# A review of routing protocols for mobile ad hoc networks

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**Abstract**

The 1990s have seen a rapid growth of research interests in mobile ad hoc networking. The infrastructureless and the dynamic nature of these networks demands new set of networking strategies to be implemented in order to provide efficient end-to-end communication. This, along with the diverse application of these networks in many different scenarios such as battlefield and disaster recovery, have seen MANETs being researched by many different organisations and institutes. MANETs employ the traditional TCP/IP structure to provide end-to-end communication between nodes. However, due to their mobility and the limited resource in wireless networks, each layer in the TCP/IP model require redefinition or modifications to function efficiently in MANETs. One interesting research area in MANET is routing. Routing in the MANETs is a challenging task and has received a tremendous amount of attention from researches. This has led to development of many different routing protocols for MANETs, and each author of each proposed protocol argues that the strategy proposed provides an improvement over a number of different strategies considered in the literature for a given network scenario. Therefore, it is quite difficult to determine which protocols may perform best under a number of different network scenarios, such as increasing node density and traffic. In this paper, we provide an overview of a wide range of routing protocols proposed in the literature. We also provide a performance comparison of all routing protocols and suggest which protocols may perform best in large networks.
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## 1. Classification of current routing protocols

The limited resources in MANETs have made designing of an efficient and reliable routing strategy a very challenging problem. An intelligent routing strategy is required to efficiently use the limited resources while at the same time being adaptable to the changing network conditions such as: network size, traffic density and network partitioning. In parallel with this, the routing protocol may need to provide different levels of QoS to different types of applications and users.

Prior to the increased interests in wireless networking, in wired networks two main algorithms were used. These algorithms are commonly referred to as the link-state and distance vector algorithms. In link-state routing, each node maintains an up-to-date view of the network by

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periodically broadcasting the link-state costs of its neighbouring nodes to all other nodes using a flooding strategy. When each node receive an update packet, they update their view of the network and their link-state information by applying a shortest-path algorithm to choose the next hop node for each destination. In distance-vector routing, for every destination $x$, each node $i$ maintains a set of distances $D_{ij}^x$ where $j$ ranges over the neighbours of node $i$. Node $i$ selects a neighbour, $k$, to be the next hop for $x$ if $D_{ik}^x = min_j\{D_{ij}^x\}$. This allows each node to select the shortest path to each destination. The distance-vector information is updated at each node by a periodical dissemination of the current estimate of the shortest distance to every node [31]. The traditional link-state and distance-vector algorithm do not scale in large MANETs. This is because periodic or frequent route updates in large networks may consume significant part of the available bandwidth, increase channel contention and may require each node to frequently recharge their power supply.

To overcome the problems associated with the link-state and distance-vector algorithms a number of routing protocols have been proposed for MANETs. These protocols can be classified into three different groups: global/proactive, on-demand/reactive and hybrid. In proactive routing protocols, the routes to all the destination (or parts of the network) are determined at the start up, and maintained by using a periodic route update process. In reactive protocols, routes are determined when they are required by the source using a route discovery process. Hybrid routing protocols combine the basic properties of the first two classes of protocols into one. That is, they are both reactive and proactive in nature. Each group has a number of different routing strategies, which employ a flat or a hierarchical routing structure.

## 2. Proactive routing protocols

In proactive routing protocols, each node maintains routing information to every other node (or nodes located in a specific part) in the network. The routing information is usually kept in a number of different tables. These tables are periodically updated and/or if the network topology changes. The difference between these protocols exist in the way the routing information is updated, [1] detected and the type of information kept at each routing table. Furthermore, each routing protocol may maintain different number of tables. This section describes a number of different proactive protocols and makes a performance comparison between them. That is illustrated in Tables 1 and 2. Note that the performance metrics represent the worst case scenario for each routing protocol.

### 2.1. Destination-sequenced distance vector (DSDV)

The DSDV algorithm [27] is a modification of DBF [3,10], which guarantees loop free routes. It provides a single path to a destination, which is selected using the distance vector shortest path routing algorithm. In order to reduce the amount of overhead transmitted through the network, two types of update packets are used. These are referred to as a "full dump" and "incremental" packets. The full dump packet carries all the available routing information and the incremental packet carries only the information changed since the last full dump. The incremental update messages are sent more frequently than the full dump packets. However, DSDV still introduces large amounts of overhead to the network due to the requirement of the periodic update messages, and the overhead grows according to $O(N^2)$. Therefore the protocol will not scale in large network since a large portion of the network bandwidth is used in the updating procedures.

### 2.2. Wireless routing protocol (WRP)

The WRP protocol [22] also guarantees loops freedom and it avoids temporary routing loops by using the predecessor information. However, WRP requires each node to maintain four routing tables. This introduces a significant amount of memory overhead at each node as the size of the network increases. Another disadvantage of WRP is that it ensures connectivity through the use of hello

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[1] Route update strategies are discussed further in Section 3.

Table 1
Basic characteristics of proactive routing protocols

| Protocol | RS | Number of tables | Frequency of updates | HM | Critical nodes | Characteristic feature |
|----------|----|------------------|----------------------|----|----------------|------------------------|
| DSDV | F | 2 | Periodic and as required | Yes | No | Loop free |
| WRP | F | 4 | Periodic | Yes | No | Loop freedom using predecessor info |
| GSR | F | 3 and a list[a] | Periodic and local[b] | No | No | Localised updates |
| FSR | F | Same as GSR | Periodic and local[b] | No | No | Controlled frequency of updates |
| STAR | H | 1 and a 5 lists | Conditional[c] | No | No | Employs LORA and/or ORA. Minimize CO |
| DREAM | F | 1 | Mobility based | No | No | Controlled rate of updates by mobility and distance |
| MMWN | H | Maintains a database | Conditional | No | Yes, LM | LORA and minimized CO |
| CGSR | H | 2 | Periodic | No | Yes, Clusterhead | Clusterheads exchange routing information |
| HSR | H | 2 (link-state table and location management)[d] | Periodic, within each subnet | No | Yes, Clusterhead | Low CO and Hierarchical structure |
| OLSR | F | 3 (Routing, neighbour and topology table) | Periodic | Yes | No | Reduces CO using MPR |
| TBRPF | F | 1 Table, 4 lists | Periodic and differential | Yes | Yes, Parent node | Broadcasting topology updates over a spanning tree |

R = routing structure; HM = hello message; H = hierarchical; F = flat; CO = control overhead; LORA = least overhead routing approach; ORA = optimum routing approach; LM = location manager.
[a] GSR also has a list of all available neighbours.
[b] In GSR and FSR link-state is periodically exchanged with neighbouring nodes.
[c] In conditional update methods, the updates occur if a particular event occurs.
[d] Number of link-state tables may vary according to the number of logical levels.

Table 2
Complexity comparison of proactive routing protocols

| Protocol | CT | MO | CO | Advantages/disadvantages |
|---|---|---|---|---|
| DSDV | $O(D \cdot I)$ | $O(N)$ | $O(N)$ | Loop free/high overhead |
| WRP | $O(h)$ | $O(N^2)$ | $O(N)$ | Loop free/memory overhead |
| GSR | $O(D \cdot I)$ | $O(N^2)$ | $O(N)$ | Localized updates/high memory overhead |
| FSR | $O(D \cdot I)$ | $O(N^2)$ | $O(N)$ | Reduces CO/high memory overhead, reduced accuracy |
| STAR | $O(D)$ | $O(N^2)$ | $O(N)$ | Low CO/high MO and processing overhead |
| DREAM | $O(N \cdot I)$ | $O(N)$ | $O(N)$ | Low CO and MO/requires a GPS |
| MMWN | $O(2D)$ | $O(N)$ | $O(X + E)$ | Low CO/mobility management and cluster maintenance |
| CGSR | $O(D)$ | $O(2N)$ | $O(N)$ | Reduced CO/cluster formation and maintenance |
| HSR | $O(D)$ | $O(N^2 \cdot L) + O(S) + O(N/S) + O(N/n)$ | $O(n \cdot L)/I + O(1)/J$ | Low CO/location management |
| OLSR | $O(D \cdot I)$ | $O(N^2)$ | $O(N^2)$ | Reduced CO and contention/2-hop neighbour knowledge required |
| TBRPF | $O(D)$ or $D + 2$ for link failure | $O(N^2) + O(N) + O(N + V)$ | $O(N^2)$ | Low CO/High MO |

CT = convergence time; MO = memory overhead; CO = control overhead; (1) = a fixed number of update tables is transmitted; $V$ = number of neighbouring nodes; $N$ = number of nodes in the network; $n$ = average number of logical nodes in the cluster; $I$ = average update interval; $D$ = diameter of the network; S = number of virtual IP subnets; $h$ = height of the routing tree; $X$ = total number of LMs (each cluster has an LM); $J$ = nodes to home agent registration interval; $L$ = number of hierarchical level.

messages. These hello messages are exchanged between neighbouring nodes whenever there is no recent packet transmission. This will also consume a significant amount of bandwidth and power as each node is required to stay active at all times (i.e. they cannot enter sleep mode to conserve their power).

### 2.3. Global state routing (GSR)

The GSR protocol [5] is based on the traditional Link State algorithm. However, GSR has improved the way information is disseminated in Link State algorithm by restricting the update messages between intermediate nodes only. In GSR, each node maintains a link state table based on the up-to-date information received from neighbouring nodes, and periodically exchanges its link state information with neighbouring nodes only. This has significantly reduced the number of control message transmitted through the network. However, the size of update messages is relatively large, and as the size of the network grows they will get even larger. Therefore, a considerable amount of bandwidth is consumed by these update messages.

### 2.4. Fisheye state routing (FSR)

The FSR protocol [12] is the descendent of GSR. FSR reduces the size of the update messages in GSR by updating the network information for nearby nodes at a higher frequency than for the remote nodes, which lie outside the fisheye scope. This makes FSR more scalable to large networks than the protocols described so far in this section. However, scalability comes at the price of reduced accuracy. This is because as mobility increases the routes to remote destination become less accurate. This can be overcome by making the frequency at which updates are sent to remote destinations proportional to the level of mobility. This is discussed in more detail in Section 3.

### 2.5. Source-tree adaptive routing (STAR)

The STAR protocol [11] is also based on the link state algorithm. Each router maintains a source tree, which is a set of links containing the preferred paths to destinations. This protocol has significantly reduced the amount of routing overhead disseminated into the network by using a least overhead routing approach (LORA), to exchange routing information. It also support optimum routing approach (ORA) if required. This approach eliminated the periodic updating procedure present in the Link State algorithm by making update dissemination conditional. As a result the Link State updates are exchanged only when certain event occurs. Therefore STAR will scale well in large network since it has significantly reduced the bandwidth consumption for the routing updates while at the same time reducing latency by using predetermined routes. However, this protocol may have significant memory and processing overheads in large and highly mobile networks, because each node is required to maintain a partial topology graph of the network (it is determined from the source tree reported by its neighbours), which may change frequently as the neighbours keep reporting different source trees.

### 2.6. Distance routing effect algorithm for mobility (DREAM)

The DREAM routing protocol [2] employs a different approach to routing when compared to the routing protocols described so far. In DREAM, each node knows its geographical coordinates through a GPS. These coordinates are periodically exchanged between each node and stored in a routing table (called a location table). The advantage of exchanging location information is that it consumes significantly less bandwidth than exchanging complete link state or distance vector information, which means that its is more scalable. In DREAM, routing overhead is further reduced, by making the frequency at which update messages are disseminated proportional to mobility and the distance effect. This means that stationary nodes do not need to send any update messages.

### 2.7. Multimedia support in mobile wireless networks (MMWN)

In MMWN routing protocol [20] the network is maintained using a clustering hierarchy. Each cluster has two types of mobile nodes: switches and

○ Switch
● Location Manager (LM)
■ Endpoint
I(x,y,...) indicates that the selected switch is the location manager for clusters x,y,...
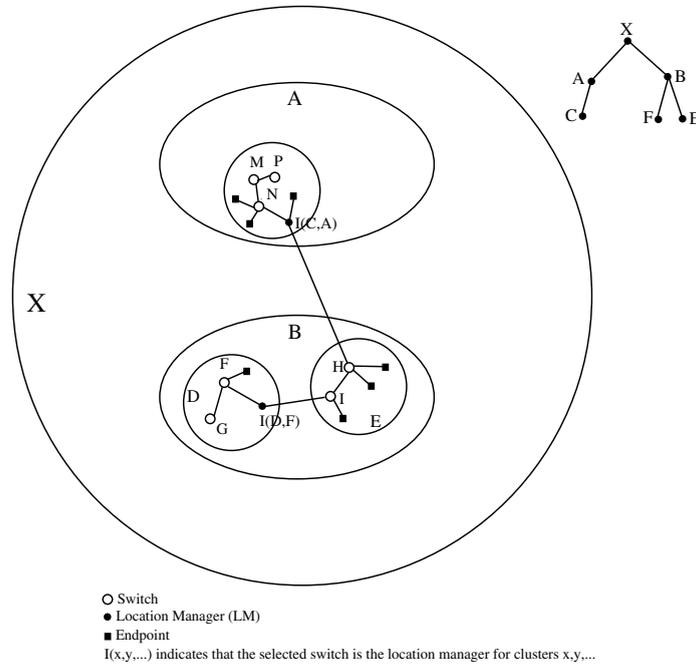
Fig. 1. An example of clustering hierarchy in MMWN.

endpoints. Each cluster also has location manager (LM), which performs the location management for each cluster (see Fig. 1). All information in MMWN is stored in a dynamically distributed database. The advantage of MMWN is that only LMs perform location updating and location finding, which means that routing overhead is significantly reduced when compared to the traditional table driven algorithms (such as DSDV and WRP). However, location management is closely related to the hierarchical structure of the network, making the location finding and updating very complex. This is because in the location finding and updating process, messages have to travel through the hierarchical tree of the LMs. Also the changes in the hierarchical cluster membership of LMs will also affect the hierarchical management tree and introduce a complex consistency management. This feature introduces implementation problems, which are difficult to overcome [26].

### 2.8. Cluster-head gateway switch routing (CGSR)

CGSR [6] is another hierarchical routing protocol where the nodes are grouped into cluster.

However the addressing scheme used here is simpler than MMWN. In CGSR, there is no need to maintain a cluster hierarchy (which is required in MMWN). Instead, each cluster is maintained with a cluster-head, which is a mobile node elected to manage all the other nodes within the cluster (see Fig. 2). This node controls the transmission medium and all inter-cluster communications occur through this node. The advantage of this protocol is that each node only maintains routes to its
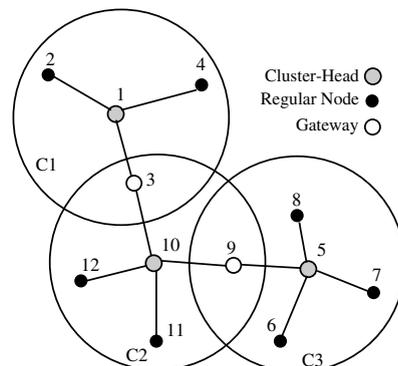


Fig. 2. Illustration of a typical cluster-based network.

cluster-head, which means that routing overheads are lower compared to flooding routing information through all the network. However, there are significant overheads associated with maintaining clusters. This is because each node needs to periodically broadcast its cluster member table and update its table based on the received updates.

## 2.9. Hierarchical state routing (HSR)

HSR [26] is also based on the traditional Link State algorithm. However, unlike the other link state based algorithm described so far, HSR maintains a hierarchical addressing and topology map. Clustering algorithm such as CGSR can be used to organise the nodes with close proximity into clusters. Each cluster has three types of nodes: a cluster-head node which acts as a local coordinator for each node, Gateway nodes which are nodes that lie in two different clusters, and internal nodes that are all the other nodes in each cluster. All nodes have a unique ID, which is typically the MAC address for each node. The nodes within each cluster broadcast their link information to each other. In HSR, each node also has a hierarchical ID (HID), which is a sequence of the MAC addresses from the top hierarchy to the source node. For example (see Fig. 3) the HID of node 8 is $\langle 2, 2, 8 \rangle$. The HID can be used to send a packet from any source to any destination in the network. For example, consider sending a packet from node 8 to node 3. Node 8 had a HID of $\langle 2, 2, 8 \rangle$ and

node 3 has a HID of $\langle 4, 4, 3 \rangle$. The packet is first sent to node 2 (top of hierarchy). Node 2 then sends the packet to node 4, which is the top hierarchy of node 3. Node 2 and 4 form a "virtual link", which is the path $\langle 2, 9, 5, 6, 4 \rangle$. Node 4 will then send the packet to node 3. Logical clustering provides a logical relationship between the cluster-head at a higher level. Here, the nodes are assigned logical address of the form $< subnet, host >$. For example the logical node 2 in the level 2 of Fig. 3 has a logical address $\langle 2, 2 \rangle$. The logical nodes are connected via logical links, which form a "tunnel" between lower level clusters. Logical nodes exchange logical link information as well as a summary information of the lower level clusters. The logical link state information is then flooded down to the lower levels. The physical nodes at the lowest level will then have a "hierarchical" topology of the network. The advantage of HSR over other hierarchical routing protocols (such as MMWN) is the separation of mobility management from the physical hierarchy. This is done via Home Agents. This protocol also has far less control overhead when compared to GSR and FSR. However, this protocol (similar to any other cluster based protocol) introduces extra overheads to the network from cluster formation and maintenance.

## 2.10. Optimised link state routing (OLSR)

OLSR [16] is a point-to-point routing protocol based on the traditional link-state algorithm. In this strategy, each node maintains topology information about the network by periodically exchanging link-state messages. The novelty of OLSR is that it minimises the size of each control message and the number of rebroadcasting nodes during each route update by employing multipoint replaying (MPR) strategy. To do this, during each topology update, each node in the network selects a set of neighbouring nodes to retransmit its packets. This set of nodes is called the multipoint relays of that node. Any node which is not in the set can read and process each packet but do not retransmit. To select the MPRs, each node periodically broadcasts a list of its one hop neighbours using hello messages. From the list of nodes in the
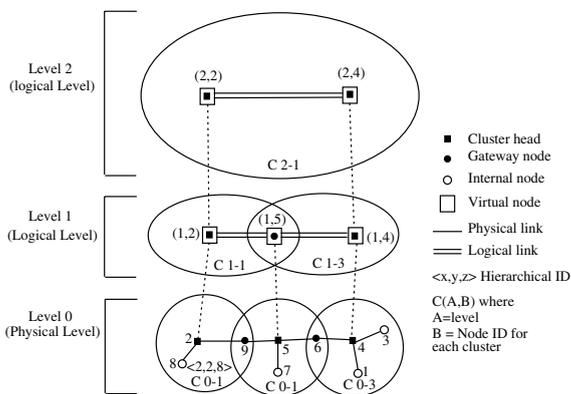


Fig. 3. An example of HSR topology.
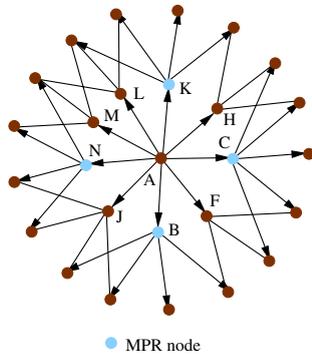
● MPR node

Fig. 4. Multipoint relays.

hello messages, each node selects a subset of one hop neighbours, which covers all of its two hop neighbours. For example, in Fig. 4, node A can select nodes B, C, K and N to be the MPR nodes. Since these nodes cover all the nodes, which are two hops away. Each node determines an optimal route (in terms of hops) to every known destination using its topology information (from the topology table and neighbouring table), and stores this information in a routing table. Therefore, routes to every destination are immediately available when data transmission begins.

### 2.11. Topology broadcast reverse path forwarding (TBRPF)

TBRPF [4] is another link-state based routing protocol, which performs hop-by-hop routing. The protocol uses the concept of reverse-path forwarding (RPF) to disseminate its update packets in the reverse direction along the spanning tree, which is made up of the minimum-hop path from the nodes leading to the source of the update message. In this routing strategy, each node calculates a source tree, which provides a path to all reachable destinations. This is done by applying a modified version of Dijkstra's algorithm on the partial topology information stored in their topology table. In TBRPF, each node minimises overhead by reporting only part of their source tree to their neighbours. The reportable part of each source tree is exchanged with neighbouring nodes by periodic and differential hello messages. The differential hello messages only report the

changes of the status of the neighbouring nodes. As a result, the hello messages in TBRPF are smaller than in protocols which report the complete link-state information.

### 2.12. Summary of proactive routing

In summary, most flat routed global routing protocols do not scale very well. This is because their updating procedure consumes a significant amount of network bandwidth. From the flat routed protocols discussed in this section, OLSR may scale the best. This increase in scalability is achieved by reducing the number of rebroadcasting nodes through the use of multipoint relaying, which elects only a number of neighbouring nodes to rebroadcast the message. This clearly has the advantage of reducing, channel contention and the number of control packet travelling through the network when compared to strategies which use blind or pure flooding where all nodes rebroadcast the messages. The DREAM routing protocol also has scalability potential since it has significantly reduced the amount of overhead transmitted through the network, by exchanging location information rather than complete (or partial) link state information. The hierarchically routed global routing protocols will scale better most of the flat routed protocols, since they have introduced a structure to the network, which control the amount of overhead transmitted through the network. This is done by allowing only selected nodes such as a clusterhead can rebroadcast control information. The common disadvantage associated with all the hierarchical protocols is mobility management. Mobility management introduces unnecessary overhead to the network (such as extra processing overheads for cluster formation and maintenance).

### 3. Reactive routing protocols

On-demand routing protocols were designed to reduce the overheads in proactive protocols by maintaining information for active routes only. This means that routes are determined and maintained for nodes that require to send data to a

particular destination. Route discovery usually occurs by flooding a route request packets through the network. When a node with a route to the destination (or the destination itself) is reached a route reply is sent back to the source node using link reversal if the route request has travelled through bi-directional links or by piggy-backing the route in a route reply packet via flooding. Therefore, the route discovery overhead (in the worst case scenario) will grow by [2] $O(N + M)$ when link reversal is possible and $O(2N)$ for unidirectional links.

Reactive protocols can be classified into two categories: source routing and hop-by-hop routing. In Source routed on-demand protocols [19,33], each data packets carry the complete source to destination address. Therefore, each intermediate node forwards these packets according to the information kept in the header of each packet. This means that the intermediate nodes do not need to maintain up-to-date routing information for each active route in order to forward the packet towards the destination. Furthermore, nodes do not need to maintain neighbour connectivity through periodic beaconing messages. The major drawback with source routing protocols is that in large networks they do not perform well. This is due to two main reasons; firstly as the number of intermediate nodes in each route grows, then so does the probability of route failure. To show this let $P(f) = a \cdot n$, where $P(f)$ is the probability of route failure, a is the probability of a link failure and n is the number of intermediate nodes in a route. From this, [3] it can be seen that as $n \to \infty$, then $P(f) \to \infty$. Secondly, as the number of intermediate nodes in each route grows, then the amount of overhead carried in each header of each data packet will grow as well. Therefore, in large networks with significant levels of multihoping and high levels of mobility, these protocols may not scale well. In hop-by-hop routing (also known as point-to-point routing) [8], each data

packet only carries the destination address and the next hop address. Therefore, each intermediate node in the path to the destination uses its routing table to forward each data packet towards the destination. The advantage of this strategy is that routes are adaptable to the dynamically changing environment of MANETs, since each node can update its routing table when they receiver fresher topology information and hence forward the data packets over fresher and better routes. Using fresher routes also means that fewer route recalculations are required during data transmission. The disadvantage of this strategy is that each intermediate node must must store and maintain routing information for each active route and each node may require to be aware of their surrounding neighbours through the use of beaconing messages.

A number of different reactive routing protocols have been proposed to increase the performance of reactive routing. This section describes a number of these strategies and makes a performance comparison between them. Table 3 provide the summary of the characteristic feature of each strategy and Table 4 provides a theoretical performance evaluation. Note that the performance metrics represent the worst case scenario for each routing protocol.

### 3.1. Ad hoc on-demand distance vector (AODV)

The AODV [8] routing protocol is based on DSDV and DSR [19] algorithm. It uses the periodic beaconing and sequence numbering procedure of DSDV and a similar route discovery procedure as in DSR. However, there are two major differences between DSR and AODV. The most distinguishing difference is that in DSR each packet carries full routing information, whereas in AODV the packets carry the destination address. This means that AODV has potentially less routing overheads than DSR. The other difference is that the route replies in DSR carry the address of every node along the route, whereas in AODV the route replies only carry the destination IP address and the sequence number. The advantage of AODV is that it is adaptable to highly dynamic networks. However, node may experience large

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[2] $N$ = number of nodes in the network, $M$ = number of nodes in the reply path, $T$ = number of source/destination pairs.

[3] Assuming that the intermediate nodes have a probability of a link failure of $a > 0$.

Table 3
Basic characteristics of reactive routing protocols

| Protocol | RS | Multiple routes | Beacons | Route metric method | Route maintained in | Route reconfiguration strategy |
|---|---|---|---|---|---|---|
| AODV | F | No | Yes, hello messages | Freshest & SP | RT | Erase route then SN or local route repair |
| DSR | F | Yes | No | SP, or next available in RC | RC | Erase route the SN |
| ROAM | F | Yes | No | SP | RT | Erase route &[a] |
| LMR | F | Yes | No | SP, or next available | RT | Link reversal & Route repair |
| TORA | F | Yes | No | SP, or next available | RT | Link reversal & Route repair |
| ABR | F | No | Yes | Strongest Associativity & SP &[b] | RT | LBQ |
| SSA | F | No | Yes | Strongest signal strength & stability | RT | Erase route then SN |
| RDMAR | F | No | No | Shortest relative distance or SP | RT | Erase route then SN |
| LAR | F | Yes | No | SP | RC | Erase route then SN |
| ARA | F | Yes | No | SP | RT | Use alternate route or back track until a route is found |
| FORP | F | No | No | RET & stability | RT | A Flow_HANDOFF used to use alternate route |
| CBRP | H | No | No | First available route (first fit) | RT at cluster head | Erase route then SN & local route repair |

RS = routing structure; H = hierarchical; F = flat; RT = route table; RC = route cache; RET = route expiration time; SP = shortest path; SN = source notification; LBQ = localised broadcast query.

[a] Start a diffusing search if a successor is available, else send a query with infinite metric.
[b] Route relaying load and cumulative forwarding delay.

Table 4
Complexity comparison of reactive routing protocols

| Protocol | TC[RD] | TC[RM] | CC[RD] | CC[RM] | Advantage | Disadvantage |
|---|---|---|---|---|---|---|
| AODV | $O(2D)$ | $O(2D)$ | $O(2N)$ | $O(2N)$ | Adaptable to highly dynamic topologies | Scalability problems, large delays, hello messages |
| DSR | $O(2D)$ | $O(2D)$ | $O(2N)$ | $O(2N)$ | Multiple routes, Promiscuous overhearing | Scalability problems due to source routing and flooding, large delays |
| ROAM | $O(D)$ | $O(A)$ | $O(|E|)$ | $O(6G_A)$ | Elimination of search-to-infinity problem. | Large CO in highly mobile environments |
| LMR | $O(2D)$ | $O(2D)$ | $O(2N)$ | $O(2A)$ | Multiple routes | Temporary routing loops |
| TORA | $O(2D)$ | $O(2D)$ | $O(2N)$ | $O(2A)$ | Multiple routes | Temporary routing loops |
| ABR | $O(D+P)$ | $O(B+P)$ | $O(N+R)$ | $O(A+R)$ | Route stability | Scalability problems |
| SSA | $O(D+P)$ | $O(B+P)$ | $O(N+R)$ | $O(A+R)$ | Route stability | Scalability problems, large delays during route failure and reconstruction |
| RDMAR | $O(2S)$ | $O(2S)$ | $O(2M)$ | $O(2M)$ | Localised route discovery | Flooding used if there is no prior communication between nodes |
| LAR | $O(2S)$ | $O(2S)$ | $O(2M)$ | $O(2M)$ | Localised route discovery | Based on source routing, flooding is used if no location information is available |
| ARA | $O(D+P)$ | $O(D+P)$ | $O(N+R)$ | $O(A+R)$ | Low overhead, small control packet size | Flooding based route discovery process |
| FORP | $O(D+P)$ | $O(D+P)$ | $O(N+R)$ | $O(N+R)$ | Employees a route failure minimisation technique | Flooding based route disovery process |
| CBRP | $O(2D)$ | $O(2B)$ | $O(2X)$ | $O(2A)$ | Only cluster-heads exchange routing information | Cluster maintenance, temporary loops |

TC = time complexity; CC = communication complexity; RD = route discovery; RM = route maintenance; CO = control overhead; $D$ = diameter of the network; $N$ = number of nodes in the network; $A$ = number of affected nodes; $B$ = diameter of the affected area; $G$ = maximum degree of the router; $S$ = diameter of the nodes in the localised region; $M$ = number of nodes in the localised region; $X$ = number of clusters (each cluster has one cluster-head); $R$ = number of nodes forming the route reply path, RREP, BANT or FLow_SETUP; $P$ = diameter of the directed path of the RREP, BANT or FLow_SETUP; $|E|$ = number of edges in the network.

delays during route construction, and link failure may initiate another route discovery, which introduces extra delays and consumes more bandwidth as the size of the network increases.

## 3.2. Dynamic source routing (DSR)

As stated earlier, the DSR protocol requires each packet to carry the full address (every hop in the route), from source to the destination. This means that the protocol will not be very effective in large networks, as the amount of overhead carried in the packet will continue to increase as the network diameter increases. Therefore in highly dynamic and large networks the overhead may consume most of the bandwidth. However, this protocol has a number of advantages over routing protocols such as AODV, LMR [7] and TORA [25], and in small to moderately size networks (perhaps up to a few hundred nodes), this protocol may perform better. An advantage of DSR is that nodes can store multiple routes in their route cache, which means that the source node can check its route cache for a valid route before initiating route discovery, and if a valid route is found there is no need for route discovery. This is very beneficial in network with low mobility. Since they routes stored in the route cache will be valid longer. Another advantage of DSR is that it does not require any periodic beaconing (or hello message exchanges), therefore nodes can enter sleep node to conserve their power. This also saves a considerable amount of bandwidth in the network.

## 3.3. Routing on-demand acyclic multi-path (ROAM)

The ROAM [29] routing protocol uses internodal coordination along directed acyclic subgraphs, which is derived from the routers' distance to destination. This operation is referred to as a "diffusing computation". The advantage of this protocol is that it eliminates the search-to-infinity problem present in some of the on-demand routing protocols by stopping multiple flood searches when the required destination is no longer reachable. Another advantage is that each router maintains entries (in a route table) for destina-

tions, which flow data packets through them (i.e. the router is a node which completes/or connects a router to the destination). This reduces significant amount of storage space and bandwidth needed to maintain an up-to-date routing table. Another novelty of ROAM is that each time the distance of a router to a destination changes by more than a defined threshold, it broadcasts update messages to its neighbouring nodes, as described earlier. Although this has the benefit of increasing the network connectivity, in highly dynamic networks it may prevent nodes entering sleep mode to conserve power.

## 3.4. Light-weight mobile routing (LMR)

The LMR protocol is another on-demand routing protocol, which uses a flooding technique to determine its routes. The nodes in LMR maintain multiple routes to each required destination. This increases the reliability of the protocol by allowing nodes to select the next available route to a particular destination without initiating a route discovery procedure. Another advantage of this protocol is that each node only maintains routing information to their neighbours. This means avoids extra delays and storage overheads associated with maintaining complete routes. However, LMR may produce temporary invalid routes, which introduces extra delays in determining a correct loop.

## 3.5. Temporally ordered routing algorithm (TORA)

The TORA routing protocol is based on the LMR protocol. It uses similar link reversal and route repair procedure as in LMR, and also the creation of a DAGs, which is similar to the query/reply process used in LMR [30]. Therefore, it also has the same benefits as LMR. The advantage of TORA is that it has reduced the far-reaching control messages to a set of neighbouring nodes, where the topology change has occurred. Another advantage of TORA is that it also supports multicasting, however this is not incorporated into its basic operation. TORA can be used in conjunction with lightweight adaptive multicast algorithm (LAM) to provide multicasting. The disadvantage

of TORA is that the algorithm may also produce temporary invalid routes as in LMR.

### 3.6. Associativity-based routing (ABR)

ABR [33] is another source initiated routing protocol, which also uses a query-reply technique to determine routes to the required destinations. However, in ABR route selection is primarily based on stability. To select stable route each node maintains an associativity tick with their neighbours, and the links with higher associativity tick are selected in preference to the once with lower associativity tick. However, although this may not lead to the shortest path to the destination, the routes tend to last longer. Therefore, fewer route reconstructions are needed, and more bandwidth will be available for data transmission. The disadvantage of ABR is that it requires periodic beaconing to determine the degree of associativity of the links. This beaconing requirement requires all nodes to stay active at all time, which may result in additional power consumption. Another disadvantage is that it does not maintain multiple routes or a route cache, which means that alternate routes will not be immediately available, and a route discovery will be required using link failure. However, ABR has to some degree compensated for not having multiple routes by initiating a localised route discovery procedure (i.e. LBQ).

### 3.7. Signal stability adaptive (SSA)

SSA [9] is a descendent of ABR. However, SSA selects routes based on signal strength and location stability rather than using an associativity tick. As in ABR, the routes selected in SSA may not result in the shortest path to the destination. However, they tend to live longer, which means fewer route reconstructions are needed. One disadvantage of SSA when compared to DSR and AODV is that intermediate nodes can not reply to route requests sent toward a destination, which may potentially create long delays before a route can be discovered. This is because the destination is responsible for selecting the route for data transfer. Another disadvantage of SSA is no attempt is made to repair routes at the point were the link failure occurs

(i.e. such as an LBQ in ABR). In SSA the reconstruction occurs at the source. This may introduce extra delays, since the source must be notified of the broken like before another one can be found.

### 3.8. Relative distance micro-discovery ad hoc routing (RDMAR)

RDMR [1] attempts to minimise the routing overheads by calculating the distance between the source and the destination and therefore limiting each route request packet to certain number of hops (as described earlier). This means that the route discovery procedure can be confined to localised region (i.e. in will not have a global affect). RDMR also uses the same technique when link failures occurs (i.e. route maintenance). Thus conserving a significant amount of bandwidth and battery power. Another advantage of RDMR is that it does not require a location aided technology (such as a GPS) to determine the routing patterns. However, the relative-distance micro-discovery procedure can only be applied if the source and the destinations have communicated previously. If no previous communication record is available for a particular source and destination, then the protocol will behave in the same manner as the flooding algorithms (i.e. route discovery will have a global affect).

### 3.9. Location-aided routing (LAR)

LAR [21] is based on flooding algorithms (such as DSR). However, LAR attempts to reduce the routing overheads present in the traditional flooding algorithm by using location information. This protocol assumes that each node knows its location through a GPS. Two different LAR scheme were proposed in [21], the first scheme calculates a request zone which defines a boundary where the route request packets can travel to reach the required destination. The second method stores the coordinates of the destination in the route request packets. These packets can only travel in the direction were the relative distance to the destination becomes smaller as they travel from one hop to another. Both methods limit the control overhead transmitted through the network and hence

conserve bandwidth. They will also determine the shortest path (in most cases) to the destination, since the route request packets travel away from the source and towards the destination. The disadvantage of this protocol is that each node is required to carry a GPS. Another disadvantage is (especially for the first method), that protocols may behave similar to flooding protocols (e.g. DSR and AODV) in highly mobile networks.

### 3.10. Ant-colony-based routing algorithm (ARA)

ARA [13] attempt to reduce routing overheads by adopting the food searching behaviour of ants. When ants search for food they start from their nest and walk towards the food, while leaving behind a transient trail called pheromone. This indicated the path that has been taken by the ant and allows others to follow, until the pheromone disappears. Similar to AODV and DSR, ARA is also made up of two phases (route discovery and route maintenance). During route discovery a Forwarding ANT (FANT) is propagated throught the network (similar to a RREQ). At each hop, each node calculate a pheromone value depending on how many number of hops the FANT has taken to reach them. The nodes then forward the FANT to their neighbours. Once the destination is reached, it creates a Backward ANT (BANT), and returns it to the source. When the source receives the BANT from the destination node, a path is determined and data packet dissemination begins. To maintain each route, each time a data packet travels between intermediate nodes the pheromone value is increased. Otherwise the pheromone value is decreased overtime until it expires. To repair a broken link, the nodes firstly check their routing table, if no route is found they inform their neighbours for an alternate route. If the neighbours do have have a route they inform their neighbours by backtracking. If the source node is reached and no route is found, a new route discovery process is initiated. The advantage of this strategy is that the size of each FANT and BANT is small, which means the amount of overhead per control packet introduced in the network is minimised. However, the route discovery process it based on flooding, which means that the protocol may have scalability problems as the number of nodes and flows in the network grows.

### 3.11. Flow oriented routing protocol (FORP)

FORP [32] Attempt to reduce the effect of link failure due to mobility during data transmission by predicting when a route is going to be broken and therefore using an alternate link before route failure is experienced. To do this, when a node requires a route to a particular destination and a route is not already available, a Flow_REQ message is broadcasted through the network in a similar manner to a Route Request in DSR. However, in FORP, each node that receives a Flow_REQ calculates a Link Expiration Time (LET) with the previous hop (using a GPS) and appends this value to the Flow_REQ packet which is then rebroadcasted. When a Flow_REQ packet reaches the destination, a Route Expiration Time (RET) is calculated using the minimum of all the LETs for each node in the route and a Flow_SETUP packet is sent back toward the source. During data transmission, each intermediate node append their LET to the data packet. This allows the destination to predict when a link failure could occur. When the destination determines that a route is about to expire, a Flow_HANDOFF message is generated and propagated via flooding (similar to a Flow_REQ). Therefore, when the source receives a Flow_HANDOFF message, it can determine the best route to handoff the flow based on the given information (such as RET and hop count, etc) in the Flow_HANDOFF packet. The source the sends a Flow_SETUp message along the newly chosen route. The advantage of this strategy compared to other on-demand routing protocols described so far is that it minimises the disruptions of real time sessions due to mobility by attempting to maintain constant flow of data. However, since it is based on pure flooding, the protocol may experience scalability problems in large networks.

### 3.12. Cluster-based routing protocol (CBRP)

Unlike the on-demand routing protocols described so far. In CBRP [17] the nodes are organised in a hierarchy. As most hierarchical

protocols described in the previous section, the nodes in CBRP or grouped into clusters. Each cluster has a cluster-head, which coordinates the data transmission within the cluster and to other clusters. The advantage of CBRP is that only cluster heads exchange routing information, therefore the number of control overhead transmitted through the network is far less than the traditional flooding methods. However, as in any other hierarchical routing protocol, there are overheads associated with cluster formation and maintenance. The protocol also suffers from temporary routing loops. This is because some nodes may carry inconsistent topology information due to long propagation delay.

### 3.13. Summary of reactive routing

Generally, most on-demand routing protocols have the same routing cost when considering the worst-case scenario. This is due to their fundamental routing nature, as they all follow similar route discovery and maintenance procedure. For example, protocols such as RDMR and LAR have the same cost as the traditional flooding algorithm in the worst-case scenario. The worst-case scenario applies to most routing protocols when there is no previous communication between the source and the destination. This is usually the case during the initial stages (i.e. when a node comes on-line). As the nodes stay longer on, they are able to update their routing tables/caches and become more aware of their surroundings. Some protocols take advantage of this more than the others. For example, in DSR when a route to a destination has expired in the route cache, the protocol initiates a network wide flooding search to find an alternate route. This is not the case for LAR or RDMR where the route history is used to control the route discovery procedure by localising the route requests to a calculated region. Clearly, this is more advantageous in large networks, since more bandwidth is available there for data transmission. Another method used to minimise the number of control packets is to select routes based on their stability. In ABR and SSR the destination nodes select routes based on their stability. ABR also allows shortest path route selection to be used

during the route selection at the destination (but only secondary to stability), which means that shorter delays may be experienced in ABR during data transmission than in SSR. These protocols may perform better than the purely shortest path selection based routing protocols such as DSR. However, they may experience scalability problem in large network since each packet is required to carry the full destination address. This is because the probability of a node in a selected route becoming invalid will increase by $O(a \cdot n)$, where "$a$" is the probability of the route failing at a node and "$n$" is the number of nodes in the route. Therefore, these protocols are only suitable for small to medium size networks. Reduction in control overhead can be obtained by introducing a hierarchical structure to the network. CBRP is a hierarchical on-demand routing protocol, which attempts to minimise control overheads disseminated into the network by breaking the network into clusters. During the route discovery phase, cluster-heads (rather than each intermediate node) exchange routing information. This significantly reduces the control overhead disseminated into the network when compared to the flooding algorithms. In highly mobile networks, CBRP may incur significant amount of processing overheads during cluster formation/maintenance. This protocol suffers from temporary invalid routes as the destination nodes travel from one cluster to another. Therefore, this protocol is suitable for medium size networks with slow to moderate mobility. The protocol may also best perform in scenarios with group mobility where the nodes within a cluster are more likely to stay together.

## 4. Hybrid routing protocols

Hybrid routing protocols are a new generation of protocol, which are both proactive and reactive in nature. These protocols are designed to increase scalability by allowing nodes with close proximity to work together to form some sort of a backbone to reduce the route discovery overheads. This is mostly achieved by proactively maintaining routes to near by nodes and determining routes to far away nodes using a route discovery strategy. Most

hybrid protocols proposed to date are zone-based, which means that the network is partitioned or seen as a number of zones by each node. Others group nodes into trees or clusters. This section describes a number of different hybrid routing protocol proposed for MANETs. Furthermore, it provides a theoretical performance comparison between the described strategies. The discussion on the performance comparison is based on Tables 5 and 6. Note that, Table 5 provides the summary of the characteristic feature of each strategy and Table 6 provides a theoretical performance evaluation. The performance metrics presented illustrates the worst case scenario for each routing protocol.

### 4.1. Zone routing protocol (ZRP)

In ZRP [14], the nodes have a routing zone, which defines a range (in hops) that each node is required to maintain network connectivity proactively. Therefore, for nodes within the routing zone, routes are immediately available. For nodes that lie outside the routing zone, routes are determined on-demand (i.e. reactively), and it can use any on-demand routing protocol to determine a route to the required destination. The advantage

of this protocol is that it has significantly reduced the amount of communication overhead when compared to pure proactive protocols. It also has reduced the delays associated with pure reactive protocols such as DSR, by allowing routes to be discovered faster. This is because, to determine a route to a node outside the routing zone, the routing only has to travel to a node which lies on the boundaries (edge of the routing zone) of the required destination. Since the boundary node would proactively maintain routes to the destination (i.e. the boundary nodes can complete the route from the source to the destination by sending a reply back to the source with the required routing address). The disadvantage of ZRP is that for large values of routing zone the protocol can behave like a pure proactive protocol, while for small values it behaves like a reactive protocol.

### 4.2. Zone-based hierarchical link state (ZHLS)

Unlike ZRP, ZHLS [18] routing protocol employs hierarchical structure. In ZHLS, the network is divided into non-overlapping zones, and each node has a node ID and a zone ID, which is calculated using a GPS. The hierarchical topology is made up of two levels: node level topology and

Table 5
Basic characteristics of hybrid routing protocols

| Protocol | RS | Multiple routes | Bc | Route metric method | Route maintained in | Route reconfiguration strategy |
|---|---|---|---|---|---|---|
| ZRP | F | No | Yes | SP | Intrazone and interzone tables | Route repair at point of failure and SN[a] |
| ZHLS | H | Yes, if more than one virtual link exists | No | SP or next available virtual link | Intrazone and interzone tables | Location request[b] |
| SLURP | H | Yes, depending on if a leading node is found by MFR | No | MFR for interzone forwarding. DSR for intrazone routing | location cache and a node_list | SN, then location discovery |
| DST | H | Yes, if available | No | Forwarding using the tree neighbours and the bridges using shuttling | Route tables | Holding time[c] or shuttling |
| DDR | H | Yes, it alternate gateway nodes are available | Yes | Stable routing | Intrazone and interzone table | SN, then source initiates a new path discovery |

RS = routing structure; H = hierarchical; F = flat; SP = shortest path; SN = source notification; Bc = beacons.
[a] The source may or may not be notified.
[b] A location request will be sent if the zone ID of a node changes.
[c] Packets are held for a short period of time during which the nodes attempts to route the packet directly to the destination.

Table 6
Complexity comparison of hybrid routing protocols

| Protocol | TC[RD] | TC[RM] | CC[RD] | CC[RM] | Advantage | Disadvantage |
|---|---|---|---|---|---|---|
| ZRP | Intra: $O(I)$/ Inter: $O(2D)$ | $O(I)$/$O(2D)$ | $O(Z_N)$/ $O(N+V)$ | $O(Z_N)$/ $O(N+V)$ | Reduce retransmissions | Overlapping zones |
| ZHLS | Intra: $O(I)$/ Inter: $O(D)$ | $O(I)$/$O(D)$ | $O(N/M)$/ $O(N+V)$ | $O(N/M)$[a]/ $O(N+V)$ | Reduction of SPF, low CO | Static zone map required |
| SLURP | Intra: $O(2Z_D)$/ Inter: $O(2D)$[b] | $O(2Z_D$/$O(2D)$ | $O(2N/M)$/ $O(2Y)$ | $O(2N/M)$/ $O(2Y)$ | Location discovery using home regions | Static zone map required |
| DST | Intra: $O(Z_D)$/ Inter: $O(D)$ | $O(Z_D)$/$O(D)$ | $O(Z_N)$/$O(N)$ | $O(Z_N)$/$O(N)$ | Reduce retransmissions | Root node |
| DDR | Intra: $O(I)$/ Inter: $O(2D)$ | $O(I)$/$O(2D)$ | $O(Z_N)$/ $O(N+V)$ | $O(Z_N)$/ $O(N+V)$ | No zone map or zone coordinator | Preferred neighbours may become bottlenecks |

TC = time complexity; CC = communication complexity; RD = route discovery; RM = route maintenance; $I$ = periodic update interval; $N$ = number of nodes in the network; $M$ = number of zones or cluster in the network; $Z_N$ = number of nodes in a zone, cluster or tree; $Z_D$ = diameter of a zone, cluster or tree; $Y$ = number of nodes in the path to the home region; $V$ = number of nodes on the route reply path; SPF = single point of failure; CO = control overhead.

[a] In ZHLS, the intrazone is maintained proactively. Therefore, a fixed number of updates are sent at a fixed interval.

[b] In SLURP, in the worst-case scenario, the source node and the home region of the destination are on the opposite edges of the network.

zone level topology, as described previously. In ZHLS location management has been simplified. This is because no cluster-head or location manager is used to coordinate the data transmission. This means there is no processing overhead associated with cluster-head or Location Manager selection when compared to HSR, MMWN and CGSR protocols. This also means that a single point of failure and traffic bottlenecks can be avoided. Another advantage of ZHLS is that it has reduced the communication overheads when compared to pure reactive protocols such as DSR and AODV. In ZHLS, when a route to a remote destination is required (i.e. the destination is in another zone), the source node broadcast a zone-level location request to all other zones, which generates significantly lower overhead when compared to the flooding approach in reactive protocols. Another advantage of ZHLS is that the routing path is adaptable to the changing topology since only the node ID and the zone ID of the destination is required for routing. This means that no further location search is required as long as the destination does not migrate to another zone. However, in reactive protocols any intermediate link breakage would invalidate the route and may initiate another route discovery procedure. The Disadvantage of ZHLS is that all nodes must have a preprogrammed static zone map in order to function. This may not feasible in applications where the geographical boundary of the network is dynamic. Nevertheless, it is highly adaptable to dynamic topologies and it generates far less overhead than pure reactive protocols, which means that it may scale well to large networks.

### 4.3. Scalable location update routing protocol (SLURP)

Similar to ZLHS, in SLURP [34] the nodes are organised into a number of non-overlapping zones. However SLURP further reduces the cost of maintaining routing information by eliminating a global route discovery. This is achieved by assigning a home region for each node in the network. The home region for each node is one specific zone (or region), which is determined using a static mapping function, $f(NodeID) \rightarrow regionID$, where $f$ is a many-to-one function that is static and known to all nodes. An example of a function that can perform the static zone mapping is $f(NodeID) = g(NodeID)modK$ [34], where $g(NodeID)$ is a random number generating function that uses the node ID as the seed and output a large number, and $k$ is the total number of home regions in the network. Now since the node ID of each node is constant (i.e. a MAC address), then the function will always cal-

culate the same home region. Therefore, all nodes can determine the home region for each node using this function provided they have their node ID. Each node maintains it current location (current zone) with the home region by unicasting a location update message towards its home region. Once the location update packet reaches the home region, it is broadcasted to all the nodes in the home region. Hence, to determine the current location of any node, each node can unicast a location_discovery packet to the required nodes home region (or the area surrounding the home region) in order to find its current location. Once the location is found, the source can start sending data towards the destination using the most forward with fixed radius (MFR) geographical forwarding algorithm. When a data packet reaches the region in which the destination lies, then source routing [4] is used to get the data packet to the destination. The disadvantage of SLURP is that it also relies on a preprogrammed static zone map (as does ZHLS).

## 4.4. Distributed spanning trees based routing protocol (DST)

As mentioned earlier, in DST [28] the nodes in the network are grouped into a number of trees. Each tree has two types of nodes; route node, and internal node. The root controls the structure of the tree and whether the tree can merge with another tree, and the rest of the nodes within each tree are the regular nodes. Each node can be in one three different states; router, merge and configure depending on the type of task that it trying to perform. To determine a route DST proposes two different routing strategies; hybrid tree-flooding (HFT) and distributed spanning tree shuttling (DST). In HTF, control packets are sent to all the neighbours and adjoining bridges in the spanning tree, where each packet is held for a period of time called holding time. The idea behind the holding time is that as connectivity increases, and the network becomes more stable, it might be useful to buffer and route packets when the network con-

nectivity is increased over time. In DST, the control packets are disseminated from the source are rebroadcasted along the tree edges. When a control reaches down to a leaf node, it is sent up the tree until it reaches a certain height referred to as the shuttling level. When the shuttling level is reached, the control packet can be sent down the tree or to the adjoining bridges. The main disadvantage of the DST algorithm is that it relies on a root node to configure the tree, which creates a single point of failure. Furthermore, the holding time used to buffer the packets may introduce extra delays in to the network.

## 4.5. Distributed dynamic routing (DDR)

DDR [24] is also a tree-based routing protocol. However, unlike DST, in DDR the trees do not require a root node. In this strategy tree are constructed using periodic beaconing messages which is exchanged by neighbouring nodes only. The trees in the network form a forest, which is connected together via gateway nodes (i.e. nodes which are in transmission range but belong to different trees). Each tree in the forest is forms a zone which is assigned a zone ID by running a zone naming algorithm. Furthermore, since each node can only belong to a single zone (or tree), then the network can be also seen as a number of non-overlapping zones. The DDR algorithm consists of six phases: preferred neighbour election, forest construction, intra-tree clustering, inter-tree clustering, zone naming and zone partitioning. Each of these phases are executed based on information received in the beacon messages. During the initialisation phase, each node starts in the preferred neighbour election phase. The preferred neighbour of a node is a node that has the most number of neighbours. After this, a forest is constructed by connecting each node to their preferred neighbour. Next, the intra-tree clustering algorithm is initiated to determine the structure of the of the zone [5] (or the tree) and to build up the intrazone routing table. This is then followed by the

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[4] In this protocol DSR is used as a source routing protocol.

[5] The terms tree and zone are used interchangeably.

execution of the inter-tree algorithm to determine the connectivity with the neighbouring zones. Each zone is then assigned a name by running the zone naming algorithm and the network is partitioned into the a number of non-overlapping zones. To determine routes, hybrid ad hoc routing protocols (HARP) [23] to work on top of DDR. HARP uses the intra-zone and inter-zone routing tables created by DDR to determine a stable path between the source and the destination. The advantage of DDR is that unlike ZHLS, it does not relies on a static zone map to perform routing and it does not require a root node or a clusterhead to coordinate data and control packet transmission between different nodes and zones. However, the nodes that have been selected as preferred neighbours may become performance bottlenecks. This is because, they would transmit more routing and data packets than every other nodes. This means that these nodes would require more recharging as they will have less sleep time than other nodes. Furthermore, if a node is a preferred neighbour for many of its neighbours, many nodes may want to communicate with it. This means that channel contention would increase around the preferred neighbour, which would result in larger delays experienced by all neighbouring nodes before they can reserve the medium. In networks with high traffic, this may also result in significant reduction in throughput, due to packets being dropped when buffers become full.

### 4.6. Summary of hybrid routing

Hybrid routing protocols have the potential to provide higher scalability than pure reactive or proactive protocols. This is because they attempt to minimise the number of rebroadcasting nodes by defining a structure (or some sort of a backbone), which allows the nodes to work together in order organise how routing is to be performed. By working together the best or the most suitable nodes can be used to perform route discovery. For example, in ZHLS only the nodes which lead to the gateway nodes the interzone route discovery packets. Collaboration between nodes can also help in maintaining routing information much longer. For example, in SLURP, the nodes within

each region (or zone) work together to maintain location information about the nodes which are assigned to that region (i.e. their home region). This may potentially eliminate the need for flooding, since the nodes know exactly where to look for a destination every time. Another novelty of hybrid routing protocols is that they attempt to eliminate single point of failures and creating bottleneck nodes in the network. This is achieved by allowing any number of nodes to perform routing or data forwarding if the preferred path becomes unavailable.

## 5. Conclusions

In this paper three categories of unicast routing protocols (some have multicast capability) where introduced (Table 7). The global routing protocols, which are derived mainly from the traditional link state or distance vector algorithm, maintain network connectivity proactively, and the on-demand routing protocols determine routes when they are needed. The hybrid routing protocols employ both reactive and proactive properties by maintaining intra-zone information proactively and inter-zone information reactively. By looking at performance metrics and characteristics of all categories of routing protocols, a number of conclusions can be made for each category. In global routing flat addressing can be simple to implement, however it may not scale very well for large networks [15]. In order to make flat addressing more efficient, the number of routing overheads introduced in the networks must be reduced. One way to do this is to use a device such a GPS. For example, in the DREAM routing protocol, node only exchange location information (coordinates) rather than complete link state or distance vector information. Another way to reduce routing overheads is by using conditional updates rather than periodic ones. For example in the STAR routing protocol, updates occur based on three conditions (as described earlier). The global routing schemes, which use hierarchical addressing, have reduced the routing overheads introduced to the networks by introducing a structure, which localises the update message propagation.

Table 7
Overall comparison of all routing categories

| Routing class | Proactive | Reactive | Hybrid |
|---|---|---|---|
| Routing structure | Both flat and hierarchical structures are available | Mostly flat, execpt CBRP | Mostly hierarchical |
| Availability of route | Always available[a] | Determined when needed | Depends on the location of the destination |
| Control traffic volume | Usually high, attempt at reduction is made. E.g., OLSR, TBRPF | Lower than Global routing and further improved using GPS. E.g., LAR | Mostly, lower than proactive and reactive |
| Periodic updates | Yes, However some may use conditional. E.g., STAR | Not required. However some nodes may require periodic beacons. E.g., ABR | Usually used inside each zone, or between gateways |
| Handling effects of mobility | Usually updates occur at fixed intervals. DREAM alters periodic updates based on mobility | ABR introduced LBQ. ROAM employs threshold updates. AODV uses local route discovery | Usually more than one path may be available. Single point of failures are reduced by working as a group |
| Storage requirements | High | Depends on the number of routes kept or required. Usually lower than proactive protocols | Usually depends on the size of each cluster or zone may become as large as proactive protocols if clusters are big |
| Delay level | Small routes are predetermined | Higher than proactive | For local[b] destinations small. Interzone may be as large as reactive protocols |
| Scalability level[c] | Usually up to 100 nodes. OLSR and TBRPF may scale higher | Source routing protocols up to few hundred nodes. Point-to-point may scale higher. Also depends on the level of traffic and the levels of multihopping | Designed for up to 1000 or more nodes |

[a] If the nodes are reachable.
[b] Local destinations represents the nodes that are in the same zone or cluster as the source. For remote, they are in different clusters.
[c] The ability to perform efficient routing for up to an approximate number of nodes.

However, the current problem with these schemes is location management, which also introduces significant overheads to the network. In on-demand routing protocols, the flooding-based routing protocols such as DSR and AODV will also have scalability problems. In order to increase scalability, the route discovery and route maintenance must be controlled. This can be achieved by localising the control message propagation to a defined region where the destination exists or where the link has been broken. For example, in the LAR1 routing protocol, which also uses a GPS, the route request packets propagate in the request zone only, and in the ABR routing protocol a localised broadcast query (LBQ) is initiated when a link goes down. Hybrid routing protocols such as the ZHLS and SLURP may also perform well in large networks. The advantage of these protocol over other hierarchical routing protocols

is that they have a simplified location management due to using a GPS and do not use a cluster-head to coordinate data transmission, which means that a single point of failure and performance bottlenecks can be avoided. Another advantage of these protocols is that they are highly adaptable to changing topology since only the node ID and zone ID of the destination is required for routing to occur. The ZRP routing protocol is another hybrid routing protocol described earlier, which is designed to increase the scalability of MANETs. The advantage of this protocol is that it maintains a strong network connectivity (proactively) within the routing zones while determining remote route (outside the routing zone) quicker than flooding. Another advantage of the ZRP is that it can incorporate other protocols to improve its performance. For example, it can use LAR1 for interzone routing.

# References

[1] G. Aggelou, R. Tafazolli, RDMAR: a bandwidth-efficient routing protocol for mobile ad hoc networks, in: ACM International Workshop on Wireless Mobile Multimedia (WoWMoM), 1999, pp. 26–33.

[2] S. Basagni, I. Chlamtac, V.R. Syrotivk, B.A. Woodward, A distance effect algorithm for mobility (DREAM), in: Proceedings of the Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom'98), Dallas, TX, 1998.

[3] R.E. Bellman, Dynamic Programming, Princeton University Press, Princeton, NJ, 1957.

[4] B. Bellur, R.G. Ogier, F.L Templin, Topology broadcast based on reverse-path forwarding routing protocol (tbrpf), in: Internet Draft, draft-ietf-manet-tbrpf-06.txt, work in progress, 2003.

[5] T.-W. Chen, M. Gerla, Global state routing: a new routing scheme for ad-hoc wireless networks, in: Proceedings of the IEEE ICC, 1998.

[6] C.-C. Chiang, Routing in clustered multihop mobile wireless networks with fading channel, in: Proceedings of IEEE SICON, April 1997, pp. 197–211.

[7] M.S. Corson, A. Ephremides, A distributed routing algorithm for mobile wireless networks, ACM/Baltzer Wireless Networks 1 (1) (1995) 61–81.

[8] S. Das, C. Perkins, E. Royer, Ad hoc on demand distance vector (AODV) routing, Internet Draft, draft-ietf-manet-aodv-11.txt, work in progress, 2002.

[9] R. Dube, C. Rais, K. Wang, S. Tripathi, Signal stability based adaptive routing (ssa) for ad hoc mobile networks, IEEE Personal Communication 4 (1) (1997) 36–45.

[10] L.R. Ford, D.R. Fulkerson, Flows in Networks, Princeton University Press, Princeton, NJ, 1962.

[11] J.J. Garcia-Luna-Aceves, C. Marcelo Spohn, Source-tree routing in wireless networks, in: Proceedings of the Seventh Annual International Conference on Network Protocols Toronto, Canada, October 1999, p. 273.

[12] M. Gerla, Fisheye state routing protocol (FSR) for ad hoc networks, Internet Draft, draft-ietf-manet-aodv-03.txt, work in progress, 2002.

[13] M. Günes, U. Sorges, I. Bouazizi, Ara—the ant-colony based routing algorithm for manets, in: ICPP workshop on Ad Hoc Networks (IWAHN 2002), August 2002, pp. 79–85.

[14] Z.J. Hass, R. Pearlman, Zone routing protocol for ad-hoc networks, Internet Draft, draft-ietf-manet-zrp-02.txt, work in progress, 1999.

[15] A. Iwata, C. Chiang, G. Pei, M. Gerla, T. Chen, Scalable routing strategies for multi-hop ad hoc wireless networks, IEEE Journal on Selected Areas in Communcations 17 (8) (1999) 1369–1379.

[16] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum, L. Viennot, Optimized link state routing protocol for ad hoc networks, IEEE INMIC, Pakistan, 2001.

[17] M. Jiang, J. Ji, Y.C. Tay, Cluster based routing protocol, Internet Draft, draft-ietf-manet-cbrp-spec-01.txt, work in progress, 1999.

[18] M. Joa-Ng, I.-T. Lu, A peer-to-peer zone-based two-level link state routing for mobile ad hoc networks, IEEE Journal on Selected Areas in Communications 17 (8) (1999) 1415–1425.

[19] D. Johnson, D. Maltz, J. Jetcheva, The dynamic source routing protocol for mobile ad hoc networks, Internet Draft, draft-ietf-manet-dsr-07.txt, work in progress, 2002.

[20] K.K. Kasera, R. Ramanathan, A location management protocol for hierarchically organised multihop mobile wireless networks, in: Proceedings of the IEEE ICUPC'97, San Diego, CA, October 1997, pp. 158–162.

[21] Y.-B. Ko, N.H. Vaidya, Location-aided routing (LAR) in mobile ad hoc networks, in: Proceedings of the Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom'98), Dallas, TX, 1998.

[22] S. Murthy J.J. Garcia-Luna-Aceves, A routing protocol for packet radio networks, in: Proceedings of the First Annual ACM International Conference on Mobile Computing and Networking, Berkeley, CA, 1995, pp. 86–95.

[23] N. Nikaein, C. Bonnet, N. Nikaein, Harp-hybrid ad hoc routing protocol, in: Proceedings of IST: International Symposium on Telecommunications, September 1–3 Tehran, Iran, 2001.

[24] N. Nikaein, H. Laboid, C. Bonnet, Distributed dynamic routing algorithm (ddr) for mobile ad hoc networks, in: Proceedings of the MobiHOC 2000: First Annual Workshop on Mobile Ad Hoc Networking and Computing, 2000.

[25] V.D. Park, M.S. Corson, A highly adaptive distributed routing algorithm for mobile wireless networks, in: Proceedings of INFOCOM, April 1997.

[26] G. Pei, M. Gerla, X. Hong, C. Chiang, A wireless hierarchical routing protocol with group mobility, in: Proceedings of Wireless Communications and Networking, New Orleans, 1999.

[27] C.E. Perkins, T.J. Watson, Highly dynamic destination sequenced distance vector routing (DSDV) for mobile computers, in: ACM SIGCOMM'94 Conference on Communications Architectures, London, UK, 1994.

[28] S. Radhakrishnan, N.S.V Rao, G. Racherla, C.N. Sekharan, S.G. Batsell, DST—A routing protocol for ad hoc networks using distributed spanning trees, in: IEEE Wireless Communications and Networking Conference, New Orleans, 1999.

[29] J. Raju, J. Garcia-Luna-Aceves, A new approach to on-demand loop-free multipath routing, in: Proceedings of the 8th Annual IEEE International Conference on Computer Communications and Networks (ICCCN), Boston, MA, October 1999, pp. 522–527.

[30] E.M. Royer, C.-K. Toh, A review of current routing protocols for ad hoc mobile wireless networks, IEEE Personal Communications 6 (2) (1999) 46–55.

[31] A. Udaya Shankar, C. Alaettinoglu, I. Matta, K. Dussa-Zieger, Performance comparison of routing protocols using MaRS: distance-vector versus link-state, in: Proceedings of the 1992 ACM SIGMETRICS and PERFORMANCE '92

Int'l. Conf. on Measurement and Modeling of Computer Systems, Newport, RI, USA, 1–5 June 1992, p. 181.

[32] W. Su, M. Gerla, Ipv6 flow handoff in ad-hoc wireless networks using mobility prediction, in: IEEE Global Communications Conference, Rio de Janeiro, Brazil, December 1999, pp. 271–275.

[33] C. Toh, A novel distributed routing protocol to support ad-hoc mobile computing, in: IEEE 15th Annual International Phoenix Conf., 1996, pp. 480–486.

[34] S.-C. Woo, S. Singh, Scalable routing protocol for ad hoc networks, Wireless Networks 7 (5) (2001) 513–529.

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