move linearly at a constant velocity in random directions but do not change their directions while moving as shown in Figure 3.3(a). The model is used to derive the expected rate of change of node-to-node connections and the expected lifespan of such connections.

![Figure 3.3(a) Mobility of all nodes](image1)  
![Figure 3.3(b) Mobility of Node $N_0$](image2)

Figure 3.3(a) Mobility of all nodes  
Figure 3.3(b) Mobility of Node $N_0$
3.3.3 Link Change Rate Analysis

The primary difficulty in the hybrid MANET is created by mobility of the mobile nodes in the path to the gateway. The motion of mobile nodes relative to one another forces the network topology or node interconnections to change abruptly. This gives rise to a factor known as link change rate. The data packet delivery ratio achieved by the hybrid MANET routing protocol decreases as the link changes. The link change rate is first analyzed in a nearly static node arrangement where only one node is moving as in Figure 3.3(b).

Suppose n nodes are randomly placed with a mobile node density ($\rho$). Only one node $N_0$ is moving linearly with a constant velocity $\overline{v}_0$; all other nodes are assumed to be stationary. $N_0$ has a transmission range ($r = R$), when the distance from the mobile node $N_0$ to a static node $N_i$ becomes shorter than $r$, the connection link is generated between $N_0$ and $N_i$. If the distance becomes longer than $r$ the link breaks. The frequency of such link generations/breaks per unit time is called the link generation/break rate. The link change rate (LCR) also called topology change rate is the sum of link generation rate and link break rate. In steady state the link generation and break rates should be equal. As the mobile node is traveling on a plane, its circular communication region sweeps the plane with a rate $2r\overline{v}_0$, and the average number of newly generated links per unit time is $2\rho r\overline{v}_0$. Hence the link generation rate is proportional to the mobile node speed.

Returning to the general model of Figure 3.3(a) it is assumed that all nodes are moving at the same constant speed $v$ but in random directions. The link generation rate $2\rho r\overline{v}_0$ does not hold anymore because the relative speed between nodes is no longer a constant $v_0$. The relative velocity of
mobile nodes has to be found out for this case. Suppose the mobile node $N_i$ is passing through the transmission range of $N_0$ as in Figure 3.4.

![Figure 3.4](image)

**Figure 3.4** Motion of a node $N_i$ passing through the transmission region of node $N_0$

Let $\vec{v}_i$ denote the velocity of node $N_i$, where for all $i$, $|\vec{v}_i|=v$. The velocity can be expressed as $\vec{v}_i = v(i\cos \theta + j\sin \theta)$ where $\theta$ denotes the movement direction of node $N_i$, a random variable uniformly distributed between 0 and $\pi$. The mobile node $N_0$ is moving in the positive direction of the X-axis, i.e., $\theta_0 = 0$. The relative velocity of $N_i$ with respect to $N_0$ is $\vec{v}_{ij} = \vec{v}_i - \vec{v}_0$, and its magnitude is $v_{ij} = \sqrt{2-2\cos \theta} = 2\sin \frac{\theta}{2}$. Thus the average link generation rate is given by equation (3.2) and the average LCR is given by equation (3.3)

$$\lambda_{gen} = \int_0^\pi 2\rho v_{ij} d\theta = \frac{8}{\pi} \rho rv$$  \hspace{1cm} (3.2)

$$\lambda_{LCR} = 2\lambda_{gen} = \frac{16}{\pi} \rho rv$$  \hspace{1cm} (3.3)

The node density is fixed at $\rho = 0.02 m^{-2}$. It is assumed in a steady state $\lambda_{LCR} = \lambda_{gen} + \lambda_{brk}$. The Table 3.1 gives the Link change rate and Link
Duration rate for average speed of 5 m/s, 20 m/s with transmission distances ranging from 10 meters to 250 meters. The Table 3.2 give the Link change rate and Link Duration for average transmission of 10 m, 250 m with speed ranging from 5 m/s to 20 m/s.

### Table 3.1 Analytical values of LCR and LD with transmission range

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<th>LD</th>
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Table 3.2 Analytical values of LCR and LD with speed

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3.3.4 Link duration and Mean Residual Duration Analysis

The link duration (LD) is one which measures the lifespan of a node-to-node link from the time a receiver enters the communication region of the transmitter to the time the receiver exits the communication region. In other words, the LD is the time from link generation to link break, and can be interpreted as a measure of the stability of single-hop connections. The success ratio of single-hop communication in the MANET is insensitive to
mobility when a packet length is not too long. The successful data delivery over multi-hop routes critically depends on the connection instability due to node movement. Data delivery over multi-hop routes takes much longer, and hence the probability that the connection changes during the data delivery is not negligible.

The mean residual duration (RD) of a multi-hop route is the mean time from the route discovery to the breaking of the route. The RD of k-hop routes is given by k-RD, i.e., a multi-hop route is regarded as broken when any of its constituent single-hop links is broken. RD is the key factor which determines the success of packet delivery over multi-hop routes. Hence RD can be interpreted as an indicator of the stability of multi-hop routes whereas link duration (LD) indicates the stability of single-hop links.

To determine LD, suppose the nodes are randomly distributed on a plane and moving in random directions towards the gateway. A node N₀ observes Nᵢ passing through the circular transmission region of N₀ as in Figure 3.4, given as before, \( v_{i0} = 2v \sin \frac{\theta}{2} \). The event that Nᵢ passes through the transmission region of N₀ with two parameters \((X, \theta)\) is given by equation (3.4)

\[
T_{LD}(x, \theta) = \frac{Y(x)}{v_{i0}(\theta)} \tag{3.4}
\]

where \( Y(x) = 2r^2 - x^2 \). The derivation of the equation (3.2) implies that the arrival rate of mobile nodes Nᵢ is proportional to their relative speed with respect to N₀. Hence the relative frequency of the event \((X, \theta)\) is proportional to \( v_{i0} \). So the joint probability density function \( f_{X, \theta}(x, \theta) \) of \((X, \theta)\) is
proportional to \( v_{\psi_0}(\theta) \), and is given by equation (3.5) and the mean LD value \( \overline{T_{LD}} \) is given by equation (3.6).

\[
f_{x,\theta}(x, \theta) = v_{\psi_0}(\theta) / \int_0^{\pi} 2\sin\frac{\theta}{2} dx d\theta = \frac{1}{2r} \sin\frac{\theta}{2}.
\]  

\[
\overline{T_{LD}} = \int_0^{\pi} T_{LD}(x, \theta) f_{x,\theta}(x, \theta) dx d\theta = \frac{\pi^2}{8} \left( \frac{r}{v} \right)
\]  

It should be noted that LD is not the reciprocal of LCR and LCR is the reciprocal of the time between two successive link changes of link generation and link break.

To determine RD in a hybrid MANET with k-hop routes consisting of k+1 mobile nodes \( \{N_i\} \), where \( 0 \leq i \leq k \), and each node pair \( (N_{j-1}, N_j), 1 \leq j \leq k \), is connected by a link \( L_j \). At time \( t = 0 \), the route is connected, and at time \( t = T_1 \), the route breaks. Let \( G_k(t) \) denote cumulative density function and \( g_k(t) \) denote the probability density function respectively of random variable \( T_1 > 0 \). Then the probability of the route remains connected until time \( t \) is \( 1 - G_k(t) \), and k-RD for this route is given by equation (3.7)

\[
\overline{T_{RD,k}} = \int_0^{\pi} t \cdot g_k(t) dt
\]  

The generation/break processes of k links that constitute the k-hop route are mutually dependent. This assumption is not strictly true, but it has been shown that the link generation/break processes of links that are far apart are nearly independent, and even the link durations of neighboring links which share a common node have a negligible correlation (Han et al 2004).
Thus the probability that the k-hop route remains connected until time $t$ is given by equation (3.8)

$$I - G_k(t) = (I - F(t))^k$$

(3.8)

In establishing a relation between LD and LCR, equations (3.3) and (3.6) are related to give the equation (3.9), which implies that the product of half of LCR and LD equals the average node degree.

$$\frac{1}{2} \lambda_{LCR} \bar{T}_{LD} = \rho \pi r^2$$

(3.9)

This relation follows from Little’s theorem (Bertsekas et al 1992), which states that the average number of customers in a system, $\rho \pi r^2$, is equal to the product of the customer arrival rate, $\lambda_{gen} = \lambda_{LCR} / 2$ and the average time customers spend in the system, $\bar{T}_{LD}$.

When the moving time of mobile node i.e. more pause time in the hybrid MANET is short, the 1-RD value is longer than in other cases. The exceptional behavior results from the fact that short moving time cause node motion to appear memoryless. When linear movement is dominant, the nodes that have already spent much time in the transmission region of another node tend to exit the region earlier than ones just entering the region. However, in this memoryless movement case, the time a node has already spent in the transmission region of another node has a very weak correlation with the time it will spend in the transmission region later. Hence the residual duration (RD) of single-hop links, that is, 1-RD tends to be close to the total link duration.
Apart from the memoryless property, $\bar{T}_{RD,1} > \bar{T}_{LD}/2$, this results from the randomness of link duration. Suppose a node $N_0$ has two types of neighbors $\{N_A\}$ and $\{N_B\}$. The neighbors have an identical arrival rate $\lambda$ and different link durations $T_A$ and $T_B$, respectively. LD is measured considering all neighbor arrivals to $N_0$, given in equation (3.10)

$$\bar{T}_{LD} = \frac{T_A + T_B}{2}$$

(3.10)

The arithmetic mean of $T_A$ and $T_B$ is equally weighted. On the other hand, if $N_0$ randomly picks one of its existing neighbors and observes the neighbors duration, the average duration is given in equation (3.11)

$$\bar{T}'_{LD} = \frac{\lambda T_A^2 + \lambda T_B^2}{\lambda T_A + \lambda T_B} = \frac{T_A^2 + T_B^2}{T_A + T_B}$$

(3.11)

The arithmetic mean of $T_A$ and $T_B$ is weighted by the expected number of neighbors of each type, i.e., $\lambda T_A$ and $\lambda T_B$, respectively. It can be seen that if $T_A \neq T_B$, then the sampled average $\bar{T}'_{LD}$ is always greater than the actual average $\bar{T}_{LD}$. The RD of a single-hop link is half of $\bar{T}_{LD}$ and exceeds $\bar{T}_{LD}/2$.

### 3.3.5 Probability of Successful Transmission

The probability of successful transmission, $p_{\text{comp}}$, measures successful delivery ratio in single-hop communication and multi-hop communication. Using $p_{\text{comp}}$ the appropriate packet length for the given mobility conditions are determined. Suppose a receiver $N_i$ enters the communication region of a transmitter $N_0$ at time $t = 0$ and exists in the region
at time \( t = T_{LD} \). For a packet with transmission time \( T_{comm} \) to complete communication before the node \( N_i \) moves out of range, the transmission should start at time \( t \), \( 0 \leq t \leq T_{LD}(x, \theta) - T_{comm} \). Hence for given \( X \) and \( \theta \), the conditional probability of successful transmission is given by equation (3.12)

\[
P_{\text{comp}}(T_{comm} | x, \theta) = \max \left[ T_{LD}(x, \theta) - T_{comm}, 0 \right] / T_{LD}(x, \theta)
\]  

(3.12)

and the total probability of complete transmission is given by equation (3.13)

\[
P_{\text{comp}}(T_{comm}) = \int_{0}^{\pi} \int_{0}^{r} p_{\text{comp}}(T_{comm} | x, \theta) g_{X, \theta}(x, \theta) dx \theta
\]

(3.13)

where \( g_{X, \theta}(x, \theta) \) denotes the joint probability density function of random variables \( X \) and \( \theta \). From Littles theorem (Bertsekas et al 1992) stating that the average number of customers in a system is equal to the product of the customers arrival rate to the system and the average time customers spend in the system. Hence the joint probability density function \( g_{X, \theta}(x, \theta) \) is proportional to \( v_{\theta}(\theta) \cdot T_{LD}(x, \theta) = Y(x) \), and is given by equation (3.14)

\[
g_{X, \theta}(x, \theta) = \frac{Y}{\int_{0}^{\pi} \int_{0}^{r} Y dx \theta}
\]

(3.14)

The normalized communication time \( \tau \) is given by equation (3.15)

\[
\tau \Delta T_{comm} \cdot \frac{v}{r} = \frac{8}{\pi^2} \cdot \frac{T_{comm}}{T_{LD}}
\]

(3.15)
and calculated Probability for successful transmission is given by equation (3.16)

\[
P_{\text{comp}}(\tau) = \int_{0}^{\frac{\pi}{2}} \int_{0}^{B(\tau, \theta)} p_{\text{comp}}(\tau | x, \theta) g_{x, \theta}(x, \theta) dx d\theta
\]  

(3.16)

The normalized communication time \(\tau\) is the ratio between node mobility and communication speed. First, consider the case \(\tau < 1\). The function \(B(\tau, \theta)\) is defined as \(B(\tau, \theta) = \frac{\sqrt{2 - \tau^2 + \tau^2 \cos \theta}}{\sqrt{2}}\). It can be seen that for all \(x < 1, T_{LD}(x, \theta) > \tau\) if and only if \(0 < x < B(\tau, \theta)\). Using this fact we can eliminate the max operator in (3.12), and change the range of the inner integral of \(p_{\text{comp}}(\tau)\) from \((0,1)\) into \((0,B(\tau, \theta))\). The equation (3.12) is written as in equation (3.17)

\[
P_{\text{comp}}(\tau) = \int_{0}^{\frac{\pi}{2}} \int_{0}^{B(\tau, \theta)} p_{\text{comp}}(\tau | x, \theta) g_{x, \theta}(x, \theta) dx d\theta
\]  

(3.17)

where \(p_{\text{comp}}(\tau | x, \theta)\) is defined as \(\frac{T_{LD}(x, \theta) - \tau}{T_{LD}(x, \theta)}\). Replace \(x\) and \(\theta\) with \(\alpha = \sin^{-1} x\) and \(\beta = \theta / 2\), respectively. Then \(p_{\text{comp}}\) is given by equations (3.18) and (3.19)

\[
P_{\text{comp}}(\tau < 1) = \frac{8}{\pi^2} \int_{\beta=0}^{\frac{\pi}{2}} \int_{\alpha=0}^{\cos^{-1}(\tau \sin \beta)} (\cos \alpha - \tau \sin \beta \cos \alpha) d\alpha d\beta
\]  

(3.18)
In the other case \( \tau > 1 \), swap the order of integration of \( x \) and \( \theta \), and eliminate the max operator by changing the integration range of \( \theta \) in a similar way.

\[
p_{\text{comp}}(\tau > 1) = \frac{8}{\pi^2} \int_0^1 c^2 \sin^{-1}\left(\frac{c}{\tau}\right) - \tau c \left(1 - \sqrt{1 - c^2 / \tau^2}\right) \frac{dc}{\sqrt{1 - c^2}}
\]

(3.19)

Suppose at time \( t = 0 \), a mobile node \( N_0 \) observes a neighbor node \( N_1 \) within its transmission range and at time \( t = T_0 \), the neighbor leaves the range. This exit time \( T_0 > 0 \) is a random variable, and its cumulative distribution function \( F(t) \) and probability density function \( f(t) \). Then the probability of transmission in changing link conditions with time is related by equation (3.20)

\[
p(T_0 \leq t) = F(t) = \int_0^t f(u) \, du
\]

(3.20)

The probability of successful transmission \( p_{\text{comp}}(T_{\text{comm}}, v / r) \) is related to \( p(T_0 > T_{\text{comm}}) \) with the probability that a link remains connected until time \( t \) given by equation (3.21)

\[
p_{\text{comp}}(t, v / r) = 1 - F(t)
\]

(3.21)

Relating equations (3.7), (3.8) with (3.21) to give an average RD in equation (3.22) and substituting equation (3.6) to give another relation to average RD in equation (3.23)

\[
\overline{T_{\text{RD}, k}} = \int_0^\infty t \left[ \frac{d}{dt} \left(1 - p_{\text{comp}}(t, v / r)^k\right)\right] \, dt
\]

(3.22)
From the equations (3.22) and (3.23) it can be seen that RD is a function of LD rather than LCR, which makes LD a good indicator of multi-hop connection stability.

3.4 ANALYTICAL OVERHEAD IN GATEWAY DISCOVERY

The mobile nodes in hybrid MANET are uniformly distributed in a rectangular lattice covering a certain area. Each vertex of the lattice is a possible location for a mobile node, but only one mobile node can be at a concrete vertex. The gateways are located in the corners of the lattice. An example of such a rectangular lattice is shown in Figure 3.5. The area covered by the rectangular lattice is assumed for simulation.

![Rectangular lattice structure of hybrid MANET](image)

**Figure 3.5 Rectangular lattice structure of hybrid MANET**

Given a mobile node m in the lattice, there are 4l nodes at a link distance of ‘l’ links from m. These mobile nodes are placed in a lth concentric ring centered on the node m. The total number of mobile nodes including m at a link distance of l links is given in equation (3.24)
\[ N(l) = 1 + \sum_{j=1}^{k} 4j = 1 + 2l(l+1) \] (3.24)

The relation between \( l \) and \( N \) is obtained, in which \([x]\) is the standard ceiling operation meaning completion to the next integer. This is used in the equation (3.24) for obtaining \( l \) because the last concentric ring might not be complete. In the proposed protocol the mobile agent broadcast messages are used to discover routes to gateway with initial pheromone decay time equal to \( x \). The value of \( N(x) \) gives the number of mobile nodes forwarding the agent broadcast message, if \( x \leq (\sqrt{2N-1}-1)/2 \) and \( N \) otherwise is given by the equation (3.25)

\[ l = \left\lceil (\sqrt{2N-1}-1)/2 \right\rceil \] (3.25)

When a mobile node in the MANET desires to access the Internet, it has to discover gateways on the border of the MANET and part of the Internet first. There are two basic approaches for gateway discovery namely reactive and proactive. The proposed protocol uses reactive gateway discovery in which the mobile nodes discover a route to gateway on demand using mobile agent broadcast messages. Since mobile nodes move freely and network topology changes dynamically in the MANET, gateway access also changes. The gateway discovery schemes in the MANET generate less overhead to give efficient packet transmission with high network connectivity for getting Internet services.

Whenever a mobile node in the MANET wants to reactively discover a gateway for reaching Internet services, an overhead is associated in using the mobile agent broadcast messages. The overhead is the sum of the forward mobile agent broadcast messages using Multicast address of all
gateways plus the number of backward mobile agent unicast messages from every gateway to the mobile node. The assumption is that the gateways are in the borders of the lattice and the mean path length is $\sqrt{N-1}$. The number of gateways is represented by $N_{GW}$, the overhead of reactive discovery of gateways by one mobile node is computed and is given in equation (3.26)

$$\Omega_{r-gw} = N + N_{GW} + N_{GW} \left( \sqrt{N-1} \right)$$

(3.26)

The equation (3.26) is expanded and simplified as equation (3.27)

$$\Omega_{r-gw} = N + N_{GW} \left( \sqrt{N} \right)$$

(3.27)

An ad hoc mobile node tries to find the route to destination within the local MANET using broadcast route request and reply messages can be calculated using equation (3.28). Six neighbors are assumed for a mobile node in the MANET.

$$\Omega_{LN} = \sum_{j=1}^{6} N(j)$$

(3.28)

Let S be the number of active sources in the MANET for communication with gateway. Let $\lambda_{adh}$ be the rate at which mobile agent messages are being sent out by the mobile nodes and t be the duration of the fixed interval under consideration. The overhead of delivering each of this mobile agent messages to the whole the MANET is $N+1$ messages. One forwarded by each of the N nodes plus the message sent out by the gateway to the source mobile node. In addition all the sources in the MANET initially made active should realize that the destination node could be in the Internet.
Let $l_{dur}$ be the link duration in our proposed protocol and it obeys an exponential random distribution with parameter $\lambda_{dur}$. Let $N_{\text{break}}$ be a random variable representing the number of route expirations during an interval of $t$ units of time. Then $N_{\text{break}}$ follows a poisson distribution with an arrival rate equal to $\lambda_{dur}$, the probability of $N_{\text{break}}$ is given in equation (3.29)

$$P[N_{\text{break}} = l] = \frac{e^{-\lambda_{dur}} \lambda_{dur}^l}{l!}$$  \hspace{1cm} (3.29)

The mean number of default route expirations per source will be given by equation (3.30)

$$E[N_{\text{break}}] = \lambda_{dur} t$$  \hspace{1cm} (3.30)

An expression for the number of mobile nodes which are at the length of $S$ links from any gateway with $s \in [0, \sqrt{N} - 1]$ is given in equation (3.31)

$$N^{GW}(s) = \sum_{j=1}^{l} (j+1) = \frac{s(s+3)}{2}$$  \hspace{1cm} (3.31)

From the given mobile node $m$ in the MANET, the probability that the mobile node will be able to get reverse mobile agent broadcast messages from any of the gateways can be computed from the equation (3.32)

$$P_c(s) = \frac{\sum_{i=1}^{N_{\text{gw}}} N^{GW}(s)}{N - N^{GW}}$$  \hspace{1cm} (3.32)
Let \( N_e \) be the number of sources being covered by any gateway when using a scope of \( S \) links. Then \( N_e \) is a random variable obeying a binomial distribution \( B \sim \left( S, P_e(s) \right) \). The mean number of sources being covered when gateways are at the length of \( S \) links can be computed as given in equation (3.33)

\[
E[N_e] = S \cdot P_e(s) \tag{3.33}
\]

The total overhead for the reactive route discovery in the proposed protocol consists of the two overheads. The first overhead is local discovery overhead given in equation (3.28). The second overhead is route discovery to the gateway using mobile agent broadcast messages given in equation (3.27). The total overhead can be computed according to equation (3.34)

\[
\Omega_r = \left[ S \Omega_{LN} + \left( \Omega_{r-gw} \cdot \lambda_{durr} \cdot t \cdot S \right) \cdot \left( 1 - P_e(s) \right) \right] \tag{3.34}
\]

From this analytical consideration the maximum number of nodes in the simulation is \( N = 50 \), \( N_{GW} = 2 \), \( \lambda_{durr} = 0.02 \), \( t = 18 \) ms, \( S = 8 \) and using equation (3.34) the total overhead is only 16 % and 84 % of data packet transfer.

### 3.5 ANALYSIS AND COMPARISON OF SIMULATION VALUES

The analysis of the analytical evaluation is done by making a simulation on the hybrid MANET the scenario in NS-2 simulator. The analytical evaluations are done by formulating the equations and obtaining values for Link duration and Link change rate. The simulation scenario set
with 100 mobile nodes, served with four gateways each having 25 mobile nodes. The gateways are connected to a router and the routers are connected to each other. Additionally, each router has a correspondent node connected to it. Mobile nodes move using a random waypoint model with changing pause times. Mobile nodes have pause times in seconds varying from 0, 30, 60, 120, 300, 600 and 900 seconds. They pick a random destination inside the simulation area and start moving to the destination at a speed uniformly distributed between 0 and 20 m/s (mean speed = 10 m/s). On reaching the destination this behavior is repeated until the end of the simulation. For each of the pause times 10 different scenarios were simulated. The results were obtained as the mean values over these 10 runs to guarantee a fair comparison among the alternatives.

The analysis gives satisfactory coincidence with simulation values. The analysis gives that Link duration increases as the transmission range varies with fixed speed. The link duration decreases as the speed varies with fixed transmission range. The link change rate increases as the speed varies with fixed transmission range. The link change rate also increases as the transmission range varies with fixed speed. The analytical values of predicting the link with high probability of successful transmission is given with packet transmission time $T_{\text{comm}}$ and normalized communication time ($\tau$). The analysis values are one which predicts the maximum time the link exists. This values can be used part of link availability probability of the next hop pheromone probability in selecting a stable path to gateway.

The analytical values of Link Duration in hybrid MANET are with transmission ranges of 10 meters to 250 meters. The speeds of mobile nodes are given as 5 m/s and 20 m/s. The plots in Figures 3.6(a) and 3.6(b) show the variations. The Link Duration increases linearly with distance. The Link Duration varies with varying speed.
The analytical values of Link Duration in hybrid MANET are speed of 5 m/s to 20 m/s. The transmission range of mobile nodes is given as 10 m and 250 m. The plots in Figure 3.7(a) and Figure 3.7 (b) show the variations.
The Link Duration decreases with speed. The Link Duration varies with varying transmission range.

Figure 3.7(a) Link duration of distance (10 m) varying with speed

Figure 3.7(b) Link duration of distance (250 m) varying with speed

The analytical values of Link change rate in hybrid MANET are with speed from 5 m/s to 20 m/s. The transmission range of mobile nodes is
given as 10 m and 250 m. The plots in Figure 3.8(a) and Figure 3.8(b) show the variations. The Link Duration increases linearly with speed. The Link Duration varies with varying transmission range.

Figure 3.8(a) Link change rate of distance (10 m) varying with speed

Figure 3.8(b) Link change rate of distance (250 m) varying with speed
The analytical values of Link Change Rate in hybrid MANET are with transmission ranges of 0 meters to 250 meters. The speeds of mobile nodes are given as 5 m/s and 20 m/s. The plots in Figure 3.9(a) and Figure 3.9(b) show the variations. The Link Change rate increases linearly with transmission range. The Link Change rate varies with varying speed.

Figure 3.9(a) Link change rate of speed (5 m/s) with varying distance

Figure 3.9 (b) Link Change rate of Speed (20 m/s) with varying distance
The analytical values of the probability of successful transmission with different link life time values based on the equations (3.18) and (3.19) are computed. The Simulation scenario in NS-2 set to get the simulated values of the probability of successful transmission by varying the network parameters such as the transmission range \( r \), the node speed \( v \). The communication time termed as packet transmission time (ms) obtained both in the analytical and simulated cases are compared. The packet transmission time \( T_{\text{comm}} \) is varying between 0 to 4.5. Table 3.3 gives the analytical and simulation values of transmission time with the probability of packet transmission. Figure 3.10 shows the probability of packet transmission with packet transmission time for analytical and simulated cases. The analytical values coincide with the simulation values with conditions of link duration and link change rate set in the simulation scenario.

**Table 3.3  Probability of packet transmission with communication time \( T_{\text{comm}} \)**

<table>
<thead>
<tr>
<th>Probability of packet transmission</th>
<th>Packet transmission time (ms) ( T_{\text{comm}} )</th>
<th>Analytical Value</th>
<th>Simulation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.05</td>
<td>0.15</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>0.163</td>
<td>0.48</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>0.189</td>
<td>0.98</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>0.206</td>
<td>1.60</td>
<td>1.51</td>
<td></td>
</tr>
<tr>
<td>0.226</td>
<td>2.08</td>
<td>2.03</td>
<td></td>
</tr>
<tr>
<td>0.235</td>
<td>2.45</td>
<td>2.52</td>
<td></td>
</tr>
<tr>
<td>0.318</td>
<td>3.1</td>
<td>3.01</td>
<td></td>
</tr>
<tr>
<td>0.402</td>
<td>3.52</td>
<td>3.52</td>
<td></td>
</tr>
<tr>
<td>0.702</td>
<td>4.05</td>
<td>4.02</td>
<td></td>
</tr>
<tr>
<td>0.862</td>
<td>4.40</td>
<td>4.50</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4.80</td>
<td>4.75</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.10 Probability of packet transmission with communication time

The analytical values of the probability of successful transmission with normalized communication time ($\tau$) of varying links based on the equations (3.18) and (3.19) are computed. The normalized communication time ($\tau$) with probability of successful transmission obtained by simulation with analytical values is shown in Table 3.4.

Table 3.4 Probability of successful transmission with link duration

<table>
<thead>
<tr>
<th>Probability of Successful transmission</th>
<th>Normalized Communication Time ($\tau$) i.e. Pheromone value</th>
<th>Analytical Value</th>
<th>Simulation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.87</td>
<td>1.50</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>0.56</td>
<td>6.75</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td>10.2</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>14.0</td>
<td>13.8</td>
<td></td>
</tr>
<tr>
<td>0.33</td>
<td>17.8</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>0.29</td>
<td>22.28</td>
<td>32.1</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>28.75</td>
<td>29.1</td>
<td></td>
</tr>
</tbody>
</table>
The analytical values of normalized time ($\tau$) give the maximum duration of the link in varying hybrid MANET situation. The simulated values coincide with the analytical values with different probability of successful transmission. This analysis used in selecting a stable path to the gateway in highly varying mobile situations. Figure 3.11 show the normalized communication time ($\tau$) increases with decreasing the probability of successful transmission. The maximum value of communication time coincides with the link duration in analytical estimation.

![Figure 3.11 Probability of successful transmission with normalized communication time](image-url)