Routing Protocols for Mobile Ad-hoc Networks: Current Development and Evaluation

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***Abstract*— Current research on routing protocols for Mobile Ad-hoc NETwork (MANET) has converged to several dominating routing protocols, including Optimized Link State Routing (OLSR), Ad-hoc On-demand Distance Vector (AODV) and Dynamic Source Routing (DSR). At the same time, classic routing protocols such as Open Shortest Path First (OSPF) and Destination Sequenced Distance Vector (DSDV) are improved for the MANET context. Research efforts also focus on issues such as Quality of Service (QoS), energy efficiency, and security, which already exist in the wired networks and are worsened in MANET. This paper examines the routing protocols and their newest improvements. We discuss the metrics used to evaluate these protocols and highlight the essential problems in the evaluation process itself.**

I. Introduction

In the recent years, research efforts have been focusing on improving the performance of routing protocols in MANET. The Internet Engineering Task Force (IETF) created a MANET working group (WG) to deal with issues related to the complexity of constructing MANET routing protocols. The MANET WG coordinates the development of several candidates among the protocols including OLSR and AODV. These protocols are classified into two classes based on the time when routing information is updated, the Proactive Routing Protocols (PRP) and Reactive Routing Protocols (RRP). The WG may also consider a converged approach such as hybrid routing protocols.

There are other classifications of routing protocols such as the distance vector (DV) class and link state (LS) class based on the content of the routing table. The DV protocols broadcast a list (vector) of distances to the destinations and each node maintains the routing table of the shortest paths to each known destination. On the other hand, the LS protocols maintain the topology of the network (links state). Each entry in LS routing table represents a known link. In LS routing, each node needs to calculate the routing table based on the local (links state) information in order to obtain a route to destination. Normally, the link state protocols are more stable and robust but much more complex than distance vector protocols. There are also instances of the above two family In MANET. The OLSR is the most widely used link state protocol, while AODV is the most popular distance vector protocol. General analysis of link state routing and distance vector routing in MANET respectively are provides in [1] and [2] respectively.

Another classification of routing protocols is source routing and hop-by-hop routing. In source routing, the source computes the complete path towards the destination, which consequently leads to loop-free routing. In hop-by-hop routing, each intermediate node computes the next hop itself. The nature of hop-by-hop routing reduces the chance of failed route in MANET, which suffers much faster topology changes than wired networks. Consequently, the source routing protocol in MANET, DSR, allows the intermediate nodes and even overhearing nodes to modify the route in order to adapt to the nature of MANET. Most MANET routing protocols such as OLSR and AODV have the hop-by-hop nature.

Besides the above traditional categories, the Relay Node Set (RNS) [3] framework is introduced to analyze the ad hoc routing protocols. According to [3], most ad hoc routing protocols including OLSR, AODV and TBRPF can be analyzed within the framework. However, there are still exceptions such as Ant Routing Algorithm for Mobile Ad hoc networks (ARAMA) [4]. The ARAMA is a biological based routing algorithm that simulates the procedure of ants to search for food.

The rest of the paper is organized as follows: we outline the proactive routing protocols and their newest improvements in Section II. The reactive routing protocols and their improvements are presented in Section III. The hybrid routing protocols are addressed in Section IV. In Section V we analyze the metrics used to evaluate the performance of the routing protocols and the problems with the evaluation methodology. We finally conclude the discussion in Section VI.

II. Proactive Routing Protocols (PRP)

In proactive (table-driven) protocols, nodes periodically search for routing information within a network. The control overhead of these protocols is foreseeable, because it is independent to the traffic profiles and has a fixed upper bound. This is a general advantage of proactive routing protocols.

DSDV: The Destination-Sequenced Distance-Vector (DSDV) [5] Routing protocol is based on the idea of the classical Bellman-Ford Routing Algorithm with certain improvements such as making it loop-free. The DSDV is the foundation of many other distance vector routing protocols such as AODV that is addressed later. The distance vector routing is less robust than link state routing due to problems such as "count to infinity" and bouncing effect. Consequently, the proactive routing protocols prefer link state routing because additional route calculation of link state routing doesn't contribute to delay.

OSPF: OSPF is the dominating link state routing protocol in wired IP networks. Consequently, it is possible to adapt OSPF to the wireless networks in order to establish a seamless ubiquitous IP network. The main goal of OSPF is to quickly update the routing tables after the topology changes in a consistent way. OSPF uses Dijkstra's shortest path algorithm to construct the forwarding tables based on the network link state database. OSPF is not suitable for the ad hoc wireless networks that have higher topology change, lower bandwidth, lower security and so forth than the wired networks. In [1], an improvement of OSPF to adapt to the MANET context is presented, by:

- introducing the OLSR multicast mechanism to OSPF to reduce the broadcasting overhead,
- replacing the unicasted acknowledgement with implicit acknowledgement.

Currently, the OSPF WG of IETF is working on the OSPF-MANET protocol that reduces the size of the "HELLO" message and optimizes flooding and routing updates [6].

OLSR: Optimized Link State Routing (OLSR) [7] is a proactive, link state routing protocol specially designed for ad hoc networks. OLSR maintains Multipoint Relays (MPRs), which minimizes the control flooding by only declaring the links of neighbors within its MPRs instead of all links. The multicast nature of OLSR route discovery procedure can be integrated with the mobile IP management by embedding the mobile-IP agent advertisement into the OLSR MPR-flooding [8]. This is important for the 4G global ubiquitous networks, which requires the wireless access network to be fully ad-hoc. Several extensions of OLSR are available that correspond to different network scenario. For fast changing MANET, [9] provides a fast-OLSR version which reacts faster to topology changes than standard OLSR by enabling the fast moving nodes to quickly discover its neighbors and select a subset of their MPRs to establish connection to other nodes. Another routing protocol commented by IETF, Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) [10], is very similar to OLSR. TBRPF achieves path optimization and uses an estimation algorithm to selectively broadcast the neighbor information, which leads to lower bandwidth overhead.

III. Reactive Routing Protocol (RRP)

The reactive (on-demand) routing protocols represent the true nature of ad hoc network, which is much more dynamic than infrastructured networks. Instead of periodically updating the routing information, the reactive routing protocols update routing information when a routing require is presented, consequently reducing the control overhead, especially in high mobility networks where the periodical update will lead to significant useless overhead.

AODV: Ad hoc On-demand Distance Vector Routing (AODV) [11] is an improvement of the DSDV algorithm. AODV minimizes the number of broadcasts by creating routes on-demand as opposed to DSDV that maintains the list of all the routes. The on-demand routing protocols suffer more from frequent broken source-to-destination links than table-driven routing due to the delay caused by on-demand route recalculation. AODV avoids such additional delay by using distance vector routing. There are some improved versions of AODV. A "source route accumulation" version of AODV is presented in [12], which modifies the Routing REQest (RREQ) and Routing REPly (RREP) messages in order to speed up the convergence of route discovery. In order to reduce control overhead, a controlled flooding (CF) mechanism to reduce overlapped flooding messages for AODV is presented in [13].

DSR: The key feature of DSR is the use of source routing, which means the sender knows the complete hop-by-hop route to the destination. The node maintains route caches containing the source routes that it is aware of. Each node updates entries in the route cache as and when it learns about new routes. The data packets carry the source route in the packet headers. The delay and throughput penalties of DSR are mainly attributed to aggressive use of caching and lack of any mechanism to detect expired stale routes or to determine the freshness of routes when multiple choices are available. Aggressive caching, however, helps DSR at low loads and also keeps its routing load down. Several additional optimizations have been proposed and evaluated to be very effective [14]. These improvements includes:

- Salvaging: An intermediate node can replace a failed route in the data packet with route information in its own cache.
- Gratuitous route repair: Source node notifies the neighbors the error found in its packet, in order to clean up similar error in the caches of its neighbors.
- Promiscuous listening: A node can update its own source routes in cache by overhearing a packet not addressed to it. The node also checks if the packet could be routed via it to gain a shorter path.

IV. Hybrid Routing Protocols

The Ad Hoc network can use the hybrid routing protocols that have the advantage of both proactive and reactive routing protocols to balance the delay and control overhead (in terms of control packages). Hybrid routing protocols try to maximize the benefit of proactive routing and reactive routing by utilizing proactive routing in small networks (in order to reduce delay), and reactive routing in large-scale networks (in order to reduce control overhead). In [15], hybrid routing protocols are compared with proactive routing protocol OLSR. The results show the hybrid routing protocols can achieve the same performance as the OLSR and are simpler to maintain due to its scalable feature.

The difficulty of all hybrid routing protocols is how to organize the network according to network parameters. The common disadvantage of hybrid routing protocols is that the nodes that have high level topological information maintains more routing information, which leads to more memory and power consumption [16].

ZRP: The Zone Routing Protocol (ZRP) [17] localizes the nodes into sub-networks (zones). Within each zone, proactive routing is adapted to speed up communication among neighbors. The inter-zone communication uses on-demand routing to reduce unnecessary communication. An improved mathematic model of topology management to organize the network as a forest, in which each tree is a zone, is introduced in [18]. This algorithm guarantees overlap-free zones. Furthermore, the concept introduced in this algorithm also works with QoS control because the topology model is also an approach to estimate the link quality. An important issue of zone routing is to determine the size of the zone. An enhanced zone routing protocol, Independent Zone Routing (IZR), which allows adaptive and distributed reconfiguration of the optimized size of zone, is introduced in [19]. Furthermore, the adaptive nature of the IZR enhances the scalability of the ad hoc network.

LAR: Location Aided Routing (LAR) [20] is another kind of hybrid routing protocol. LAR is a scalable routing protocol that uses landmarks, location and distance of the nodes to reduce the periodical update costs. LAR is suitable for networks with large number of nodes, which need to establish a hierarchy. This protocol is more complex than zone routing protocols due to the fact that the maintenance of hierarchical network is more difficult when determining the level of the nodes in the hierarchy.

Some research effort has been put on the adaptation of classic ad hoc routing protocols, such as DSR and AODV, to the scalable networks. The possibility of applying the DSR and AODV to scalable networks is studied and an improvement of DSR and AODV is presented in order to apply them to scalable networks In [21].

V. Analysis

There are two approaches to evaluate routing protocols: using simulation or performing experiments on real hardware. In both cases, the performance metrics as well as the network context are equally important. In the rest of this paper we focus on the simulation approach in which the network parameters must be specified first.

A. Network Environment Parameters

The network context has a strong impact on the performance of routing protocols. The essential network parameters include:

- network size: presented as number of nodes;
- connectivity: the average degree of a node, normally presented as number of neighbors;
- mobility: the topology of the network, relative position and speed of the nodes;
- link capacity: bandwidth, bit error rate (BER), etc.

The above metrics form the basic subset of network parameters. In order to design realistic mathematical network models, additional metrics are required. A good description of novel mobility models and their parameters is proposed in [22]. In this model, however, there is a very complex relation between the properties of the routing protocols and those of the mobile nodes. For example, node speed changes have impact on several parameters of the routing protocol functions (introduced in [3]).

B. General Performance Metrics of Routing Protocols

The major four metrics used for evaluation of the relative performance of ad hoc routing algorithms are as follows:

- message delivery ratio: the total number of messages received at their intended destination divided by the total number of generated messages. Please note that there is a heavy dependence of the measured results and the test duration for certain protocols;
- control overhead: this can be measured in terms of number of control packets or as the ration of the number of control bytes and the total number of bytes transmitted by the network;
- hop count: also referred as path optimization, the average number of hops that successful messages did travel to reach their final destination.
- end-to-end delay: the average delay time of all successfully delivered packets.

A lot of publications have compared the performance of the routing protocols using the above metrics. Some general conclusions are described hereafter.

Because the proactive protocols update routing information peradically, normally proactive routing protocols have a fixed, but higher control overhead than reactive protocols. In DSDV, because each node maintains a list of all destinations, the control overhead is heavier comparing to OLSR. DSR has a lower control overhead (in terms of number of control messages) than AODV due to aggressively use of the routing cache and source routing. The difference is often significant if routing load is presented in terms of packet counts. Presenting routing loads in terms of bytes is, however, less impressive (at most about 20%) [23] due to the fact that each package in DSR includes the complete routing information to the destination in its header.

AODV is better than DSR in terms of data delivery ratio [14], [24]. Furthermore, Lundgren et al. used their Ad Hoc Protocol Evaluation test bed (APE) [24] to evaluate the performance of AODV and OLSR with up to 37 nodes moving along indoor hallways. Their results show AODV performs better than OLSR when mobility is high.

Generally, reactive algorithms are reported to perform better for (relatively) large number of nodes and modest traffic load due to their inclusion of the original message in the flooded route-discovery packets. The performance of AODV improves when the nodes can all connect to each other due to the different levels of contention and packet loss [21], [14], [24]. In [24], it is clearly shown that indoor experiments cannot predict the outdoor performance of common routing algorithms because of the fast changing outdoor environment and heavy interference. Therefore, the indoor performance does suggest that contention may play a larger role outdoors than might be expected. Their results also change dramatically depending on the "clustering" of the network.

C. Additional evaluation criteria

In addition to the above performance parameters, several important non-quantitative aspects are used to compare the routing protocols, more precisely QoS support, energy efficiency and security.

QoS Support: Traditional ad hoc routing protocols just consider links as available for transmissions or not existing. In MANET, however, the link stability is dynamic and has a direct impact on QoS. In [25], a general model of MANET link stability is established for QoS analysis. Another approach is to apply an algorithm that enables link quality-awareness in cognitive packets [3]. Those packets observe the quality of the links and other network metrics (e.g. delay), and exploit this information in the establishment of robust multi-hop routes.

Because OLSR supports multiple routing searches, it is possible to support QoS routing with little modification within the frame [26]. The QoS routing mechanism for is introduced in [25]. However, to guarantee QoS in on-demand routing is more difficult in wireless networks than in wired networks, because in wireless networks, links are much more likely to break and network topology frequently changes. A new routing protocol, load-balanced ad hoc routing protocol (LBAR) is introduced in [27]. By weighing total nodal activity of a path, congested paths can be avoided in LBAR, as packets are transmitted along the least-activity path.

Security: Without some form of network-level or link-layer security, MANET routing protocols are vulnerable to many forms of attack. While the concern exists within wired infrastructures and routing protocols as well, maintaining the "physical" security of the transmission media is harder in MANET. A study of possible attacks against OLSR is conduct in [28]. Furthermore, the paper supposes to add digital signature into the transmission of OLSR. As the control overhead of proactive protocols is already heavy, the OLSR control packets can be reused in order to support certificate authority (CA) without introducing additional overhead [29]. The potential attacks and vulnerabilities of AODV are studied in [30]. The paper also provides an improved data structure of AODV control message by introducing link stability estimation into the control message. Furthermore, a serial of security checks are introduced in [25] to avoid the Denial-of-Service (DoS) attack.

Energy Efficiency: As most of the ad hoc mobile nodes are standalone and depends on battery energy, the ad hoc routing protocols must be energy efficient when forwarding data packages among the nodes. One example of the energy consumption model of routing protocols in MANET is presented in [31], considering topology related broadcasting, state of the nodes, and traffic characteristics. As the topology has a strong impact on energy consumption, dedicated algorithm that constructs a multicast tree in MANET considering energy efficiency is defined in [32]. For cluster-based networks, an improvement of topology construction process is presented in [16].

D. The current evaluation methodology evaluated

Various open source and commercial simulators are used for MANET routing protocols evaluation, e.g. NS-2, OPNET and APE, just to name a few. There is, however, not a clear commonly accepted testing environment or benchmark that will allow standardized evaluation. In addition, the lack of non-experimental methodology for selecting the simulation parameters results in highly deviating test results. Furthermore, different simulators implement MANETs in unique ways and some of them can be characterized as platform dependent. For example, the produced results may be influenced by certain properties of the simulation platform such as processor architecture, clock frequency and memory sizes and speed. To clarify this we selected three different studies of DSR and AODV protocols performed using similar test scenarios [33], [34], [22]. The three studies did use the following test setting:

- Mobility model: random waypoint [22];
- Node speed: 0-20m/sec;
- Number of nodes: 40-50;
- Traffic type: Constant Bit Rate (CBR), 20 sources;
- Test duration: 900 sec.

In table I, the results of the different studies in the form Value$_{AODV}$ / Value$_{DSR}$ are depicted.

TABLE I
AODV AND DSR SIMULATION RESULTS

data references	[33] (40 nodes)	[34] (50 nodes)	[22] (40 nodes)
end-to-end delay[a]	$\sim 45/\sim 68sec$	$\sim 1.8/\sim 8ms$	NA
control overhead	$\sim 20k/\sim 5k$	$\sim 2/\sim 0^b$	$\sim 50k/\sim 10k$
throughput	NA	99%/99%	85%/97%

[a]those are average values of the reported results
[b]packet overhead normalized per data packet is reported [34]

It can be observed from table I, the results can give only a relative indication that AODV performs better than DSR in terms of average delay under the considered test scenario. The exact ratio, however, can not be clearly defined. In addition, repeating the experiments using GloMoSim simulator and NS-2 simulator results differently [33].

After various simulation, we found the performance of DSR is heavily influenced by the start points of nodes. The following figures show the impact of starting position on DSR. The first scenario represents a more densely network. The area is 4km * 4km and the radio range of each node is 250m. The second scenario is less densely. The 40 nodes moving in a same 4km * 4km area are initially placed uniformly within this area, and the power range for each node is also 250m. The rest of configurations in these two scenarios are the same.

TABLE II
IMPACT OF STARTING POINTS ON DSR IN TERMS OF CONTROL MESSAGE

pause time (s)	Scenario 1	Scenario 2
0	31050	21052
100	41809	21048
400	32336	25921
800	58744	28024

TABLE III

IMPACT OF STARTING POINTS ON DSR IN TERMS OF PACKAGE DELIVERY

pause time (s)	Scenario 1	Scenario 2
0	5023	6616
100	3997	6473
400	6134	8982
800	145	307

Obviously from table II and III, the simulation results cannot represent the performance of DSR precisely, even when only starting points are changed. All the above tables indicate that the simulation results serve as a good reference for studying protocol features and for comparing different protocols, but are not accurate enough for deriving conclusions about the expected performance of a given protocol in a real network. We envision that a generic test environment and benchmark are needed to allow such precise studies. A critical part of such generic environment is a platform-independent (open source) simulator. For instance, instead of using system time of the computing platform used for the simulation to evaluate the delays, such simulator should maintain its internal notion of time. This is to avoid the influence of CPU speed and memory constrains on the generated results.

Considering power consumption of the routing protocols, it is currently estimated based on the total number of packets (control and data) and their size. The costs of link and physical layers such as retransmission, handling shadowing and multi-path fading, however, have a strong impact on the energy consumption. In this respect, more precise energy simulation models have to be developed and implemented into the proposed general simulator.

VI. CONCLUSIONS

The recent research efforts have made big progress on ad hoc network routing, both in theory and in practical implementation. The tendency in proactive routing protocol research is to apply OLSR-like multicast mechanism to other proactive routing protocols in order to optimize flooding. On the other hand, the competitive reactive routing protocols, AODV and DSR, both show better performance than the other in terms of certain metrics. It is still difficult to determine which of them has overall better performance in MANET. From the study of the performance evaluation of routing protocols in MANET, we know the results are highly disturbed by the network model and network parameters.

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