Theoretical Analysis and Overhead Control Mechanisms in MANET: A Survey

Gowrishankar.S [1], T.G.Basavaraju [2], Manjaiah D.H [3], M.Singh [4], Subir Kumar Sarkar [5]

***Abstract*—A mobile ad hoc network (MANET) is a self-organizing wireless network made up of mobile nodes and requires no fixed infrastructure. Routing is a critical task in MANET as the nodes are moving. So, the primary goal of an ad hoc routing protocol is to establish a correct and efficient route between any pair of nodes with minimum overhead. Routing overhead is a very important metric. If the control overhead of a proposed method is very high, then that method cannot work well in MANET. In this paper we present a survey of theoretical analysis of the routing overhead involved and the various approaches that are employed to minimize the control overhead incurred by various routing protocols.**

***Index Terms*—ad hoc, MANET, overhead, survey, routing protocols.**

1. INTRODUCTION

Mobile Ad hoc networks are autonomous systems formed by mobile nodes without any infrastructure support. Routing in MANET is challenging because of the dynamic nature of the network topology. Fixed network routing protocols can assume that all the routers have a sufficient description of the underlying network, either through global or decentralized routing tables. However, dynamic wireless networks do not easily admit such topology state knowledge. The inherent randomness of the topology ensures that a minimum overhead is associated with the routing in MANET and is greater than that of fixed networks. It is therefore of interest to know how small the routing overhead can be made for a given routing strategy and random topology [11].

To evaluate the performance of routing protocols in MANET, several performance metrics such as packet delivery ratio, average end-to-end delay and routing overhead are commonly used. Among these metrics routing overhead is the important one as it determines the scalability of a routing protocol. Routing Overhead means how many extra messages were used to achieve the acceptance rate of improvement.

To evaluate the routing overhead in mobile ad hoc routing protocols, we follow different methods like a) Simulations b) Physical experiments and c) Theoretical analysis [1].

In simulations a controlled environment is provided to test and debug many of the routing protocols. Therefore, most of the literature [2, 3, 4] evaluates the routing overhead in routing protocols using software simulators like NS-2 [22], Glomosim [23], Qualnet [36] and OPNET [24]. However, simulations are not foolproof method and it may fail to accurately reveal some critical behaviors of routing protocols, as most of the simulation experiments are based on simplified assumptions.

Physical experiments evaluate the performance of routing protocols by implementing them in real environment. Some of the papers in the literature evaluate routing overhead in real physical environment [5, 6]. But, physical experiments are much more difficult and time consuming to be carried out.

Analysis of routing overhead from a theoretical point of view provides a deeper understanding of advantages, limitations and tradeoffs found in the routing protocols in MANET. Some of the papers in literature [7, 8, 9, 10] have evaluated routing protocols in MANET from theoretical analysis perspective.

The remainder of this paper is organized as follows. We provide a detailed overview of current proposals that investigate the theoretical analysis of the overhead involved as well as various approaches that reduce the control overhead like hierarchical routing scheme, cluster routing scheme, header compression and Internet connectivity to mobile ad hoc networks based on main objective to minimize the routing overhead. The last section concludes the paper.

2. THEORETICAL ANALYSIS OF OVERHEAD IN HIERARCHICAL ROUTING SCHEME

Traditionally the routing schemes for ad hoc networks are classified into proactive and reactive routing protocols. Proactive protocols like DSDV [33] and OLSR [35] maintain routing information about the available paths in the network even if these paths are not currently used. The drawback of such paths is that it may occupy a significant part of the available bandwidth. Reactive routing protocols like DSR, TORA [4] and AODV [34] maintain only the routes that are currently available. However, when the topology of network

[1]Department of computer science, Mangalore University, Mangalore 574199, Karnataka, India.
Email: gowrishankarsnath@acm.org
[2]Department of Computer Science and Engineering, Acharya Institute of Technology, Visvesvaraya Technological University, Belgaum 590014, Karnataka, India.
Email:tgbasava@hotmail.com
[3]Reader and Chairman, Department of Computer Science, Mangalore University, Mangalore 574199, Karnataka, India.
Email: ylm321@yahoo.co.in
[4]Institute of Engineering and Management, Kolkata, India.
[5]Department of Electronics and Telecommunication Engineering, Jadavpur University, Kolkata 700032 , West Bengal, India.
Email: sksarkar@etce.jdvu.ac.in

changes frequently, they still generate large amount of control traffic.

Therefore, the properties of frequent route breakage and unpredictable topology changes in MANET make many of the routing protocols inherently not scalable with respect to the number of nodes and the control overhead. In order to provide routing scalability a hierarchy of layers is usually imposed on the network. Scalability issues are handled hierarchically in ad hoc networks. Many hierarchical routing algorithms are adopted for routing in ad hoc wireless networks. For e.g., cluster based routing and the dominating set based routing.

Sucec and Marsic provide a formal analysis of the routing overhead i.e., they provide a theoretical upper bound on the communication overhead incurred by the clustering algorithms that adopt the hierarchical routing schemes. There are many scalability performance metrics like hierarchical path length, least hop path length and routing table storage overhead. Among these metrics, control overhead per node (Ψ) is the most important one because of scarce wireless link capacity, which has severe performance limitation. The control overhead Ψ is expressed as a function of $|V|$, where V is the set of network nodes. It is shown that with reasonable assumptions, the average overhead generated per node per second is only polylogarithmic in the node count i.e., $\Psi = O\left(\log^2|V|\right)$ bits per second per node [13].

Communication overhead in hierarchically organized networks may result from the following phenomenon: a) Hello Protocols b) Level-k cluster formation and cluster maintenance messaging, $k \in \{1,2...L\}$, where L is the number of levels in the clustered hierarchy c) Flooding of the cluster topology updates to cluster members d) Addressing information required in Datagram headers e) Location management events due to changes in the clustered hierarchy and due to node mobility between clusters f) Hand off or transfer of location management data g) Location query events. Total communication overhead per node ψ in hierarchically organized networks is the sum of the above contributing elements.

The control overhead and network throughput under a cluster based hierarchical routing scheme is discussed in [12]. The authors claim that when the routing overhead is minimized in a hierarchical design then there is a loss in the throughput from the same hierarchical design. A strict hierarchical routing is assumed which is not based on any specific routing protocol. In MANET, hierarchical routing protocols do not require every node to know the entire topology information. Only a few nodes called the cluster head nodes need to know about the topology information and all the other nodes can simply send their packets to these cluster heads.

Hierarchical routing protocols reduce the routing overhead, as lesser nodes need to know the topology information of an ad hoc network. The throughput of ad hoc network with hierarchical routing scheme is smaller by a factor of $O\left(\frac{N2}{N1}\right)$, where N2 is the number of cluster head nodes and N1 is the number of all the nodes in the network. Hence, the authors claim that there is a tradeoff between the gain from the routing overhead and the loss in the throughput from the hierarchical design of the ad hoc routing protocols.

The control overhead in a hierarchical routing scheme can be due to packet transmissions per node per second (ϕ), due to the maintenance of routing tables as well as due to the address management or location management. Therefore the overhead ϕ required by hierarchical routing is a polylogarithmic function of the network node count (N) i.e., $\Phi = \Theta\left(\log^2|N|\right)$ packet transmissions per node per second. In this equation, overhead due to hierarchical cluster formation and location management are identified [10].

3. THEORETICAL ANALYSIS AND OVERHEAD MINIMISING TECHNIQUES FOR AD HOC NETWORK USING CLUSTERING MECHANISMS

The concept of dividing the geographical regions into small zones has been presented as clustering in the literature.

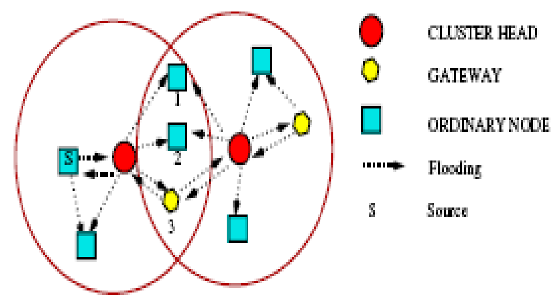

Fig 1. Route Establishment in Clustering Mechanism

Clustering basically transforms a physical network into a virtual network of interconnected clusters or group of nodes. These clusters are dominated by clusterheads (CH) and connected by gateways or border terminals as shown in Fig 1. Any node can be CH, if it has the necessary functionality such as the processing and transmission power. The node registered with the nearest CH becomes the member of that cluster. By partitioning a network into different clusters both the storage and communication overhead can be reduced significantly.

Different clustering algorithms may use different clustering schemes but generally three different types of control messages are needed: a) Beacon messages also known as Hello messages are used to learn about the identities of the neighboring nodes b) Cluster messages are used to adapt to cluster changes and to update the role of a node c) Route messages are used to learn about the possible route changes in the network. [21]

The various types of control messages overhead are *a) Hello Overhead:* To reduce the hello overhead messages the frequency of hello messages generated by a node to learn about its neighboring node when a new link is formed should be at least equal to the link generation rate. The link generation between any two nodes can be notified by sending the hello messages and each of the nodes can hear the hello message sent by the other node. *b) Cluster message overhead due to link* *break between cluster members and their cluster heads:* This event causes the node to change its cluster or become a cluster head when it has no neighboring clustering heads. The cluster members send the cluster messages due to this type of link changes. To minimize the control message overhead the ratio of such link breaks to total link breaks should be equal to the ratio of links between the cluster members and cluster heads divided by the total number of links in the entire network. c*) Cluster message overhead due to link generation between two cluster heads:* When a link is generated between two cluster heads, one of the cluster heads needs to give up its cluster head role, which is decided by the clustering algorithm. Every time a link between two cluster heads appears, the number of cluster messages generated is same as the number of nodes in the cluster that needs to undergo reclustering. *d) Routing overhead:* When a particular node in the cluster should be updated with the route to other nodes in the cluster, the routing storage overhead is proportional to the size of the cluster.

An analytical study on routing overhead of two level cluster based routing protocols for mobile ad hoc networks is done in [1]. Routing protocols can be summarized into generic proactive routing protocol and a generic reactive routing protocol. It's generic because there may be some different strategy employed for each of the groups, but the underlying nature of the routing is similar.

In two level cluster based routing scheme, the routing is divided into two separate parts, i.e. routing among different clusters (i.e., intercluster routing) and routing within a cluster (i.e., intracluster routing). Since there are two types of routing schemes i.e., proactive and reactive which can be employed in intercluster routing and intracluster routing, there are totally four types of two level hierarchical routing schemes with different combinations of them. Hence we have proactive to proactive, reactive to reactive, proactive to reactive and reactive to proactive routing scheme.

When a proactive scheme is adapted for intercluster routing each cluster head periodically collects its local cluster topology and then broadcasts it to its direct neighbor cluster head via gateways. When a reactive routing scheme is used for inter cluster routing, a route request for a route to the destination node that is in another cluster will be broadcasted among cluster heads. When a proactive routing scheme is utilized for intracluster routing, each node broadcasts its local node topology information, so the route to the destination within the same cluster will be available when needed. When a reactive routing scheme is employed for intracluster routing, a route request to the destination will be flooded within the same cluster.

Thus a proactive to proactive routing scheme will work as a proactive routing protocol with a hierarchical structure. The proactive to proactive routing scheme produces overhead due to periodical topology maintenance of $O\left(\frac{1}{n}N^2 + \frac{1}{kN_c}N^2\right)$ where n is the total number of clusters in the network, N is the network size, k is the cluster radius, N_c is the cluster size.

A reactive to reactive routing protocol operates as a purely reactive routing protocol with a hierarchical structure. Reactive to reactive routing protocol yields a routing overhead due to route discovery of $O\left(\frac{1}{k}N^2\right)$.

In a proactive to reactive routing scheme the cluster heads periodically exchange topological information and a node always sends a route request to its cluster head where there is no available route to an expected destination. Then the cluster head will send a route reply packet to the node, which indicates that the destination is within the local cluster or contains a route to the destination node, which is in another cluster. Proactive to reactive routing protocol have a basic routing overhead due to topology maintenance, cluster maintenance and route discovery which is found to be $O\left(\frac{1}{kN_c}N^2 + \frac{r}{nk}N^2\right)$ where r is average route lifetime.

In a reactive to proactive routing scheme each node in the cluster will periodically broadcast local node topology information within the cluster. Thus, when the destination is within the cluster, the route is immediately available. Otherwise, the node will send a route request packet to its cluster head, which will be broadcasted among the cluster heads. Reactive to proactive routing protocol have a basic routing overhead due to cluster maintenance and route discovery, which is approximately equal to $O\left(\frac{1}{n}N^2 + \frac{1}{k}N^2\right)$.

A mathematical framework for quantifying the overhead of a cluster based routing protocol (D-hop max min) is investigated by Wu and Abouzeid [8]. The authors provide a relationship between routing overhead and route request traffic pattern. From a routing protocol perspective, 'traffic', could be defined as the pattern by which the source destination pairs are chosen. The choice of a source destination pair depends on the number of hops along the shortest path between them. Also the network topology is modeled as a regular two-dimensional grid of unreliable nodes. It is assumed that an infinite number of nodes are located at the intersections of a regular grid. The transmission range of each node is limited such that a node can directly communicate with its four immediate neighbors only. It is reported that the clustering does not change the traffic requirement for infinite scalability compared to flat protocols, but reduces the overhead by a factor of $O\left(\frac{1}{M}\right)$ where *M* is the cluster size.

Wu and Abouzeid show that the routing overhead can be attributed to events like a) Route discovery b) Route maintenance and c) Cluster maintenance.

Route discovery is the mechanism where by a node i wishing to send a packet to the destination j obtains a route to j. When a source node i wants to send a packet to the destination node j, it first sends a route request (RREQ) packet to its cluster head along the shortest path. The route reply (RREP) packet travels across the shortest path back to the cluster head that initiated the RREQ packet. So the route discovery event involves an RREP and RREQ processes. The overhead for RREQ is generally higher than the RREP since it may involve flooding at the cluster head level. Therefore, the minimum average overhead of finding a new route is

$$\frac{f(k-3)\left(6M+6+\frac{3}{M}\right)+f(k-2)\left(4M^{2}+2\right)-f(k-1)M\left(M^{2}-1\right)}{3\left(2M^{2}+2M+1\right)f(k-1)}$$

Where, M is the radius of the cluster and changing the value of k controls the traffic pattern.

Route maintenance is the mechanism by which a node i is notified that a link along an active path has broken such that it can no longer reach the destination node j through that route. When route maintenance indicates a link is broken, i may invoke route discovery again to find a new route for subsequent packets to j. In cluster based routing, the neighboring node sends a RERR packet to its cluster head rather than the source node itself. The cluster head could patch a path locally without informing the source node, if the failed node is not the destination node. This is called local repair. In this case, the path is locally fixed. Also, the RERR packet sent from a neighboring node to the cluster head is considered as the cluster maintenance overhead. Therefore the minimum overhead required for route maintenance is $4C\left(f\left(k-2\right)-f\left(k-1\right)\right)$ where, k>3 and C is a constant.

Clustering incurs cluster maintenance overhead, which is the amount of control packet needed to maintain the cluster membership information. The membership in each cluster changes overtime in response to node mobility, node failure or new node arrival. The average cluster maintenance overhead is

$$\frac{4(M-1)M(M+1)}{3\left(2M^{2}+2M+1\right)}+2M$$

Where, M is the radius of the cluster.

The work done in [9] by Zhou, provide a scalability analysis of the routing overheads with regard to the number of nodes and the cluster size. Both the interior routing overhead within the cluster and the exterior routing overhead across the clusters are considered. The routing protocol includes a mechanism for detecting, collecting and distributing the network topology changes. The process of detecting, collecting and distributing the network topology changes contribute to a total routing overhead R_t. The routing overhead can be separated into interior routing overhead (R_i) and the exterior routing overhead (R_e). The interior routing overhead R_i is the bit rate needed to maintain the local detailed topology. This includes the overhead of detecting the link status changes by sending “HELLO” message, updating the cluster head about the changes in link status and maintaining the shortest path between the regular nodes to their cluster head.

Exterior routing overhead (R_e) is the bit rate needed to maintain the global ownership topology, which includes the overheads of the distributing the local ownership topologies among the cluster heads. Hence $R_t=R_i+R_e$

4. MINIMISING OVERHEAD IN AD HOC NETWORKS BY HEADER COMPRESSION

In literature it has been studied that [14] approximately half of the packets sent across the Internet are 80 bytes long or less. This percentage has increased over the last few years in part due to widespread use of real time multimedia applications. The multimedia application’s packet size is usually smaller in size and these small packets must be added with many protocol headers, while traveling through the networks. In Ipv4 networks there can be at least 28 bytes (UDP) or 40 bytes (TCP) overheads per packet. These overheads consume much of the bandwidth, which is very limited in wireless links. Small packets and relatively larger header size translates into poor line efficiency. Line efficiency can be defined as the fraction of the transmitted data that is not considered overhead. Fig. 2 shows some of the common header chains and size of each component within the chain.

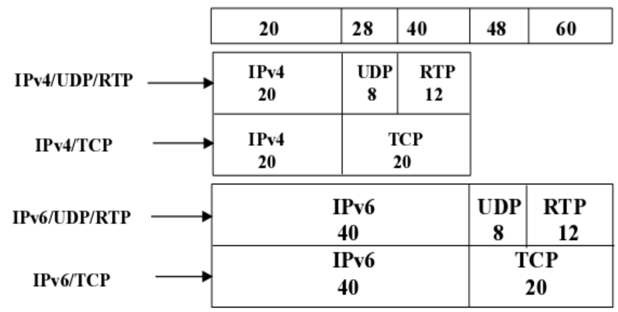

Fig 2. Common Header Chains and their Sizes

Ad hoc networks create additional challenges such as context initialization overhead and packet reordering issues associated with node mobility. The dynamic nature of ad hoc networks has a negative impact on header compression efficiency.

A context is established by first sending a packet with full uncompressed header that provides a common knowledge between the sender and receiver about the static field values as well as the initial values for dynamic fields. This stage is known as context initialization. Then the subsequent compressed headers are interpreted and decompressed according to a previously established context. Every packet contains a context label. Here the context label indicates the context in which the headers are compressed or decompressed.

A novel hop-by-hop context initialization algorithm is proposed in [15] that depends on the routing information to reduce the overhead associated with the context initialization of IP headers and uses a stateless compression method to reduce the overhead associated with the control messages. Context initialization of IP headers is done on a hop-by-hop basis because the headers need to be examined in an uncompressed state at each of the intermediate nodes. The context initialization overhead is reduced by caching the address information that is transmitted in the routing messages, in order to reduce the size of the context initialization headers.

Also a stateless header compression is proposed. It is stateless because the state of the context is fixed and it does not

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change with time. Header compression improves the line efficiency by exploiting the redundancies between the header fields within the same packet or consecutive packets belonging to the same stream.

The overall result is the reduced overhead, increased network capacity and line efficiency even in the presence of rapid path fluctuations.

An Ad hoc robust header compression protocol has been proposed (ARHC) in [16]. ARHC protocol can be used to compress UDP, TCP and raw IP headers in ad hoc network. The mechanism of ARHC is that when the first packet of a session arrives, the compressor generates a unique number called context ID, which indexes the quintuplet (source address, destination address, source port, destination port, protocol) and all the constant fields. Compressor then records the context id, quintuplet and all the constant fields. Then the compressor will send the full packet header along with the context ID. Upon receiving the very first packet the decompressor records this information. When the subsequent packets arrive later, the compressor and decompressor act as follows. The compressor will remove the constant fields and the quintuplet from the header and transmits only the context ID. The decompressor then retrieves the quintuplets and the constant fields from the context tables indexed by the context ID, thereby restoring the original header.

5. MINIMISING OVERHEAD FOR AD HOC NETWORK CONNNECTED TO INTERNET

Today Internet has become the backbone of the wired and wireless communication. Also mobile computing is gaining in popularity. In order to meet the rapid growing demand of mobile computing, many of the researchers are interested in the integration of MANET with the Internet.

When a mobile node in MANET wants to exchange packets with the Internet, first the node must be assigned a global IP address and then the available Internet gateways has to be discovered to connect to the Internet as shown in Fig 3. But, this is achieved at the cost of higher control overhead.

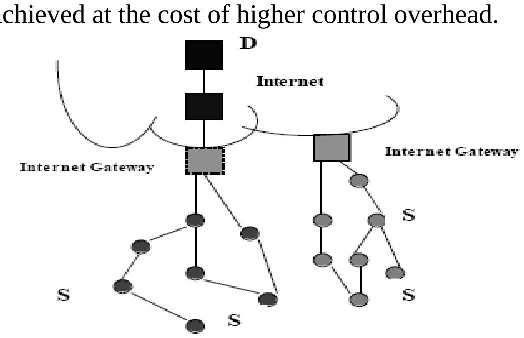

Fig 3. MANET connected to Internet Scenario

For gateway discovery, a node depends on periodic gateway advertisement. To make efficient use of this periodic advertisement, it is necessary to limit the advertisement flooding area.

A complete adaptive scheme to discover IG in an efficient manner for AODV is given in [8]. In this approach both the periodic advertisement and adaptive advertisement schemes are used. At a relatively long interval each gateway sends the periodic advertisement messages. Periodic advertisements performed at a widely spaced interval do not generate a great deal of overhead but still provides the mobile nodes with a good chance of finding the shortest path to a previously used gateway. The TTL of the periodic gateway message is used as a parameter to adjust the network conditions. A heuristic algorithm called “Minimal Benefit Average” [19] decides the next TTL to be used for the periodic gateway advertisement messages.

The goal of the adaptive advertisement scheme is to send advertisement packets only when the gateway detects the movement of nodes, which would result in the paths used by the source mobile nodes communicating with the gateway to be changed. Adaptive advertisement is performed when needed, regardless of the time interval used for periodic advertisement. [18]. In this approach there is reduction in overhead messages since the periodic advertisements are sent at a long time interval and perform adaptive advertisement only if there is mobility in the network.

The various parameters that affect the control overhead created by interoperating the ad hoc routing protocols and IP based mobility management protocols is addressed in [17]. Mobile IP is used as the baseline mobility management protocol and AODV is chosen as the ad hoc routing protocol. IP tunneling is used to separate the ad hoc network from the fixed network. In mobile IP, a mobile node can tell which router is available by listening to router advertisements, which are periodically broadcasted by the routers.

A fixed access router is assigned the role of mobility agent and has connection to at least one of the MANET nodes. Such router is referred to as Ad hoc Internet Access Router (AIAR) and it maintains a list called ad hoc list, which keeps a list of IP address of the mobile nodes that wish to have Internet connectivity. In an integrated network the control overhead comprises of AIAR registration packets, routing protocol control packets, mobile IP registration packets and mobile IP router advertisement.

In mobile IP majority of the overhead is due to the route advertisement packets that are being repeatedly and periodically forwarded among the mobile nodes. Also, the router advertisement used by the mobility management protocol to carry network information is the major source of unnecessary control overhead within MANET. Varying TTL value is an effective mechanism to control the amount of advertisement packets [17].

A multihop router is developed in [20] for non-uniform route connectivity with low routing overhead. To achieve efficient route discovery and route maintenance a new routing scheme called hopcount based routing (HBR) protocol is developed. HBR is an on demand routing protocol. When a source node needs to discover a route to a node on the wired network, it initiates a route discovery to the nearest access point by broadcasting a route request packet. By utilizing the hop counts referring to access points, the route discovery region is

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localized to a small area. On receiving the route request packet, the access point responds by sending a route reply packet to the source node. Once a route is found, the source node begins to forward data to the access point. After the access point receives these data packets from the source node, it then forwards these packets through the wired line to the destination node on the wired network using the routing protocol in the wired network. By using the hop count information an attempt is made to reduce the number of nodes to whom the route request is propagated. Thus in HBR routing protocol to construct routes from mobile nodes to access points hop count information is utilized to localize the route discovery within a limited area in order to reduce the routing overhead.

6. CONCLUSION

In this survey we go through the theoretical analysis of the overhead involved and also provide descriptions of several techniques that are proposed for minimizing the routing overhead in ad hoc routing protocols. We classify different algorithms into several categories such as clustering, hierarchical, header compression and Internet connectivity to mobile ad hoc networks based on main objective to minimize the routing overheads. The overhead complexity involved in various schemes is listed in table 1.1. Clearly, the selection of areas in this paper is highly subjective. Besides, the routing overhead minimizing schemes which we have surveyed, there are dozen of research schemes that are currently the focus of the community.

With this survey, readers can have a comprehensive understanding of different schemes that are employed to reduce the routing overhead. We hope that this survey can facilitate researchers to move in new direction and devise new methods to reduce the control overheads that are inherently associated with the routing protocols.

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Table 1.1 Overhead complexity involved in Various Schemes

Routing Scheme	Overhead Complexity
Overhead in Hierarchical Routing Scheme	$\Psi = O(\log^2 \lvert V \rvert)$ Bits per node per second $\Phi = \Theta(\log^2 \lvert N \rvert)$ Packet transmissions per node per second
Overhead in a Proactive to Proactive Routing Scheme	$O\left(\frac{1}{n}N^2 + \frac{1}{kN_c}N^2\right)$
Overhead in a Reactive to Reactive Routing Scheme	$O\left(\frac{1}{k}N^2\right)$
Overhead in a Proactive to Reactive Routing Scheme	$O\left(\frac{1}{kN_c}N^2 + \frac{r}{nk}N^2\right)$
Overhead in a Reactive to Proactive Routing Scheme	$O\left(\frac{1}{n}N^2 + \frac{1}{k}N^2\right)$

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