Classification of Ad Hoc Routing Protocols

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Abstract

Mobile ad hoc networks (MANET) are networks which routing is based on multi-hop routing from a source to a destination node or nodes. These networks have quite a many constrains because of uncertainty of radio interface and its limitations e.g. in available bandwidth. Also some terminals have limitations concerning energy in use.

There are numerous applicable protocols for ad hoc networks, but one confusing problem is the vast number of separate protocols. Each of these protocols is designed to perform its task as well as it is possible according to its design criteria. The protocol to be chosen must cover all states of a specified network and never is allowed to consume too much network resources by protocol overhead traffic.

This paper deals with a classification of ad hoc routing protocols and which protocol work better than others for a specific network. We discuss all the protocols and for which network it will give optimum results. The emphasis of this paper is not to present protocols in detail but to present main features of wide variety of different protocols and evaluate their suitability and tradeoffs.

1 Introduction

Ad hoc network is a multi-hop wireless network, which consists of number of mobile nodes. These nodes generate traffic to be forwarded to some other nodes or a group of nodes. Due to a dynamic nature of ad hoc networks, traditional fixed network routing protocols are not viable. Based on that reason several proposals for routing protocols have been presented.

Ad hoc radio networks have various implementation areas. Some areas to be mentioned are military, emergency, conferencing and sensor applications. Each of these application areas has their specific requirements for routing protocols. For example in military applications low probability of detection and interception is a key factor such is routing efficiency during fading and disturbed radio channel conditions. At sensor applications low or minimum energy consumption is a precondition for an autonomous operation. In conference applications a guaranteed quality of service for multimedia services is a needed feature.

All application areas have some features and requirements for protocols in common.

2A Taxonomy for Routing Protocols

Because of multiple and diverse ad hoc protocols there is an obvious need for a general taxonomy to classify protocols considered. Traditional classification is to divide protocols to table-driven and to source-initiated on-demand driven protocols [1]. Table-driven routing protocols try to maintain consistent, up-to-date routing information from each node to every other node. Network nodes maintain one or many tables for routing information. Nodes respond to network topology changes by propagating route updates throughout the network to maintain a consistent network view.

Source-initiated on-demand protocols create routes only when these routes are needed. The need is initiated by the source, as the name suggests. When a node requires a route to a destination, it initiates a route discovery process within the network. This process is completed once a route is found or all possible route permutations have been examined. After that there is a route maintenance procedure to keep up the valid routes and to remove the invalid routes.

One very attractive taxonomy has been introduced by Feeney [3]. This taxonomy is based on to divide protocols according to following criteria, reflecting fundamental design and implementation choices:

- **Communication model.** What is the wireless communication model? Multi - or singlechannel?
- **Structure.** Are all nodes treated uniformly? How are distinguished nodes selected? Is the addressing hierarchical or flat?
- **State Information.** Is network-scale topology information obtained at each node?
- **Scheduling.** Is route information continually maintained for each destination?

This model does not take an account for if a protocol is unicast, multicast, geocast or broadcast. Also the taxonomy doesn't deal with the question how the link or node related costs are measured. These properties are however worth to be considered in classification and evaluating applicability of protocols.

Based on that lack the taxonomy has been slightly modified by adding such features as **type of cast** and **cost function**. Type of cast feature is an upper level classification and so the protocols to be classified must firstly divide by type of cast and after that the more accurate taxonomy can be applied. The above mentioned taxonomy is applied to unicast protocols, while in the context of multicast and geocast protocols a specified taxonomy has been introduced. The overall taxonomy and specially the unicast protocol classification can be seen in figure 1.

The cost function is a classification to be concatenated after presented taxonomy. It is like a remark to be noticed when considering the applicability of the protocol to be chosen.

2.1 Communication Model

Protocols can be divided according to communications model to protocols that are designed for **multi-channel** or **single-channel** communications. Multi-channel protocols are routing protocols generally used in TDMA or CDMA-based networks. They combine channel assignment and routing functionality. That kind of protocol is e.g. Clusterhead Gateway Switched Routing (CGSR) [4].

Single -channel protocols presume one shared media to be used. They are generally CSMA/CA-oriented, but they have a wide diversity in which extend they rely on specific link-layer behaviors.

2.2 Structure

Structure of a network can be classified according to node uniformity. Some protocols treat all the nodes uniformly, other make distinctions between different nodes. In **uniform protocols** there is no hierarchy in network, all nodes send and respond to routing control messages at the same manner.

In **non-uniform protocols** there is an effort to reduce the control traffic burden by separating nodes in dealing with routing information.

2.3 State Information

Protocols may be described in terms of the state information obtained at each node and / or exchanged among nodes. **Topology-based protocols** use the principle that every node in a network maintains largescale topology information. This principle is just the same as link-state protocols use.

Destination-based protocols do not maintain large-scale topology information. They only may maintain topology information needed to know the nearest neighbors. The best known such protocols are distance-vector protocols, which maintain a distance and a vector to a destination (hop count or other metric and next hop).

2.4 Scheduling

The way to obtain route information can be a continuous or a regular procedure or it can be trigged only by on demand. On that basis the protocols can be classified to proactive and on-demand protocols. **Proactive protocols**, which are also know as table-driven protocols, maintain all the time routing information for all known destinations at every source. In these protocols nodes exchange route information periodically and / or in response to topology change.

In on-demand i.e. in **reactive protocols** the route is only calculated on demand basis. That means that there is no unnecessary routing information maintained. The route calculation process is divided to a route discovery and a route maintenance phase.

2.5 Type of Cast

Protocols can be assumed to operate at unicast, multicast, geocast or broadcast situations.

In **unicast protocols** one source transmits messages or data packets to one destination. That is the most normal operation in any network.

Multicast routing protocols try to construct a desirable routing tree or a mesh from one source to several destinations. These protocols have also to keep up with information of joins and leave ups to a multicast group.

The purpose of **geocast protocols** is to deliver data packets for a group of nodes which are situated on at specified geographical area. That kind of protocol can also help to alleviate the routing procedure by providing location information for route acquisition. **Broadcast** is a basic mode of operation in wireless medium. Broadcast utility is implemented in protocols as a supported feature. Protocol only to implement broadcast function is not a sensible solution.

2.6 Cost Function

When making routing decisions in ad hoc environments, it is normally not enough to take only considerations to hop count. In ad hoc networks there is a wide variety of issues to consider such as link capacity, which can vary in large scale, latency, link utilization percentage and terminal energy issues to mention a few most relevant. That is why there is a need to adapt cost functions to route calculations. Rough classification of protocols according to cost function can be based on **hop count** approach (no special cost function applied) and to **bandwidth** or **energy** based cost functions. Also quite a different approach to routing metrics is used by Associativity Based Routing (ABR) protocol, which uses **degree of association stability** for a metric to decide for a route. That means that presumably more permanent routes are preferred. [5]

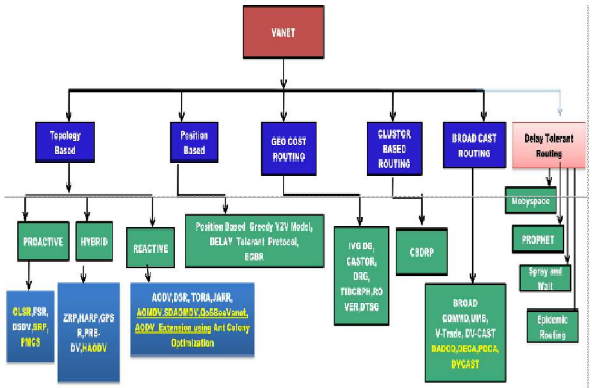

Figure 1: Taxonomy of Protocols. Classification of unicast protocols shown.

3 Overview of selected Protocols

There are unicast, single channel protocols, which are uniform or non-uniform. Uniform protocols are divided to topology-based protocols, in where nodes are aware of the topology information of all other nodes in the network or to destination-based protocols, in where nodes only know the preferred next hop to a destination.

One protocol to belong to that topology-based class is GSR (Global State Routing) and the other is DSR (Destination Source Routing). One main difference between these protocols is the scheduling method. GSR is a proactive protocol, which will all the time have the information needed for routing. DSR is on its behalf a reactive protocol, which will obtain needed information only on demand.

To destination-based protocols belong such protocols as DSDV, AODV, TORA, ABR and WRP. The well known difference between e.g. DSDV and AODV is the scheduling method. The DSDV is proactive as is WRP, but AODV, TORA and ABR all are reactive protocols.

To be classified to single channel, non-uniform protocols there are such protocols as ZRP, FSR, OLSR, CEDAR and CBRP. Form these protocols ZRP, FSR, and OLSR belong to neighbor selection protocols, which have a common feature to select network subsets by individual nodes themselves. In partitioning protocols there are some kind of clustering and cluster head selection mechanism. To partitioning protocols belongs e.g. CEDAR and CBRP.

To unicast multi-channel protocols include such protocols as CGSR and Epidemic. CGSR is a non uniform protocol and Epidemic is a uniform protocol.

The unicast protocols presented here shortly are the following:

- GSR
- WRP
- OLSR
- FSR
- CEDAR
- CGSR
- Epidemic

3.1 Topology Based Protocols

3.1.1 GSR

Global State Routing (GSR) [6] is a uniform, topology oriented, proactive routing protocol. It is a variant of traditional link-state protocols, in which each node sends link-state information to every node in the network each time its connectivity changes. GSR reduces the cost of disseminating link-state information by relying on periodic exchange of sequenced data rather than flooding.

In GSR, each node periodically broadcasts its entire topology table to its immediate neighbors. The topology table includes the node's most recent assessment of its local connectivity and its current link-state information for the whole network topology. Each entry is tagged with a sequence number. A destination's link-state entry is replaced only if the received entry has a larger sequence number. Based on the complete topology information in the topology table, any shortest-path algorithm can be used to compute a routing table containing the optimal next - hop information for each destination. GSR defines a variant of Dijkstra's algorithm for this purpose.

3.2 Destination Based Protocols

3.2.1 WRP

The Wireless Routing Protocol (WRP) [7] is a proactive, destination-based protocol. WRP belong to the class of path finding algorithms. The typical feature for these algorithms is that they utilize information about distance and second-to-last hop (predecessor) along the path to each destination. Path-finding algorithms eliminate the counting-to-infinity problem of distributed Bellman- Ford-algorithms by using that predecessor information, which can be used to infer an implicit path to a destination and thus detect routing loops.

In WRP there is a quite complicated table structure. Each node maintains four different tables as in many other table-driven protocols only two tables are needed. These four tables are: 1) distance table, 2) routing table, 3) linkcost table and 4) message retransmission list (MRL) table.

The distance table of a node (i) contains the distance of each destination node (j) via each neighbor (k): (D_{ijk}) and the predecessor of destination (j) reported by neighbor (k): (p_{ijk}). The equivalent routing table contains the distance to the destination (D_{ij}), the predecessor of the chosen shortest path to destination (p_{ij}), the successor (s_{ij}) of the chosen shortest path to destination and also a marker (tag $_{I\ j}$) used to update routing table. The link-cost table of a node lists the cost of relaying information through each neighbor (l_{ik}). Each entry of MRL contains the sequence number of the update message, a retransmission counter, an acknowledgement-required flag with one entry per neighbor and a list of updates sent in the update message. The MRL records which updates in an update message need to be retransmitted and which neighbors should acknowledge the retransmissions.

In WRP nodes exchange routing-table update

Figure 2: An example of WRP-routing protocol's operation [7]

3.3 Neighbor selection protocols

3.3.1 OLSR

Optimized Link State Routing (OLRS) [8] is a topology based, neighbor selection protocol, in which each node only maintains a subset of network topology information. OLRS is a proactive protocol, because it exchanges the topology information with other nodes regularly to maintain information required for routing.

OLRS reduces the cost of distributing network-scale link-state information by two ways. First, it uses multipoint relays (MRP) [9] to reduce redundant rebroadcasting during flooding operation. That is the key concept of the protocol. MRPs are selected nodes, which forward broadcast messages during the flooding process.

In figures 3 (a) and 3 (b) there is an illustrative example what is the cost difference between broadcast by flooding and by multipoint relays.

(a) (b)

Figure 3: Diffusion of broadcast message using pure

flooding (a) and multipoint relays (b) [9].

Secondly each node only broadcast the state of nodes in its own multi-point relay set. That is a method to reduce the contents of the control messages. A node's multipoint relay set is the minimal subset of its one-hop neighbors, which must rebroadcast a message so that it is received by all of its two-hop neighbors.

When a node sends a broadcast message, all of its neighbors receive and process the data. However, only those neighbors, which belongs to the source node's MPR set and have not previously received the message re-broadcast it. This reduces the number of broadcast messages needed to flood a message through the network. Since each node selects its MPR set independently, it must know the topology of its two-hop neighborhood, but additional inter-nodal coordination is not required.

In the OLSR protocol, each node uses this flooding technique to distribute the link-state of its own MPR set. This is done periodically. The update period is in its minimum when there is detected a change and when the network is in its stabile state there is a updates only between refresh intervals. Each node uses the attained topology information to construct its routing tables. For the neighbor sensing purposes the OLSR uses HELLO-messages, because each node should detect the neighbor interfaces with which it has a direct and symmetric link. OLSR supposes bi-directional links and so the connectivity must be checked in both directions.

HELLO-messages are broadcast to all one-hop neighbors, but are not relayed to further nodes. OLSR is well suited to large and dense mobile networks, as the optimization achieved using the MRPs works well in this context. The larger and more dense the network, the more optimization can be achieved. OLSR is well suited for networks, where traffic is random and sporadic between several nodes rather than being almost exclusively between a small specified set of nodes. [8]

3.3.2 FSR

Fisheye Source Routing (FSR) [10], [11] is based on a method to divide each node's neighborhood to blurred zones so that the information details and accuracy is better for nodes to be near. The name's basis is on the phenomenon of fish eye's ability to see objects the better the nearer they are. In FSR zones are classified according to the distance, measured by hops, from the node. In figure 4 there can be seen three differed zones.

Figure 4: Scope of fisheye [10]

FSR is a protocol to be built on top of another protocol. It can be applied to work together with some link-state protocols as GSR. In GSR link state packets are not flooded but nodes maintain a link state table based on the up-to-date information received from neighboring nodes and periodically exchange it with their local neighbors.

The drawbacks of GSR are the large size update messages and the latency of the link state change propagation. FSR is applied to alleviate that situation by reducing the size of update messages without seriously affecting routing accuracy.

The reduction of update message size is obtained by using different exchange periods for different entries in the table. The entries corresponding to nodes within the smaller scope are propagated to the neighbors with the highest frequency. As a result, a considerable fraction of link state entries are suppressed, thus reducing the message size. The imprecise knowledge of best path to a distant destination is compensated by the fact that the route becomes progressively more accurate as the packet gets closer to its destination.

3.4 Partitioning Protocol

3.4.1 CEDAR

Core Extraction Distributed Ad hoc Routing (CEDAR) [12] is a partitioning protocol, emphasizing QoS support. Each partition includes a core node. The core nodes use a reactive source routing protocol to outline a route from a source to a destination. Partitioning uses minimum dominating set (MDS). This is the minimum subset of nodes such that all nodes are at most one hop away from a dominating node. The core consist of the dominators and tunnels, which are unicast paths to connect each core node with nearby core nodes. By definition of MDS, these tunnels consist of at most two intermediate non-core nodes and form a connected graph. In order to discover their core neighbors and select tunnels, core nodes advertise their presence in the three-hop neighborhood.

Figure 5: CEDAR core with dominators (large dots) and tunnels (small dots) [12]

When a source has no route to destination, it forwards a "route request"-message to its dominator. Instead of using broadcast flooding to disseminate the request, CEDAR uses a unicast mechanism, which is called core broadcast. That causes the request to be forwarded to all dominators core neighbors. This mechanism is used to discover a core path or source route from the dominator of source to the dominator of the destination. A "route reply" message containing this route is sent back to the source.

Figure 6: CEDAR core broadcast [12]

CEDAR has three key components: 1) the establishments and maintenance of self-organizing routing infrastructure (core) for performing route computations, 2) the propagation of the link-states of high-bandwidth and stable links in the core through increase/ decrease waves 3) a QoS route computation algorithm that is executed at the core nodes using only locally available state.

QoS routing in CEDAR is achieved by propagating the bandwidth availability information of stable links in the core sub-graph. The propagation of link-state is performed by slow-moving increase-waves, which denotes increase of bandwidth and by fast moving decrease waves, which denotes decrease of bandwidth correspondingly.

3.5 Multichannel Protocols

The main distinct feature for multichannel protocols is the ability to support different communications channels. Some nodes may have access to more than one physical medium or a node may be allowed to change the channel during routing operation.

Multichannel protocols may also be divided at the same way as single channel protocols to different subclasses.

They can be treated as uniform or non-uniform as is the case with the two protocols presented in here. The two protocols appearing here is CGSR (Clusterhead Gateway Switch Routing) protocol and quite an exceptional protocol called Epidemic. CGSR is a non-uniform hierarchical protocol, which is based to forming clusters among nodes and selecting a cluster head to control routing to outside the cluster area. Epidemic is a uniform protocol where routing is based to "infect" a node with a message and spread the message over nodes by that way.

3.5.1 CGSR

Clusterhead Gateway Switch Routing protocol [4] is a multichannel operation capable protocol. It enables code separation among clusters. The clusters are formed by cluster head election procedure, which is quite intensive process. On that reason the protocol uses so called Least Cluster Change (LCC) algorithm for that election. By using LCC can cluster heads only changed when two cluster heads come into contact with each other or when a node moves out of contact of all other cluster heads CGSR is not an autonomous protocol. It uses DSDV as the underlying routing scheme. The DSDV approach is modified to use a hierarchical cluster head-to-gateway routing. A packet sent by a node is first routed to its cluster head, and then the packet is routed from the cluster head to a gateway to another cluster head, until the destination node's cluster head is reached. That destination cluster head then transmits the packet to the destination node.

Figure 7: CGSR routing example [4]

In figure 7 there is a example how the protocols manages to transmit a packet from node A to node C in CMDA network:

1. Node A (cluster head of C1) must get the permission to transmit (receives a token) in cluster C1.
2. Node B (gateway) must select the same code as node A to receive the packet from node A.
3. Node B must select the same code as node C (cluster head of C2) and get the permission to transmit in cluster C2 (receives a token from node C).

3.5.2 Epidemic

Epidemic [13] is a routing protocol which is aimed for separated networks never having a connected path form source to a destination node. The goals of epidemic routing are to maximize message delivery rate, minimize message latency and minimize the total resources consumed in message delivery rate. Epidemic routing supports the eventual delivery of messages to arbitrary destinations with minimal assumption regarding the underlying topology and connectivity of the underlying network. Only periodic pair-wise connectivity is required to ensure eventual message delivery.

The protocol relies upon the transitive distribution of messages through ad hoc networks, with messages eventually reaching their destination. Each host maintains a buffer consisting of messages that it has originated as well as messages that it has received from other nearby hosts. Each hosts stores a bit vector called the summary vector that indicates which entries in their local hash tables are set. When two hosts come into communication range of one another, the host with the smaller identifier initiates an anti-entropy session with the host with the larger identifier. To avoid redundant connections, each host maintains a cache of hosts that it has spoken recently.

During anti-entropy session the two hosts exchange their summary vectors to determine which messages stored remotely have not been seen by the local host. In turn, each host then requests copies of messages that it has not yet seen. The receiving host maintains total autonomy in deciding whether it will accept a message.

(a) (b) Figure 8: Delivering a message between two separated networks [13]

In figure 8 a source S wants to transmit a message to a destination but no connected path is available (a). Carriers, C1-C3 are leveraged to transitively deliver the message to its destination at some later point in time (b).

3.6 Other than Unicast Protocols

3.6.1 Multicast Protocols

There is a need for multicast traffic also in ad hoc networks. The value of multicast features with routing protocols is even more relevant in ad hoc networks, because of limited bandwidth in radio channels. Some multicast protocols are based to form and maintain a routing tree among group of nodes. Some other are based on to use routing meshes that have more connectivity than trees. This approach is justified by the reason that maintaining a routing tree can have remarkable control traffic. The problem with a mesh is a tendency to form long-term or permanent routing loops. [14]

Figure 9: Difference between multicast mesh and tree

[14]. The multicast routing protocols can be classified into the following categories: [15]

- **Flooding**, in which the multicast packet is flooded to all nodes in the network and with some simple method a broadcast storm will be prevented.

- **Source-based multicast tree (SBT)**, in which a multicast tree is established and maintained for each multicast source node in each multicast group. The multicast packet is forwarded along that tree to every multicast group member.

- **Core-based multicast tree (CBT)**, in which a single shared multicast tree is used to connect all different multicast groups and their members.

- **Multicast mesh**, in which a multicast mesh is constructed instead of a tree.

- **Group-based multicast forwarding**, in which a group of nodes acts as multicast forwarding nodes for each multicast group. Multicast packets are forwarded only by these forwarding nodes. All received multicast packets that are not duplicated are rebroadcast by forwarding nodes to their neighbors.

Figure 10: Taxonomy of Multicast Protocols

Also location based multicast routing protocols could be classified to belong to the multicast categories, but it is even more reasonable to deal these protocols in their own group called geocasting.

Some multicast protocols to be worth mentioning at least by name are DVMRP, CAMP, ODMRP and multicast-AODV.

The Distance Vector Multicast Routing Protocol (DVMRP) is a multicast routing protocol initially designed for wired networks. The modifications to apply the protocol to wireless environments are a method for leaf-node detection, dynamic grafting/pruning and the use of packet duplication check. DVMRP maintains source-based multicast trees so it is a SBT-protocol. The source-based tree is created by first flooding the whole network with the multicast traffic. After that the normal prune operations are conducted. [14] Core-Assisted Mesh Protocol (CAMP) [14] is a meshbased multicast routing protocol, which establishes a multicast mesh for each multicast group. One or more core nodes are delegated to assist in join operations so that flooding is not needed. To join a multicast group, a node first checks if any of its neighbors already is a member of the multicast mesh. If this is true, the node announces a membership request to its neighboring nodes. If there are no nodes to belong the mesh, node sends a join message to one of the core node. The core nodes are not necessarily needed. Because if there is no available core nodes, an expanded ring search is used to find at least one node to belong the mesh.

Table 1: Characteristics of Various Ad Hoc Mobile
Multicast Routing Protocols [15]

Parameters DVMRP AODV CAMP ODMRP

Multicast
delivery
structure
Sourcebased
tree
Core-based tree Multicast
mesh
Groupbased
Use of
centralized
node
No Yes (Multicast
group leader
Yes
(Core
nodes)
No

Core node
recovery
N/A Yes Yes N/A
Routing
scheme
Tabledriven
On-demand Tabledriven
Ondemand
Dependence
on unicast
routing
protocol
No No Yes No
Routing
approach
Flat Flat Flat Flat
Routing
metric
Shortest
path
Shortest path to
another
multicast
member along
the existing
shared tree
Shortest
path
Shortest
path

3.6.2 Geocast Protocols

The goal of geocast protocols is to deliver data packets to a group of nodes that are inside a specified geographical area. Geocast could be understood to a some kind of enlargement of multicast operations. In multicasting nodes may join or leave multicast group as desired. In geocasting nodes join or leave the group by entering or leaving the defined geocast region.

The applications of geocast can vary from military purposes to civil traffic coordination areas. The applicability of these protocols require some location information at hand. Systems to provide location information can be e.g. GPS-based systems. Also other integrated location systems to be based on e.g. communication base stations are probably to be viable.

The protocols to perform geocast operations can be divided to two categories: data-transmission oriented protocols and routing-creation oriented protocols.

To the data-transmission oriented category belons such protocols as Location Based Multicast (LBM), Voronoi diagram based geocasting and GeoGRID. To routingcreation oriented category belongs protocols GeoTora and Mesh-based Geocast Routing Protocol. As an example of geocast protocols one could mention GeoTORA, which uses the unicast routing protocol TORA to transmit geocast packets to a geocast region. In GeoTORA a source node performs an anycast to any geocast group member via TORA. When a node in the geocast region receives the geocast packet, it floods the packet such that the flooding is limited to the geocast region. [16]

3.7 Protocols by Cost Function

The classification of protocols according to cost function is based on the idea that there is some variable in network to be minimized or maximized. For example that variable can be the energy consumed by nodes, available bandwidth for a connection or latency.

In ad hoc environment battery energy constrains has gain much attention. This is because of battery energy is more limited from its nature as is e.g. available memory space or computing power.

Protocols to minimize energy used will have the following advantages:

- Minimizing emitted power will allow spatial reuse of frequencies. That will increase the total throughput of network.
- Multiuser interference will be minimized. That will improve the quality of communications channels.
- The battery driven terminals will have longer operation time.
- In military applications low probability of intercept and low probability of detection could be attained.

One protocol to minimize the energy consumed or as it is said – energy conscious protocol - is Minimum Power Routing (MPR). It incorporates physical layer link and link layer statistic to conserve power, while compensating for the propagation path loss, shadowing and fading effects and also interference effects.

The main idea of MRP is to select the path between a given source and destination that will require the least amount of total power expected, while still maintaining an acceptable signal-to-noise ratio at each receiver. [17] [18].

4 Applicability of different Protocols

4.1 Evaluation criteria

Different kind of ad hoc routing protocols are suitable for different kind of network structures and node behaviors. When evaluating protocols one needs some appropriate classification also for the features of performance metrics.

The critical features for ad hoc networks can be classified according to Subbaro [19] to following quantitative and qualitative features. Quantitative features are:

- **Network settling time**, which is the time for a network to reach a stable state and be able to send its first message reliably.
- **Network join time**, which is the time for an entering node or group of nodes to become integrated into the ad hoc network.

- **Network depart time** , which is the time required for the ad hoc network to recognize the loss of one or more nodes, and reorganize itself to manage lacking links.

- **Network recovery time**, which is the time for a network to recover after a condition that dictates reorganization of the network.

- **Frequency of updates**, which is the number of control packets or overhead bytes inside packets to be sent in a given time to maintain proper network operation. This means also same as overhead.

- **Memory required**, which is the storage space required for routing tables and other management tables.

- **Network scalability number**, which is the number of nodes that a network can scale to and still preserve communications.

According to RFC 2501 [20] quantitative metrics for Network routing protocol performances are:

- End-to-end data **throughput** and **delay**.

- **Route acquisition time**, which is a particular concern for on-demand protocols

- **Percentage out-of-order delivery**, which can affect how efficiently transport layer protocols can perform it's own task.

- **Efficiency**, which is an internal measure of protocols effectiveness. It deals with the protocol overhead questions. It could be said to be some kind of utilization ratio between routing effectiveness and overhead.

Network recovery time is an important factor for fast changing dynamic networks. If the recovery time is too long, it causes the network to maintain a too long a time an unstable state. That causes routing errors to happen, which on its side causes lost packets and needs for retransmissions.

Frequency of updates is also a meaningful parameter for bandwidth constrained radio networks. If the protocol needs too often or too large update packets to be sent, it will consume in dynamic networks too much available total capacity.

Network scalability number has a meaning when there is a need for large scale networks to be constructed. The large scale is not a clear term, but the number of nodes can surprisingly grow up, when ad hoc environments reach their success. In military environments scalability is an essence.

The qualitative critical features are the following:

- **Knowledge of nodal locations**. Does the routing algorithm require local or global knowledge of the network?

- **Effect to topology changes**. Does the routing algorithm need complete restructuring or incremental updates?

- **Adaptation to radio communications environment**. Do nodes use estimation knowledge of fading, shadowing or multiuser interference on links in their routing decisions?

- **Power Consciousness**. Does the network employ routing mechanisms that consider the remaining battery life of a node?

- **Single or multichannel**. Does the routing algorithm utilize a separate control channel?

- **Bidirectional or unidirectional links**. Does the routing algorithm perform efficiently on unidirectional links?

- **Preservation of network security**. Does the routing algorithm uphold the fidelity of the network, for example low probability of detection or interception and overall security features.

- **QoS routing and handling of priority messages**. Does the routing algorithm support priority messaging and reduction of latency for delay sensitive real time traffic? Can the network send priority messages even when it is overloaded with routine traffic levels?

- **Real-time voice and video services**. Can the network support simultaneously real-time multicast voice and/ or video on-demand services while supporting other routine traffic services?

The RFC 2501 also mention some qualitative properties. One feature not mentioned above is **ability to use multiple routes** to avoid congestion.

One very important question is, if a protocol is able to use only bi-directional links. Decision not to use unidirectional links, may have noticeable effects to total network throughput. Quite many ad hoc protocols are only operating at bi-directional links, some to mention are e.g. DSDV and AODV. Unidirectional links in ad hoc environment are not exceptions, because of asymmetrical nature of radio channel caused by interference, jamming and different receiver or transmitter characteristics.

Quality of services and support for real time services, including priority messages and data packets, is an acute problem to be solved. Applications to need these services will emerge most probably in all ad hoc network solutions, so the implemented routing method should support that need. Also scalability and congestion avoidance / management will be a main feature for any routing protocol to be used in any real life implementations.

4.2 Small Scale Static Networks

When choosing a routing protocol for a small-scale static network there is not so many constrains to take into account. Because of small size and minor node movements, proactive protocols have no problems to keep up with their tables. Non-uniform protocols would surely be overkill. The question to be important may be closely associated to energy constrain issues, when dealing with e.g. sensor networks or with laptop computers. Also questions related to real time voice or video services may be relevant.

Ability to use multiple routes could be an important issue. That is because of ever increasing interference phenomena, typical for license-free radio bands. A sudden appearing interference should not interrupt the ongoing voice transmission, but the routing protocol should be able to manage that situation seamlessly.

From presented protocols GSR or WRP may be the right selection, but also one should consider to use some mesh based multicast protocols e.g. CAMP. The advantage for the mesh-based approach is the ability to maintain several routes, which is a robust method against interference as well as for managing the movement.

Also with small scale static networks there can be quite heterogeneous assortment of devices, each of these having different capabilities to forward traffic. So even when selecting a protocol for an "easy" case there is still some constrains to be considered. But if a protocol is able to use e.g. different metrics per link, this is probably a resolvable question.

4.3 Large Scale Networks

Scalability is a problem to suddenly pop-up. Normally engineers are able to forecast the use of their inventions, but there are too many opposite examples. In military and also in civil defence areas there is an evitable need to scale networks up to several hundreds or even thousands nodes. Normally networks simulations have been conducted only node numbers around 20-50 nodes [21], [7]. Although sometimes simulation has been conducted by node numbers e.g. 500 [22]. In large-scale networks some kind of node partitioning comes its right value. The traditional method has been to use hierarchy for partitioning, but neighbor selection methods are emerging. With the hierarchical structures there is a problem that routes not necessarily are not always the best possible. Nearby nodes to belonging different clusters are not able to use the shortest and in many case the best route. Neighbor selection protocols as FSR, ZPR and OLSR may be the answer to scalability problems in large networks.

In large-scale networks there is also a problem of separated networks lately to join as a part of the main network. There will be quite much control traffic to join two, say as an example one 100 nodes and the other 20 nodes, networks together. If we could use a protocol like Epidemic to carry with some probability the control traffic between networks before the actual joining, the control traffic storm would be alleviated. One obvious feature for large-scale networks is that not every node is equal. Obviously some nodes require to use energy saving protocols as some would like to use protocols to ensure maximum QoS. The question arises if we need to separate large networks to cluster, which inside uses different protocols according their needs. Or should we have a meta-protocol to deal with all different kind of protocols that are needed to cover all states of a large network.

4.4 Dynamic Networks

Dynamic networks are the main challenge, because we are able to manage with many large different networks, as is the case with the Internet. But when we have same problems in dynamic environments, there is vast number of trade-offs to consider. If we want the route acquisition time to be modest we should prefer table-based i.e. proactive protocols, but when using proactive protocols with dynamic networks, there is a burden of too many and too frequent update messages.

With dynamic networks we obviously have to apply reactive protocols and admit some kind of increase in route acquisition time and also we have to accept that in case of route interrupt it will take some time to reestablish a connection. The use of unidirectional links comes at stage in that situation. If we have remaining unidirectional link towards receiving node, it makes no sense to interrupt the whole connection if we still can use that route for voice stream to one direction. At the same time a route acquisition process could be started and a new route should be taken in use when it is operational.

For dynamic networks some kind of reactive protocols are most probably the right selection. But at the same time we have to think if there are some parts of the network, which are not in dynamic state. These static nodes could be used to maintain some kind of core for routing purposes. The core nodes could be used by mobile nodes to behave as some kind of base-stations, and a mobile node should only to decide if it directs its traffic to a neighboring node or to a core node. That is exactly the idea used by hierarchical protocols, but that time the application area is to manage the mobility not as much the size.

4.5 Summary of Applicability

It is possible to construct some kind of suitability chart to be used for protocol evaluation. Below there is one such chart, which is based only to intuitive assumptions about earlier mentioned design principles.

Figure 11: Suitability of Different kind of Ad hoc Routing Protocols

The assumptions made are the following:

- Proactive protocols have poorer performance characteristics with high mobility networks than reactive have. This is based on the fact that with high mobility it is not an easy task to manage consistent network information in all nodes.

- Topology-based protocols have the disadvantage to disseminate the topology information over the network. As the network size grows, it is a complicated task to transfer high amount of topology information especially over low bandwidth wireless links. Destination based protocols are assumed to scale a little bit better, because of smaller control traffic amounts.
- With very large size some kind of differentiation is an essence. The differentiation can be based on hierarchical structures, but these are hard to maintain while the network is in high mobile state. So the neighbor selection protocols are preferred over partitioning protocols when mobility increases.

5 Conclusions

As it can be seen, there is vast number of different kinds of protocols. Only minority of the presented protocols will attain a technical or commercial success, one would forecast. Each of these protocols has some common goals. Every protocol has the ability of distributed routing calculations and every protocol try to manage the consequences caused by mobility of nodes. But the means are such different as they can be.

The presented taxonomy of routing protocols is a meaningful attempt to clarify the vast field of ad hoc routing protocols. It is so because it tries to reveal the main design and implementation principles behind protocols. The taxonomy is a little bit complicated and it is not always an easy task to classify a protocol according to that taxonomy, but the meaning of classifying is try to get some rough basis for protocol's performance evaluation. It should be assumed that same kinds of protocols behave quite the same way in simulations.

When comparing the simulation result of presented protocols, there is a little difficult situation to reach a common understanding about the results. This is because of every simulation has been conducted according to different premises. One question arises if there should be a common framework for tests and simulations. That definition could be a part of e.g. RFC 2501, which concentrates to routing performance issues and evaluation of protocols.

When choosing a protocol to a specified network one should consider the following issues:
- What is the size of the network? If the network could be considered or forecasted to be large, the chosen protocol should support scaling issues.
- What is the degree of mobility; how often links are assumed to cut off. Some protocols (usually reactive) have better performance over some other protocols (usually proactive) when mobility is high
- What are the requirements of user applications for the underlying network. Real-time applications require quite different services compared to non-time critical message delivery. When the network structure and the node behaviors are understood, the right or at least near optimal protocol could be chosen. It is quite inevitable that inside the same network many different protocols should be implemented to cover all the networks states. Some kind of mixture of mutually compatible protocols could be needed. The other way to reach the goal is that protocols will merge and form a protocol, which has all the wished properties, but none of the weak ones. This can be a way to make a giant protocol to be good at theory, but in practice not a viable solution.

To fulfill all different demands some kind layer-based approach would be a considerable solution. One layer of the protocol stack could perform the task of managing scalability, as is the case with FSR, the other layers could handle the needs for power consciousness, multior geocast operations and unicast respectively.

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