SURVEY AND TAXONOMY OF UNICAST ROUTING PROTOCOLS FOR MOBILE AD HOC NETWORKS

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ABSTRACT

The purpose of this paper is to survey the unicast routing protocols for mobile ad hoc networks (MANETs) and study their primary route selection principle. In this context, we did an exhaustive survey of unicast MANET routing protocols proposed in the literature. Qualitatively, based on their primary route selection principle, we show that all these protocols could be placed under one of two broad route selection categories: routing based on minimum-weight path and routing based on stability. In addition to the primary route selection principle, we also identify the underlying routing metric and the routing philosophy (proactive, reactive, flat, hierarchical, location-awareness, power-sensitiveness and multi-path capability) adopted by the different routing protocols. We believe the survey can be a great source of information for researchers in ad hoc networks.

KEYWORDS

Routing Protocols, Survey, Mobile Ad hoc Networks, Unicast, Stability, Minimum-Weight Path

1. INTRODUCTION

A mobile ad hoc network (MANET) lacks a fixed infrastructure and has a dynamically changing topology. Nodes in a MANET move freely and independently of one another. Two nodes can communicate directly if they are within each other's transmission range. The transmission range of mobile nodes is often limited due to battery power constraints, frequency reuse, channel fading, etc. Thus, routes between nodes are often multi-hop, necessitating the development of efficient routing protocols with an objective to optimize one or more routing qualities or metrics. In a dynamic environment like that of the MANETs, optimal routes, with respect to a particular metric, keep changing with time. To maintain optimality in their design metric (like hop count, delay and bandwidth usage) routing protocols incur a large network overhead. The commonly used approach of flooding the route request and/or reply packets can easily lead to congestion and also consume battery power.

Stability is an important design criterion to be considered while developing multi-hop routing protocols for resource-constrained environments like MANETs. MANETs are easily prone to congestion due to the low to moderate capacity of the wireless links. Also, mobile nodes used in energy-constrained environments like sensor networks and embedded networks cannot afford to lose their battery power quickly. Frequent route changes can also result in out-of-order packet delivery, causing high jitter in multi-media, real-time applications. The application layer is overloaded as it has to take care of lost and out-of-order packets, leading to reduced throughput. Thus, stability is also important from Quality of Service (QoS) point of view.

Routing protocols belonging to different routing philosophies have been proposed in the literature. A proactive routing protocol pre-determines the routes between any two nodes irrespective of the need for such routes. On the other hand, reactive routing protocols discover routes only when required (i.e., on-demand). Some protocols consider all nodes as peers (flat network topology), while others consider a hierarchy among nodes and only nodes in the same level of the hierarchy are treated as peers. Some protocols assume each node is aware of its current location in the network and also can learn the locations of other nodes in the network. Routing protocols that are sensitive to the available battery power at the nodes and the energy to be spent in packet transfer have been also proposed in the literature. Some routing protocols discover and maintain multi-paths for a given node pair. The motivation and usage for these multiple paths depends on the protocols.

We present an exhaustive survey of unicast routing protocols for ad hoc networks proposed in the literature. It is impossible to say which routing protocol is better for a given condition. Hence, the motivation is to group these routing protocols under different routing strategies or categories and then compare these strategies as such instead of the individual protocols. To our surprise, we found that based on their primary route selection principle, all of these protocols could be grouped under either minimum-weight path based routing or stability based routing strategies. In [45], we have used this observation and compared the shortest hop based routing (a common case for minimum-weight path based routing) and stability-based routing strategy for minimizing energy consumption under different conditions of node mobility, density, offered traffic load and different levels of overhearing at the intermediate nodes. Similarly, the results presented in this survey can be used by the research community and this can lead to a new paradigm for the comparison of routing protocols in mobile ad hoc networks.

The survey is organized as follows: In Section 2, we present the unit disk graph approximation of ad hoc networks, which we use as the basis for placing a routing protocol under either one of the two routing strategies. In Section 3, we present the survey of the protocols in alphabetical order. We describe the basic functionality of each routing protocol including the routing metrics, and then present our classification of the protocol under one of the two categories. We also describe the routing philosophies (proactive, reactive, flat, hierarchical, location-awareness, power-sensitiveness and multi-path capability) of the protocols. Section 4 concludes the paper.

2. UNIT DISK GRAPH APPROXIMATION OF AD HOC NETWORKS

An ad hoc network is often approximated as a unit disk graph [36]. In this graph, the vertices represent the wireless nodes and an edge exists between two vertices u and v if the Euclidean distance between u and v is at most 1. Each node is assumed to be located in the Euclidean plane and have a transmission coverage represented by a unit disk of radius 1. Two nodes can communicate only if each node lies within (or on the edge of) the unit disk of the other node. The unit disk graph model neatly captures the behaviour of many practical ad hoc networks.

2.1 Minimum-Weight Path based Routing

The edges in the unit disk graph could be assigned weights depending on the route selection metric of the protocol analyzed. For example to analyze a routing protocol that selects minimum hop paths, all edges could be assumed to be of unit weight. For routing protocols that are designed to select the least congested route, the edge weight could be the number of packets in the queue of the downstream node. The minimum-weight path among the set of available paths is the path with the minimum total weight summed over all its edges. Many ad hoc routing protocols designed to optimize a particular route metric (e.g., hop count, delay, route relaying load per node, end-to-end energy consumption per packet, etc.) exist in the literature.

2.2 Stability based Routing

In the presence of node mobility, a route failure occurs when any of its constituent edges disappears. Route discovery in ad hoc networks is a very expensive operation involving the flooding of control packets throughout the network. Frequent flooding can prohibitively increase the energy consumption and bandwidth usage. Thus, routing protocols for ad hoc networks are often designed to stay with a selected route as long it exists. Under such a design strategy, the route discovery overhead depends on the lifetime of the routes selected. Protocols classified under stability category are primarily designed to minimize the number of route discoveries or the route discovery overhead. The weights of the edges in the unit disk graph capture the lifetime of a link in some fashion (e.g., signal strength, number of beacons exchanged, etc.) and the route expected to exist for a longer time is preferred. Such a route need not be a minimum-weight path in the unit disk graph as there might exists a bottleneck link whose weight itself could decide the final route selected.

3. SURVEY OF UNICAST ROUTING PROTOCOLS

3.1 Ad hoc On-demand Distance Vector (AODV) Routing Protocol

AODV [55] is a single-path, reactive routing protocol. Route discovery is using a route request (RREQ) – route reply (RREP) cycle. When a source node has data to be sent to a destination node and does not know the route to the destination node, floods a route request (RREQ) packet throughout the network. Several RREQ packets, each travelling on a different path, will reach the destination. The destination node replies (RREP packet) only to the first RREQ packet and drops subsequent RREQ packets with the same source sequence number and broadcast ID. The RREQ packet that arrived at the earliest is likely to have traversed a path with low delay and/or hop count. Representing the weight of each link in the network by the delay incurred on the link, AODV reduces to finding a minimum-weight path between the source and the destination.

3.2 AODV-Backup Routing Protocol (AODV_BR)

AODV-BR [37] is a backup route maintenance strategy using AODV. According to this scheme, neighbours of nodes that lie on the primary path overhear the RREP packet sent by the destination to the source. These neighbours record the sender of the RREP packet as the next hop (downstream node) to the destination in an alternate routing table. This strategy reduces the number of route discoveries significantly when the mobility is less. As the primary path is selected similar to the procedure used in AODV, it is most likely to be a minimum delay path, while the alternate paths have hop counts shorter or equal to the primary path. Thus, AODV – BR could fit into the category of routing protocols based on minimum-weight path routing.

3.3 Ad hoc On-demand Multi-path Distance Vector Routing (AOMDV)

AOMDV [44] is based on AODV and obtains multiple loop-free link-disjoint paths using the following property observable in flooding: Let S be a node that floods a packet m to the network. At any node I ($\neq S$), the set of copies of m received via different neighbours of S constitute a set of node disjoint paths (and hence the link-disjoint paths) from I to S.

Loop freedom is guaranteed using the notion of "advertised hop count" for a given destination sequence number (or RREQ packet) at each node in the network. The "advertised hop count" of a node I is basically the hop count incurred by the first RREQ packet for a given destination sequence number from the source S to node I. When a node has no route to the destination, it forwards only the first arriving RREQ packet. When a node has a valid route to the destination and receives a duplicate RREQ packet, it checks whether the RREQ packet arrived on a new node-disjoint path using the above flooding property. If so, the node checks whether the hop count incurred by this RREQ is less than that of the primary path. As the primary path is selected similar to the procedure used in AODV, it is most likely to be a minimum delay path, while the alternate paths have hop counts shorter or equal to the primary path. Thus, AOMDV could fit into the category of routing protocols based on minimum-weight path routing. Since, AOMDV selects only link-disjoint or node-disjoint paths, the multiple paths are likely to have infrequent route discoveries at low mobility compared to single-path AODV.

3.4 Ant-based Routing Algorithm (ARA)

ARA [21] is a reactive routing protocol based on swarm intelligence, especially the ant colony based meta heuristic. Ant colony algorithms are based on the simple ability of ants to solve complex problems by cooperation. Interestingly, ants do not need to communicate directly to solve the problem. They communicate indirectly by modifying their environment (stigmergy). The meta heuristic is based on the food searching behavior of ants. Ants deposit a cumarin (hydroxyl cinnamic acid) like substance called pheromone. Ants deposit pheromone on the way from their nest to the food. The usage of a certain path is indicated by the concentration of pheromone on that path. Due to diffusion effects, the concentration of pheromone decreases. Ants taking the shortest path from the nest are the first to reach the place where the food is. As a result, concentration of the pheromone on the shortest path increases relatively faster than that of the other paths. Eventually, the shortest path will be identified by all the ants after sometime and is the only path used. Thus, ARA is based on minimum-weight routing.

Initially, the pheromone tracks are established using the FANT and BANT packets. A FANT (Forward Ant) packet is similar to the route request packet and it establishes the pheromone track to the source. A BANT (Backward Ant) packet is similar to the route reply packet and it establishes the pheromone track to the destination. No further route discovery is initiated. Subsequent data packets are used to maintain the path. When nodes forward a data packet on a path, they increase the pheromone concentration along the edges of the path by a constant value. As a result, the path to the destination is strengthened. When a path is not used for sometime, the pheromone concentration along the non-used links gets reduced.

3.5 Associativity-Based Routing (ABR)

ABR [68] is a reactive routing protocol and is one of earliest works on path stability. Each node maintains an associativity table which records the associativty ticks (the number of beacons received from a node) with respect to each of its neighbors. Associativity ticks greater than an associativity threshold A_{thresh} represent periods of association stability. Association stability defines the strength of the link (i.e., connection stability) between two nodes over time and space. The destination examines the associativity ticks along each of the learned paths and selects the best one (the path with the highest association stability). If more than one path has the same overall degree of association stability, the destination selects the shortest-hop path. The destination then sends a REPLY packet along the reverse direction of the selected route.

3.6 Backup Source Routing (BSR) Protocol

BSR [22] is an extension of Dynamic Source Routing (DSR, [32]) in which the primary path is a shortest delay (shortest hop) path and the backup path is a more durable (stable) path connecting the source and destination. The backup path is less similar with respect to the links and has more disjoint sub-paths in comparison to the primary path. The heuristic function used to select the most durable path is $C(\pi,\pi') = \frac{L(\pi,\pi') + |\pi'|}{D(\pi,\pi')}$ where π is the primary path and π' is the backup path. L(π, π') is the number of common links between the two paths, D(π, π') is the number of sub-disjoint paths between π and π', |π'| is the number of hops in π'. If Q is the set of candidate backup paths learnt during route discovery and π is the primary path selected, then the most durable backup path $\pi' \in Q$ is the one which has the least value of the heuristic cost function C (π, π'). BSR is a mix of both minimum-weight based and stability based routing.

3.7 Battery Energy Efficient (BEE) Routing Protocol

The cost function in the power-sensitive BEE protocol [9] includes a node-specific parameter (residual battery power) and a link-specific parameter (the packet transmission energy). The routing protocol chooses the route that has a minimum value for this cost function. Hence, BEE could fit into the category of routing protocols based on minimum-weight path routing.

3.8 Caching and Multi-path Routing Protocol (CHAMP)

CHAMP [70] is designed to select the shortest multi-path from the source to the destination. A shortest multi-path is defined as the directed acyclic graphs formed by the successor entries of the routing tables of the routers in all the loop-free paths from the source to the destination [73]. A node forwards the data packet to the least used next hop neighbour along the shortest multi-path. This ensures that routes are refreshed periodically and also load balancing along the multiple paths is done in a round-robin basis. Representing the link weights as the load on the downstream node, CHAMP chooses the path with the least weight. Hence, CHAMP belongs to the category of routing protocols based on minimum-weight path based routing.

3.9 Cluster-Based Routing (CBR)

The network is divided into clusters. Cluster heads are elected using the “min-ID” algorithm. Route discovery in CBR [30] is similar to that in DSR except that the forwarding nodes of the route discovery packets are only the cluster heads and gateways. Route shortening is done if two gateways or cluster heads can directly reach each other without one or more intermediate nodes on the route. Thus, CBR is designed to aim for the shortest hop route from the source to the destination across one or more intermediate clusters. CBR could be grouped under the category of routing protocols based on the minimum-weight path routing.

3.10 Cluster head Gateway Switching Routing (CGSR) Protocol

Nodes are grouped into clusters and a cluster head controls the cluster. One of the important criteria for cluster-head election algorithms is stability. Frequent cluster head election can result in prohibitive overhead. In CGSR [8], a stable least cluster change (LCC) clustering algorithm is preferred over the widely used lowest (highest) ID and the highest connectivity algorithms. According to the LCC algorithm, cluster heads change only when two cluster heads come into contact, or a node moves out of the range of all cluster heads. At each mobile node, a “cluster-member-table” is maintained where in information about the destination cluster head of each mobile node in the network is stored. In addition, a routing table that stores information about the next hop to reach the destination is stored at each node. On receiving a packet, a node uses the cluster member table to determine the nearest cluster head along the route to the destination; then uses the routing table to determine the next hop node used to reach the selected cluster head. Using DSDV, the cluster member table is periodically exchanged among all nodes in the network and the routing table is periodically exchanged within a cluster. Traffic from a source to destination is routed using a hierarchical cluster head-gateway routing approach where DSDV is the underlying routing scheme. CGSR fits under the minimum-weight path routing category.

3.11 Compass Routing

According to the compass routing algorithm [35], a node u having a data packet to be sent to a node t, forwards the packet to the neighbouring node v such that the angle between the lines joining v, u and v, t is minimum. The strategy is prone to loops and several improvements are reported in [71]. It has been shown in [35] that compass routing produces shortest hop paths for certain geometric embeddings (e.g., trees) of planar graphs. Hence, compass routing could be included in the class of protocols based on minimum-weight path based routing.

3.12 Conditional Min-Max Battery Cost Routing (CMMBCR)

The basic idea behind CMMBCR [69] is that if all nodes in one or more routes between a given source-destination (S-D) pair have residual battery power above a threshold value γ, the route with the minimal total transmission power among these routes is chosen. If all routes between the *S-D* pair comprise nodes with residual battery power less than the threshold value, the algorithm avoids routes that include nodes with little residual battery power. The performance of CMMBCR thus depends on the threshold γ. If γ=0, the algorithm always uses MTPR [69]. If $\gamma = B_{init}$, the maximum value of the residual battery power of a node, the algorithm always uses MMBCR [69]. The actual value of γ at which the transition from MTPR to MMBCR occurs depends on the traffic load and the mobility conditions. As we have shown that MTPR and MMBCR could fit into one of the two routing categories, CMMBCR also could fit all in either of the two routing categories.

3.13 Core Extraction Distributed Ad hoc Routing (CEDAR) Algorithm

CEDAR [63] approximates a core as a minimum dominating set of the ad hoc network. Nodes in the core establish a unicast virtual link (via a tunnel) with peer core nodes that are at most three hops away. Link state information corresponding to stable high-bandwidth links are propagated across the core. An add wave is generated when a link comes up and a delete wave is initiated when a link goes down. The add wave is propagated at a constant delay at each node; while the delete wave is propagated immediately to the next hop. The slow moving add wave corresponds to an increase in the available bandwidth of the link, while the fast moving delete wave corresponds to a decrease in the available bandwidth of the link. The route computed using the set of stable links is called the shortest widest path or the maximum bandwidth path. If there is a tie among two or more paths with the same maximum bandwidth, the one with the least hop count is chosen. CEDAR falls under the category of routing using stable paths as the maximum bandwidth path is composed of stable, reliable links.

3.14 Destination Sequenced Distance Vector (DSDV) Routing Protocol

DSDV [56] is a pro-active, table-driven protocol based on the distributed version of the classical Bellman Ford algorithm [16]. Each mobile node stores a routing table that contains information about all the possible destinations in the network. Each entry in the routing table is marked with a sequence number assigned by the destination node and contains information like the number of hops required to reach the destination and the next hop on the path to the destination. The route labelled with the latest sequence number is always used to avoid stale routes. If two updates have the same sequence number, the route with the minimum number of hops to reach the destination is used. Routing table updates are propagated periodically across all nodes to maintain table consistency. Thus, in spite of the high communication overhead, a node always learns of the shortest hop route to the destination. DSDV fits under the minimum-weight path routing category.

3.15 Distance Routing Effect Algorithm for Mobility (DREAM)

DREAM [3] is a proactive, multi-path, location-aware routing protocol. DREAM makes use of the so called distance effect to regulate the frequency of topological updates. According to the distance effect, the greater the distance between two nodes, the lower is their relative mobility. DREAM also makes use of the mobility rate of the nodes to regulate the frequency of location updates: the faster a node moves, the higher is the frequency of location updates from that node. A node records the locations of all its peer nodes in a location table. Using this location information, a node forwards the data packet to a set of neighbours that lie in the direction to the destination. If no such neighbours could be selected, the data packet is dropped. The destination responds with an ACK when it receives the data packet forwarded by a designated set of nodes. The ACK is forwarded to the source node in a fashion similar to that of the data packet. If the source node fails to receive an ACK through a designated set of nodes, it floods the data packet. Once at least one path between the source and destination are learnt, the source could start sending data packets using the learned paths, preferably the shortest hop path. The routing metric in DREAM has been referred to as shortest hop path in [27]. Hence, DREAM belongs to the class of protocols based on minimum-weight path based routing.

3.16 Dynamic Address Routing (DART)

Dynamic addressing and DART [15] have been proposed as a solution for scalable routing in ad hoc networks. Each node possesses a network-wide unique permanent identifier (node id) and a transient routing address that indicates the location of the node in the network at any given time. A distributed lookup table maps every node identifier to its present routing address. When a node newly joins the network, it chooses an unoccupied address by listening to the periodic routing updates from its neighbouring nodes. The node then registers its unique identifier and the newly obtained routing address in the distributed lookup table. The routing address changes with mobility and the lookup table is updated accordingly. When a source node wants to send packets to a destination node whose identifier is only known, the lookup table is consulted to get the routing address of the destination node. The routing function used is a proactive distance vector routing and DART fits under the category of minimum-weight based routing. The average table size using dynamic addressing is O(*logn*) where as the message overhead in a reactive lookup protocol is O(n) where n is the number of nodes in the network. For sufficiently large networks and/or high connection establishment rates, the message overhead due to a flat reactive routing protocol would exceed the periodic update overhead in DART.

3.17 Dynamic Source Routing (DSR) Protocol

DSR [32] uses shortest hop path from the source to the destination. The destination replies to *all* requests in a single request cycle. Thus, the source learns multiple routes to the destination and stores them in the route cache. It does not check for node disjoint or link disjoint properties before using these routes. DSR fits into the category of routing protocols based on minimum-weight path routing.

3.18 Fisheye State Routing (FSR) Protocol

FSR [54] belongs to the class of proactive routing based on the hazy link-state algorithm used in wired networks. In link-state routing, the global topology information is stored at each node, using periodic and triggered flooding of link state updates. Hence, the time for a node to converge to a new topology is significantly less compared to the distance-vector based algorithm. Unfortunately, the flooding overhead becomes prohibitively high when the topology changes dynamically. FSR reduces the flooding overhead by employing only periodic link state updates in the network. The frequency of the link state updates at a node to the other nodes is decided based on the scope of those nodes. The scope is a set of peer nodes that can be reached with a given number of hops. A node updates its peers within a smaller scope more frequently in comparison to peers that are farther away. The tradeoff between the frequency of updates and the optimality of routes is analyzed in [59]. To find a route to the destination, a source node uses the approximate global topology map and finds the shortest hop route to the destination. The route has to be accurate enough to an extent that the packets sent in it would travel towards the destination. As the packet approaches the destination, it finds increasingly better routing instructions from nodes that get frequent link state updates from the destination. As the routing strategy is still to use minimum hop paths, FSR is based on minimum-weight path routing.

3.19 Flow Augmentation and Redirection Algorithms

These algorithms [6] proposed to maximize the system lifetime (the time at which the first node failure occurs) use the notion of shortest cost path routing using a distributed version of the Bellman Ford algorithm. The link cost c_{ij} of link (i, j) is defined as $c_{ij} = e_{ij}^{x1}\underline{E}_i^{-x2}E_i^{x3}$, where e_{ij} is the energy expenditure for unit transfer on link (i, j), $\underline{E}_i$ is the residual battery energy at node i, E_i is the initial battery power at node i and x_1, x_2 and x_3 are the non-negative weighting factors.

These weights can be suitably altered depending on the quality of the paths required, energy reserves at nodes and the desired system life time. For example, in the beginning when all the nodes have high residual battery power, it is better to go for a minimum hop (minimum energy) routing; while as time progresses, it is better to find routes that avoids power-depleted nodes. In the flow augmentation algorithm, the shortest cost path from an origin node to its destination nodes is determined and flow along this path is augmented by λQi where λ is the augmentation step size and Qi is the information generation rate at node i. The shortest cost paths are computed again and the flow augmentation is done. This procedure is repeated until any system node i fails. Lifetime of a path is the minimum of the lifetimes of the nodes on the path. In the flow redirection strategy, flow is redirected from paths with shorter lifetime to paths with longer lifetime; the result is the lifetimes of all the paths are equal and the system lifetime is increased.

The flow augmentation algorithm requires frequent route computations and transitions but it selects the shortest cost route each time. Hence it belongs to the category of routing protocols based on minimum-weight path routing. The flow redirection algorithm requires the computation of shortest cost route only once, and only the magnitude of the flows is altered across the routes. Hence it could fit into the category of routing protocols based on stability.

3.20 Flow Oriented Routing Protocol (FORP)

FORP [66] is a stable path routing protocol that utilizes the mobility and location information of the nodes to approximately predict the expiration time of a wireless link (LET). During the RREQ flooding process, before broadcasting the RREQ to the neighbourhood, a node records the LET of the link from which the RREQ message was received. The destination receives RREQs through several paths. The Route Expiration Time (RET) of a path is the minimum of the LET values of all the constituent wireless links on the path. The destination selects the route with the maximum value of the RET and the RREP is sent on the selected route. FORP falls under the category of stability-based routing.

3.21 Gafni-Bertsekas Link Reversal Routing (GB)

This is the first work for a highly adaptive loop-free multi-path routing algorithm [17] proposed for packet radio networks. A destination-oriented directed acyclic graph, d-DAG, is constructed at each source node. As a result, multiple paths are available from a source to the destination. A source may use these paths alternately or use the minimum hop path among those that are available. When all the paths get invalidated, the source node becomes a sink in the d-DAG and has no outgoing links. Paths are re-established using a sequence of "link reversals". During link failures, GB based routing protocols converge in portions of the network where the source and destination are connected, but may not converge when the source and destination are partitioned. GB algorithm is designed to minimize the route discovery overhead by maintaining multiple paths using the d-DAG, even though the paths may not be optimal. Hence it could fit into the category of routing protocols based on stability.

3.22 Geographic Distance Based Routing (GEDIR)

Three variations of greedy forward progress techniques were proposed in [41]. All the three techniques support efficient multi-path discovery. The first technique called "original GEDIR" is similar to that of MFR [28] – every intermediate node forwards the packet to the neighbor that is closest to the destination (called the best neighbor). The forwarding stops if the message is received from the best neighbor itself. In "alternate GEDIR", an intermediate node receiving a message the i^{th} time forwards the message to the i^{th} best closest neighbor to the final destination. Forwarding stops when the node has fewer neighbors than the number of copies received. In "disjoint GEDIR", an intermediate node upon receiving a message forwards it to the best neighbor node that has not yet received the same message and forwarded it previously. After this, the node stops further copies of the same message received. Simulation results in [41] show the hop count of paths discovered using “alternate GEDIR” and “disjoint GEDIR” are 5-8% and 15-25% larger than that of “original GEDIR”. This is because in the latter two strategies, the best neighbor node for a forwarding node is no longer the neighbor closest to the destination. Neighbor nodes closer to the forwarding node are likely to be selected which could possibly result in more stable but sub-optimal paths in terms of hop count. Thus, “original GEDIR” could be grouped under the category of minimum-weight routing, where as “alternate GEDIR” and “disjoint GEDIR” fall under the category of routing protocols based on stability.

3.23 Global State Routing (GSR) Protocol

GSR [7] maintains the knowledge of the full topology at each node as in link state routing, but adopts the link state dissemination mechanism used in DBF (distributed Bellman Ford) based algorithms like DSDV. In GSR, each node maintains its link state table based on the updates received from neighboring nodes and periodically exchanges it with its local neighbors only. Using the global topology map, each node computes the shortest hop path tree rooted at each node using Dijkstra’s algorithm modified to get the next hop table and the distance table parallel in tree construction. GSR belongs to the class of minimum-weight path routing protocols.

3.24 Greedy Perimeter Stateless Routing (GPSR) Protocol

GPSR [33] is similar to MFR when there is a neighbor node in the forward progress to the final destination. However, there could be topologies in which the only path from a transmitting node to the final destination would require the packet to move temporarily in a direction farther away from the destination (backward progress). In such cases, the algorithm traverses the boundaries of the gaps in the network until greedy forwarding is feasible. This is called perimeter routing. The protocol is called stateless because an intermediate node decides the next node to forward the received message only based on the knowledge about the location of the destination and the location information of neighboring nodes. In networks of reasonable node density, the necessity to do perimeter routing would occur less frequently and the protocol could be grouped under the category of minimum-weight based routing.

3.25 GRID Protocol

GRID [40] is a hierarchical location-aware routing protocol. The entire geographical area of the MANET is divided into logical grids each of size $d * d$. Grids are identified using the conventional (x, y) co-ordinate system, while hosts have their own unique ids. Routing information is maintained in a grid-to-grid basis rather than the usual host-to-host manner. Each grid has a gateway node that (i) forwards route discovery requests to neighbouring grids (ii) propagates data packets to neighbouring grids and (iii) maintains routes passing through the grids. Non-gateway nodes in a grid do not forward packets. Nodes near the centre of the grid are preferred to be the gateway of the grid. Such a gateway-election rule increases the probability of connectivity between grids. Route discovery procedure is similar to that employed in AODV, the exception being the route discovery RREQ packets are forwarded by the gateway nodes and routes are maintained on a grid-to-grid basis. When a gateway node moves into a neighbouring grid, the route could be still maintained by electing a new gateway node locally within the grid. The route discovery overhead is reduced drastically and routes generally fail, only when the source or destination moves out to a grid that is not the neighbouring grid in the existing route. Hence, GRID could be grouped under the category of stability-based routing protocols. The grid size represents the tradeoff between grid connectivity, route optimality and stability.

3.26 Implicit Source Routing (ISR) Protocol

ISR [29] is an extension of DSR to reduce the per-packet overhead incurred due to the route record carried in each data packet. The protocol uses the flow identification techniques similar to that used in MPLS [58] and ATM virtual circuits [66]. Each data packet is tagged with a flow identifier at the source. The flow identifier represents a logical flow from the source to the destination. Intermediate nodes along the route record the mapping of the flow identifier to the next hop to which packets belonging to a particular flow is to be forwarded. The mapping of flow identifier to the next hop is maintained in a soft-state basis. ISR belongs to the family of routing protocols based on minimum-weight path routing.

3.27 Landmark Routing Protocol (LANMAR)

A landmark node [53] is a representative node (or sometimes location) of a subnet of nodes that have commonality of interests and are more likely to move as a group. The underlying routing scheme is similar to that of FSR [54]. FSR table is bound to contain information about “all” nodes in the network; where as LANMAR table has information only about nodes in the scope and the landmark nodes. When a packet is to be forwarded, if the destination is within the scope of the sender, the packet is transmitted directly to the destination. If the destination is in another subnet, the subnet id field of the destination is searched and the packet is forwarded towards the landmark for that subnet. As stated before a landmark need not be a physical node and the packet need not go through a landmark node. Once the packet gets to the scope of the destination, it is directly delivered. LANMAR belongs to the category of minimum-weight path routing as it is similar to FSR and is a combination of link state and distance vector routing.

3.28 Lightweight Mobile Routing (LMR) Protocol

The LMR protocol [11] is based on the concept of “link reversal” similar to that of GB [17] and Temporally Ordered Routing Algorithm (TORA) [51]. The main difference between LMR and TORA is their reaction to link and route failures. LMR’s reaction to link failures is more pessimistic as it uses an erase and build mechanism, while TORA is more optimistic, reverses links to re-orient the destination-oriented DAG. LMR requires two passes to re-establish and converge to an alternate route, if one exists. When an alternate path exists, TORA requires only a single pass to detect it. On the other hand, LMR can erase invalid routes and detect partition in a single pass; TORA requires three passes to do the same. It has been conjectured in [12] that LMR may be used for sparse topologies where network partitions are more frequent and TORA be used for dense networks where network partitions are less frequent. LMR is also designed to reduce the control message propagation in the presence of highly dynamic mobile networking environment. As a result, shortest hop paths are given only secondary importance. LMR fits under the stability category.

3.29 Link-life Based Routing (LBR) Protocol

LBR [42] is a stability-based distributed adaptive routing protocol that uses the expected lifetime of wireless links (link lifetime) for path selection. The link life time is predicted by using linear regression of the variation of distance between nodes over a number of previous distance samples, sampled over time. During route discovery, a node i upon receiving the route request packet from a peer node j, attaches its own node id and also its expected link life time with node j. The packet is forwarded further if node i did not forward the packet before. The destination then selects the path with the maximum expected lifetime of the bottleneck link (the link with the minimum lifetime on the path).

3.30 Location-aided Routing (LAR) Protocol

The operation of LAR [34] is similar to that of DSR, except that the flooding of control packets is limited only towards the direction in which the source node is expected to be located. In this context, the source node defines the expected zone and request zone for a route request. The expected zone is centred in the vicinity of the destination node and is calculated purely based on the destination’s last known location and time combined with the current time and the average speed. The request zone is larger than the expected zone and it includes both the source and destination and is preferred to be as small as possible to reduce the magnitude of redundant broadcasts. The route selected is the shortest hop among the routes learnt by flooding across the request zone. LAR could be grouped into the category of routing protocols based on minimum-weight path based routing.

3.31 Location Prediction Based Routing (LPBR) Protocol

LPBR [46] attempts to minimize the number of route discoveries and the hop count of the paths for an *s-d* session. During a regular flooding-based route discovery, LPBR collects the locality and mobility information of nodes in the network and stores the collected information at the destination node of the route search process. When the minimum-hop route discovered through the flooding-based route discovery fails, the destination node attempts to predict the current location of each node using the location and mobility information collected during the latest flooding-based route discovery. A minimum hop Dijkstra algorithm is run on the locally predicted global topology. If the predicted minimum hop route exists in reality, no expensive flooding-based route discovery is needed and the source continues to send data packets on the discovered route; otherwise, the source initiates another flooding-based route discovery. LPBR falls under the category of minimum-weight path based routing as it always to determine minimum hop routes through flooding-based route discoveries and predicted global topologies.

3.32 Maximum Residual Packet Capacity (MRPC) Routing

Given the battery power level at all nodes, the MRPC algorithm [49] selects the path that maximizes the total number of packets that may be ideally transmitted. Such a path should exist for a long time; otherwise it is most likely not to transmit more packets. Hence, MRPC could be put under the category of stability based routing. Let the battery power of a node i at a certain time instant be B_i. Let $E_{i,j}$ be the transmission energy required by node i to transmit a packet over link (i, j) to node j. Let r be a route between the source S and destination D and it includes the link (i, j). Assuming all other flows sharing the path r do not transmit any further traffic, the maximum number of packets node i can forward over the link (i, j) to node j is defined as the node-link metric $C_{i,j} = \frac{B_i}{E_{i,j}}$. The maximum lifetime of the route r is determined by the weakest intermediate node – the one with the least $C_{i,j}$ value. $Life_r = \underset{(i,j)\in r}{Min}\{C_{i,j}\}$. If Q is the set of all available *S-D* routes, the MRPC algorithm selects the route $k \in Q$, such that

$$Life_k = \max\{Life_r \mid r \in Q\}$$

3.33 Maximum Survivable Routing (MSR)

MSR [43] takes into account the residual battery power at a node and the expected draining rate of this battery power. Accordingly, the remaining lifetime of a node I at time t, $(T_I(t))$ is defined as the ratio of the residual battery power of node I $(P_I(t))$ to the draining rate at the node $((P_I(0) – P_I(t))/t)$. In other words, $T_I(t) = \frac{P_I(t)}{\left(\frac{P_I(0) - P_I(t)}{t}\right)}$, where $P_I(0)$ is the initial battery power at node I. The utility function of node I at time t is then given by $u_I(t) = 1/T_I(t)$. The cost function for a route R at time t is defined as $C_R(t) = \left(\sum_{I\in R}(u_I(t))^{\beta}\right)^{1/\beta}$, where $\beta \geq 1$ is a tunable parameter. The route with the minimum cost function value is selected. Thus, MSR also fits into the category of category of minimum-weight routing.

3.34 Minimum Battery Cost Routing (MBCR)

MBCR [69] aims for a route with the maximum remaining battery capacity. Let B_i be the residual battery power at node i. The battery cost function at node i is given by $f_i(B_i) = \frac{1}{B_i}$. The battery cost of a route between a source S and destination D consisting of l nodes is given by $C_r^{S-D} = \sum_{i=0}^{l-1} f_i(B_i)$. Let Q be the set of all S-D routes. The desired route (route with the maximum remaining battery capacity) is the route $k \in Q$ that has the minimum battery cost and is given by $C_k^{S-D} = \underset{r \in Q}{Min}\{C_r^{S-D}\}$. The link weight can be mapped to the battery cost function of the downstream node i. The links to the destination have zero cost. MBCR basically reduces to the problem of computing the minimum-weight path from the source to the destination.

3.35 Minimum Interference (MIF) Routing Protocol

MIF [47] minimizes the end-to-end delay per data packet. MIF does not require periodic exchange of beacons in the neighbourhood. During the broadcast of RREQ messages, each node inserts its identification and location information. The interference index of a link is the number of interfering links surrounding it. Two links are said to interfere with each other, if the distance between the mid-points of the two links is within the interference range. The interference range is a function of the transmission range of the nodes. The interference index of a path is the sum of the interference index values of the constituent links. The destination uses the RREQs to locally construct a weighted graph of the network topology and selects the path with the minimum interference index value. MIF falls under the minimum-weight path based routing as it attempts to determine the path with the minimum interference index value so that the end-to-end delay can be minimized.

3.36 Minimum Transmission Power Routing (MTPR)

The MTPR scheme [69] uses the energy consumed per hop (n_i, n_j) between hosts n_i and n_j as the link metric. The total transmission power for route r, from a source S to destination D, P_r^{S-D}, is given by, $P_r^{S-D} = \sum_{i=0}^{l-1} P(n_i, n_{i+1})$ $\forall$ $n_i \in r$ and n_0 = source S, n_l = destination D. Let Q be the set of all available S-D routes. The desired S-D route $k \in Q$ is given by $P_k^{S-D} = \underset{r \in Q}{Min}\{P_r^{S-D}\}$. MTPR falls under the category of minimum-weight path based routing as it aims at minimizing the sum of the energies consumed along each of the hops.

3.37 Min-Max Battery Cost Routing (MMBCR)

MMBCR [69] assigns the battery power of a route to the minimum residual battery power of a node (bottleneck node) along the route. The desired route is then the route with the maximum battery power. If there is a tie, MMBCR chooses the route with the shortest hop count. When all nodes in the network have almost identical residual battery power, MMBCR would result in frequent route changes. This is because the algorithm is sensitive to even slight changes in the residual battery power of the nodes and path selection often has to be done using the secondary criteria of hop count. When nodes have fairly different residual battery power, MMBCR would result in less frequent route changes. This is because MMBCR chooses nodes that have a larger residual battery power and these nodes are more likely to survive for a long time in comparison to nodes that have a lesser residual battery power. The desired maximum battery power route could be chosen without using the secondary criteria of hop count. Thus, paths chosen would be more stable, but sub-optimal in terms of hop count. MMBCR fits into the category of minimum-weight routing when the residual battery power of the nodes is almost identical and stable path routing when nodes have fairly different power.

3.38 Most Forward with Fixed Radius (MFR)

MFR [28] minimizes the number of hops from the source to the destination by letting a node to always transmit to the neighbor with the largest forward progress. Progress is the distance between the transmitter and the receiving node projected on to the line joining the transmitter and the final destination [41]. If the progress is positive, a neighbor is said to be in the forward direction on the path towards the destination. If the progress is negative, a neighbor is said to be in the backward direction. MFR falls under the category of minimum-weight routing.

3.39 Nearest with Forward Progress (NFP)

In NFP [28], a node transmits the packet to the nearest neighbour that will result in forward progress to the final destination. The goal is to reduce the transmission power per hop and also to reduce collisions. Since the physical length of each hop is less, paths selected using NFP are likely to exist for longer time. Hence, NFP could fit into the category of routing protocols based on stability.

3.40 Node-Disjoint Multi-path Routing (NDMR) Protocol

NDMR [39] uses a routing overhead filtering approach very similar to that of AOMDV. The difference being AODV modified to include path accumulation in the RREQ packets. The destination could now explicitly select the node-disjoint paths from the list of successful RREQ packets that reach it as part of the route discovery. Both AOMDV and NDMR are capable of selecting multiple node-disjoint shortest hop paths. NDMR fits into the category of routing protocols based on minimum-weight path routing.

3.41 Node Velocity based Stable Path (NVSP) Routing Protocol

NVSP [48] is the only beaconless stable path routing protocol that has been proposed for MANETs. NVSP is an on-demand routing protocol that uses the RREQ-RREP cycle to discover routes whenever required. During the propagation of the RREQ messages, every forwarding node includes its current node velocity information in the RREQs. The bottleneck velocity of a path is the maximum of the velocity of an intermediate node on the path. The destination chooses the path with the smallest bottleneck velocity and sends a RREP packet on the chosen path. The end-to-end delay and the energy consumed per data packet incurred by NVSP are significantly lower than that of FORP and are lower or equal to that incurred for DSR.

3.42 Optimized Link State Routing (OLSR) Protocol

OLSR [10] incorporates two optimizations over the conventional link state routing in ad hoc networks. Each node selects a set of neighbour nodes called multi-point relays (MPRs) and generates link state updates only about the links with the MPRs and not with all its neighbours. Further, the link state updates are diffused throughout the network only using these MPRs thus significantly reducing the number of retransmissions. The MPRs of a node *I* are basically the smallest set of neighbours who can effectively reach all the two hop neighbours of node *I*. The MPRs of a node changes with node mobility and are updated using periodic HELLO messaging. A source-destination route is basically a sequence of hops through the multipoint relay nodes. Routes selected are shortest hop as in the conventional link state algorithm. OLSR fits under the minimum-weight path routing category.

3.43 Optimized Spine based Routing (OSR)/ Partial Knowledge Spine Routing (PSR) Protocols

The spine structure is a virtual backbone of the ad hoc network and is constructed using an approximation algorithm to the minimum connected dominating set, MCDS (distributed implementation of the approximation algorithm of Guha and Khuller [20]). Two routing algorithms using this spine structure are proposed [62]: (1) Optimal Spine Routing (OSR) – the global knowledge of the network is stored at all the spine nodes and shortest hop routes between any two nodes are locally determined at a spine node. (2) Partial-knowledge Spine Routing (PSR) – each spine node uses only the local state information (non-spine nodes and peer spine nodes directly connected to the spine node) and stable non-local state information (obtained through add and delete waves) about the rest of the network. An add wave is generated when a link comes up and a delete wave is initiated when a link goes down. The add wave is propagated at a constant delay at each spine node; while the delete wave is propagated immediately to the next hop. When a delete wave of an edge catches up with an add wave generated for itself, the two cancel each other and do not propagate further. The combined effect of the difference in the rates of the two waves ensures that only stable edge information is conveyed to spine nodes. As a result, nodes determined using PSR are more stable than those by OSR, but sub-optimal in terms of hop count. Thus, OSR falls under the category of minimum-weight path routing, while PSR falls under stability category.

3.44 Power-Aware Routing Optimization (PARO) Protocol

PARO [19] is a dynamic power controlled routing scheme to minimize the overall transmission power per packet (end-to-end energy consumption per packet). The protocol assumes a fully connected network, where in nodes are located within the maximum transmission range of each other. Even though the source and destination can directly reach each other, intermediate forwarding nodes called redirectors are used so that the end-to-end transmission power per packet is reduced. The algorithm converges to the optimal number of redirector nodes in a sequence of iterations. In the first iteration, the source node directly sends the data packet to the destination without involving any redirector nodes. Any node on overhearing this packet transmission computes whether its forwarding can reduce the end-to-end transmission power in comparison to the original data exchange. If this is feasible, the intermediate node elects itself as the redirector and sends a route-redirect message to the source and destination informing them of a more power-efficient route for their communication. The above optimization strategy is also applicable across any pair of intermediate redirector nodes if adding another redirector node could reduce the overall transmission power. Thus, the optimal sequence of redirector nodes is determined iteratively. As the objective of PARO is to minimize the end-to-end transmission power, it has to be sum of the energy consumed per hop. If the energy consumed per hop can be modeled as link weights, PARO reduces to finding a minimum-weight path (optimum end-to-end transmission power) from the source to the destination.

3.45 Preferred Link Based Routing (PLBR) Algorithm

In PLBR [61], control packet overhead due to route discovery packets is reduced by selectively allowing some nodes to forward the packets using a preferred list. Two algorithms have been proposed to compute the preferred list: based on the degree of the neighbour nodes and based on the stability information of the neighbours. Routes determined using the preferred list based on neighbour degree are shorter hop paths; while routes obtained based on stability information are long-living, but sub-optimal in hop count.

3.46 Relative Distance Micro Discovery Ad hoc Routing (RDMAR) Protocol

The RDMAR protocol [2] localizes its reaction to link failures to a very small region of the network near the change. The query flood is localized by estimating the relative distance between the source and the destination. The RD for the new query is estimated using the average nodal velocity, time since the latest communication and the previously used RD. When load balancing is not considered, the protocol chooses the shortest hop routes. When load balancing is considered, the protocol chooses the least congested route, where the load of a link is given by the number of ongoing connections at the downstream node of the link. The links to the destination have zero cost. The destination chooses the path with the minimum aggregate load. Thus, protocols for load balancing can also be grouped under the category of minimum-weight path routing.

3.47 Route-lifetime Assessment Based Routing (RABR) Protocol

RABR [1] is similar to LBR, the difference lies in how the lifetime of a link is predicted. RABR uses the average signal strength variation with respect to time called link affinity as the basis for estimating the link lifetime. A similar work based on link affinity has been proposed in [52]. RABR and [52] fit into the category of protocols based on stability. Note that when two nodes move with a constant relative velocity, the distance variation with respect to time is linear, while the variation of signal strength with respect to time is non-linear.

3.48 Scalable Routing Protocol (SLURP) for Ad hoc Networks

SLURP [72] is based on the geographic location management strategy proposed in [72]. The geographic routing algorithm used in SLURP is based on MFR and DSR. Thus, SLURP falls under the category of minimum-weight routing.

3.49 Signal Stability Adaptive (SSA) Routing Protocol

The Signal Stability-Based Adaptive (SSA) routing protocol [14] selects routes based on the signal strength between nodes. Signal strength of the link with a neighbouring node is determined using the periodic beacons received from that node. If the signal strength is beyond a threshold, the link is considered stable; otherwise, the link is designated to be weak. Preference is given to paths on the stronger stable channels, SSA fits under the stability category. Route discovery in SSA is through source-initiated broadcast request messages. A node forwards the request message to the next hop only if it is received over a stronger channel and has not been previously processed. The destination, unlike in ABR, chooses the first arriving route-search packet and sends back a route-reply in the reverse direction of the selected route. In addition to choosing the path of strongest signal stability, it is most likely that first arriving route-search packet traversed over the shortest and/or the least congested path. If no route-reply message is received within a specific timeout period, the source initiates another route-search and also indicates its acceptability of weak channels in the search packet header.

3.50 Source Tree Adaptive Routing (STAR) Protocol

The source tree of a node is the set of links in the node's preferred path to a destination. Each node maintains a source tree. Each node builds a partial topology graph using aggregates of neighbour information learnt using an underlying neighbour discovery protocol and source trees reported by the neighbours. Dijkstra's shortest path algorithm is then run on the constructed topology graph to choose a path to the destination. Thus, STAR [18] belongs to the category of routing protocols based on minimum-weight path based routing.

3.51 Split Multi-path Routing (SMR) Protocol

The goal of SMR [38] is to build two maximally disjoint paths, the primary path being the shortest hop path (the path along which the route query first reached the destination) and the second path has to be maximally disjoint with the primary path. In order to overcome the problem of disjoint paths getting suppressed, SMR allows intermediate nodes to forward duplicate route queries under the following two conditions: (1) the query is received from an upstream node that does not send the first route query and (2) the hop count in the received query is no larger than that in the first query. Condition (1) paves the way for learning multiple routes at the destination. But condition (2) restricts all the learned paths to have a hop count closer to that of the primary path. This could be seen in the simulation results in [38]. Thus, SMR could be included among the routing protocols based on minimum-weight path.

3.52 Temporally Ordered Routing Algorithm (TORA)

TORA [51] is a scalable, highly adaptive distributed routing algorithm designed to operate in a highly dynamic mobile networking environment. TORA is based on the concept of "link reversal". The protocol is particularly designed to localize algorithmic reactions to topology changes by maintaining multiple routes to the destination. Shortest hop paths are given secondary importance and longer routes are often used to reduce the overhead of discovering newer routes. Thus, TORA fits under the stability category.

3.53 Terminode Routing Protocol

The Terminode Routing Protocol [5] is a hierarchical location-aware routing protocol for large-scale self-organizing mobile ad hoc networks. The network nodes are referred to as termniodes; each terminode possesses a permanent end-system unique identifier (EUI) and a temporary location dependent address (LDA). The routing protocol is composed of two components: Terminode Local Routing (TLR) and Terminode Remote Routing (TRR). TLR is location-unaware and is similar to the Intra zone routing protocol. TLR is used when the source and destination are within a specified number of hops. TLR uses distance-vector based shortest path routing. TRR is location-aware and is used to send data for non-TLR-reachable destinations. TRR uses anchored paths determined using a technique called Friend Assisted Path Discovery (FAPD). FAPD is based on the concept of small world graphs in which a node *A* is said to have a logical link (friendship) with a node *B* if *A* knows of at least one well-defined path to *B* (possibly using TLR). Paths are basically discovered using a sequence of friends (anchors) from the source to destination. An anchor node forwards the packet to the neighbouring node such that the distance to the successive anchor in the path is minimized the maximum. A terminode learns of multiple anchored paths to the destination and uses the least congested route frequently. In this sense, the terminode routing protocol fits into the category of routing protocols based on minimum-weight-path.

3.54 Topology Broadcast-based on Reverse Path Forwarding (TBRPF)

Each source node broadcasts link state updates on its outgoing links that are part of a minimum hop broadcast tree rooted at the source. The minimum hop broadcast tree is specific to the source node is a collection of minimum hop paths from all the nodes to the source node. The minimum hop paths are computed using the topology information received through the same broadcast tree. Since link state updates (topology information) is propagated in the reverse direction along the spanning tree formed from minimum hop paths from all the nodes to the source of the update, the approach is called Topology Broadcast based on Reverse Path Forwarding (TBRPF) [4]. Routes are computed locally as in any conventional link state routing protocol using the topology information obtained along the minimum hop broadcast trees. The routing algorithm easily fits into the category of minimum-weight routing like any other link state based routing protocol.

3.55 Wireless Routing Protocol (WRP)

WRP [50] is a table-based proactive routing protocol similar to DSDV. Its novelty lies in its ability to quickly get rid off looping situations (count-to-infinity problem [67]) by forcing the routing nodes to communicate the distance and the second-to-last hop information for each destination in the wireless networks. The routing metric is still hop count and shortest hop paths are used. Thus, WRP belongs to the category of protocols based on minimum-weight path.

3.56 Zone Hybrid Link State (ZHLS) Routing Protocol

The network is divided into zones. Each node is assumed to know its location and hence be able to map a given location to its corresponding zone id. Two zones are assumed to be connected if at least one node in one zone is connected to a node in the other zone. Routing within and in between zones is based on shortest path routing. Hence, ZHLS [31] belongs to the category of routing protocols based on minimum-weight path based routing.

3.57 Zone Routing Protocol (ZRP)

ZRP [26] is a hybrid protocol taking advantage of a proactive routing strategy within a node's local neighborhood and a reactive routing protocol for communication between the neighborhoods. Each node defines a zone around itself and the zone radius is the number of hops to the perimeter of the zone. The reactive global search is done efficiently by querying only a selected set of nodes in the network [23]. The number of nodes queried is in the order of $[r_{zone} / r_{network}]^2$ of the number of nodes queried using a network-wide flooding process [13]. Unless the zone radius is carefully chosen, a node can be in multiple zones and zones overlap. As a result, the efficiency in route discovery decreases. Also, in the presence of node mobility, the zone radius may fluctuate rapidly and also affect the functionality of nodes within and at the periphery of the zone. The intra zone routing protocol (IARP) [25] used within a zone is not a specific routing protocol; it is rather a family of limited-depth table-driven pro-active routing protocols. Similarly, the Inter zone routing protocol (IERP) [24] is a family of reactive routing protocols which could provide enhanced route discovery and maintenance services using the local connectivity information provided by IARP. Thus, we do not classify ZRP into neither of the two categories and view it as a framework for the proactive and reactive routing protocols.

4. CONCLUSIONS

We presented an exhaustive survey of the unicast routing protocols for mobile ad hoc networks. We discussed the characteristics, routing metrics and routing philosophies of each of these protocols and placed each protocol under one of the two route selection categories: minimum-weight-path based routing and stability-based routing. To the best of our knowledge, we could not find such an exhaustive survey on MANET routing protocols in the literature. The classification of the primary route selection principle of the routing protocols as being one of either minimum-weight path based routing and stability-based routing can simplify the task of a network designer in deciding the routing strategy (and the routing protocol) to be adopted at a given condition. One such example is our comparison of the two routing strategies for minimizing energy consumption for on-demand routing, presented in [45]. We believe our survey will be very useful to the research community and also serve as a great introductory material for someone embarking onto research in ad hoc networks.

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