

Routing Techniques in Wireless Ad Hoc Networks

—Classification and Comparison*

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ABSTRACT

Routing (and forwarding) is a core problem in networks for delivering data from one node to another. Today wireless networks are becoming popular because of their “3 Anys”—Any person, Anywhere and Any time. Wireless ad hoc networks are termed as mobile distributed multihop wireless networks without predetermined topology (preexisting fixed infrastructure) or central control. In this paper, we present a comprehensive review for routing features and techniques in wireless ad hoc networks. For more than a dozen typical existing routing protocols, we compare their properties according to different criteria, and categorize them according to their routing strategies and relationships.

Keywords. Routing protocols, Wireless communications, Ad hoc networks.

1 INTRODUCTION

Routing (and forwarding) is a core problem in networks for delivering data from one node to another. Today, wireless networks are becoming popular because of their “3 Anys”—Any person, Anywhere and Any time [22, 25]. However, wireless networks have special limitations and properties such as *limited bandwidth*, *highly dynamic topology*, *link interference*, *limited range of links*, and *broadcast*. Therefore, routing protocols for wired networks cannot be directly used in wireless networks; routing protocols for wireless networks need to be designed and implemented separately [28].

There are two typical categories of wireless networks [13, 24]: cellular (one hop) networks and wireless ad hoc (multi hop) networks. Wireless ad hoc networks (formerly called packet radio networks) are defined as mobile distributed multihop wireless networks [7]. In a wireless ad hoc network, there is no predetermined topology (preexisting fixed infrastructure) and no central control. The nodes in ad hoc networks communicate without wired connections among themselves by creating a network “on the fly” [7]. Wireless ad hoc networks are traditionally used in battlefield communications, law enforcement, disaster recovery (fire, earthquake, etc.), and emergency search and rescue. Recently, wireless ad hoc networks have been extensively used in civilian forums (i.e., “ad hoc personal” communications) such as

electronic classrooms, convention centers, construction sites, and special events (concerts, festivals, etc.) [13, 20].

There have been several routing protocols proposed for wireless ad hoc networks. There have also been several articles written which compare the performance and characteristics of different protocols [1, 5, 24, 26]. Among them, three articles [1, 5, 26] compare a few (up to four) protocols based on the *simulation of the compared protocols* and the authors of [24] provide a comprehensive survey including *qualitative comparisons* of nine protocols.

In this paper, we identify various techniques used for classifying routing protocols for wireless ad hoc networks (Section 2), which will help the understanding of current protocols and the designing of new protocols. Moreover, we examine more than a dozen typical routing protocols, giving qualitative comparisons of their characteristics and categorizing them according to their routing strategies and relationships (Section 3).

2 CLASSIFICATION

There are different criteria for designing and classifying routing protocols for wireless ad hoc networks. For example, what routing information is exchanged; when and how the routing information is exchanged, when and how routes are computed and so on. We will discuss these criteria in this section.

Link state routing (LSR) vs. distance vector routing (DVR)

As with conventional wired networks, *Link state* routing (LSR) and *distance vector* routing (DVR) are two underlying mechanisms for routing in wireless ad hoc networks. In LSR [28], routing information is exchanged in the form of *link state packets* (LSP). The LSP of a node includes link information about its neighbors. Any link change will cause LSPs to be flooded into the entire network immediately. Every node can construct and maintain a global network topology from the LSPs it receives, and compute, by itself, routes to all other nodes. The problem with LSR is that excessive routing overhead may be incurred because nodes in a wireless ad hoc network move quickly and the network topology changes fast.

In DVR [28], every node maintains a distance vector which includes, but is not limited to, the triad (destination ID, next hop,

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(shortest) distance) for every destination. Every node periodically exchanges distance vectors with its neighbors. When a node receives distance vectors from its neighbors, it computes new routes and updates its distance vector. The complete route from a source to a destination is formed, in a distributed manner, by combining the next hop of nodes on the path from the source to the destination. The problems with DVR are slow convergence and the tendency of creating routing loops.

Precomputed routing vs. on-demand routing

Depending on when the route is computed, routing protocols can be divided into two categories: precomputed routing and on-demand routing.

Precomputed routing is also called *proactive* routing or *table-driven* routing [24]. In this method, the routes to all destinations are computed *a priori*. In order to compute routes in advance, nodes need to store the entire or partial information about link states and network topology. In order to keep the information up to date, nodes need to update their information periodically or whenever the link state or network topology changes. The advantage of precomputed routing is that when a source needs to send packets to a destination, the route is already available, i.e., there is no latency. The disadvantage is that some routes may never be used. Another problem is that the dissemination of routing information will consume a lot of the scarce wireless network bandwidth when the link state and network topology change fast (this is especially true in a wireless ad hoc network). The conventional LSR and DVR are examples of proactive routing. We will use *precomputed* and *proactive* interchangeably in this paper.

On-demand routing is also called *reactive* routing. In this method, the route to a destination may not exist in advance and it is computed only when the route is needed. The idea is as follows. When a source needs to send packets to a destination, it first finds a route or several routes to the destination. This process is called *route discovery*. After the route(s) are discovered, the source transmits packets along the route(s). During the transmission of packets, the route may be broken because the node(s) on the route move away or go down. The broken route needs to be rebuilt. The process of detecting route breakage and rebuilding the route is called *route maintenance*. The major advantage of on-demand routing is that the precious bandwidth of wireless ad hoc networks is greatly saved [15] because it limits the amount of bandwidth consumed in the exchange of routing information by maintaining routes to only those destinations to which the routers need to forward data traffic. On-demand routing also obviates the need for disseminating routing information periodically, or flooding such information whenever a link state changes. The primary problem with on-demand routing is the large latency at the beginning of the transmission caused by *route discovery*. We will use *on-demand* and *reactive* interchangeably in this paper.

Apart from proactive route computation and reactive route discovery, there is another routing mechanism, called flooding [9, 15]. In flooding, no route will be computed or discovered. A packet is *broadcast* to all nodes in a network with the expectation that at least one copy of the packet will reach the destination. Scoping [9] may be used to limit the overhead of flooding. Flooding is the easiest routing method because it requires no knowledge of the network topology. Under light traffic con-

ditions flooding can be reasonably robust. However, it generates an excessive amount of traffic in heavy traffic or in a large network [15], and it is difficult to achieve flooding reliably [21] when the topology is highly dynamic. Flooding is generally used to transmit control packets (e.g., routing information), not data packets.

Periodical update vs. event-driven update

Routing information needs to be disseminated to network nodes in order to ensure that the knowledge of link state and network topology remains up-to-date. Based on when the routing information will be disseminated, we can classify routing protocols as periodical update and event-driven update protocols.

Periodical update protocols disseminate routing information periodically. Periodical updates will simplify protocols and maintain network stability, and most importantly, enable (new) nodes to learn about the topology and the state of the network. However if the period between updates is large, the protocol may not keep the information up-to-date. On the other hand, if the period is small, too many routing packets will be disseminated which consumes the precious bandwidth of a wireless network.

In an event-driven update protocol, when events occur, (such as when a link fails or a new link appears), an update packet will be broadcast and the up-to-date status can be disseminated over the network soon. The problem might be that if the topology of networks changes rapidly, a lot of update packets will be generated and disseminated over the network which will use a lot of precious bandwidth, and furthermore, may cause too much fluctuation of routes. One solution is to use some threshold [12, 19].

Periodical update and event-driven update mechanisms can be used together, forming what is called a hybrid update mechanism. For example, in DSDV [19], a node broadcasts its distance-vector periodically. Moreover, whenever a node finds that a link is broken, it distributes a message immediately.

Flat structure vs. hierarchical structure

In a flat structure, all nodes in a network are at the same level and have the same routing functionality. Flat routing is simple and efficient for small networks. The problem is that when a network becomes large, the volume of routing information will be large and it will take a long time for routing information to arrive at remote nodes.

For large networks, hierarchical (cluster-based) routing may be used to solve the above problems [12, 15]. In hierarchical routing the nodes in the network are dynamically organized into partitions called clusters, then the clusters are aggregated again into larger partitions called superclusters and so on. Organizing a network into clusters help maintain a relatively stable network topology [15]. The high dynamics of membership and network topology is limited within clusters. Only stable and high level information such as the cluster level or the supercluster level will be propagated across a long distance, thus the control traffic (or routing overhead) may be largely reduced [10, 15]. Within a cluster, the nodes may have complete topology information about its cluster and proactive routing may be used. If the destination is

in a different cluster from the source, intercluster routing must be used. Intercluster routing is generally reactive, or a combination of proactive and reactive routing as in [10]. Similar to cellular structure in cellular systems, a hierarchical cluster is readily deployable to achieve some kind of resource reuse such as frequency reuse and code reuse [9, 10] and interference can be reduced when using different spreading codes across clusters [9].

Decentralized computation vs. distributed computation

Based on how (or where) a route is computed, there are two categories of routing protocols: decentralized computation and distributed computation.

In a decentralized computation-based protocol, every node in the network maintains global and complete information about the network topology such that the node can compute the route to a destination itself when desired. The route computation in LSR is a typical example of decentralized computation.

In a distributed computation-based protocol, every node in the network only maintains partial and local information about the network topology. When a route needs to be computed, many nodes collaborate to compute the route. The route computation in DVR and the route discovery in on-demand routing belong to this category.

Source routing vs. hop-by-hop routing

Some routing protocols place the entire route (i.e., nodes in the route) in the headers of data packets so that the intermediate nodes only forward these packets according to the route in the header. Such a routing is called “source routing”. Source routing has the advantage that intermediate nodes do not need to maintain up-to-date routing information in order to route the packets they forward, since the packets themselves already contain all the routing decisions. This fact, when coupled with on-demand route computation, eliminates the need for the periodic route advertisement and neighbor detection packets required in other kinds of protocols [14]. The biggest problem with source routing is that when the network is large and the route is long, placing the entire route in the header of every packet will waste a lot of scarce bandwidth.

In hop-by-hop routing, the route to a destination is distributed in the “next hop” of the nodes along the route. When a node receives a packet to a destination, it forwards the packet to the next hop corresponding to the destination. The problems are that all nodes need to maintain routing information and there may be a possibility of forming a routing loop.

Single path vs. multiple paths

Some routing protocols will find a single route from a source to a destination, which results in simple protocol and saves storage. Other routing protocols will find multiple routes which have the advantages of easy recovery from a route failure and being more reliable and robust. Moreover, the source can select the best one among multiple available routes.

Table 1: Complexity of Typical Routing Protocols.

Protocols	Storage Comp.	Time Comp.	Control Packet Size	Comm. Comp.
LSR	$O(N \times A)$	$O(D)$	$O(A)$	$O(N)$
DVR	$O(N)$	$O(D)$	$O(N)$	$O(N)$
DSDV	$O(N)$	$O(D)$	$O(N)$	$O(N)$
GSR	$O(N \times A)$	$O(D)$	$O(N)$	$O(N)$
FSR	$O(N \times A)$	$O(D)$	determined by fisheye	$O(N)$
CGSR	$O(2N)$	$O(D)$	$O(N)$	$O(N)$
WRP	$O(N \times A)$	$O(D)$	$O(N+A)$	$O(N)$
DSR	$O(D)$	$O(2D)$	$O(D)$	$O(2N)$
AODV	$O(D_d)$	$O(2D)$	$O(D_d)$	$O(2N)$
TORA	$O(D_d \times A)^*$	$O(2D)$	$O(1)$	$O(2N)$
SDT	$O(D_d \times A)$	$O(2D)$	$O(D_d)$	$O(2N)$
ABR	$O(D+A)$	$O(D+Z)$	$O(D)$	$O(N+Y)$
SSA	$O(D+A)$	$O(D+Z)$	$O(1)$	$O(N+Y)$
ZRP	$O(M+B+D_d)$	Intrazone: $O(M)$ /Interzone: $O(2D)$	$O(M)/O(1)$	$O(M)/O(2B \times D)^{**}$
ZHLS	$O(M+N/M)$	Intrazone: $O(M)$ /Interzone: $O(D)$	$O(A)$ node LSP/ $O(N/M)$ zone LSP	$O(M)/O(N)$
CEDAR	Core/other nodes: $O(N)/O(A)$	$O(D)$	$O(1)$	$O(C+D)^{***}$
HSR	$O(M \times \log_M N)$	$O(D)$	$O(M)$	$O(N)$

Table 2: Comparison of Typical Routing Protocols.

Protocols	Route Computation	Structure	#Routes	Source Routing	RRM*	BR*
LSR	Proactive/itself	Flat	Single or multiple	No, may Yes	N/A	No
DVR	Proactive/distributed	Flat	Single	No	N/A	No
DSDV	Proactive/distributed	Flat	Single	No	N/A	No
GSR	Proactive/distributed	Flat	Single or multiple	No, may Yes	N/A	No
FSR	Proactive/distributed	Flat	Single or multiple	No, may Yes	N/A	No
CSGR	Proactive/distributed	Hierarchy	Single	No	N/A	No
WRP	Proactive/distributed	Flat	Single		N/A	Yes
DSR	Reactive/broadcast QUERY	Flat	Multiple	Yes	Erase route, Notify source	No
AODV	Reactive/broadcast QUERY	Flat	Multiple	No	Erase route, Notify source	Yes
TORA	Reactive/broadcast QUERY	Flat	Multiple (DAG)	No	Link reversal, Route repair	No
DST	Reactive/broadcast QUERY	Flat	single but may multiple	No, may yes	Route repair	No
ABR	Reactive/broadcast QUERY	Flat	Single	Yes	Localized broadcast query	Yes
SSA	Reactive/broadcast QUERY	Flat	Single	No	Erase route, Notify source	Yes
ZRP	Proactive(intra)/Reactive(inter)	Flat	Single or multiple	Yes for interzone	Route repair	No
ZHLS	Proactive/Reactive (hier. addr.)	Hierarchy	Single	No	N/A	No
CEDAR	Reactive/core broadcast QUERY	Hierarchy	Single	Yes	Route repair	Yes
HSR	Proactive/Reactive (hier. addr.)	Hierarchy	Single	No	N/A	No

Table 3: Comparisons of Typical Routing Protocols (cont.).

Proto.	Stored Information	Update Period	Update Information	Update Dest.	Method
LSR	Entire topology	Hybrid	Neighbors' link state	All nodes	Flooding
DVR	Distance-vector	Periodical	Distance vector	Neighbors	Broadcast
DSDV	Distance vector	Hybrid	Distance vector	Neighbors	Broadcast
GSR	Entire topology	Periodical	All nodes link state	Neighbors	Broadcast
FSR	Entire topology	Periodicals(dif. freq.)	Link state of fisheye scope	Neighbors	Broadcast
CSGR	Clus. mem. table, Dist. Vec.	Periodical	clus. mem table, Dist. Vec.	Neigh.&Clus. head	Broadcast
WRP	Dist./routing/link-cost table, MRL	Hybrid	Dist. Vec., List of Resp.	Neighbors	Broadcast
DSR	Routes to desired Dest.	Event-driven RM	ROUTE-ERROR	Source	Unicast
AODV	Next hops for desired dest.	Event-driven RM	ROUTE-ERROR	Source	Unicast
TORA	Neighbors' heights	Event-driven	Node's height	Neighbors	Broadcast
DST	Distance/routing/query table	Event-driven	Routing table	Neighbors	Broadcast
ABR	Neighbors' asso. ticks	Period./Eve.-dri. RRC	Node's ticks/ROUTE-ERROR	Neigh./Source	Bro./Unicast
SSA	Signal stability/routing table	Period./Eve.-dri. RRC	ROUTE-ERROR	Source	Unicast
ZRP	Local (within zone), topology	Periodical	Link state of nodes in the zone	Neighbors	Broadcast
ZHLS	Local/zone topology	Period./Event-driven	Node/Zone link state	Zone/all nodes	Broadcast
CEDAR	Core/other nodes:global/local	Period./Event-driven	Dynamic/stable link state	Neigh./Core nodes	Bro./Core bro.
HSR	Hierarchy topology	Period./Event-driven	Virtu. link state/High lev. topo.	Nodes in clus.	Broadcast

3 COMPARISON

There have been several routing protocols proposed for wireless ad hoc networks. In this section, we will compare fifteen typical routing protocols according to different criteria introduced in section 2. These protocols are: 1) Destination-Sequence Distance Vector (DSDV) [19], 2) Clusterhead Gateway Switch Routing (CGSR) [3], 3) Dynamic Source Routing (DSR) [11, 14], 4) Ad hoc On-Demand Distance Vector routing (AODV) [18], 5) Temporally-Ordered Routing Algorithm (TORA) [17], 6) Wireless Routing Protocol (WRP) [16], 7) Dynamic Source Tracing (DST) [23], 8) Associativity Based Routing (ABR) [24, 29, 30], 9) Signal Stability-based Adaptive Routing protocol (SSA) [6], 10) Global State Routing (GSR) [2], 11) Fisheye State Routing (FSR) [9], 12) Core-Extraction Distributed Ad hoc Routing Algorithm (CEDAR) [27], 13) Zone Routing Protocol (ZRP) [8, 20], 14) Zone-based Hierarchical Link State routing (ZHLS) [10], 15) Hierarchical State Routing (HSR) [9].

Because many routing protocols use distance vector or link state as their underlying mechanism to disseminate update packets and compute the route, we include Link State Routing (LSR) and Distance Vector Routing (DVR) as the basis of our comparison. The meanings of some items in Table 2 and Table 3 are discussed below. *Stored Information* denotes the information stored in each node. In some protocols, nodes may have different functions and therefore, store different information. As for *Update Period*, it is mainly applicable to proactive protocols and assumes values such as “periodical”, “event-driven” or “hybrid”. For reactive protocols, when a link on a route is broken, route maintenance is activated. which is called event-driven route maintenance or event-driven RRC (route re-construction). The *Update Information* is generally the link state and *Update Destination* is “neighbors”. However, for event-driven route maintenance, the *Update Information* is generally “ROUTE-ERROR” message and the *Update Destination* is the source. *Update Method* is generally “broadcast” with some exceptions such as “unicast” or “core broadcast¹”. *Route Computation* indicates when the route is computed. There are three cases: precomputed, on-demand, and hybrid. Furthermore, for proactive protocols the computation may be done by nodes themselves or collaboratively. However, in reactive protocols, the computation is done by broadcasting (“bordercasting” in ZRP, or “core broadcasting” in CEDAR) a QUERY message which propagates through the network to discover the route.

In Table 1 we compare the complexities of all above-mentioned protocols using four criteria: storage complexity which is the storage size every node needs to save necessary information; control packet size which may be different for different protocols; time complexity which is the number of steps needed to perform a protocol operation [4, 24, 30]; and communication complexity which is the number of messages needed to perform a protocol operation [4, 24, 30]. Also, the values for these metrics represent *worst-case* behavior.

We show the evolution of the above fifteen routing protocols² in Figure 1. As shown in the figure, the protocols may generally be categorized as precomputed or on-demand. The solid lines in the figure represent direct descendants, the dashed lines depict logical descendants, and the dotted lines indicate that a protocol

¹A core node sends routing-related packets to other core nodes by unicast [27]. Since there are limited number of core nodes in an ad hoc network, unicast is effective.

²A similar figure for nine protocols can be found in [24]

is the combination of two other protocols.

Note: In table 2, RRM stands for Route Reconfiguration Methodology, BR stands for Beacon Requirement (or Hello Message Requirement).

The meanings of symbols in table 1 are as follows:

M: the average number of nodes in a cluster (zone).

N: the total number of nodes in the network.

A: the average number of adjacent nodes (neighbors).

B: the average number of border (gateway) nodes of a cluster (zone).

D: the diameter of the network (the maximum number of nodes in the longest path).

Y: total number of nodes forming the directed path where the REPLY packet passes

Z: diameter of the directed path where the REPLY packet passes
 D_d : the number of maximum desired destinations.

* TORA has one copy for each desired destination.

** ZRP uses bordercast and the zones overlap heavily.

*** CEDAR uses core broadcast.

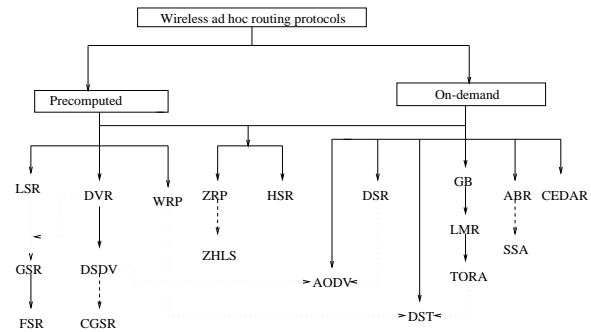


Figure 1: Genealogy of wireless ad hoc routing protocols

4 CONCLUSION

In this paper, we discussed various criteria for classifying routing protocols and provided comparisons of more than a dozen routing protocols for wireless ad hoc networks. There are still many challenges facing wireless ad hoc networks. However, because of their inherent advantages, wireless ad hoc networks are becoming more and more prevalent in the world.

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