Component Based Modeling of Routing Protocols for Mobile Ad Hoc Networks

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***Abstract*—Routing protocols perform several functionalities and can be considered as complex software systems. The design and performance analysis of these protocols is difficult and complex and most of them are not adaptable to changes of the environment. In this paper, we present a component based methodology for modeling mobile ad hoc routing protocols. Componentization is used for modeling and analysis of complex systems, because it introduces modularity in protocol design and reusability of designed components across protocols of the same class. We define the fundamental components of the routing protocols based on their functionalities and investigate their interactions. More specifically, we present an initial investigation of the influence of the separate components on the performance metrics of the protocol, such as delay, packet delivery ratio and routing overhead. Proactive routing protocols are being examined and we consider OLSR and DSDV as use cases for our methodology. In addition, we propose an adaptive reusable modification in the Routing Metrics component of OLSR that lead to better overall performance in energy constrained environments.**

***Keywords*-Components, Routing, MANET, OLSR, DSDV**

I. Introduction

Communication systems without centralized management infrastructure have been gaining popularity and interest in the research community in the form of Mobile Ad-Hoc Networks (MANETs), sensor networks and in the Internet of Things (IoT) architecture. Such networks have wide range of applications from military scenarios, resilient communications, infrastructure monitoring to crowdsourcing and distributed processing of data.

A fundamental building block for these networks is the routing protocol, which discovers the network connectivity and provides communication paths to the network nodes. The routing protocol contains a variety of different functionalities from neighbor discovery to path selection, which affect significantly its operation and performance. There are also two major concerns that need to be taken into consideration on the modeling and designing of new routing protocols and their distinct functionalities: scalability and lightweight design. The novel designed or modified protocol should be scalable to larger networks due to the dynamic nature of mobile ad-hoc networks, where nodes can enter and leave the network. It should also be lightweight in terms of the overhead introduced by control traffic.

Routing needs to adapt to different environmental conditions like diverse mobility, different data rates, energy constrained and malicious environments. Therefore, a large number of routing protocols have been developed to address different performance demands and particular scenarios. However, as far as we are aware of, there exists no systematic way to enable modeling and reusability of existing solutions for different deployments and application demands. Thus, a modeling approach that will allow reusability in protocol design to adapt to different demands is necessary.

In this paper, we propose a systems engineering approach [1] for the modeling and design of routing protocols for mobile ad hoc networks. The approach is based on separating the protocols into components according to their different functionalities. The distinct protocol components interact with each other and exchange useful information related to the routing procedure. The methodology was first proposed by Baras et. al in [2] and [3]. A cross layer analysis of MAC and routing protocols, based on the idea of component based modeling, was also introduced in [4]. Our method provides a systematic approach that can be used in the design, performance analysis and optimization of routing protocols. The main objective of the approach is the separation of concerns between the different components, which overlap as little as possible in functionality.

The component based approach provides two major contributions in protocol design and modeling. First, it allows *modularity* in protocol design. Routing protocols are usually implemented as large monolithic software, which are very difficult to adapt to varying environmental conditions. By using the component based approach, we abstract the functionalities of the protocol into fundamental building blocks and we can easily design and model each of these blocks to adapt to the environmental changes. Furthermore, our approach allows *reusability* of existing components across current and future protocols of the same class. The objective is to create a library of components that can be easily plug into each protocol and configure its functionality according to the environmental conditions to increase the performance. The novel components should be designed in a way that allow reusability with minor modifications. Minor modifications are needed based on the implementation details of each protocol.

In our work, we focus on a specific class of routing protocols, called proactive routing protocols [5]. In this class of

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protocols, each node constructs a priori the routing tables, by exchanging topology information periodically across the network through control messages. Examples of proactive routing protocols are OLSR [6], DSDV [7] and B.A.T.M.A.N. [8].

The main contributions of this paper are:

1) propose a decomposition of proactive routing protocols into components and specify their interactions
2) define the performance metrics, which are affected by the separate components and present some initial thoughts about their interdependence
3) use OLSR and DSDV as a case study to examine the interaction between the components and conduct performance evaluation in terms of routing overhead
4) propose a modification in the Routing Metrics component of OLSR that will lead to better performance in energy constrained environments

II. Related Work

Component-based design of wireless routing protocols was first proposed by Baras and He in [3]. In this work, the authors proposed a general decomposition of reactive routing protocols, such as AODV [9] and DSR [10] into four main components, based on the different operations of this type of protocols: path discovery, route maintenance, topology database maintenance and data packet forwarding component. They also defined component related performance metrics and examined the effect of them in the overall performance metrics of this type of protocols. In addition, they proposed a methodology to detect and replace the weak component, i.e. the component that leads to significant performance degradation.

Baras et. al introduced a decomposition of proactive routing protocols in [2] and used OLSR as a case study. The authors proposed a decomposition of this type of routing protocols into components and analyzed the operation of three of the fundamental building blocks. In addition, they focused on the Neighborhood Discovery Component (NDC) and provided a methodology for design and modification of this component that leads to a routing protocol with reliable performance. The authors conducted performance analysis among the modified version of OLSR with the proposed NDC component and the standard OLSR protocol.

A software framework called CONFab for component based optimization of wireless sensor networks protocol stacks is proposed in [11]. The authors treated the protocol stacks as a collection of interdependent configurable components. Based on the scenario and the desired performance metrics the framework suggested suitable protocol stacks and selection of parameters. It also took advantage of a deployment feedback mechanism that uses knowledge of previous deployments of protocol stacks (combined routing and MAC layer protocols) in order to select the protocol stack to meet the performance requirements.

Furthermore, a component-based architecture for power-efficient MAC protocol development in wireless sensor networks, named MAC Layer Architecture (MLA), is presented in [12]. The authors defined and implemented a set of fundamental components for MAC layer protocols in wireless sensor networks. These components are optimized and reusable across different protocols as they implement a set of common features shared by existing MAC protocols. The authors examined the flexibility of the architecture by implementing five well-known MAC layer protocols using the defined reusable components. Performance evaluation showed that these implementations have comparative performance with the monolithic implementations of the same protocols. Finally, a declarative perspective on adaptable extensible MANET protocols is presented in [13]. The authors proposed the construction of composite protocols using two mechanisms: policy-driven hybrid protocols and component-based routing. In component-based routing they presented some initial thoughts of specifying declaratively common functionalities of routing protocols as components that will be used across multiple protocols and will be activated upon occurrence of certain events in the network.

III. Brief Review of Proactive Routing Protocols

A. *Optimized Link State Protocol (OLSR)*

Optimized Link State Protocol (OLSR) [6] is an optimization of link state routing protocol, which inherits the stability of a traditional link state algorithm and adds the advantage of its proactive routing nature to provide routes immediately when needed. In OLSR, like in all proactive routing protocols, the nodes periodically broadcast control packets (HELLO and topology control packets (TC)) to find their 1-hop neighbors and advertise a subset of their links. Upon receipt of these packets, each node calculates and updates routes to each known destination. The key concept of reducing the overhead in OLSR is the multipoint relays (MPRs) [14]. The multipoint relays of a mobile node are nodes in its 1-hop neighborhood that are selected in order to forward the node's topology control (TC) packets. Every node maintains a set of these nodes which constitutes its MPR Selectors set. In addition, every node chooses to advertise only the neighbors that are in its MPR selectors set in the topology control (TC) packets that it broadcasts. Thus, MPRs are used as intermediate nodes to form a route from a given node to any destination.

MPRs of a given node are selected based on some criteria. First, they should have a bi-directional link with the node. Second, the MPR set should cover all nodes that are in the 2-hop neighborhood of the given node. The protocol is designed to work in a distributed way without the need of a central entity. In addition, it performs hop by hop routing, which means that each node has the information for the next hop towards the destination in its routing table and it forwards the packet accordingly. Finally, OLSR has good performance in large and dense networks.

B. *Destination-Sequenced Distance Vector Protocol (DSDV)*

Destination-Sequenced Distance Vector Protocol (DSDV) [7] is a proactive protocol that guarantees loop free routes. To guarantee loop-freedom, it adds a new attribute, sequence number, to each route table entry. Using the newly added sequence number, the mobile nodes can distinguish old from new route information and thus prevent the formation of routing loops. DSDV provides a single path to a destination, which is selected using the distance vector shortest path routing algorithm. To reduce the amount of overhead transmitted through the network, two types of update packets are used: full dump and incremental packets. These packets are responsible for topology control and appropriate update of the topology information, when there are sudden changes in the network.

The full dump packet carries all the available routing information, i.e. the information in the routing tables, and the incremental packet carries only the information changed since the last full dump. The incremental update messages are sent more frequently than the full dump packets, because they are designed to capture sudden topology changes. However, DSDV still introduces large amount of routing overhead to the network due to the requirement of the periodic update messages and overhead grows according to $O(N^2)$, where N is the number of nodes in the network. Thus, the protocol will not scale in large network scenarios.

IV. Component-Based Architecture for Routing Protocols

Component based modeling of routing protocols for mobile ad hoc networks is a novel approach to analyze and model the performance of routing protocols. Component based protocol design defines a collection of elementary modules that can be combined to synthesize protocols with various capabilities. Components are fundamental abstractions of the protocols based on their distinct common functionalities. Therefore, we can create a taxonomy of protocol components for various classes of link-layer and routing layer protocols for mobile ad hoc and other wireless networks, in such a way that the protocol becomes a system of dependent and collaborative subsystems (components). This will introduce modularity in protocol design and performance analysis. One other significant contribution of this approach is that the novel designed components can be easily reused across protocols of the same class with minor modifications.

The concept allows customization of protocols to operating conditions in the environment, traffic demands, mobility and network attacks. For example, if we define a Routing Metrics component class, then this component will change a routing protocol's parameters influencing path costs. The adjusted metrics embedded to this component class will cause packets to choose different paths according to the environmental conditions in order to restore performance, e.g. throughput.

A. Decomposition of Proactive Routing Protocols

In this section, we propose a decomposition of proactive routing protocols into components according to the protocol's operations. Proactive routing protocols is a class of routing protocols that constructs a priori the paths and therefore the routing tables, based on topology information that is being disseminated periodically across the network. We decompose the protocol based on the different functionalities of this class of routing protocols and formalize and define the interactions between the separate components. The different components are illustrated in Fig 1.

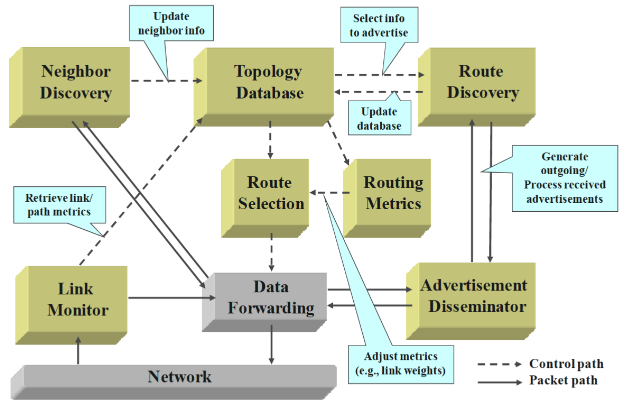


Fig. 1: Decomposition of Proactive Routing Protocols into Components

We will briefly describe the different components, their functionalities and the dependencies between them:

- **Neighbor Discovery**: Describes the operation of the routing protocol to discover its immediate neighbors, which have stable links. A performance model for the Neighbor Discovery component (NDC) in proactive routing protocols is described in [2] and [15]. The Neighbor Discovery, as we see in Fig 1, has an immediate association with the Topology Database component, in order to update the set of links stored in the Topology Database component.
- **Topology Database**: this component is responsible for storing the updated topology information that will be used in the route selection. It has a direct association with Neighbor Discovery component, Route Discovery and Link Monitor. It takes from the Neighbor Discovery component the immediate neighbors at each time and from the link monitor the information regarding the link weights. From the Route Discovery it receives the relay set that it decides to advertise to the rest of the network and the links advertised from the rest of the network to update appropriately the database. It stores all the topology information for the mobile ad hoc network at each time and each node can create its routing tables in a proactive way, i.e. know the optimal paths before a routing request is instantiated by the source node.
- **Route Discovery**: this component (RDC) is responsible for the selection of topology to disseminate to the network. It uses information through topology database component to find the set of links that the node is going to advertise to the rest of the network through the Advertisement Disseminator component. Thus, this component executes the pruning algorithms [16] in order to select the relay set. In the case of OLSR the Route Discovery component selects the Multi-point relays (MPR) of the node [14]. In addition, the Route Discovery class of components receives the advertisements from the other nodes of the network, process them and sends the updated information to the Topology Database component. Therefore, at each time in a proactive routing protocol that follows these functionalities, we have an updated topology database that has the information about the advertised links and the link weights. This information can been taken as

an input to the route selection component to construct the routing tables of the mobile node.

- **Advertisement Disseminator**: this component sends the topology control packets to the rest of the nodes of the network. Topology control packets contain the set of links that the node wants to advertise to the network to be used for routing selection. It gets the information as an input of Route Discovery component and it uses the Data Forwarding component to flood the packets to the rest of the mobile network (through the relay set of the originator node). It also receives the advertisements from the rest of the nodes and it sends it to the Route Discovery component to process them and send updated information to the topology database component.
- **Route Selection**: the component is responsible for selecting the route for the specific source and destination pair. It takes as an input the updated topology information and the adjusted routing metrics in order to decide the route that it will choose. It uses some optimization framework or some online learning techniques in order to make the decision. The simplest example is a minimization algorithm on the sum of weights among the set of possibles paths.
- **Routing Metrics**: this component is adjusting the routing metrics for the links according to the routing requirements and the environmental conditions.
- **Data Forwarding**: this component is crucial to forwarding packets to the rest of the network. It stores the routing tables and therefore the least-cost paths information. It is associated with four components: the Route Selection, the Advertisement Disseminator, the Link Monitor and the Neighbor Discovery component.

B. Performance Metrics

The overall performance metrics that are influenced partially by the separate components and we will examine in our analysis are:

a) Delay: End-to-end delay of the protocol is a crucial performance metric. Based on proactive routing protocols operation, the routing paths are constructed a priori with periodic transmission of control messages. Therefore, there is no delay from neighbor discovery or route discovery component imposed to the overall end-to-end delay of the protocol, since the packet is directly forwarded to the updated next hop node. The only component that introduces delay to the routing protocol is the data forwarding component.

b) Packet Delivery Ratio (PDR): Average rate of successful message delivery throughout the routing procedure. Failures of the routing procedure may lead to significant performance degradation in terms of PDR. This performance metric is also directly related to data forwarding component and is crucial for investigating the performance of the protocol in the case we modify the functionality of some of its components.

c) Routing Overhead: Routing overhead is the percentage of bytes of the control traffic transmitted in the network in the overall number of bytes transmitted in the network, including data and control traffic. As we discussed, it is crucial the routing protocol to be lightweight and not use a large number of control traffic in order to construct the routing path. Neighbor discovery and route discovery components affect directly this performance metric. Hence, the total routing overhead can be expressed as the sum of the overhead of the two components:

$$O_{total} = O_{NDC} + O_{RDC} \tag{1}$$

d) Expected Network Lifetime: The expected network lifetime is the estimated time until one node of the network depletes completely from energy. It is computed by the following equation:

$$Lexpected = \frac{E_{min}}{Drain\_Rate}, \tag{2}$$

where E_{min} is the energy of the most depleted node. Network lifetime is affected by the transmission of both control and data traffic. Thus, it is partially affected by neighbor discovery, route discovery (which includes topology information dissemination) and data forwarding components. We will examine the expected network lifetime as a performance metric in the case that we modify a component of the protocol to adapt to the environmental conditions.

V. Enhanced OLSR for energy constrained environments

In this section, we propose a reusable modification of Routing Metrics component to improve the performance of OLSR protocol in energy constrained environments. The modified component adjusts the routing metrics based on the residual energy of the nodes, in order to increase the network lifetime in the case that we detect a sudden decrease of energy level at one of the nodes of the network.

The new routing metrics component configures the link weights based on the residual energy level of the nodes. The new energy-aware weights that are used are given by equation:

$$w_i = (1 - \alpha) * (1 - E_{i,old}) + \alpha * (1 - E_{i,new}), \tag{3}$$

where $E_{i,old}$ and $E_{i,new}$ are the node's i updated and old energy fraction and α is selected appropriately to take into account the previous value of the energy fraction. For our experimentation we choose $\alpha = 0.5$.

We propose a dynamic modification of OLSR routing protocol that takes advantage of the newly designed and reusable component in the case that the node detects that any node in the network has energy fraction less than a threshold $E_{threshold}$. The new version of OLSR, called Enhanced OLSR, swaps the regular routing metrics component that computes the paths based on the number of hops with the new one once it detects the change in energy fraction. The threshold is defined based on the performance requirements that we require at each scenario. For our experimentation we choose $E_{threshold} = 0.5$.

This application of component-based modeling in the context of energy constrained networks shows that by using this approach we are able to adapt to changing environmental conditions. This can be done by swapping reusable protocol components that are proved to have good performance to the current conditions (mobility, rate, energy level, percentage of malicious nodes etc.).

VI. SIMULATION

In this section we present the experimental setup, the investigation of the routing overhead metric across OLSR components and between OLSR and DSDV and an extensive performance analysis of the Enhanced OLSR protocol.

A. Simulation Setup

For our experiments we used the OLSR and DSDV modules provided by the NS3 network simulator [17]. We designed and implemented a reusable modification of Routing Metrics component in the OLSR protocol to be used in the Enhanced OLSR module. We simulated a MANET with 30 nodes in a dense 2000 x 2000 meter square area, which has 4 hop network diameter. There are 5 CBR/UDP sources generating packets of 512 bytes in a CBR of 10 packets/sec. To examine the effect of different mobility patterns to the performance of the protocols and the individual components, we generated five different scenarios. We examine a static scenario and four different mobile scenarios using Random Waypoint mobility model with node speeds 2, 10, 20 and 30 m/sec respectively. The scenarios are generated using Bonnmotion [18]. To compute the average value of the performance metrics we simulated each scenario 3 times. In each different simulation, we choose different source-destination pairs. The common simulation parameters are summarized in Table I.

TABLE I: Common Simulation parameters

Area	2000m x 2000m
Nodes	30
Traffic Sources	5
Traffic Type	CBR/UDP
Packet Size	512 bytes
Data rate	10 packets/sec
Start of Traffic	30 sec
Initial Node Energy	10 Joules
Transmission Power	5 dbm
Simulations/Scenario	3
Link bandwidth	1 Mbps

B. Routing Overhead Investigation

In this section, we investigate the footprint of the individual components to the routing overhead performance metric. As we discussed in section IV-B the routing overhead is being affected directly from neighbor discovery and route discovery components. In OLSR, which we use as our case study, the routing overhead of neighbor discovery is the amount of bytes in the HELLO packets and the overhead of route discovery the amount of bytes in the TC packets. From Table II we observe that the route discovery component of OLSR has higher impact in the total routing overhead of the protocol under various mobility scenarios.

TABLE II: Routing overhead (in %) in OLSR

	Static	2 m/sec	10 m/sec	20 m/sec	30 m/sec
NDC	27.46	25.13	25.42	25.29	25.45
RDC	72.54	74.87	74.58	74.71	74.55

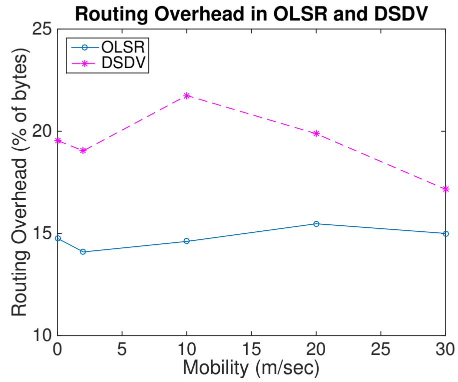
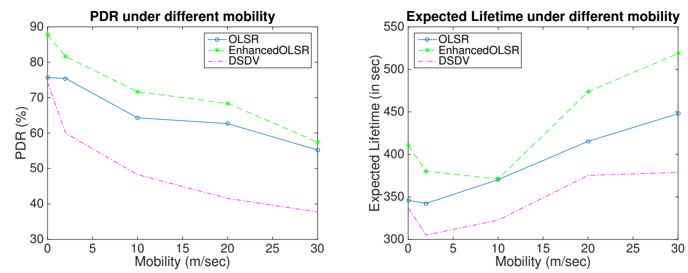


Fig. 2: Routing Overhead in OLSR and DSDV under different mobility scenarios



(a) PDR comparison under different mobility (b) Expected Network Lifetime under different mobility

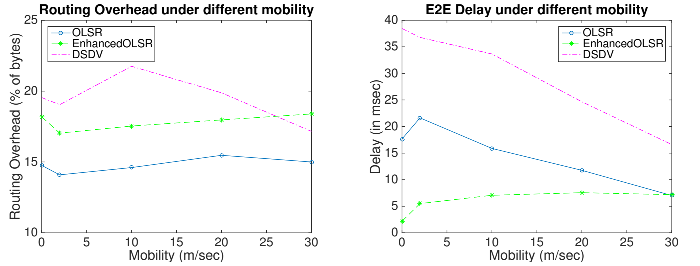
Fig. 3: PDR and Lifetime

In addition, we compare the performance in terms of routing overhead between OLSR and DSDV that use a different implementation of neighbor discovery and route discovery components. The percentage of routing overhead used in DSDV is higher than the routing overhead of OLSR under all mobility scenarios as we can see in Fig. 2. The use of full dump and incremental packets from DSDV for route discovery is responsible for the high routing overhead, because these packets are transmitted whenever a sudden change is detected. Hence, in our scenarios it is reasonable OLSR to have better performance in terms of routing overhead in comparison to DSDV.

C. Performance Evaluation of Enhanced OLSR in Energy Constrained Environments

In this section, we conduct extensive performance evaluation of the Enhanced OLSR protocol proposed in Section V, which dynamically swaps components when it detects a sudden energy depletion in the network. We compare its performance with standard OLSR and DSDV protocols under different mobility scenarios. The performance metrics that we examine are PDR at Fig. 3a, expected network lifetime at Fig. 3b, routing overhead at Fig. 4a and end-to-end delay at Fig. 4b.

As we observe in Fig. 3b the enhanced version of OLSR which adaptively changes the routing metrics component configuration leads to significant increase of expected network



(a) Routing Overhead comparison under different mobility

(b) End-to-end delay under different mobility

Fig. 4: Routing Overhead and End-to-end Delay

lifetime in comparison with standard OLSR and DSDV. The increase of expected network lifetime in high mobility scenarios is around 15-20%. In addition, the packet delivery ratio of the enhanced version, shown at Fig. 3a is slightly higher from standard OLSR and significantly higher from standard DSDV. The end-to-end delay (in *msec*) is also better in enhanced OLSR protocol in comparison with OLSR and DSDV under all mobility scenarios (Fig. 4b). However, the percentage of routing overhead of the enhanced OLSR protocol, shown in Fig. 4a, is slightly higher than the standard OLSR protocol. This imposes a performance limitation on the enhanced version of OLSR protocol.

VII. Conclusion

In this paper, we present a methodology for routing protocol design and modeling, based on the idea of components. We define the separate components and their interactions. In addition, we examine how the components affect some performance metrics of the protocol, such as the routing overhead. We also present an application of component based design by creating a enhanced version of OLSR for energy constrained environments that modifies adaptively the configuration of routing metrics component once it detects energy depletion. Enhanced OLSR achieves better performance in terms of network lifetime and PDR compared to standard OLSR.

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