Introduction to Ad-Hoc Network Routing Algorithms

FINAL TERM PAPER

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Abstract

An ad-hoc network is a multi-hop wireless network where all nodes cooperatively maintain network connectivity without a centralized infrastructure. If these nodes change their positions dynamically, it is called a mobile ad-hoc network (MANET). Due to the limited transmission range of wireless nodes, as well as the rapid change in network topology, multiple network hops may be needed for one node to exchange data with another across the network. Thus, each mobile node operates not only as a host but also as a router, forwarding packets for other mobile nodes in the network that may not be within the transmission range of the source. Each node participates in an ad-hoc routing protocol that allows it to discover multi-hop paths through the network to any other node.

Two conflicting requirements have to be kept in mind when designing a MANET routing algorithm— frequent topology updates are required because of mobility, yet, frequent updates result in higher message overhead and greater power loss. Different routing protocols use different metrics to dynamically determine the optimal path between the sender and the recipient. These cost parameters include number of hops, delay, link quality, location stability and power conservation.

The aim of this paper is to classify and qualitatively describe different network routing algorithms, with particular emphasis on power-awareness. A few common routing protocols have been explored in detail and refinements proposed.

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1. Ad-Hoc Networks

1.1 Introduction

An ad-hoc network is a multi-hop wireless network where all nodes cooperatively maintain network connectivity without a centralized infrastructure. If these nodes change their positions dynamically, it is called a mobile ad-hoc network (MANET). Thus, a MANET may simply be defined as a collection of mobile nodes that maintain inter-connection without the intervention of a centralized access point. Each mobile node of an ad-hoc network operates not only as a host but also as a router, forwarding packets for other mobile nodes in the network that may not be within the transmission range of the source. Each node participates in an ad-hoc routing protocol that allows it to discover multi-hop paths through the network to any other node.

MANETs have the following salient characteristics: **[8]**:

- **Dynamic topologies:** Nodes are free to move arbitrarily; thus network topology—which is typically multihop—may change randomly and rapidly at unpredictable times. Adjustment of transmission and reception parameters such as power may also impact the topology.
- **Bandwidth-constrained, variable capacity links:** Wireless links will continue to have significantly lower capacity than their hard-wired counterparts. One effect of this relatively low to moderate link capacities is that congestion is typically the norm rather than the exception; *i.e.* aggregate application demand is likely to exceed network capacity frequently.
- **Power-constrained operations:** Some or all the nodes in a MANET rely on batteries for their energy. Thus, for these nodes, the most important design criteria may be that of power conservation.
- **Limited physical security:** Mobile wireless networks are generally more prone to physical security threats than fixed, hard-wired networks. Existing link security techniques are often applied within wireless networks to reduce security threats.

1.2 History

Not surprisingly, mobile wireless distributed multi-hop networking developed out of the military need for survivability, operation without preplaced infrastructure, and connectivity beyond line-of-sight communication. Although packet-switching technology was first introduced by ARPANet in the 1960s, it was not until the growth of the Internet infrastructure and the microcomputer revolution that packet radio network ideas became truly applicable and feasible **[13]**. Mobile ad-hoc networking (also known as Mobile Packet Radio Networking) is the name given to a technology under development for the past twenty years or so, principally by the Defense Advanced Research Projects Agency (DARPA), the U.S. Army and the Office of Naval Research (ONR) **[8]**.

One of the original motivations for MANET is found in the military need for battlefield survivability **[4]**. Soldiers must be able to move about freely without any of the restrictions imposed by wired communications devices. An additional motivation for MANET is that the military cannot rely on access to a fixed, pre-placed communications infrastructure in battlefield environments. A rapidly deployable self-organizing mobile network is the primary factor that differentiates MANET design issues from those associated with commercial cellular systems.

1.3 Applications

Any commercially successful network application can be considered a candidate for useful deployment with nodes that can form ad hoc networks **[13]**. Some of the potential applications of mobile ad-hoc networks that can lend themselves for commercially successful products are as follows:

- **Conferencing:** Mobile computer users can exchange ideas even outside the business network infrastructure.
- **Home networking:** An ad-hoc network may maintain connection between the home PC and a laptop which is taken to and from home to the office work environment and on business trips. In the *Home of the 21st Century* that is being implemented in The George Washington University's campus at Ashburn, Virginia, this idea is being taken one step further by forming a wireless network with other network-compatible devices such as motion detectors and security cameras **[20]**.
- **Emergency services:** An ad-hoc network can also come in handy when the existing infrastructure is damaged or out of service for reasons like power outage or natural calamities.
- **Personal Area Networks (PAN):** The idea of a PAN is to create a very localized network populated by some network nodes that are closely associated with a single person. For instance, Bluetooth **[5]** is an emerging short-range radio technology targeted at eliminating wires between devices like personal digital assistants (PDAs).

2. Ad-Hoc Routing

2.1 Introduction

Routing protocols within the Internet provide the information necessary for each node to forward packets to the next node using the most optimum hop from the source to the destination. This observation motivates attempts to adapt existing routing protocols for use in ad-hoc networks. Routing protocols are typically self-starting, adapt to changing network conditions, and offer multi-hop paths across a network from a source to the destination.

2.2 Routing Protocols

Routing protocols may be broadly classified into two categories:

1. **Proactive or Table-Driven Routing:** Such a protocol keeps track of routes for all destinations in the network. It is based on traditional wired LAN/WAN routing wherein the routing information is disseminated among all nodes in the network throughout the operating time irrespective of the need for such a route.
   - **Advantage:** Communications with arbitrary destinations experience minimal initial delay, since the route can be immediately selected from the route table.
   - **Disadvantage:** Additional control traffic is needed to continually update stale route entries. Unlike the Internet, an ad-hoc network contains numerous mobile nodes and therefore links are continuously broken and re-established.

2. **Reactive or On-Demand Routing:** Since a node in an ad-hoc network does not need a route to a destination until that destination is to be the recipient of packets sent by the node (either as the actual source of the packet or as an intermediate path along a node from the source to the destination), this protocol has been defined to acquire routing information only when needed.
   - **Advantage:** Uses far less bandwidth to maintain route tables at each node.
   - **Disadvantage:** Since the route to an application will have to be acquired before communications can begin, the latency period for most applications is likely to increase drastically.

Proactive or table-driven routing protocols may again be subdivided depending on the manner in which route tables are constructed, maintained and updated. The two primary classes are as follows: **[11]**

- **Link State:** In this protocol, each node maintains a view of the entire network topology with a cost for each link. To keep these views consistent, each node periodically broadcasts the link costs of its outgoing links to all other nodes using a protocol such as flooding. As a node receives the information, it updates its view of the network topology and applies a minimum-cost algorithm to choose its next hop for each destination.
- **Distance Vector (DV):** In DV routing, each node maintains a routing table consisting of a destination IP address, distance to the destination (number of hops) and the next node in the path. Each router periodically broadcasts this

table information to each of its neighboring routers, and uses similar routing updates received from its neighbors to update its own table.

The different routing algorithms that have been discussed later in this section are:

1. Destination-Sequenced Distance Vector (DSDV) **[11]**
2. Ad-Hoc On Demand Distance Vector (AODV) **[12]**, **[16]**
3. Dynamic Source Routing (DSR) **[6]**

The problem of routing is essentially the distributed version of the minimum cost problem **[11]**. Each node in the network maintains for each destination a preferred neighbor (or next hop), the selection of which minimizes the cost function. The cost function that is used differs from protocol to protocol.

2.3 Cost Metrics

The problem of routing in mobile ad-hoc networks is difficult because of node mobility **[18]**. As has been discussed above, there are two conflicting goals—frequent topology updates are required to optimize routes, while frequent topology updates result in higher message overhead and bandwidth wastage. In this section the different metrics used for routing have been enumerated, and their effects on node and network life briefly examined.

Different routing protocols use one or more of a small set of metrics to determine the optimal path:

- The most common metric used is shortest hop routing, as in the case of Dynamic Source Routing (DSR) **[6]**, Destination-Sequenced Distance Vector (DSDV) **[11]**, Temporally-Ordered Routing Algorithm (TORA) **[10]**, Wireless Routing Protocol (WRP) **[9]** and the DARPA packet radio protocol. These protocols can also use shortest delay as the metric, as the shortest distance leads to the shortest amount of time.

- Link quality is a metric that is used by Signal Stability based Adaptive Routing (SSA) **[3]** and by the DARPA protocol. Since link quality information is used to select one among many different routes, sometimes a shortest hop route may not be used. In addition to link quality, SSA also uses location stability to bias route selections towards routes with relatively stationary nodes (which will require fewer updates).

- The Spine Routing Algorithm (SRA) **[2]** attempts to minimize the message and time overhead of computing routes. In this protocol, nodes are assigned to clusters (one or two hops in diameter) and clusters are joined together by a virtual backbone, so that packets destined for other clusters get routed by this backbone.

- In Associativity Based Routing (ABR) **[19]**, each mobile node periodically transmits beacons to identify itself and constantly updates its associativity ticks in accordance with the mobile hosts sighted (*i.e.* hearing others' beacons) in the neighborhood.

- Power-aware routing is the most recent cost metric and the most popular algorithms in this field include Power-Aware Multi-Access Protocol with Signaling (PAMAS) **[17]**, Minimum Energy Mobile Wireless Networks **[15]** and Routing for Maximum System Lifetime (MSL) **[1]**. While the Minimum Energy Protocol aims at designing a network that consumes the minimum overall energy, MSL uses a maximum residual energy path routing algorithm to maximize the time until any node fails.

Some of these routing algorithms have been discussed in greater detail later in this paper.

2.4 Destination-Sequenced Distance Vector (DSDV) [11]

In the DSDV algorithm, each route table entry is tagged with a sequence number that is originated by the destination code. Thus, the data broadcast by each node contains the following information:

- Destination address
- Number of hops required to reach the destination
- Sequence number of information received, as originally stamped by the destination.

Routing information is advertised by broadcasting or multicasting the packets that are transmitted periodically and incrementally as topological changes are detected. In addition, each mobile computer agrees to relay data packets to other computers on request.

The DSDV algorithm differs from other distance vector algorithms in including the sequence number of the destination, which ensures that routes with more recent sequence numbers are preferred as the basis for forwarding decisions. If more than one path has the same sequence number, the path with the smallest distance metric is chosen. A disadvantage with this algorithm is that it requires bi-directional links to operate.

2.5 Ad-Hoc On Demand Distance Vector (AODV) [12], [16]

In the AODV algorithm, every node maintains its own monotonically increasing sequence which it increases each time it learns of a change in the topology of its neighborhood. Unlike DSDV which issues broadcasts every change in the overall connectivity of the network (*i.e.* local movements have global effects), AODV triggers a broadcast only if the new link status affect the ongoing communications. Thus, the aim of the AODV algorithm is to reduce the number of system-wide broadcasts to as few as possible.

Moreover, there is a lifetime associated with each route table entry that is updated whenever a route is used. If a route is not used within its lifetime, it is expired and consequently discarded, which reduces the effects of stale routes, as well as the need for route maintenance for unused routes.

The AODV algorithm also utilizes symmetric links between neighboring nodes for its operation. Thus, it uses the idea of unicast route establishment and multicast route maintenance as outlined below:

1. When a node needs a route to a destination, it broadcasts a RREQ (route request packet).
2. Any node with a current route to that destination (including the destination itself) can unicast a RREP (route reply message) back to the source node.
3. Route information is maintained by each node in its route table.
4. Information obtained through RREQ and RREP messages is kept with other routing information in the route table.
5. Sequence numbers are used to eliminate stale routes.
6. Routes with old sequence numbers are aged out of the system.

2.6 Dynamic Source Routing (DSR) [6]

The DSR algorithm allows nodes to dynamically discover a source route across multiple network hops to any destination in the ad-hoc network. Each data packet that is sent then carries in its header the complete ordered list of nodes through which the packet must pass.

The main advantages of this routing algorithm over the previous two that were discussed are as follows:

- The DSR protocol can successfully discover and forward packets over paths that contain unidirectional links.
- The DSR protocol operates entirely on-demand. It does not use any periodic routing advertisement, link status sensing, or neighbor detection packets; nor does it rely on these functions from any underlying protocols in the network.

The following two mechanisms define the operation of the DSR to form a completely self-organizing and self-configuring network:

1. **Route Discovery;** by which a node *S* wishing to send a packet to a destination node *D* obtains a source route to *D*. Route discovery is used only when *S* attempts to send a packet to *D* and does not already know a route to it.
2. **Route Maintenance;** by which a node *S*, while using a source route to *D*, is able to detect that the network topology has changed such that it can no longer use its route to *D* because a link along the route no longer exists. When route maintenance indicates that a source route is broken, *S* can attempt to use any other route to *D* that it may know, or it can invoke Route Discovery again to find a new route.

The key reason for the popularity of DSR is that it operates entirely on demand, and requires no periodic activity of any kind at any level within the network. As a result, there are absolutely no routing overhead packets when all node are approximately stationary with respect to each other, and all routes needed for the current communication have already been discovered. As nodes begin to move more or as communication patterns change, the routing packet overhead of DSR automatically scales to track the routes currently in use.

3. Power Conservation

3.1 Introduction

Most nodes in an ad-hoc network are battery-powered and therefore power conservation issues in MANETS have seen a rapid growth of interest in recent years. Shortest hop algorithms, while resulting in minimum delay, often result in early death for some nodes, especially the nodes that tend to have widely differing energy consumption profiles **[18]**.

Some of the recent works addressing the issue of energy efficiency are as follows:

- Lazy Packet Scheduling (LPS) **[14]**
- Minimum Energy Routing **[15]**
- Power-Aware Routing **[18]**
- Maximum System Lifetime (MSL) Routing **[1]**

These algorithms have been discussed in greater detail below.

3.2 Lazy Packet Scheduling (LPS) [14]

Most power control schemes deal with mitigating the effect of interference that one user causes to others, *i.e.* maximize the amount of information sent for a given average power constraint. In contrast, this scheduling algorithm considers the minimization of power subject to a specified amount of information being successfully transmitted. It considers the problem of minimizing the energy used by a node on a point-to-point link to transmit packetised information within a given amount of time.

To minimize transmission energy, the transmission power is lowered and the packet is transmitted over a longer period of time, and hence it is called lazy scheduling. However, the energy is minimized subject to a deadline or a delay constraint.

3.3 Minimum Energy Routing [15]

The main idea of this protocol is that a node does not need to consider all nodes in a network to find the global minimum power path. By defining updated relay regions corresponding to every node, the search for the next-hop node is restricted to a localized search, which leads to lowest total energy consumption.

The common sources of loss in a power consumption model have been classified into three categories— path loss, large-scale variations and small-scale variations. Since small-scale variations may be prevented by using diversity techniques, only path loss and large-scale variations have been considered, and are afforded the same treatment, *viz*. power drops as $1/d^n$ (where d is the distance between transmitter and receiver, and n• 2 depending on the path loss model being used). Taking cue from the fact that in the case of collinear nodes, relaying a message through the middle node results in lower transmit power consumption than transmitting directly, the problem reduces to finding the positions for relay nodes (on a two-dimensional plane, assuming constant height) which will consume less total power than direct transmission.

The general mathematical theory used to design the minimum power network comprises the definition of relay regions consistent with all transmitter nodes, so that a localized search is sufficient to find the global minimum power path to a destination node. For a mobile network, this requires each node to broadcast its position so that the relay regions are constantly updated, and this is followed by a localized search algorithm to find the neighbor set. Once this graph has been obtained, a cost distribution algorithm is applied from the transmitter to every node. The cost metric, in this case, is the total power required for a node to reach the destination along a directed path. Simulations suggest that the implementation of this algorithm results in significantly lower average power consumption per node **[7]**.

However, this protocol requires strong connectivity, *i.e.* there should exist a bi-directional path from any node to any other node in the graph. Also the research is geared towards mobile telephone or other sophisticated applications, since it relies on the Global Positioning System (GPS) to determine the positions of the nodes.

3.4 Power-Aware Routing [18]

Power aware routing in mobile ad-hoc networks aims at increasing node and network life by using power-aware metrics for routing. The key to choosing the optimum metric for power conservation (*i.e.* to increase individual node and hence, network life) is to carefully share the cost of routing packets, a sentiment that is also reflected in **[1]**. This protocol has a twin objective— to reduce the cost/packet of routing packets, as well as reducing the overall energy consumption, resulting in maximization of the mean time until node failure. The first goal may be achieved by four different means, while the second objective is met by the use of a MAC layer protocol called the Power-Aware Multiple Access protocol with Signaling (PAMAS) **[17]**. The five metrics are not entirely mutually exclusive however, and a typical implementation would require a judicious mixture of shortest-hop routing and one of them.

- **Minimize energy consumed per packet:** This metric will however result in early death for some nodes, since some nodes which allow a shorter hop will quickly become congested.
- **Maximize time to network partition:** This load-balancing concept attempts to evenly distribute routing through critical nodes, an early death of which will cause the network to partition.
- **Minimise variance in node power levels:** This metric increases the life of the network by keeping the amount of unfinished work in all nodes the same. While Join the Shortest Queue (JSQ) seems a reasonable strategy to meet this end, its implementation is complicated by the uncertain demands of future arrivals in an ad-hoc mobile network.
- **Minimise cost/packet:** This improves upon the first metric enumerated above by restricting routes through nodes with depleted energy reserves, thus maximizing the life of all nodes in the network.

PAMAS **[17]** proposes to reduce overall energy consumption by simply turning off nodes when they are not capable of transmitting or receiving. A simple scenario when a node cannot transmit or receive packets is if one of its neighbors is busy, and thus any attempted transmission would result in interference. Specifically, a node powers itself off if it is overhearing a transmission and does not have a packet to transmit, or if atleast one neighbor is transmitting and/or atleast one neighbor is receiving. Both these conditions assume that the node itself is not the intended recipient.

To sense whether a node is busy, transmitting nodes send an RTS (request to send) and do not begin transmission until a CTS (clear to send) is received. This ensures that from the transmitter's point of view, the node being switched off does not cause delay. However the moot point is how long a node should remain switched off and this may be considered a study in its own right. In a deterministic scenario the node could be switched off for the entire duration of the neighbor's transmission time, but for ad-hoc networks a probe protocol would have to be defined which would cause the node to power back on at certain intervals.

However, the protocol does not discuss whether switching the nodes on and off frequently causes any adverse effects on energy. Although PAMAS claims a 40%-70% reduction in energy consumption, it increases the node overhead considerably and possibly explains why the protocol did not gain the popularity it deserves.

3.5 Maximum System Lifetime (MSL) Routing [1]

The MSL routing algorithm selects routes so that the time until the batteries of the nodes drain out is maximized. In order to maximize the lifetime, traffic is routed such that the energy consumption is balanced among the nodes in proportion to their energy reserves, instead of routing to minimize the absolute consumed power. This may be considered to be a simple max-min linear programming problem since the lifetime of a system (under a particular flow rate) is defined as the *minimum* battery lifetime over all nodes, and this lifetime is *maximized*.

This algorithm assumes two classes of nodes in its analysis—wireless static nodes and static gateway nodes, but work is in progress to expand the scope to include mobile nodes, which would fit into the scenario of a MANET.

4. Conclusion

As had been proposed, this study introduces the idea of Ad-Hoc networking as an exciting new paradigm of wireless networks, and carefully discusses different cost metrics that lead to its optimum performance. Particular importance has been placed on the conservation of power since mobile nodes have limited power supply.

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