Analysis of pervasive mobile ad hoc routing protocols

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Chapter 19
Analysis of Pervasive Mobile Ad Hoc Routing Protocols

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Abstract Mobile ad hoc networks (MANETs) are a fundamental element of pervasive networks and therefore, of pervasive systems that truly support pervasive computing, where user can communicate anywhere, anytime and on-the-fly. In fact, future advances in pervasive computing rely on advancements in mobile communication, which includes both infrastructure-based wireless networks and non-infrastructure-based MANETs. MANETs introduce a new communication paradigm, which does not require a fixed infrastructure – they rely on wireless terminals for routing and transport services. Due to highly dynamic topology, absence of established infrastructure for centralized administration, bandwidth constrained wireless links, and limited resources in MANETs, it is challenging to design an efficient and reliable routing protocol. This chapter reviews the key studies carried out so far on the performance of mobile ad hoc routing protocols. We discuss performance issues and metrics required for the evaluation of ad hoc routing protocols. This leads to a survey of existing work, which captures the performance of ad hoc routing algorithms and their behaviour from different perspectives and highlights avenues for future research.

19.1 Introduction

Mobile ad hoc networks (MANETs) are a fundamental element of pervasive networks and therefore, of pervasive systems that truly support pervasive computing, where users can communicate anywhere, anytime and on-the-fly. In fact, future advances in pervasive computing rely on advancements in mobile communication,

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which includes both infrastructure-based wireless networks and non-infrastructure-based MANETs. The traditional infrastructure-based communication model is not adequate for today's user requirements. In many situations the communication between mobile hosts cannot rely on any fixed infrastructure. The cost and delay associated with installation of infrastructure-based communication model may not be acceptable in dynamic environments such as disaster conditions, battle field, intervehicular communications, etc. MANET would be an effective solution in these scenarios.

MANETs introduce a new communication paradigm, which does not require a fixed infrastructure – they rely on wireless terminals for routing and transport services. A MANET is characterized as "the art of networking without a network" [1]. The network topology of such a system is changeable and unpredictable; therefore, the traditional wired network routing protocols are not applicable for these networks. The special features of a MANET bring about great opportunities together with severe challenges. Due to their highly dynamic topology, the absence of an established infrastructure for centralized administration, bandwidth constrained wireless links, and limited resources, MANETs are hard to design in terms of efficient and reliable routing.

A robust and flexible routing approach is required to efficiently use the limited resources available, while at the same time being adaptable to the changing network conditions, such as network size (scalability), traffic density and mobility. The routing protocol should be able to provide efficient route establishment with minimum overhead, delay and bandwidth consumption, along with a stable throughput. Furthermore, the possibility of asymmetric links, caused by different power levels among mobile hosts and other factors such as terrain conditions, makes routing protocols more complicated than in other networks.

For this purpose, a wealth of innovative protocols has been introduced and authors of each proposed protocol claim that the algorithm proposed by them brings in enhancements and improvements over a number of different strategies under different scenarios and network conditions. However, only few protocols have actually been implemented (beyond the simulation stage) and not all of these have been assessed in depth. Many articles have provided a protocol assessment which is specific and often does not allow drawing general conclusions. Therefore, it is difficult to determine which protocols may perform better under different network scenarios.

To address these shortcomings, this chapter reviews the key studies carried out so far on the performance of mobile ad hoc routing protocols. First, we introduce taxonomy of a wide variety of different protocols based on mechanisms including route construction, maintenance and update, topology formation, network configuration and exploitation of specific resources. An overview of the most significant protocols presented and widely used in literature is given. Then we discuss the requirements of Mobile ad hoc routing protocols and performance metrics required for the evaluation of ad hoc routing protocols. This leads to a survey of existing work, which captures the performance of ad hoc routing algorithms and their behaviour from different perspectives. A critical discussion of the state-of-the-art will yield the identification of the key areas that require further research. We conclude with discussion and our view on this topic.

19.2   Taxonomy of Mobile Ad Hoc Routing Protocols

Mobile ad hoc routing protocols can be classified in many ways depending upon their route construction and maintenance mechanisms, route selection strategy, topology formation, update mechanism, utilization of specific resources, type of cast, etc. [2]. Here we have classified them using few characteristics – the bases of classification are discussed below. Taxonomy of routing protocols is shown in Fig. 19.1. In this section, we focus on those that will be discussed in the later part of this chapter.

19.2.1   Approaches Based on Route Construction, Maintenance and Update Mechanisms

These protocols can be described as the way the route is constructed, updated and maintained and route information is obtained at each node and exchanged between the nodes. Based upon these characteristics, routing protocols can be divided broadly into three categories.

19.2.1.1   Proactive (Table-Driven) Routing

In proactive or table-driven routing protocols, each node consistently maintains up-to-date routing information for all known destinations. These types of protocols keep routing information in one or more tables and maintain routes at each node by periodically distributing routing tables (RTs) throughout the network or when the topology changes. Each node keeps information of all the routes, regardless of weather or not these routes are needed. Therefore, control overhead in these protocols would be significantly high, especially for large networks or in a network where nodes are highly mobile. However, the main advantage of these protocols is that the routes are readily available when required and end-to-end delay is reduced during data transmission in comparison to the case in which routes are determined reactively, which introduces a latency to discover a route to the destination.

19.2.1.2   Reactive (On-Demand) Routing

In Reactive or on-demand routing protocols, the routes are discovered only when they are actually needed. These protocols consist of route discovery and route maintenance processes. The route discovery process is initiated when a node wants to send data to a particular destination. Route discovery usually occurs by flooding the network with route-request packets. When a destination node or node holding a route to destination is reached, a route-reply is sent back to the source node by
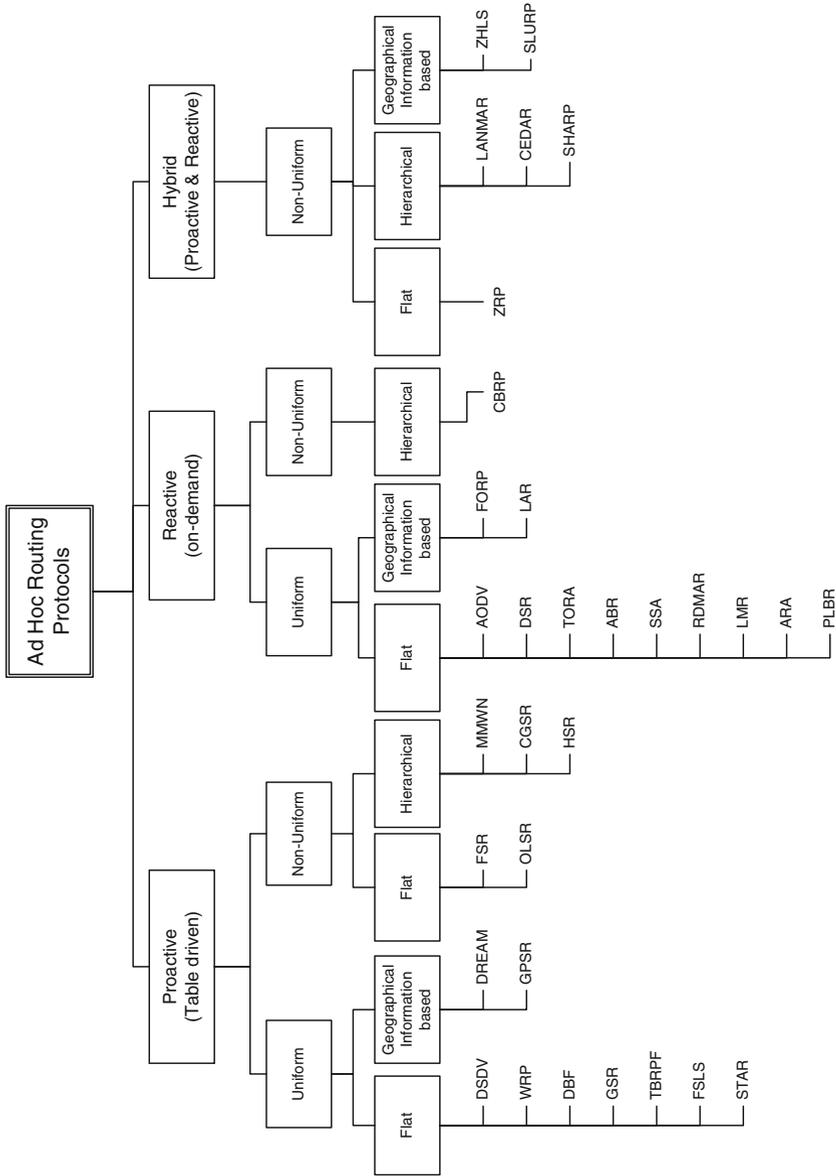
Fig. 19.1 Taxonomy of mobile ad hoc routing protocols (for abbreviations please refer list of abbreviations)

instantiating routing information at the appropriate intermediate nodes. Once the route reply reaches the source, the data can be sent to the destination. The route maintenance process deletes failed routes and re-initiates route discovery in case of topology change. The advantage of this approach is that overall overhead is likely to be reduced compared to proactive approaches. However, as the number of sessions increases, the overhead generated by route discovery became high and may exceed that of proactive protocols.

19.2.1.3 Hybrid Routing

The hybrid routing protocols combine the advantages of both proactive and reactive routing. These protocols usually divide the network in zones such that each node sees the network in number of zones. The routes to nodes close to each other or within a particular zone are proactively maintained and the routes to far-away nodes are determined reactively using a route discovery strategy.

19.2.2 Approaches Based on Logical Organization, Network Configuration, and Utilization of Specific Resources

19.2.2.1 Uniform Routing

In uniform routing, all nodes are equal and each node participates in route computations. Each node generates routing control messages and replies to routing control requests in the same way. So, every node accomplishes exactly the same functionality as the other. Uniform protocols can be sub-divided into Flat and Geographical Information-based routing protocols. The geographical information-based protocols proposed to date are mostly uniform except for the zone-based hierarchical link state (ZHLS) [3] and scalable location update routing protocol (SLURP) [4] routing protocols, which are nonuniform routing protocols.

Flat Uniform Routing

In flat routing, nodes do not form a specific structure or hierarchy. Each node has similar roles. Nodes that are within the transmission range of each other form a connection, where the only limitations are determined by connectivity conditions or security constraints. The major advantage of this routing structure is that there are multiple paths between source and destination, which reduce traffic congestion and traffic bottlenecks in the network. Single points of failure in case of cluster head could lead to larger control overheads arising from network reconfiguration. Nodes in flat routing require significantly lower power for transmission in comparison to cluster heads [5].

Geographical Information Based Uniform Routing

In these types of protocols, the location of the nodes can be obtained by utilizing global positioning system (GPS); alternatively, the relative coordinates of nodes can be obtained by calculating the distance between the nodes and exchanging this information with neighbouring nodes. The distance between nodes can be estimated on the basis of incoming signal or time delays in direct communications [6]. The main advantage of this approach is that the protocols can improve routing performance and reduce control overheads by effectively utilizing location information. All the protocols in this category assume that all nodes know their positions and the network topology of nodes corresponds well with the geographical distance between them. The drawback of this approach is that its above mentioned assumptions are often not acceptable and location information may not be accurate at all times [7,8].

19.2.2.2 NonUniform Routing

In Nonuniform routing, the way of generating and/or replying to routing control messages may be different for different groups of nodes. In these protocols, only few nodes are involved in route computation. For instance, some nodes shall broadcast received routing requests, others shall not. Nonuniform protocols attempt to reduce routing overhead by reducing the number of nodes involved in route computation. Moreover, they have a cost introduced for maintaining a high-level structure complexity and use of complex algorithms. Nonuniform protocols can be logically sub-divided into Flat (based on neighbour selection) and Hierarchical routing.

Flat NonUniform Routing

In this routing approach, each node selects some subset of its neighbours to take a distinguished role in route computation and/or traffic forwarding. Each node makes its selection independently, and there is no negotiation between nodes to attain nodes consensus and the node's selection is not affected by nonlocal topology changes [9].

Hierarchical NonUniform Routing

In hierarchical routing protocols, the nodes organize themselves into groups, called clusters. Within each cluster, a cluster head or gateway node is selected which co-ordinates all the traffic in and out of their clusters. Routing between two nodes from different clusters is usually performed by their cluster heads. The depth of the network can vary from single to multiple levels depending upon the number of hierarchies. The advantage of this approach is that each node maintains route to its cluster head only, which means that routing overheads are much lower compared to flooding routing information through the network. However, these protocols require

complex algorithms for the creation and reconfiguration of clusters in case of single point of failure by cluster heads. Along with that, there are significant overheads associated with maintaining clusters [5].

19.3   An Overview of the Most Common Ad Hoc Routing Protocols

In this section we give an overview of the protocols that are most widely and frequently used in existing work, illustrating key strength and weaknesses as indicated by the reviews described in [2,10,11]. The analysis of these protocols will be further discussed in Sect. 19.5.

19.3.1   Destination Sequence Distance Vector (DSDV)

Destination sequence distance vector (DSDV) is a proactive, uniform routing protocol [12]. It is an improved version of distributed Bellman-Ford (DBF) routing algorithm, which guarantees loop free routes. Each node maintains a RT that contains routes for and number of hops to all possible destinations in the network [9]. The path to destination is selected using the shortest path distance vector algorithm and each node periodically broadcasts RT updates throughout the network in order to maintain table consistency. Each entry is tagged with sequence number assigned by the destination in order to indicate the freshness of route and avoid the formation of routing loops. Sequence numbers are incremented each time a node sends an update. A route is considered to be more favourable if its sequence number is higher or in case of the routes with same sequence number, the one with shortest path would be considered. The availability of routes to all destinations at all times is the main advantage of this protocol as less delay will be involved in the route setup process. However, periodic updates and updates due to broken links in high mobility lead to a large amount of overhead. Therefore, this protocol will not scale well in large networks; even a small network with high mobility can block the network.

19.3.2   Wireless Routing Protocol (WRP)

Wireless routing protocol (WRP) is a proactive uniform type protocol [13]. It is an advanced version of DBF and also guarantees loop-free routing similar to DSDV, but differs from DSDV in terms of table maintenance and update mechanisms.

WRP requires each node to maintain four RTs, i.e., distance table (DT), RT, link cost table (LCT) and a message retransmission list (MRL). This requires a significant amount of memory and greater processing power from each node for the

maintenance of these tables. In contrast to DSDV, WRP periodically exchanges a simple HELLO packet, rather than exchanging the whole table even when there is no link change. In case of link changes, only information that reflects the updates is sent. To improve reliability, every neighbour is required to send acknowledgements with respect to update packet received. Retransmissions are sent if no positive acknowledgements are received within a given timeout period. This avoids temporary loops by using predecessor information [14]. When there is no recent packet transmission, hello messages are exchanged between nodes. This requires each node to stay active all the times (i.e., they cannot enter into sleep mode to save their power), which consumes a large amount of bandwidth and battery power. Control overheads involved in WRP are comparable to those of DSDV, which makes it unsuitable for highly dynamic and large networks.

19.3.3 Source Tree Adaptive Routing (STAR)

Source tree adaptive routing (STAR) is a proactive, uniform routing protocol [15]. It is a variation of other table-driven routing protocols that attempt to provide feasible paths that are not guaranteed to be optimal, but involve much less control overhead using the least overhead routing approach (LORA). This approach reduces the average control overhead as compared to other proactive protocols by eliminating the periodic updating procedures, making update dissemination conditional. In STAR, every node maintains source-tree information, which consists of a set of wireless links of preferred paths to destination used by nodes [2]. STAR can scale very well due to its reduced consumption of bandwidth by routing updates. However, maintaining source tree information at each node may result in significant memory and processing overheads in large and highly dynamic networks, since the source tree may change frequently as the neighbours keep reporting different source trees.

19.3.4 Distance Routing Effect Algorithm for Mobility (DREAM)

Distance routing effect algorithm for mobility (DREAM) is a proactive, location-based routing protocol [16]. In DREAM, the data are partially flooded to nodes laying in the direction of destination, using location information to limit the flood of data packets to a small region. Nodes are required to periodically broadcast their physical location to inform all other nodes. Nearby nodes are updated more frequently than far away nodes. The RT maintains the co-ordinates of the nodes instead of route vectors. Therefore, it consumes significantly less bandwidth than exchanging complete link-state or distance-vector information. DREAM adjusts to network dynamics by making the frequency at which update messages are disseminated proportional to mobility and to the distance effect. Therefore, stationary nodes do not need to send any update messages, which results in reduced routing overhead.

19.3.5   Fisheye State Routing (FSR)

Fisheye state routing (FSR) is a proactive, non-uniform routing protocol [17, 18], employing a link-state routing algorithm. To reduce the overhead incurred by periodic link-state packets, FSR modifies link-state routing in the following three ways:

1. Link-state packets are no longer flooded – instead, only neighbouring nodes exchange the topology table information
2. The link-state exchange is solely time-triggered and not event-triggered
3. Instead of periodically transmitting the entire link-state information, FSR uses different exchange intervals for different types of entries in the topology table

Link-state entries corresponding to nodes within a predefined distance (scope) are propagated to neighbours more frequently (intra updates) than entries of nodes outside the scope (inter updates). FSR is suitable for large and highly mobile network environments as it triggers no control messages on link failures. Broken links will not be included in the next link state message exchange. This means that a change on a far away link does not necessarily cause a change in the RT. However, scalability comes with a price of reduced accuracy because as mobility increases, the route to remote destinations becomes less accurate.

There are the four following configuration parameters for FSR, the value of which depends on factors, such as mobility, node density and transmission range:

1. Size of the scope: This parameter specifies the scope radius of a node in number of hops.
2. Time-out for the neighbouring nodes: If a node does not hear from a neighbour specified by this value, the neighbour node will be deleted from the neighbour list.
3. Intra scope update interval: Update interval of sending the updates of the nodes within the scope radius.
4. Inter scope update interval: Update interval of sending the updates of the nodes outside the scope radius.

19.3.6   Ad Hoc On-Demand Distance Vector (AODV)

The ad hoc on-demand distance vector (AODV) routing protocol is a type of on-demand (reactive) protocol based on DSDV [19, 20]. AODV and DSDV share the same on-demand characteristics of DSR and use the same discovery process to find routes when required. AODV uses the periodic beaconing and sequence numbering procedure of DSDV, but minimizes the number of required broadcasts by creating routes on demand, as opposed to maintaining a complete list of routes as in DSDV [2].

There are two major differences between AODV and DSR. AODV uses a traditional RT with one entry per destination, whereas DSR maintains multiple route

cache entries for each destination. Another difference is that AODV relies on RT entries to propagate route replies back to the source and subsequently to route data packets to their destination. Along with that, AODV uses sequence numbers carried by all routing packets to determine the freshness of routing information and prevent routing loops. Therefore, its connection setup delay is smaller.

One of the disadvantages of AODV is that intermediate nodes can lead to inconsistent routes if the source's sequence number is very old and the intermediate nodes have a higher (but not the latest) destination sequence number, thereby having stale entries. Also multiple RouteReply packets in response to a single RouteRequest packet can lead to heavy control overheads, thereby introducing extra delays as the size of network increases. Another shortcoming is that periodic beaconing leads to unnecessary bandwidth consumption.

19.3.7 Dynamic Source Routing (DSR)

Dynamic source routing (DSR) is an on-demand routing protocol based on the concept of source routing [21–23]. Mobile nodes are required to maintain route caches that contain the source routes of which the mobile is aware. The route cache entries are continually updated as new routes are learned. The protocol consists of two main phases: route discovery and route maintenance. When a node wants to send a packet to destination, it first checks its route cache to determine whether it already has a valid route to the destination. If it has a valid route to the destination, it will use that route to send the packet. Otherwise, it initiates a route discovery process by broadcasting a route request packet.

Maintaining a route cache is highly beneficial for networks with low mobility as in this way, routes will be valid for a longer period. In addition, the route cache information can also be utilized by intermediate nodes to efficiently reduce control overheads. However, the broken links are not locally repaired by route maintenance mechanism, which is a disadvantage of this protocol. Along with that, stale route cache information could also result in variations during the route reconstruction phase. The connection setup delay is higher than in table-driven protocols. The protocol performs better with static nodes and slow moving nodes, but its performance degrades rapidly with increase in mobility. Also, due to the source routing mechanism, adapted in DSR results in considerable routing overhead.

19.3.8 Temporally Ordered Routing Algorithm (TORA)

Temporally ordered routing algorithm (TORA) is a reactive, uniform routing protocol [24]. It is highly adaptive, loop-free distributed routing algorithm based on a link reversal algorithm. TORA is specially designed to discover routes reactively, provides multiple routes to a destination, establish routes quickly and minimize

communication overheads by localizing algorithmic reaction to topological changes when possible. Route optimality (shortest path routing) is considered to be of secondary importance, and longer routes are usually used to avoid the overhead of discovering newer routes [25]. This increases the reliability of the protocol. Nodes use a "height" metric to establish a directed acyclic graph (DAG) rooted at the destination during route creation and maintenance phases. The process of establishing a DAG is similar to the query/reply process used in light-weight mobile routing (LMR) [26]. Also, the link reversal and route repair procedures are the same as in LMR. The advantage of TORA is that it supports multicasting. One of its disadvantages is that it may produce temporary invalid routes.

19.3.9 *Associativity-Based Routing [5]*

Associativity-based routing (ABR) is a uniform source initiated-based reactive routing protocol [27]. In ABR, routes are established based on the degree of association stability of the mobile nodes. Here association is referred to a spatial, temporal and connectivity relationship of a mobile host with its neighbours. Associativity is measured by recording the number of control beacons received by a node from its neighbours. For each beacon received, the associativity tick of the current node with respect to the beaconing node is incremented. Associativity ticks are reset when the neighbours of a node or the node itself move out of proximity [28]. The advantage of ABR is that routes tend to live longer. Therefore, fewer route reconstructions are needed and hence, more bandwidth remains available for data transmission. The disadvantage of this protocol is that it requires periodic beaconing to determine the associativity of the links; therefore, all nodes are required to be alive all the time, which may result in additional power consumption. Another disadvantage is that alternative routes are not readily available as ABR does not maintain multiple routes or route caches. However, its localized route discovery procedure compensates to some degree for not having multiple routes.

19.3.10 *Location Aided Routing [29]*

Location aided routing (LAR) is analogous to on-demand routing protocols such as DSR, but it uses location information to reduce routing overheads [30,31]. LAR assumes that each node knows its physically location by using GPS. GPS information is used to restrict the flooded area of route request packets. In [31], two different schemes are proposed. In Scheme 1, the source defines a circular area in which the destination may be located. The position and size of the circle are decided based on the location, speed and time instance of the destination. The smallest rectangular area that includes this circle and the source is the request zone. This information is attached to a route request by the source and only nodes inside the request zone

propagate the packet. In Scheme 2, the source calculates the distance between the destination and itself. The source includes the distance and location of destination in route request and sent it to neighbours. When neighbour nodes receive this packet, they compute their distance to the destination and relay the packet only if their distance to destination is less than or equal to the distance indicated by the packet. When forwarding the packet, the node updates the distance field with its distance to destination. In both schemes, if no Route Reply is received within the timeout period, the source retransmits a route request via pure flooding [14]. The major advantages of LAR are an efficient use of geographical position information, reduced control overhead and increased utilization of bandwidth. The disadvantage is that each node must support GPS.

19.3.11   Cluster-Based Routing Protocol (CBRP)

Cluster-based routing protocol (CBRP) is an on-demand, hierarchical nonuniform routing protocol [32]. In CBRP, nodes are organized in a hierarchy and form clusters. Each cluster has a cluster-head that knows the addresses of its cluster members. Cluster head co-ordinates the data traffic within the cluster and with/to other clusters. Broadcasting route requests to the cluster head are equivalent to broadcasting route requests to every node in the network. Each node is required to keep the cluster adjacency table and neighbour table, which also contain link type. CBRP uses a simple cluster formation strategy in which the cluster diameter is only two hops, with a cluster-head in each cluster. Clusters can overlap, but each node must be a part of at least one cluster [33]. The advantage is that only cluster heads exchange routing information and therefore, the control overhead is much less than the traditional flooding methods. However, there are overheads associated with cluster formation and maintenance. Another disadvantage is that in CBRP, some nodes may have inconsistent topology information due to long propagation delay, which may result in routing loops.

19.4   Mobile Ad Hoc Routing Protocol Requirements and Performance Evaluation Metrics

Due to the highly dynamic nature of MANETs, designing suitable ad hoc routing protocols are a challenging issue. The ultimate goal of an ad hoc routing protocol is to provide proper, efficient and effective route establishment among nodes, so that messages may be delivered in a reliable and timely manner. Route construction and maintenance should be done with minimum overhead and bandwidth consumption.

Many routing protocols have been proposed since the conception of MANETs, mainly focusing on solving specific issues and under particular ad hoc scenarios. To achieve the required efficiency, routing protocols for MANETs must satisfy special

characteristics. Important characteristics are identified by the Internet engineering task force (IETF) MANET Charter in RFC 2501 [34]. These will be discussed in the next subsection.

The research goal of the IETF MANET charter group is to concentrate on standardization of functionalities of routing protocols for both static and mobile wireless applications. Several IETF MANET Internet drafts have been produced so far, but only two proactive routing protocols, namely optimized link state routing (OLSR) [35] and topology dissemination based on reverse-path forwarding (TBRPF) [36] and two reactive routing protocols, namely AODV and DSR, have reached a reasonable level of development in terms of analytical studies and prototyping [37]. In the following two subsections, the requirements of an ideal ad hoc routing protocol and some common metrics to evaluate a performance of an ad hoc routing protocol identified by the IETF MANET charter group will be discussed, which can give a better understanding of strengths and weakness of a protocol.

19.4.1   Characteristics of Ad Hoc Routing Protocols

The fundamental characteristics of mobile ad hoc routing protocols are exemplified below.

- *Distributed routing*: Routing protocols must be fully distributed, as this approach is more fault tolerant than centralized routing.
- *Adaptive to topology changes*: Routing must adapt to frequent topological and traffic changes that result from node mobility and link failure.
- *Proactive/reactive operation*: The routing algorithm may intelligently discover the routes on demand. This approach will be useful to efficiently utilize the bandwidth and energy resources, but comes with the cost of additional delay. However, in certain conditions, the delay incurred by on-demand operation would be unacceptable.
- *Loop free routing*: Routes free from loops and stale paths are desirable. Perhaps to increase robustness, multiple routes should be available between each pair of nodes.
- *Robust route computation and maintenance*: The smallest possible number of nodes must be involved in the route computation and maintenance process, to result in minimum overhead and bandwidth consumption.
- *Localized state maintenance*: To avoid propagation of overheads, localized state maintenance is desirable.
- *Optimal usage of resources*: The efficient utilization and conservation of resources such as battery power, bandwidth, computing power and memory are required.
- *Sleep mode operations*: To reduce energy consumption, the routing protocol should be able to employ some form of sleep mode operation. Nodes that are inactive should switch to "sleep mode" for arbitrary periods.
- *Quality of Service*: Routing algorithms are required to provide certain levels of QoS in order to meet specific application requirements.

- *Security*: Some form of security protection is desired to prevent disruption due to malicious modifications of protocol operations.

In the next subsection, we will discuss the metrics that can analyze the performance of protocols with respect to the characteristics mentioned above.

19.4.2 Performance Evaluation Metrics

To evaluate the performance of a routing protocol, it is necessary to have some common metrics to assess the level of efficiency, scalability and adaptability. These metrics should be independent of the context. A protocol can be evaluated in different ways and from various angles, depending on the metrics adopted. Effective metrics identified by IETF MANE charter group are listed below:

- Packet delivery ratio/packet loss rate.
- End-to-end throughput.
- End-to-end delay.
- Routing/control overhead (can be measured in number of bits or packets).
- Hop Count.
- Route Acquisition time.

These metrics can be evaluated in terms of the following changing network conditions. Changing any of these factors can affect the protocols' behaviour:

- Mobility – node speed expressed in metres per second (m/s).
- Network size – number of nodes.
- Traffic flow/traffic patterns – the rate at which packets are transmitted, measured in packets per second (pkts/s).
- Network connectivity – average node degree, i.e., the average number of neighbours of a node.
- Topological rate of change – the speed at which network topology changes.
- Link capacity – bandwidth, measured in bits per second (bps).
- Traffic load – number of sources and average traffic injected by each source.
- Fraction and frequency of sleeping nodes – percentage of sleeping and awakening nodes.

In Sect. 19.5, we will look at the work done in literature to assess different protocols (defined in Sect. 19.3) performance with some of the metrics discussed above.

19.5 Performance Analysis Based on Existing Literature

In recent years, a variety of routing protocols for MANETs have been proposed. However, the analysis of existing systems is often restricted to specific scenarios and fails to identify the protocol limitations and causes. A good review is provided

in [10, 11]. Many other articles provide a protocol assessment, which is specific and often does not allow drawing general conclusions. For brevity we mention below the most significant articles, dividing them into three groups.

19.5.1 Approaches Based on Varying Pause Time and Traffic Load

The first attempt to analyze the performance of ad hoc routing protocols was made by Samir et al. in which DSDV, AODV, DSR and TORA were evaluated over a network of 30 nodes in an area of $1,000\,\mathrm{m} \times 1,000\,\mathrm{m}$, considering varying number of conversations per node (traffic flow) and speed in two different scenarios. In lower speed scenario, the speed was uniformly distributed between 0.4 and 0.6 m/s. At higher speed scenario, speed was uniformly distributed between 3.0 and 4.5 m/s. The evaluation was based on packet delivery ratio, end-to end delay and routing load. The mobility model adopted was based on a discrete-event framework. Each node chooses a direction, speed and distance of move based on a predefined distribution and then computes its next position accordingly.

The authors found that DSDV provides excellent performance by delivering almost 100% packets at around 6 ms delay. However, this is countered by a high routing overhead. AODV and DSR performance was comparable in all scenarios. However, at lower speeds, DSR introduces a smaller routing load than AODV. Per contra, at higher speeds, the result was reversed [38, 39].

Broch et al. investigated packet delivery ratio, routing overhead and path optimality of DSDV, AODV, DSR and TORA in a network of 50 and 60 nodes, considering varying pause time from 0 to 900 s, speeds of 1, 10 and 20 m/s, and an area of $1,500\,\mathrm{m} \times 300\,\mathrm{m}$ [25]. Similar work was done by Jiang et al. who investigated the amount of data delivered, control overhead and average latency of AODV, STAR and DSR over varying pause time in the range of 0–900 s and a network of 40 nodes with constant speed of 20 m/s, in an area of $4,000\,\mathrm{m} \times 4,000\,\mathrm{m}$ and $5,000\,\mathrm{m} \times 3,000\,\mathrm{m}$ [8]. The mobility model used in both cases was the random way point mobility model [40].

In the first case, the performance of DSR was better than all other protocols, for all values of pause time and mobility speed. This was achieved at the expense of higher routing overheads. AODV performs almost the same as DSR, but incurs lower routing overheads. DSDV performance is good at higher pause time between 100 and 900 s and lower mobility, but fails to converge as node mobility increases. TORA performance was the worst in all scenarios.

In the latter case in [8], the performance of all the protocols were almost similar in all scenarios and only minor differences were observed. However, STAR introduces less control overheads than others. The performance of all the protocols degrades at higher pause times, making them unable to delivery any data packet for values greater than 600 s.

Other work results from the same simulation setup, but analyzes different protocols. In [41] the authors investigate packet delivery fraction, average end-to-end delay, normalized routing load and normalized medium access control (MAC) load of DSR and AODV. On the other hand, Boukerche considers AODV, CBRP, DSR, DSDV and preemptive AODV (PAODV) [33]. The author adopts throughput, average end-to-end delay and routing overheads as evaluation metrics.

In both works, the simulation model was based on two different groups of experiments. The simulation model has 50 nodes over a 1,500 m × 300 m area in the first group of experiments and 100 nodes over 2,200 m × 600 m area in the second group of experiments, with varying pause time in the range of 0–800 s, constant speed of 20 m/s, along with number of sources varying from 10 to 40. The random way point mobility model was used for the simulations.

In [41], DSR outperforms AODV in terms of delay and throughput, but with smaller number of nodes and at a lower load and/or mobility speed, and generates less routing load. However, AODV outperforms DSR at higher load and mobility, but with a slightly higher routing overhead.

Whereas in [33], CBRP and DSR outperform all others in terms of higher throughput, but introduce higher delay. AODV comes next, but with a lower delay. However, DSR produces less routing overheads than CBRP and AODV. DSDV performance was worst among all. PAODV performance was slightly better than AODV.

This first group of works carries out a performance comparison between proactive and reactive protocols by varying pause time or mobility at invariable network size. The pause time is varying in the range of 0–900 s, which reflects low mobility because after 100 s of pause-time, nodes become almost stationary.

It is worth noting that most of the above mentioned analyses were performed on high-density networks. An exception is represented by [8] in which nodes are sparsely connected. The results observed from all above research papers were slightly contradictory for few protocols. This is due to different scenario setups.

Overall, in some cases, DSDV performs better at higher pause time (more static conditions), but introduces larger overheads. DSR performance was satisfactory at lower mobility and load conditions. However, AODV performance was better under highly dynamic conditions with lower delay, but with more routing overhead. STAR performance was moderate. The performance of TORA observed was worst among all of these scenarios.

19.5.2 *Approaches Based on Varying Mobility and/or Traffic Flow*

In the second group of work, Johansson et al. focus on the evaluation of delay, throughput and routing overheads of DSDV, AODV and DSR in a network of 50 nodes, varying speed from 0 to 3.5 m/s and varying traffic flow from 5 to 20 pkts/s, in an area of 1,000 m × 1,000 m and a constant pause time of 1 s. The mobility model used in this case was proposed by the authors. Both AODV and DSR perform quite

well in almost all scenarios, but DSDV performance degrades with the increase in mobility. However, DSR performs better than AODV at low traffic flow; at higher traffic flow, AODV was better [29].

A similar simulation setup was adopted by Camp et al., but with varying speed from 0 to 20 m/s [42], in which DSR, DREAM and LAR were analyzed by evaluating packet delivery ratio, average end-to end delay, data overhead, control overhead and total number of packets transmitted per data packets delivered. In this case, DSR and LAR achieve higher packet delivery ratio (at lower speeds), which decreases when speed increases.

DREAM was quite stable with increases in mobility. Similar results were observed at delay and at overheads for DREAM; at low mobility, these were higher than others, but remain constant with the increase in mobility. Delay introduced by DSR was higher than LAR and overheads generated by both were almost similar.

Lee et al. investigate five different protocols, WRP, FSR, DSR, LAR and DREAM on 50 nodes, varying speed from 0 to 20 m/s and an area of 750 m × 750 m. These protocols were evaluated by analyzing the packet delivery ratio, hop count, data overhead, control overhead, total number of packets transmitted per data packets delivered and varying traffic load. The results were observed in two different mobility models (random way point and group mobility model).

In case of random way point, DREAM performance was more promising at increasing speed, but with slightly higher overhead than LAR and DSR. LAR and DSR performance was better, but slightly degraded with mobility. FSR was found to be sensitive to mobility and its performance decreased with the increase in speed. WRP was unable to reach the same level of efficiency at higher mobility, as performance degraded significantly. Along with that, the overheads generated by FSR and WRP were also the highest among all. However, in the case of group mobility model, most performance factors gave comparable results, with the exception of DREAM. In the case of WRP, packet delivery ratio increased with mobility, instead of decreasing. LAR and DSR were still the best performing protocols [14, 28].

In almost all the work mentioned in this group, overall DSR, LAR and AODV outperform than others. DREAM performance was contradictory in different papers, but overall it was considered a reliable one. FSR comes next, performing better than WRP.

19.5.3   Approaches Based on Varying Number of Nodes

In the third group, Layuan et al. evaluate packet delivery ratio, end-to-end delay, data throughput, routing load, jitter and number of broken links in DSDV, AODV and TORA, by varying the number of nodes [43]. The nodes were randomly placed in a 1,000 m × 1,000 m area with constant speed of 40 m/s and pause time of 0 s. The throughput for AODV and DSR was higher and it was increasing with the number of nodes. Then comes DSDV which performed better than TORA, which was unaffected by changing number of nodes, but lower among all. The routing load for

all protocols was increasing with the increase in number of nodes except for TORA. Delay produced by DSR was much higher with more nodes than any other protocol. However, the delay introduced by AODV and DSDV was very low than TORA.

In [44], we have made a comparison between AODV, DSR, FSR and LAR1. We evaluated the packet delivery ratio, average end-to-end delay, throughput and routing overhead by varying network size (from 10 to 50 nodes), mobility (from 1 to 21 m/s) and traffic flow (20–100% sources). The nodes were randomly placed in a 1,400 × 1,400 area. We placed particular care in choosing simulation parameters and their ranges to obtain four scenarios that complement existing studies.

The study shows that the performance of LAR was promising in almost all scenarios, but with a high end-to-end delay varying between 10 and 100 s. AODV was the second best performing protocol, but resulted to be more sensitive than the others to network size and traffic load. AODV performance is better than DSR for dynamic changing conditions. However, FSR performance was poor in all scenarios, which mainly depends on the scope of fisheye and the frequencies at which updates are sent.

19.6 Discussion

From the above discussion, it is clear that some protocols perform better under specific scenarios, but also exhibit significant drawbacks when simulation conditions vary considerably. In fact, the analysis of the same protocols performed by different authors often leads to contradictory results. In many cases, this is due to different simulation setups, the adoption of different mobility models or even the use of different simulation environments.

Some work is based on random node placements. Others adopt a uniform model with continuously moving nodes. In either cases, the topology changes randomly and unpredictably, which makes it difficult to replicate experiments and produce comparable results.

The analytical studies presented in the literature so far take into consideration mainly mobility, pause time, traffic flow, traffic load and network size. However some other evaluation network conditions are equally important, as identified by IETF MANET charter. The ones discussed in this chapter include network connectivity, link capacity, topological rate of change and fraction of sleeping nodes. An in-depth analysis based onthese factors should be the subject of future investigations, as this will most probably unveil new, noticeable effects on protocol behaviour. Referring back to Fig. 19.1, we see that a broad variety of protocols has been proposed to date. Nevertheless, only few of them have been studied in depth and very few have actually been prototyped, beyond the simulation stage. Addressing these shortcomings should be a priority in future work, along with a greater effort to achieve interoperability among different systems and eventually, some level of standardization.

19.7 Conclusion

This chapter provides a detailed analysis of different MANET routing protocols. We present a taxonomy that extends existing ones, identifying also key parameters, metrics and mechanisms for the classification and evaluation of routing in MANETs. After that, we use this classification to capture the state-of-the-art in the performance evaluation of the most significant routing approaches. This review leads to the identification of promising research issues beyond the study of new protocols. We come to the conclusion that there is also a need to improve simulation environments, design and assessment methodologies, allowing for the study of protocols under a broader range of parameters, factors and scenarios.

Abbreviations

ABR   Associativity-based routing
AODV   Ad hoc on-demand distance vector
CBRP   Cluster-based routing protocol
DAG   Directed acyclic graph
DBF   Distributed Bellman Ford
DREAM   Distance routing effect algorithm for mobility
DSDV   Destination sequence distance vector
DSR   Dynamic source routing
FSR   Fisheye state routing
GPS   Global positioning system
IETF   Internet engineering task force
LAR   Location aided routing
LMR   Light-weight mobile routing
LORA   Least overhead routing approach
MANET   Mobile ad hoc network
OLSR   Optimized link state routing
SLURP   Scalable location update routing protocol
STAR   Source tree adaptive routing
TBRPF   Topology dissemination based on reverse-path forwarding
TORA   Temporally ordered routing algorithm
WRP   Wireless routing protocol
ZHLS   Zone-based hierarchical link state

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