Energy Optimization for Proactive Unicast Route Maintenance in MANETs under End-to-End Reliability Requirements

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Many time-critical applications for Mobile Ad hoc NETworks (MANETs), such as the military applications and disaster response, call for proactive link and route maintenance to ensure low latency for reliable data delivery. The goal of this paper is to minimize the energy overhead due to the high *control traffic* caused by the periodic route and link maintenance operations in the proactive routing protocols for MANETs. This paper — i) categorizes the proactive protocols based on the maintenance operations performed; ii) derives analytical estimates of the optimum route and link update periods for the different protocol classes by considering a) the data traffic intensity, b) link dynamics, c) target reliability, measured in terms of Packet Delivery Ratio (PDR), and d) the network size; and iii) proposes a network layer dynamic Optimization of Periodic Timers (OPT) method based on the analytical estimates to locally vary the update periods in the distributed nodes. Simulation results show that DSDV-Opt, a variation of DSDV protocol using OPT, — i) achieves the target PDR with 98.7% accuracy while minimizing the overhead energy; ii) improves the protocol scalability; and iii) reduces the control traffic for low data traffic intensity.
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1. Introduction

Routing is a challenging task in Mobile Ad hoc Networks (MANETs), mainly because of the dynamic nature of the wireless medium and the mobility of the wireless nodes leading to frequent disconnection of routes. In many time-critical and high reliability demanding applications, such as disaster response, the network has to perform proactive routing to ensure application-tolerable delay for information delivery [18]. However, limitations on the available energy in the battery-powered mobile nodes compound the routing problem.

Proactive routing protocols, which extend the traditional table-driven routing techniques found in the wired networks, can be very expensive in terms of energy consumption [24]. These protocols maintain and update routes periodically between all the pairs of nodes even when there is no data traffic. Consequently, these protocols do not scale well in large networks [29]. *Adjusting the periodicity of route maintenance is therefore required to minimize the energy overhead and increase the scalability of proactive protocols.*

There are two principal periodic maintenance operations performed in the proactive protocols: i) individual link maintenance, and ii) end-to-end route maintenance. Optimization of end-to-end route maintenance, based on the link dynamics in MANETs, have been explored in Link Dynamics (LD) [25]. However, LD does not address the low scalability of proactive protocols in large networks. Additionally, requirements on the route availability are also not considered. Intuitively, there is no requirement to update routes even with high link dynamics unless there is data to transmit. Similarly, if the network reliability target, usually specified as the *Packet Delivery Ratio (PDR)* [27], is not high (e.g. in elastic traffic models in real-time applications [27]), the update frequencies can be further reduced—leading to a further reduction in the energy consumption, and hence improving the energy-efficiency (and scalability) of the routing protocol.

This paper incorporates the data traffic intensity and the target reliability considerations in optimizing the link and route maintenance periods to minimize the energy overhead. Specifically, the goal of this paper is to *optimize the update frequencies of the proactive routing protocols in MANETs in order to minimize the overhead energy of the control traffic, based on the average rate of data traffic and link changes in the network, without compromising the protocol scalability and reliability, as long as that is feasible within the link (channel) capacity.* In this work, we measure the protocol scalability as the growth rate in the per node energy consumption with respect to the number of nodes in the network. Further, we perform the analysis and optimization from the perspective of a given source-destination pair in the network. Optimization for incorporating requirements of multiple source-destination pairs is left for future work.

Paper Contributions

Following are the major contributions of this paper:

1. A classification of the proactive routing protocols based on the maintenance operations is performed. This classification abstracts the proactive protocols and identifies the optimization goals for the periodic update operations performed by them.

2. An analytical model is developed to derive the optimum period of beaconing, β_{opt}, and the optimum period of route maintenance, φ_{opt}, for all classes of proactive protocols, minimizing the energy overhead of *control traffic* (messages exchanged for performing the route and link maintenance operations). The proposed optimization achieves the following for the proactive protocols in MANETs:
   a) makes control traffic aware of the data traffic intensity, and the network target PDR.
   b) improves scalability by ensuring reduction in the growth rate in energy consumption per node with respect to the number of network nodes. This is achieved by reducing the frequency of the route-update flooding for increase in the network size.

3. A dynamic technique for optimizing periodic timers (OPT) for the update operations is proposed.
   a) The impact of OPT is analytically evaluated with respect to LD [25].
   b) The performance of DSDV protocol in conjunction with OPT (called DSDV-Opt) is compared with DSDV to verify how the proposed optimization can reduce energy consumption without affecting the PDR, while improving the protocol scalability.

The rest of the paper is organized as follows. Section 2 gives the related work on research efforts to reduce the energy impact of the control overhead by proactive routing protocols. Section 3 presents different control operations along with the classification of the proactive protocols for MANETs. Section 4 presents an analytical technique for estimating the optimal beaconing and route update periods. In Section 5 we present a dynamic optimization technique for periodic timers (OPT). Section 6 compares our dynamic optimization scheme with a modified version of LD technique based on the analytical results in Section 4. Simulation results are presented in Section 7. Finally, Section 8 concludes the paper.

2. Related Work

This paper deals with the problem of targeting the periodic maintenance operations of proactive protocols toward the network target PDR, data traffic intensity, protocol scalability and channel capacity. Related work on reducing the energy overhead of the routing protocols has primarily focused on three major approaches: i) restricting the route maintenance operations, ii) varying the data rate, and iii) optimizing the update frequency.

2.1. Restricted route maintenance and hybrid protocols

Adaptive protocol synthesis is introduced by Bamis et. al. [3] [4], which employs complementary routing protocols based on the network dynamics. In this approach, the nodes in MANETs are classified based on the mobility and instead of using a single routing protocol, different routing protocols are employed to adapt to the node mobility. This approach can leverage the benefits of different protocols at different node mobility; however, it does not consider the data traffic intensity which might further affect the applicability of different protocols [29]. This paper, on the other hand deals with a single proactive protocol to adapt its behavior based on both the network dynamics and the data traffic intensity.

A different approach is taken in the hybrid routing protocols such as ZRP [20], EAGER [30], and SHARP [23]. These protocols restrict the pro-activity in smaller network regions, called *zones*, and perform inter-zone routing in a reactive manner. If the size of the zones are determined properly, these protocols can achieve the required balance between the route maintenance overhead and the route reconstruction latency [20]. However, the optimum size of the zones, which achieves this balance, is affected if the periodic route maintenance of the proactive protocols employed within the zones is optimized [30]. Further, as in proactive protocols, nodes inside a region are engaged in periodic maintenance of routes, thereby wasting energy in case of little or no data traffic. Although SHARP and EAGER adapt the size of the zones based on the traffic intensity, each node, at the least, has to periodically maintain the links with the neighboring nodes (i.e. one-hop routes) [23] [30].

2.2. Dynamic variation of data transmission rate at the transport layer

Techniques for optimizing the periodicity of transport layer packet retransmissions have been explored in the context of Wireless Sensor Networks (WSN). The event reporting frequency in WSNs is dynamically varied based on the network condition and congestion for maintaining a certain level of reliability [26]. This however is a transport layer solution tuned toward meeting the WSN transport layer requirements. The focus of this paper, on the other hand, is on optimizing the control overhead in the network layer for MANETs.

Apart from this, in traditional networks and MANETs, congestion control has been introduced at the transport layer, which regulates the data traffic based on the network condition [1] [15]. In contrast, the proposed optimization in this paper varies the *control* traffic at the network layer with respect to the network condition and data traffic rate. In this regard, the proposed optimization is complementary to the transport layer congestion control.

2.3. Optimization of proactive route update frequency

A technique for optimizing the frequency of update operations in proactive routing protocols, called Link Dynamics (LD), has been proposed by Samar et. al. [25]. LD adjusts the route updates based on a proposed model for link dynamics among the mobile nodes. The optimization is based on the idea that the route update frequency has to be adjusted to compensate for the rate of link breakages. However, LD does not consider the data traffic rate and the network target PDR, which necessitates the availability of routes. In this paper, we show that optimizing the proactive updates can further reduce the control traffic when taking these parameters into consideration. Further, proactive protocols are in general not scalable with the size of the network. LD can not guarantee this scalability because it does not consider the effect of the network's size on the overhead. In this paper, we have further taken the network size into consideration and show how we can reduce the control traffic for large networks.

A preliminary version of the proposed optimization has been presented in [16]. The primary contributions of the preliminary version include: i) a classification of the proactive routing protocols based on the maintenance operations performed; and ii) an analytical model to derive the optimal update periods, β_{opt} and φ_{opt}. This paper enhances the preliminary work with a per-node adaptive optimization for the DSDV protocol, and a comprehensive simulation study.

3. Maintenance Operations in Proactive Routing Protocols

With *proactive* routing, network topology and route information are maintained for any pair of nodes regardless of the application data traffic. Messages exchanged and energy consumed in performing this maintenance are defined as the *control traffic* and *overhead energy*, respectively. The terms *control traffic*, *overhead energy*, *control overhead*, and *overhead* are interchangeably used.

3.1. Proactive Protocol Model

Each node maintains the link status with every node in the communication range (i.e. the *neighboring nodes* or *neighbor set*). Periodic *beacon* messages are exchanged among the neighboring nodes for this purpose [29]. The routes are updated immediately when a change in the link status is detected and/or after the expiry of a pre-defined period. The *route-update* messages, triggered on the detection of the changes in the link status, can be initiated by any node that detects the change. Fresh route information for nodes is maintained through periodic route-update messages. These periodic messages are initiated by either the source or the destination and flooded across the network.

In link state routing, each node floods its neighborhood information across the network with the route update messages. In distance vector routing, the route update messages contain the next hop information to reach any other node. This update is transmitted to all the neighboring nodes. Similarly, all the neighboring nodes transmit their local information to all of their respective neighbors. In the worst case, the update has to be transmitted by every node leading to the same message complexity as for the link state routing.

3.1.1. Maintenance Operations

There are three different *operations* for maintaining the network topology and the route information in the proactive protocols; two of which are periodic in nature as noted in Section 1, and one of which is a triggered operation. Figure 1 summarizes the different operations in the proactive protocols.

1. Periodically Monitoring the Link Status (PMLS): This operation is required to maintain the topology of the network. If a node does not receive any beacon message from a neighbor for a certain number of consecutive beacon periods, the corresponding link is assumed to be disconnected (broken). Routes are updated depending on the topology maintained by PMLS.

2. Triggering Route Updates for every change in the Link Status (TRULS): This operation performs update of route information across the network whenever there is a change in the status of a link in a route. Flooding of the route-update messages takes place to diffuse the updates across the network [5,22]. In the rest of the paper, we use the terms 'broadcasting' and 'flooding' interchangeably.

3. Periodically Updating Routes (PUR): Unlike TRULS, this operation accumulates all the link changes in a specified interval before broadcasting the route updates. Note that PUR builds fresh routes based on the current topology. PMLS and PUR are the two periodic operations described in Section 1.

In the following subsection, we classify the proactive protocols based on the operations they employ.

3.1.2. Classification of Pirating Routing Protocols

All proactive protocols employ PMLS. However, a proactive protocol may or may not employ one of the TRULS and PUR operations for updating routes. We abstract the proactive protocols in four different classes as follows, depending on the employment of the TRULS and PUR operations.

1. Proactive protocols with all the operations (PP+BTP[1]): In this approach, all the three aforementioned operations are performed. Protocols, in this category, include the Destination Sequenced Distance Vector (DSDV) [22], and the Topology Broadcast based on Reverse Path Forwarding (TBRPF) [5]. Although the PUR operation may seem redundant because of the employment of TRULS, it has a certain significance. TRULS in these protocols may lead to routing loops, which get corrected by the PUR operations. The PUR operation includes transmission of destination sequence numbers to monitor and maintain the freshness of the routing structures. The routing loops, after performing TRULS, are broken by PUR with the latest sequence numbers.

2. Proactive Protocols with PMLS & PUR (PP+BP): A principal disadvantage of PP+BTP is the large amount of control traffic generated to maintain the routing structures. As TRULS is performed with every change in the link status, the PP+BTP protocols become very cumbersome in terms of the messages exchanged, especially with the high dynamics in the MANETs. Instead, a liberal approach is taken in protocols such as the DARPA packet radio network project [14], Intra-zone Routing Protocol (IARP) [12] [13], Fisheye State Routing protocol (FSR) [21], and the Optimized Link State Routing (OLSR) [6] where TRULS is not performed at all.

[1]Naming convention: PP: "Proactive Protocol", "B": for beaconing (PMLS operation), "T": for TRULS operation, and "P" for PUR operation.

3. Proactive Protocols with PMLS & TRULS (PP+BT): One of the main challenges in PP+BP is to address the trade-off between the amount of the control traffic and the consistency of the route information. To address this, another class of proactive protocols has been proposed, which do not perform PUR but only perform TRULS to maintain fresh routes. Unlike PP+BTP, these protocols do not rely on the destination initiated sequence numbers in maintaining fresh loop-free routes. Examples include the Source Tree Adaptive Routing (STAR) [7], and the Wireless Routing Protocol (WRP) [19].

4. Proactive Protocols with PMLS (PP+B) Distributed routing protocols of another class have been developed which do not require the PUR and TRULS operations. These protocols use the beacon messages to exchange local information between the neighbors. When any change in the link status is detected, each node takes decisions based on the local knowledge in such a way that information regarding topological changes is automatically diffused across the network. Examples of these protocols include the Self-Stabilizing Shortest Path Spanning Tree (SS-SPST) [10] [11], the Energy-aware SS-SPST (SS-SPST-E) [17] and the Breadth First Spanning Tree (BFST) [8] [9] protocols. Although these protocols may reduce the volume of the control messages, they may incur higher end-to-end delay due to a slower diffusion of local changes across the network.

Figure 2 further illustrates the control messages exchanged among the nodes for performing these operations. As shown in the figure, there are two basic timers that are maintained for proactive routing: 1) the periodic beacon timer and 2) the route update timer. Periodic firing of these timers initiates PMLS and PUR respectively. For simplicity, the figure shows that the route update timers are maintained in the source node. However, in reality, it can be maintained in the destinations as well (as in DSDV [22]). Note that TRULS in the figure is sent to a neighbor node that can potentially be in a new route from the source to the destination.

Table 1 summarizes the operations employed in the aforementioned approaches. The following subsection motivates our timer period optimization and presents different parameters impacting the optimization.

3.2. Optimization of the update operations' timer periods

This section offers a brief discussion on the factors that influence the determination of the optimal timer period used in the proactive protocols.

In general, the control traffic of a proactive protocol depends on the type of the protocol as described in the previous section. Controlling the timer period provides some flexibility in controlling the volume of the control traffic. For example, by increasing the timer periods the control traffic of the protocol can be reduced. This increase, however, may result in stale routing structure due to infrequent update of the routes. Decreasing the period, on the other hand, results in a high control overhead. Determination of the proper (optimal) timer periods is therefore mandatory to minimize the control traffic without hindering the performance of the proactive protocols.

In determining the optimal periods of the update timers, the following factors should be considered:

- **Network target reliability**: The reliability of the routing protocols depends on their ability to successfully deliver the application packets to the destination. The freshness of the routes, required for the successful packet delivery, is therefore a principal driving factor toward achieving the network target PDR.

- **Data traffic intensity**: The intensity of the data traffic determines the requirement of routes between the source-destination pairs. For very little or no data traffic scenarios, the requirement for maintaining fresh routes can be relaxed compared to the high data traffic scenarios, which require frequent route updates for successful data packet delivery.

- **Rate of change in the link states**: Changes in the link status in the MANETs can occur due to node mobility and energy depletion in the battery-powered nodes. For low rate of changes in the link status, the requirement for maintaining the fresh routes can be further relaxed. However, this is not affordable in most situations for dynamic networks such as MANETs with high rate of link changes.

- **Capacity of the wireless channel**: The amount of control traffic that can be sustained for route maintenance, however, depends on the channel capacity of the wireless medium. This capacity, usually measured by the channel bandwidth, constrains the feasibility of the control traffic volume in the proactive protocols. For low bandwidth, it may be infeasible to perform fresh route maintenance even with high rate of link changes.

- **Network size** (diameter and number of nodes): The overall end-to-end reliability and latency depend on the diameter of the network. Moreover, the scalability of the protocol depends on the number of nodes in the network. A proactive protocol should adjust the update frequencies so that the routes are fresh and reliable yet the energy spent scales well with number of nodes in the network.

4. Modeling and Analysis of Timer Periods

In this section, we develop an analytical model that will enable optimum period determination of the aforementioned timers. In our study, the protocol delay, the data traffic rate, and the link change rate are correlated to the achievable reliability of the protocols. Our main goal is to minimize the overhead cost due to the control traffic in the proactive protocols. The required reliability and the channel capacity provides the constraints in achieving this goal.

4.1. System Model and Problem Statement

4.1.1. Network Model

We consider a network of N nodes. Each node has a bidirectional communication link with any other node that is within the range of communication. The communication delay of a link is denoted as d_{hop}, which includes the queuing and propagation delay for that link. A link can break only if the corresponding nodes get out of each other's communication range. For simplicity, link-layer reliability for interference and contention is assumed. However, for completeness, the simulation study (Section 7) relaxes these assumptions.

The average number of neighboring nodes in the communication range of each node is given by n, and the average diameter (in number of hops) of the network is given by D. The mobility assumptions are based on the work of link dynamics [25], which assumes a random way-point mobility model, and establishes that the number of link changes is exponentially distributed; consequently, in this paper, the analysis assumes that the link changes observed in the network are exponentially distributed with a mean value of μ, while the simulations use a random way-point model.

Each node in the network periodically transmits *beacon* messages (with β being the beacon interval in seconds, i.e. the time interval between two successive beacon transmissions). The beacon messages contain the transmitter node id (size of $\lceil logN \rceil$) to advertise the transmitter's existence to the neighboring nodes. If a node does not receive any beacon from a neighbor for k number of consecutive beacon periods, the corresponding link is assumed to be broken. The data packets are sent from the source to the destination. It is further assumed that there is a single source-destination pair in the network. For protocols employing PUR (PP+BTP, and PP+BP), the *route update* timers are maintained at the sources (or the destinations depending on the specific protocol), with φ being the average route update interval.

The energy consumption model focuses on energy overhead of the control traffic, thus on the transmission and reception of packets. Optimization of control traffic does not affect the idle state energy consumption. There are two modes of energy consumption at each node: (1) the reception energy consumption e_{rx} per bit received, and (2) the transmission energy consumption e_{tx} in transmitting one bit by a node to all the nodes in the communication range. Should a sleep mechanism be employed, that would have an effect on the idle state energy consumption and on the link (hop) delay. As the optimization is not affected by the idle state, we only assume that the sleep mechanism employed affects the hop delay, i.e. d_{hop}.

The network intends to provide a target service reliability measured in terms of the PDR as defined below:

Definition 1: *PDR is defined as the ratio of the total number of packets successfully delivered to the destination to the total number of packets transmitted from the source.*

PDR gives the probability of successful packet delivery from the source to the destination. It is an effective measure to characterize the reliability of MANETs [27]. We assume that the network target PDR is denoted as Γ.

4.1.2. Data Traffic Model

We assume the Bulk Poisson traffic generation model [2,25] for our analysis. In the Bulk Poisson model, the rate of data message generation at the source is exponentially distributed with the average λ messages per unit time. The message generation is therefore a Poisson process. Each such message consists of multiple data packets in a bulk. We assume each message contains α data packets on an average. Packets inside a message arrive after every constant time τ. This traffic model characterizes many real-time applications (such as voice, video and multimedia) which we believe would be the major MANET targets in many situations such as the military applications, disaster rescue missions etc.

4.1.3. Problem Statement

The goal is to calculate the optimum beacon interval β_{opt} and the optimum route update interval φ_{opt} to minimize the control overhead in the proactive protocols as a function of – average link change rate (μ), number of nodes (N) in the network, data traffic intensity (given by λ, α, and τ), and network target PDR (Γ) – i.e. $\boldsymbol{\beta_{opt} = f(\mu, \lambda, \alpha, \tau, \Gamma, N)}$, and $\boldsymbol{\varphi_{opt} = g(\mu, \lambda, \alpha, \tau, \Gamma, N)}$.

Table 2 summarizes all the symbols used in the analysis.

4.2. Analytical Estimation of Overhead Energy Consumption for PMLS, TRULS and PUR

We start by first analyzing the energy expended for the three control operations (PMLS, TRULS, and PUR) in proactive protocols. As explained previously, PMLS employs periodic beacon messages. The energy consumed for the transmission of one beacon message is $\lceil logN \rceil E_{tx}$, where $\lceil logN \rceil$ is the length of the beacon message and E_{tx} is the energy consumed per bit transmitted by a node and decoded by all its neighbors. Therefore E_{tx} is given by $(e_{tx} + ne_{rx})$ (n being the average number of neighbors). As there are N nodes in the network, and all of them transmit beacons after every β time, the energy consumption per unit time is

$$E_{PMLS} = \frac{N}{\beta} \lceil logN \rceil E_{tx}. \tag{1}$$

TRULS initiates route update with each change in the link status. The time taken to detect a link change is $k\beta$ (as detection is performed with non-reception of beacons for k consecutive beacon periods). Further, the average time between link changes is $1/\mu$. Therefore, the time before an occurrence of link change and the initiation of TRULS is $1/\mu + k\beta$, giving the rate of the TRULS operation as $1/(1/\mu + k\beta)$. This rate however is multiplied by the network diameter, as any intermediate node between a source and destination can initiate TRULS. Each route update packet has a maximum size of $N\lceil logN \rceil$. This has to get flooded across the network among N nodes (i.e. N such transmissions) leading to the average energy expended per unit time as:

$$E_{TRULS} = \frac{DN^2\mu}{1 + \mu k\beta} \lceil logN \rceil E_{tx}. \tag{2}$$

The size of route update packets for PUR has the same value as TRULS, however, the rate of such update is $1/\varphi$, resulting in the energy consumption per unit time as,

$$E_{PUR} = \frac{N^2}{\varphi} \lceil logN \rceil E_{tx}. \tag{3}$$

The total overhead cost of the proactive protocols is the sum of these individual overheads for the operations employed (Table 1).

4.3. Correlation between PDR (Γ), traffic rate (λ) and link change rate (μ)

This section analyzes the average PDR achieved by the proactive protocols. PDR gives the probability of successful delivery of the data packets from the source to the destination (Definition 1). If η_p denotes the probability of packet loss for a single link failure in the route, then the probability of successful packet delivery from the source to the destination is given by $(1 - \eta_p)^D$, D being the average network diameter in number of hops (Section 4.1). If Γ is the network target PDR then we have the following constraint:

$$(1 - \eta_p)^D \geqslant \Gamma \tag{4}$$

Note here that η_p is dependent on the rate of the link changes and the traffic rate. Further, if η_p is one, i.e. if all the packets are lost, the PDR becomes zero, which is clearly unacceptable. In the following paragraphs, we analyze η_p in terms of μ and λ assuming that η_p is not one.

Packet Loss Analysis: The average rate of packet generation includes the constant data packet generation in a message and the exponential message arrival. Under the same traffic model it has been proved [2] that if, on average, there are α packets per message where the arrival of messages is distributed exponentially with the mean rate λ and if the packets in a message is generated after every constant time τ, then the average number of data packets per unit time is given by,

$$\Lambda = \frac{\lambda\alpha}{1 - \lambda\alpha\tau(1 + \lambda\alpha - \frac{\lambda+1}{\alpha})e^{-\lambda\alpha\tau}} \tag{5}$$

It can be easily verified from the above equation that if α is one, then the rate of packet arrival degenerates to λ. Now, we can quantify η_p as follows:

Theorem 4.1 *If δ is the worst-case delay to re-establish a valid route after a single link disconnection in the route, then the estimated probability of a packet loss, assuming that not all the packets are lost, due to the link failure is:*

$$\eta_p = \Omega\delta \tag{6}$$

where $\Omega = \frac{\lambda\alpha+\Lambda}{\lambda\alpha+\mu}\mu + \left(\frac{1}{\alpha} - \frac{\lambda}{\alpha(\lambda+\mu)} - \frac{\mu}{\lambda\alpha+\mu}\right)(\Lambda - \mu)e^{-(\lambda\alpha+\mu)\tau}$.

Proof: There are two possible cases.
(I) One or more packets are generated before a link breakage: Since not all the packets are lost, $\delta < 1/\mu$ (Figure 3). The average number of undelivered packets during the time δ is $\delta\Lambda$ as Λ is the rate of packet arrival. Moreover, between two consecutive route disconnections there are on an average Λ/μ number of packets from the source. The probability of packet loss can therefore be given by

$$\eta_1 = \frac{\delta\Lambda}{\frac{\Lambda}{\mu}} = \mu\delta. \tag{7}$$

(II) One or more link breakage happen before a packet arrival: Since not all the packets are lost, $\delta < 1/\Lambda$ (Figure 4). Similar argument as Case I would give the probability of packet loss as,

$$\eta_2 = \frac{t'\Lambda\delta}{t'} = \Lambda\delta. \tag{8}$$

The probability P_m that a link is broken when a packet needs to be transmitted (Case II), under the same set of assumptions [2] is given by:

$$P_m = \left[\frac{1}{\alpha} - \frac{\lambda}{\alpha(\lambda+\mu)} - \frac{\mu}{\lambda\alpha+\mu}\right]e^{-(\lambda\alpha+\mu)\tau} + \frac{\mu}{\lambda\alpha+\mu}. \tag{9}$$

The probability of a packet loss can be given as follows:

$$\eta_p = (1 - P_m)\eta_1 + P_m\eta_2 \tag{10}$$

We replace P_m, η_1 and η_2 in Equation 10 to get the result. □

4.4. Optimization for PP+BTP

Since PP+BTP employs all the three operations (Table 1), the overhead for such protocols is given as,

$$E_{ov} = E_{PMLS} + E_{TRULS} + E_{PUR}. \tag{11}$$

Minimizing the E_{ov} is the objective of the optimization problem. Following are the two constraints for the optimization problem.

4.4.1. PDR Constraint

In case of a route disconnection, the worst case delay before the re-establishment of a valid route is dependent on i) the maximum time before update to a valid route is initiated; and ii) the end-to-end delay to propagate the update across the network. The detection of any change in a link's status is performed after the non-reception of k beacon messages, leading to a detection delay of $k\beta$. Although a TRULS operation updates routes whenever a change in the link's status is detected, it does not affect the worst case delay. As explained in Section 3, it is possible in PP+BTP protocols that a TRULS operation may generate invalid routes with one or more cycles. A subsequent PUR operation is required to break these cycles and generate valid routes. Consequently, the worst case delay (δ) in re-establishing a valid route after a link change is $k\beta + (\varphi + d_{rec})$, where d_{rec} is the end-to-end propagation delay, which is $D \times d_{hop}$. Replacing this in Equation 6 and taking δ to the left hand side of Equation 4 we get,

$$k\beta + \varphi + d_{rec} \leqslant \frac{1 - \Gamma^{\frac{1}{D}}}{\Omega}. \tag{12}$$

It can be easily verified that with the increase in μ, λ or Γ, the right hand side of the above equation decreases. As a result, the control overhead required to maintain the PDR (Γ) becomes high.

4.4.2. Channel Capacity Constraint

We want to ensure that the control traffic generated by a proactive protocol does not overwhelms the network. In presence of ample node buffering, we should ensure that on an average, the total of data and control traffic does not exceed the average bottleneck link bandwidth (channel capacity), C ($bits/second$), that is available along the path from the source to the destination.

First, we describe the average channel usage due to the control traffic. The channel availability of a node is affected by the control traffic within the range. As described in Section 4.1, the size of each beacon message is $\lceil logN \rceil$, and the average number of nodes within the range is n. Therefore, the average number of $bits/second$ required for the beacon messages is given by $n \lceil logN \rceil / \beta$. Similarly, for the route update message it is given by $nN \lceil logN \rceil (1/\varphi + \mu D/(1 + \mu k\beta))$ (Section 4.2). Assuming, a data packet has d bits on an average, we have the following constraint:

$$\frac{n}{\beta} \lceil logN \rceil + nN \left(\frac{1}{\varphi} + \frac{\mu D}{1 + \mu k\beta} \right) \lceil logN \rceil + d\Lambda \leqslant C, \tag{13}$$

where the average number of $bits/second$ for the control traffic is given by the first two terms on the left hand side. The last term on the left hand side of the equation accounts for the data traffic.

4.4.3. Joint Optimization of Timer Periods

We first describe how the optimal timer period values are found for the PP-BTP class of proactive protocols and subsequently derive optimal values for the other classes of protocols as special cases.

Given the constraints in Equations 12 and 13, our objective is to minimize E_{ov}, the overhead of the protocol, where both β and φ are real positive numbers. Although the problem is not linear, it can be solved as follows. The optimum solution can be found when we increase β and φ as far as possible while still meeting the constraint in Equation 12. Therefore, first, the constraint in Equation 12 is converted to an equality. Based on this, one variable is replaced in the objective function in terms of the other. Equating the objective function's first order derivative to zero gives a quartic equation (fourth order). Among the four roots found, we get the optimal point by checking for the positive value of the second order derivative of the objective.

Note that if the values of β_{opt} and φ_{opt}, found in this way, do not satisfy the constraint in Equation 13, then the problem is infeasible. It is not possible to further increase β_{opt} or φ_{opt} (to satisfy equation 13) because of the constraint in equation 12. Intuitively, the control overhead becomes very high when the rate of changes in the link-status, the data traffic rate, and the required PDR are high. The channel capacity is however limited and may not support the high overhead incurred. In other words, under these conditions the maximum achievable PDR may become less than the target PDR.

Therefore, given the target PDR requirement and the channel capacity, we find the range of β_{opt} and φ_{opt}. When $\mu \to 0$, both β_{opt} and φ_{opt} tend to infinity, i.e. there is no need to send control packets if the link-status between the nodes do not change. However, in MANETs, this is hardly the case due to high link dynamics among the nodes. The other extreme is given by the situation when $\mu \to \infty$. The ranges of the optimum periods are:

$$\infty > \beta_{opt} \geqslant \frac{\frac{1-\Gamma^{\frac{1}{D}}}{\lambda\alpha+\Lambda} - d_{rec}}{k} \left(1 + \sqrt{\frac{N}{k+ND}}\right)^{-1}, \tag{14}$$

$$\infty > \varphi_{opt} \geqslant \left(\frac{1-\Gamma^{\frac{1}{D}}}{\lambda\alpha+\Lambda} - d_{rec}\right)\left(1 + \sqrt{\frac{k}{N} + D}\right)^{-1}. \tag{15}$$

Note here that for simplicity, we provide a range of optimum values when μ is varied. The solution of the quartic equation gives complicated notational terms and is not presented to avoid confusion.

4.5. Optimization for PP+BP, PP+BT and PP+B

Optimizations for PP+BP, PP+BT and PP+B follow the same procedure as PP+BTP. The objective function and the capacity constraint are determined by the operations employed in these protocols (Table 1). PP+BTP leads to the worst case situation in terms of the overhead and the channel usage because of the employment of all the three operations. The problem becomes simpler for the other protocol classes. The worst case delay to recover to a valid route (δ) for PP+BP is same as PP+BTP as TRULS does not affect δ in PP+BTP. However, the objective function in PP+BP do not have to consider the TRULS operation.

For PP+BT and PP+B protocols, the number of variables reduces to one (only the beacon interval, β). For PP+BT, the optimization is straightforward, as the equality of the PDR gives

β_{opt}. For PP+B, however, the diffusion of route update is more than the end-to-end delay d_{rec}. The recovery for any change is performed based on the local actions and no route update broadcast is employed. Starting from a given change in the link status and assuming that there are no further changes during the recovery process, the routing structure in PP+B recovers to a valid route with a worst case latency of $\beta \sum_{i=0}^{i=D-1} c^i$ [11], where c is the average number of one-hop downstream neighbors of each node. Replacing this value (in place of d_{rec}) in the PDR constraint can give the β_{opt} for PP+B. Table 3 presents the β_{opt} and φ_{opt} for PP+BP, PP+BT, and PP+B.

5. OPT: Dynamic Optimization of Periodic Timers

In this section, we propose a network layer dynamic Optimization of Periodic Timers (OPT) method based on the analytical derivation modeling (in the previous section) of the optimal timer periods for the four classes of proactive protocols.

5.1. Overview

The proposed optimization depends on the cross layer parameters such as the data traffic rate, the link change rate, and the network target PDR. These information are not available at the network layer. Hence, OPT has to estimate these values at the network layer. We assume that the network target PDR is known to each node through pre-calibration or pre-communication. Details of how the data traffic and the link change rates are estimated are described in the following sections.

Each node maintains an estimate of β_{opt} and φ_{opt}. Based on the estimates of the data traffic rate, the link change rate and the target PDR, each node dynamically varies the local estimates of β_{opt} and φ_{opt} based on the analytical results described in the previous section. The local estimation of β_{opt} is further transmitted as part of the beacon message so that the neighbors wait for an appropriate amount of time before discarding the corresponding link in case of a link disconnection. As φ_{opt} is maintained only in either the source or the destination (Section 3), the local estimation of φ_{opt} is performed only in the corresponding nodes.

5.2. Estimation of Data Traffic Parameters

The principal challenge in developing a per node optimization at the network layer is the proper estimation of the data traffic parameters (τ, α, and λ). There are two different steps in performing the estimation: i) distinguishing the packet bursts from the set of packets received (to derive τ, and α), and ii) estimating the mean of the Poisson process (λ) of the burst arrival. The first step is achieved through monitoring the inter arrival time of the consecutive data packets. Packets in a single burst have a constant inter arrival time (τ). A change in the inter arrival time of the data packets signifies the end of a burst and the beginning of a new burst. The parameter α is the total number of counted packets between the beginning and end of a burst.

A new Poisson event is detected with the beginning of a new burst. A Poisson event count is maintained at the network layer to keep track of the number of such events from the start of the packet reception. The localized view of the rate of Poisson event (λ) is revised based on the detected Poisson events. For simplicity of implementation, the estimation of λ is performed with a linear division of the number of Poisson events with the elapsed simulation time.

5.3. Estimation of Link Dynamics

The links are tested for connectivity using the beaconing process at the link layer initiated by the network layer. The beacons are used to identify the nodes to their neighbors. Each node constructs a fresh list of neighbors at each beacon period. Nodes that are removed from the fresh list of neighbors are considered to be disconnected. The network layer keeps a counter of disconnections, which is incremented with every disconnection detected. The localized view of the link breakage rate is revised based on the detected disconnections. Similar to the estimation of λ, for simplicity, the estimation of μ is also performed with a linear division of the number of link disconnections with the elapsed simulation time.

6. Numerical Evaluation

In this section, we use the analytical results 1) to compare the proposed method OPT with a modification of an existing optimization method called the Link Dynamics (LD) optimization [25] and 2) to quantify the impact of the parameters such as the rate of link-change, the traffic rate, the target PDR requirement, and the network size on the optimal beacon interval and route update interval. We begin with describing our modified LD scheme.

6.1. Modified LD

LD performs optimization based only on the rate of change in the link-status in the MANETs, and does not consider the data traffic intensity and the network target PDR. The upper bound on the delay for updating the routes is dependent on these two parameters. For a fair comparison, we enhance the LD model with our packet loss analysis (Section 4.3) and apply the right hand side of Equation 12 as the upper bound in delay. This enhancement enables LD to be aware of the data traffic intensity, and the network target PDR. The modified LD will henceforth be referred to as **LD-m**. However, even LD-m optimizes the route update interval (φ) only and does not address the optimization of β (Table 4).

LD-m assumes the detection of the changes in the link-status as an instantaneous process. This can only be achieved through infinite beacon frequency, leading to infinite overhead ($E_{PMLS} \rightarrow \infty$, $E_{TRULS} \rightarrow \infty$). The proposed analytical model, on the other hand, optimizes both β and φ. It should be noted here that LD-m leads to high φ_{opt} (Figures 5 and 6) than the proposed optimization because of the implicit assumption of no delay in the detection of the changes in the link-status. This assumption results in increasing the value of φ while meeting the constraints in Equation 12, as $\beta = 0$.

6.2. Effect of Link Change, Traffic, and PDR to the optimal β , φ

Figures 5 and 6 show the optimum update intervals (both β_{opt} and φ_{opt}) for different values of the PDR (Γ), the rate of change in the link-status (μ) and the data message arrival rate (λ). As shown in Figure 5, when μ is higher, lower intervals (i.e. higher update frequencies) are required in order to ensure a network target PDR. Similarly, Figure 6 shows that the update intervals decrease with the increase in the rate of data traffic. When there is no data traffic i.e. $\lambda \rightarrow 0$, it can be verified from equations 14 and 15 that both the update intervals become ∞ i.e. it is not required to maintain fresh routes when there is no data to transmit even when the rate of changes in the link-status is very high. However, as the rate of data traffic increases, the requirement of maintaining fresh routes also increases. Table 5 summarizes these trends.

6.2.1. Optimum Route Update Intervals

PP+BTP and PP+BP employ both PUR and PMLS (Table 1). Interestingly, φ_{opt} in PP+BTP is always less than that of PP+BP, whereas β_{opt} in PP+BTP is always greater than that of PP+BP (Figures 5 and 6). This phenomenon is attributed to the fact that both PP+BTP and PP+BP have the same worst case delay in terms of route update. It is better to increase β_{opt} for PP+BTP in order to reduce the control traffic due to TRULS. However, to maintain the worst case delay constraints, φ_{opt} has to be reduced.

6.2.2. Optimum Beacon Intervals

Both PP+BTP and PP+BP have low β_{opt} compared to PP+BT and PP+B (Figures 5 and 6). PP+BT has the highest β_{opt} under all conditions to reduce the number of triggered broadcast due to TRULS. It should be noted here that as there is no PUR involved in PP+BT, the β_{opt} can be relaxed compared to the other protocols. The route update in PP+B however has a higher delay compared to PP+BT. This is because PP+B requires possibly a higher number of beacon intervals to diffuse the information across the network. This diffusion is faster in PP+BT which employs TRULS for this purpose. Therefore, to meet the delay criteria, PP+B has to reduce β_{opt} compared to PP+BT. Table 6 summarizes the results.

6.3. Effect of Number of Nodes on the Optimal β, φ

Figures 7(a) and 7(b) compare the effect of number of network nodes to β_{opt} and φ_{opt}. The protocol delay for PP+BT and PP+B is dependent on the diameters of the network. As a result, the number of nodes does not have any effect on these protocols (as per Figures 7(a) and 7(b)). However, for PP+BTP and PP+BP, with increase in the number of nodes, it is better to increase φ_{opt} reducing the number of route broadcast. Consequently, the scalability of these protocols is increased with high number of nodes in the network. To meet the delay requirements, however, the beacon frequency has to be increased (reducing β_{opt}). In other words, higher number of changes in the link-status is accumulated in every route update. Note here that LD-m does not change the periodic route update interval with the increase in the number of nodes. Although PP+BT employs triggered broadcast, it can not increase β_{opt}, which is already maximum.

6.4. Effect of Network Diameter on the Optimal β, φ

Figures 7(c) and 7(d) compare the effect of change in network diameter (with same number of nodes) to β_{opt} and φ_{opt}. Optimum frequencies for PP+BTP show completely opposite characteristics from variation in the number of nodes in Figure 7. As the number of nodes does not change, the number of messages for periodic flooding does not increase. Therefore, it is beneficial to reduce the triggered broadcast (TRULS) by increasing β_{opt} in PP+BTP. This would mean that to meet the delay criteria, φ_{opt} is reduced. For PP+BP, as the diameter increases φ_{opt} is decreased as it takes higher time to reach the extreme nodes in the network. The same reason is applicable to explain the reduction in β_{opt} for both PP+B and PP+BT with the diameter increase.

7. Simulation Study

This section describes the simulations performed to validate the effect of the proposed optimization. The analytical evaluation studied the impact of various parameters on the optimal route update period and beacon interval. The simulation study, on the other hand, intends to determine the accuracy of the analytical results. To this effect, OPT is used in conjunction with the DSDV protocol, which is a PP+BTP type of proactive protocol (Section 3.1.2). The combination of OPT and DSDV protocol is referred to as DSDV-Opt. The performance of DSDV-Opt is compared with the DSDV protocol in diverse scenarios.

Simulation results show that DSDV-Opt minimizes the energy consumption while achieving a PDR with a maximum of 1.3% error from the desired PDR. This variation is attributed to the changes in the link level reliability imposed by the signal interference and channel contention. These factors, although not considered in the analytical study for simplicity, has been incorporated in the simulation for completeness.

7.1. Simulation Model

Network simulator (ns-2) is used for the simulation. A 750 m × 750 m simulation area is modeled with nodes placed at random positions. Two-ray ground reflection model is used as the radio propagation model with the maximum range of transmission for each node set to 250 m. This model gives an accurate prediction of propagation range at a long distance. One node is chosen as the source node sending Bulk Poisson data packets, with 1000 packets separated by 0.01 sec in each burst. The network target PDR (Γ), which determines the amount of packets to be delivered to the destination, is fixed to be 0.75. There is an upper limit to the achievable PDR (while maintaining the capacity constraint in Equation 13). The value 0.75 was chosen for the target PDR so that DSDV-Opt can achieve the PDR in all the scenarios that were simulated. The rate of the bulk Poisson traffic generation (Λ) is dependent on the rate of generation of each burst (λ), following Equation 5. The value of λ is varied as in Section 6 to vary Λ. However, the results are presented with respect to Λ, which denotes the average bit rate of the data traffic. The λ values can be calculated as per Equation 5 (given that α and τ are selected to be 1000 and 0.01 respectively). For example, a λ of 0.06 would give the bit rate of 8 Kbps when each packet is considered to be 16 bytes long.

Experiments were performed for different number of nodes (N) in the MANET, and different node velocity. Varying the number of nodes (N) is essential to observe the scalability of the protocols. The variation in the node velocity is necessary to simulate different rate of link changes (μ) in the network [25]. We used the random way point mobility model with variation of the maximum velocity of nodes from 1 m/s to 20 m/s. As pointed by Noble et al. [28] one has to guard against the velocity-decay problem of this model. The use of the random-way point model in our simulation conforms to the fix suggested by Noble et al. Specifically, the settings of simulation parameters ensures that the nodes use non-zero minimum velocity.

The reliability is measured by the PDR as described in Section 4.1.2. In order to estimate the energy-efficiency of the various protocols, we use the following metric:

> **Energy consumed per node**: This is the ratio of total energy consumed per node to the total number of data packets successfully delivered. The total energy consumed per node is calculated by taking the ratio of the total energy consumed in all the nodes in the network and the total number of nodes.

For each experiment with a specific set of parameters (N, Λ, and μ), several different scenario files were generated (in *tcl*) and the experiments were repeated for all of the scenarios with different source-destination pairs in each scenario. Each simulation ran for 1800 seconds of simulated time and same scenarios were evaluated for all the protocols to compare their respective performances. The average values of the performance metrics are taken for these scenarios and plotted with respect to the three parameters (N, Λ, and μ). The scalability of the protocols is measured by the growth in the energy consumption for higher number of nodes in the network.

7.2. Simulation Results

First, the results for the energy consumption for DSDV-Opt are presented under different scenarios to verify the analytical model (Section 7.2.1). Next, the scalability of DSDV-Opt is verified (Section 7.2.2). Lastly, the performance of DSDV-Opt is compared with the DSDV (Section 7.2.3) protocol.

7.2.1. Energy Consumption for DSDV-Opt and DSDV

Figures 8(a) and 8(b) show the energy consumption for DSDV-Opt and DSDV, respectively, for same set of scenarios varying the number of nodes and their velocity in the network. As the node velocity increases, the rate of link change (μ) increases leading to a reduction in β_{opt} and φ_{opt} (Figure 5). Consequently, the overhead increases as per Equations 1, 2, and 3. The plots show that *the DSDV protocol's energy performance is sensitive to the size of the network*, and it is quite indifferent to the node velocity (i.e. the link breakage rate). On the other hand, the proposed analysis makes the DSDV-Opt's energy performance sensitive to the node velocity, i.e. to the link breakage rate, while it *significantly reduces the energy performance differences across the network size*. This serves as an evidence of improved scalability with respect to the network size.

The β and φ values for DSDV under these experiments have been selected to be the ns default values i.e. 1 and 15 seconds respectively. Unlike DSDV-Opt, the node velocity does not increase the control traffic in DSDV due to the PUR operations. However, the increase in the node velocity decreases the number of successful packets delivered for DSDV. This, along with the increased rate of TRULS operation (Equation 2), accounts for the small increase in the energy consumption per node (Figure 8(b)). As shown in Figure 9 and explained in Section 7.2.3, such non-delivery of packets fail to meet the target PDR for the DSDV protocol with increase in node mobility. Further, Figure 8(b) shows that changes in the number of nodes significantly affect the energy consumption for DSDV. This verifies the trend predicted by the Equations 1, 2, and 3.

7.2.2. Scalability of DSDV-Opt over DSDV

The increase in the number of nodes does not increase the energy consumption of DSDV-Opt as much as it does for DSDV. DSDV-Opt allows high φ_{opt} reducing the periodic route update messages with the increase in the number of nodes (Figure 7(b)). Consequently, the possible increase in the energy consumption due to the route update flooding is avoided as far as possible. For a given mobility and traffic rate when the number of nodes in the network is increased from 10 to 50, the increase in energy consumption when using DSDV-Opt is less than 14% of the increase in energy consumption when using DSDV. Although for high mobility, DSDV may seem to be more energy-efficient than DSDV-Opt, it **does not** meet the PDR requirement.

7.2.3. Performance comparison of DSDV-Opt and DSDV

Figure 9 shows the energy consumption and PDR with respect to the node velocity. The energy consumption and achieved PDR of DSDV-Opt is shown as the dashed line in the figure. The solid lines represent the energy consumption and the PDR for the DSDV protocol with different values of β and φ. DSDV-Opt dynamically varies the β and φ depending on the velocity.

As DSDV does not vary the β and φ, the values selected as optimum for one situation perform badly in the other cases. The portion above the dashed line in the graph in Figure 9(a) shows higher PDR achieved by DSDV with the cost of high energy consumption (left of the dashed line in the graph in Figure 9(b)). DSDV-Opt, on the other hand, can achieve the PDR between 0.745 and 0.76, i.e. with 98.7% accuracy of the required PDR.

8. Conclusions

Proactive routing protocols have been categorized into four classes based on the link and route maintenance operations they perform. Optimization of the periods of the maintenance operations for all the classes of proactive protocols has been performed, with the goal of minimizing the energy overhead. The analysis takes into account cross-layer parameters such as the rate of link-changes, the rate of data traffic and the network target PDR. The proposed optimization scheme leads to a significant reduction of the control traffic in the proactive protocols for low data traffic intensity. We further developed an adaptive scheme, called OPT, for varying the update frequencies locally at each node. Simulation results show that OPT when used in conjunction with DSDV (DSDV-Opt) can reduce the energy overhead while meeting the target PDR with 98.7% accuracy. Further, it allows higher scalability of the proactive protocols with increased network size.

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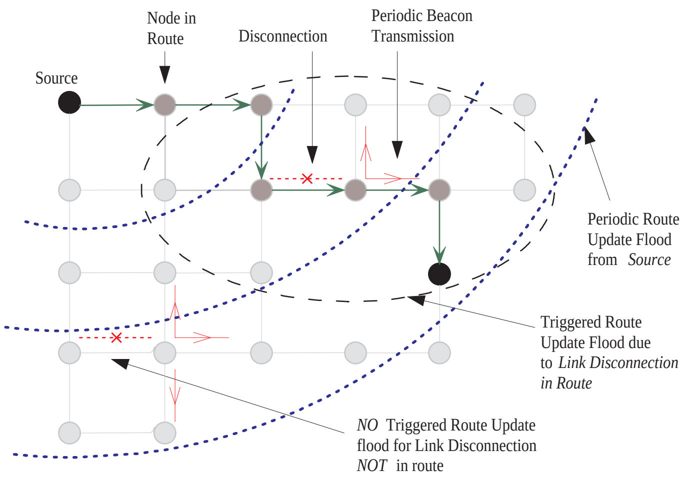


Figure 1. Maintenance Operations in Proactive Protocols

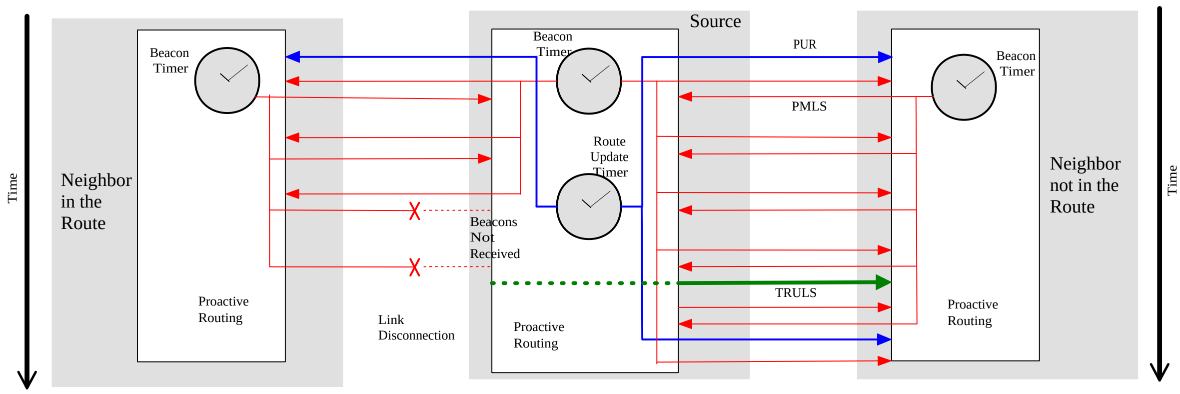


Figure 2. Periodic messages exchanged in proactive routing for MANETs

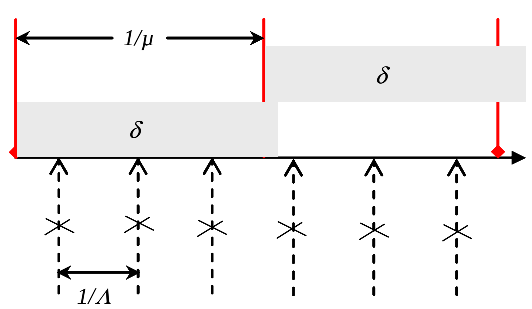


Figure 3. $\mu \leqslant \Lambda$: No packet reception when $\delta \geqslant \frac{1}{\mu}$

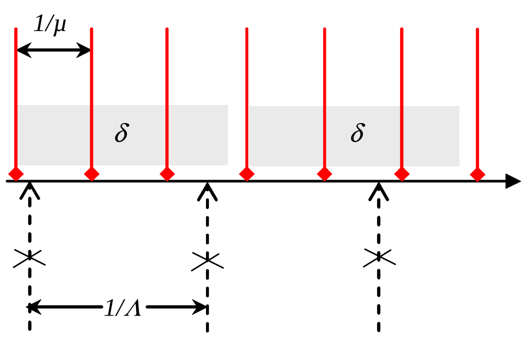
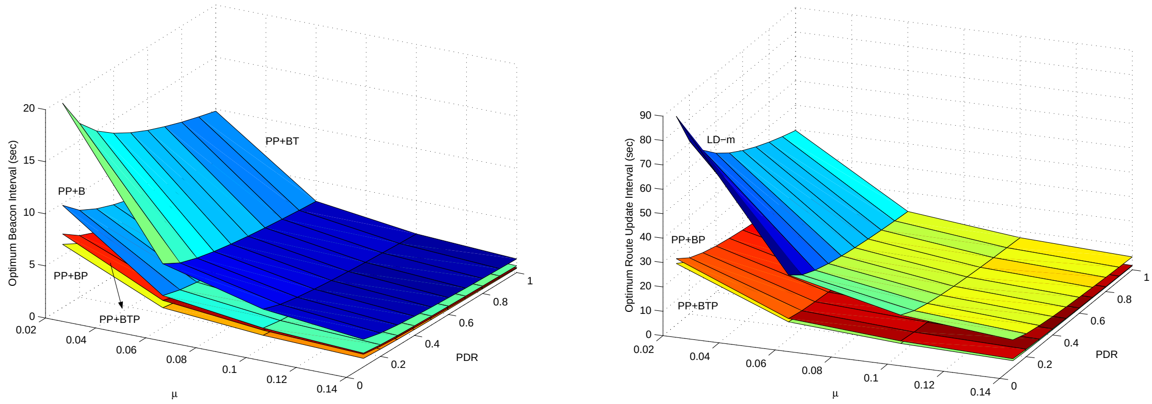


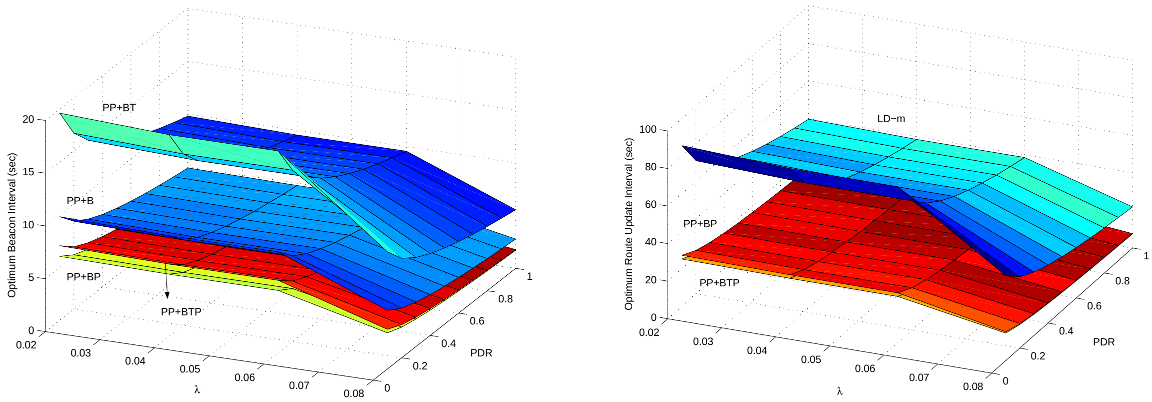
Figure 4. $\mu > \Lambda$: No packet reception when $\delta \geqslant \frac{1}{\Lambda}$



(a) Optimum Beacon Interval

(b) Optimum Route Update Interval

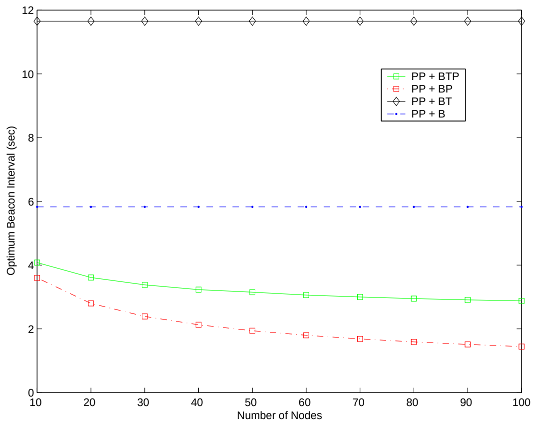
Figure 5. β_{opt} and φ_{opt} with respect to Γ for varying μ. Here $k = 2$, $N = 10$, $\lambda = 0.02$, $D = 10$, $\alpha = 100$, $\tau = .01$ sec.



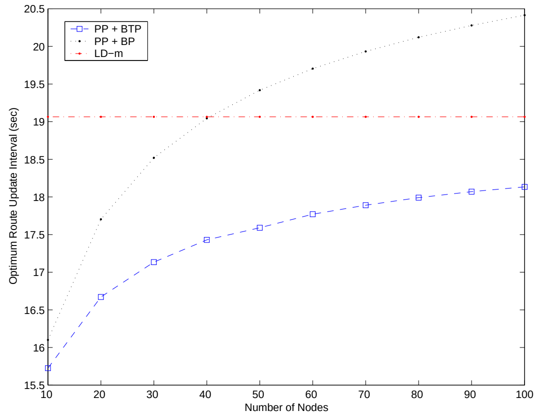
(a) Optimum Beacon Interval

(b) Optimum Route Update Interval

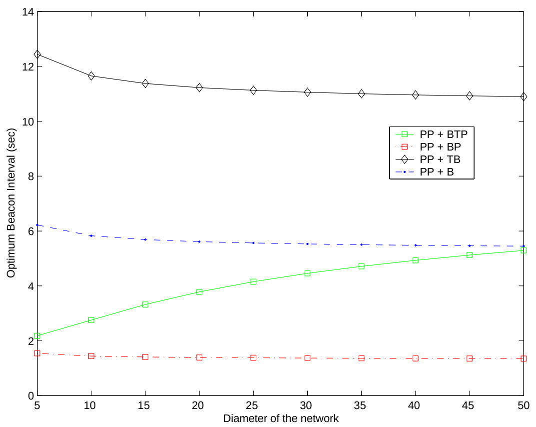
Figure 6. β_{opt} and φ_{opt} with respect to Γ for varying λ. Here $k = 2$, $N = 10$, $\mu = 0.02$, $D = 10$, $\alpha = 100$, $\tau = .01$ sec.



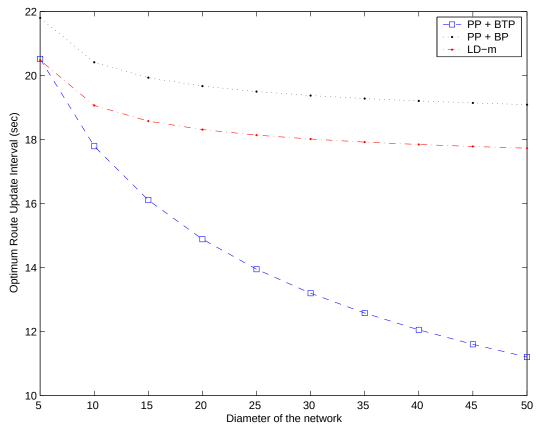
(a) Optimum Beacon Interval with respect to N (D = 10)



(b) Optimum Route Update Interval with respect to N (D = 10)

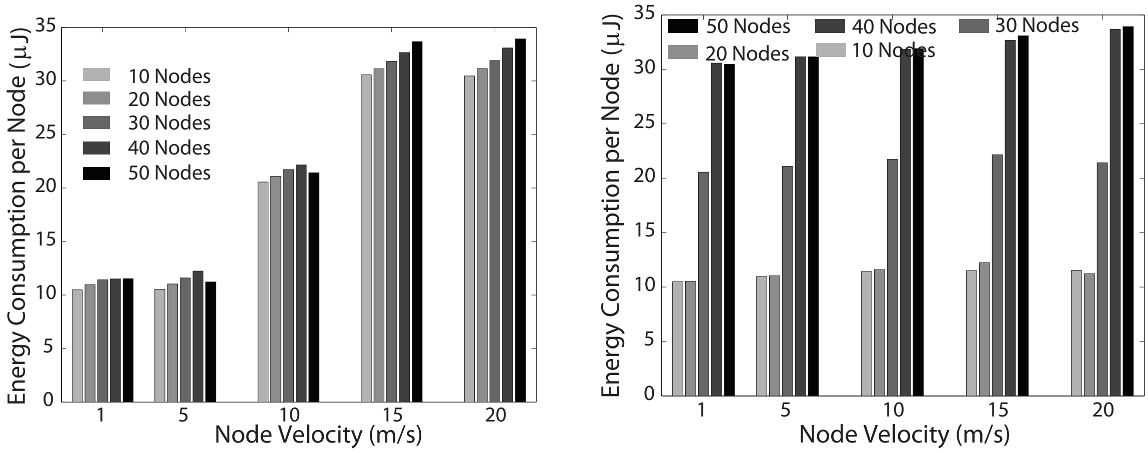


(c) Optimum Beacon Interval with respect to D (N = 100)



(d) Optimum Route Update Interval with respect to D (N = 100)

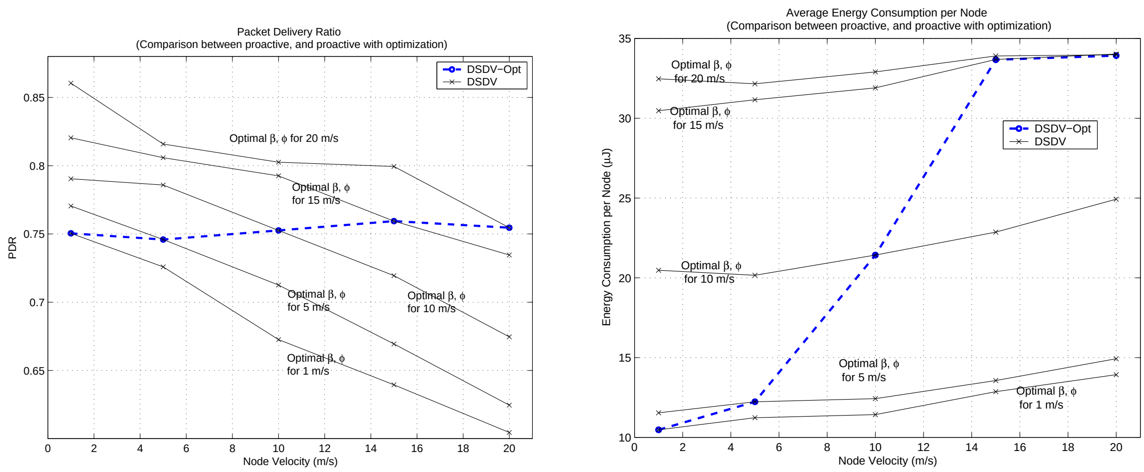
Figure 7. β_{opt} and φ_{opt} with respect to network size. Here k = 2, μ = 0.02, λ = 0.02, α = 100, τ = .01 sec.



(a) Energy Consumption per node per packet delivered Vs. Velocity for DSDV-Opt (Traffic Rate = 128 Kbps)

(b) Energy Consumption per node per packet delivered Vs. Velocity for DSDV (Traffic Rate = 128 Kbps)

Figure 8. Comparison of Energy Consumption for DSDV-Opt and DSDV for different Number of Nodes and the Velocity of the Nodes. Energy consumption for the unmodified DSDV is sensitive to the network size, while energy consumption for DSDV-Opt is sensitive to node velocity (i.e. topological change rate). Note that when the energy consumption for DSDV is less than the energy consumption for DSDV-Opt, DSDV does not achieve the target PDR of 0.75 (Figure 9).



(a) PDR Vs. Node Velocity

(b) Energy Consumption per node per packet delivered Vs. Node Velocity

Figure 9. Comparison of DSDV and DSDV-Opt with respect to node velocity (traffic rate = 128Kbps, number of nodes = 50). The optimum values of β and φ are as selected by the DSDV-Opt. The target PDR is 0.75.

Table 1
Control operations in proactive protocols

Proactive Protocols	PMLS	TRULS	PUR
PP+BTP (DSDV [22], TBRPF [5])	✓	✓	✓
PP+BP (FSR [21], IARP [12])	✓	✗	✓
PP+BT (WRP [19], STAR [7])	✓	✓	✗
PP+B (BFST [9], SS-SPST [11])	✓	✗	✗

Table 2
Symbols and Definitions.

Symbol	**Definition**
λ	the average rate of Poisson distributed message arrival
α	the average number of packets per message
τ	the constant time between consecutive packets inside each message
Λ	the average rate of Bulk-Poisson packet arrival (given by Equation 5)
Γ	the network target PDR
d	average number of bits per data packet
N	the number of nodes in the network
D	the diameter (in number of hops) of the network
μ	the average rate of change of every link in the network
η_p	the probability of packet loss over a single link in a route between any two nodes
k	the number of consecutive beacon intervals after which link disconnection is detected if no beacons are received during the time
d_{hop}	the propagation delay of a single link (hop); it may include the delay imposed by queuing or a sleep protocol.
d_{rec}	the end-to-end propagation delay for disseminating a route update
δ	the worst case delay to re-establish valid route from any link failure
Ω	the ratio of the probability of packet loss (η_p) to the worst-case route reconstruction delay (δ) due to link failure (this is a function of λ, α, τ, Λ, and μ as shown in Equation 6)
β	average beacon interval
β_{opt}	optimum value of average beacon interval
φ	average route update interval
φ_{opt}	optimum value of average route update interval
E_{ov}	the total overhead energy consumption for maintenance operations in a proactive protocol
E_{PMLS}	the energy consumption for PMLS operations
E_{TRULS}	the energy consumption for TRULS operations
E_{PUR}	the energy consumption for PUR operations
e_{tx}	the energy consumption in transmitting one bit by a node
e_{rx}	the energy consumption in receiving one bit by a node
E_{tx}	the total energy consumed to transmit a bit from a node and receive in all the neighbors

Table 3
Optimum Intervals for Different Protocols

	PP+BP	PP+BT	PP+B
φ_{opt}	$\frac{1-\Gamma^{\frac{1}{D}}}{\Omega\sqrt{N}+\sqrt{k}}\sqrt{N}$	N/A	N/A
β_{opt}	$\frac{1-\Gamma^{\frac{1}{D}}}{\Omega\sqrt{k}\left(\sqrt{N}+\sqrt{k}\right)}$	$\frac{1-\Gamma^{\frac{1}{D}}}{\Omega k}$	$\frac{1-\Gamma^{\frac{1}{D}}}{\left(k+\sum_{i=0}^{D} c^{i}\right)\Omega}$

Table 4
Period Optimizations in LD and Proposed Model

	PP+BTP		PP+BP		PP+BT	PP+B
Model	β	φ	β	φ	β	β
Proposed Model	✓	✓	✓	✓	✓	✓
LD Model		✓		✓		

Table 5
Variation of β_{opt} and φ_{opt} ('↑', '↓', and '–' mean "increase", "decrease", & "no change" respectively).

	PP+BTP		PP+BP		PP+BT	PP+B
Parameters	β_{opt}	φ_{opt}	β_{opt}	φ_{opt}	β_{opt}	β_{opt}
$\uparrow \mu, \lambda, \Gamma$	↓	↓	↓	↓	↓	↓
$\uparrow N$	↓	↑	↓	↑	-	-
$\uparrow D$	↑	↓	↓	↓	↓	↓

Table 6
Comparative study of β_{opt} and φ_{opt}

Protocols	β_{opt}	φ_{opt}
PP+BTP	*greater* than PP+BP	*minimum*
PP+BP	*minimum*	*greater* than PP+BTP
PP+BT	*maximum*	
PP+B	*greater* than protocols with PUR	