Analytical Model for Optimizing *Periodic Route Maintenance* in Proactive Routing for MANETs*

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ABSTRACT

Many applications, such as disaster response and military applications, call for proactive maintenance of links and routes in Mobile Ad hoc NETworks (MANETs) to ensure low latency during data delivery. The goal of this paper is to minimize the wastage of energy in the network due to high *control traffic*, which restricts the scalability and applicability of such protocols, without trading-off the low latency. We categorize the proactive protocols based on the periodic route and link maintenance operations performed; and analytically derive the optimum periods for these operations in different protocol classes. The analysis takes into account data traffic intensity, link dynamics, application reliability requirements, and the size of the network. The proposed optimization significantly reduces the control traffic for low data traffic intensity in the network and increases protocol scalability for large networks without compromising the low latency of proactive protocols.

Categories and Subject Descriptors: C.2.2 [Network Protocols]: Routing Protocols G.1.6 [Optimization] Constrained optimization ; I.6.5 [Model Development]: Modeling methodologies

General Terms: Performance, Reliability, Theory.

Keywords: Proactive Computing, Energy Efficiency, MANETs.

1. INTRODUCTION

Routing is a fundamental and challenging task in Mobile Ad hoc Networks (MANETs). The dynamic nature of the wireless medium and the mobility of the wireless nodes lead to frequent disconnection of routes between sources and destinations. In many applications, such as disaster response, the network has to perform proactive routing to ensure application tolerable delay for information delivery [11]. However, limitations of energy availability in the battery-powered mobile nodes compound the 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 [18]. These protocols maintain and update routes periodically between source-destination pairs even if there is no data traffic between the pairs. Consequently, these protocols do not scale for large networks [22]. *Adjusting the periodicity of route maintenance is therefore required to minimize the energy overhead and increase the scalability of proactive protocols.*

One possible solution, as taken in reactive routing protocols, is to set up a session between a source and destination only when there is data to deliver. Although this extreme measure solves the problem of high energy overhead, it however raises the following performance issues: (i) high end-to-end data delivery latency, as no predefined route is available at the beginning of the sessions; and (ii) high energy consumption if the rate of establishing new sessions becomes very high [22].

A different approach is taken in hybrid routing protocols (such as ZRP [14], and SHARP [17]). These protocols restrict the proactivity in small network regions. However, nodes inside a region are engaged in periodic maintenance of routes, thereby wasting energy in case of little or no data traffic. An appropriate solution, instead, would be to optimize the periodic route maintenance operations in proactive protocols based on the rate of data traffic.

There are two principal periodic maintenance operations performed in the proactive protocols: i) individual link maintenance, and ii) overall route maintenance. Optimization of overall route maintenance, based on the link dynamics in MANETs, have been explored in [19]. However, the low scalability of proactive protocols in large networks is not addressed in this optimization. Further, the application requirements on route-availability are not considered in the optimization. Intuitively, there is no requirement to update routes even with high link dynamics unless there is data to transmit. Similarly, if the reliability requirement, usually specified as the *Packet Delivery Ratio (PDR)* [20], is not high (e.g. in elastic traffic models in real-time applications [20]), the update frequencies can be further reduced.

In this paper, we intend to incorporate all these considerations while optimizing the periods for link and route maintenance. The goal of this paper is to *optimize the update frequencies of proactive routing protocols in MANETs based on the average rate of data arrivals and link changes in the network, without compromising the scalability and reliability as long as it is feasible within the capacity of the network.* We denote the optimum periods for link and route maintenance as β_{opt} and φ_{opt}, respectively. An analytical model to derive β_{opt} and φ_{opt} is developed so that the energy wastage is minimized. Such an optimization achieves significant reduction in control traffic (messages exchanged for performing route and link maintenance) for low data traffic and low application required PDR. Further, the optimization predicts a reduction of the route update frequencies with the increase in network size, thereby addressing the scalability issues of the proactive protocols. This is achieved

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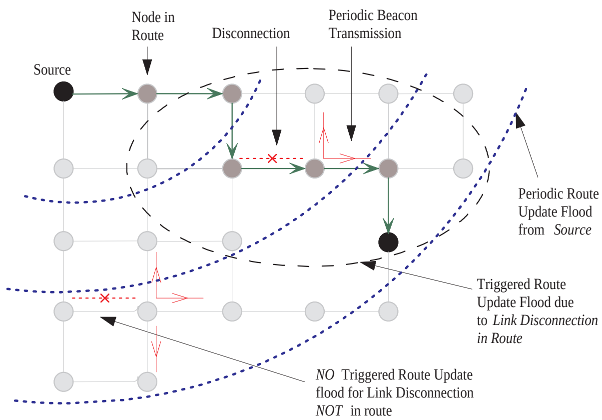


Figure 1: Maintenance Operations in Proactive Protocols

by performing frequent link maintenance and accumulating more topological information in each route-update flooding.

2. MAINTENANCE OPERATIONS IN PROACTIVE 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.

2.1 Proactive Protocol Model

Each node maintains the link status with every node in the communication range (i.e. the *neighbor nodes* or *neighbor set*). Periodic *beacon* messages are exchanged among the neighbor nodes for this purpose [22]. When a change in link status is detected, the routes are updated immediately and/or after the expiry of a pre-defined period. The *route-update* messages, triggered on detection of changes in link status, can be initiated by any node that detects the change. Fresh route information for nodes, not in the route between source and destination, are 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 message contains the next hop information to reach any other node. This update is transmitted to all the neighbor nodes. Similarly, all the neighbor nodes transmit their local information to all of their respective neighbors. In worst case, the update has to be transmitted by every node leading to same message complexity as in link-state routing.

2.1.1 Maintenance Operations

There are three different *operations* for maintaining network topology and 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 routing information across the network whenever there is a change in the status of a link in route. Flooding of route-updates takes place to diffuse the updates across the network [16] [2]. 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 route updates. PMLS and PUR are the two periodic operations described in Section 1.

We classify the proactive protocols in the following subsection based on which of these operations are employed.

2.1.2 Proactive Protocol Classification

Proactive protocols 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 TRULS and PUR operations.

1. Proactive protocols with all operations (PP+BTP): In this approach, all the three aforementioned operations are performed. Protocols, in this category, include Destination Sequenced Distance Vector (DSDV) [16], and Topology Broadcast based on Reverse Path Forwarding (TBRPF) [2]. 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 gets corrected in the PUR operations. The PUR operation includes transmission of destination sequence numbers to monitor and maintain the freshness of the routing structures. 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 with 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 messages exchanged, especially with the high dynamics in the MANETs. Instead, a liberal approach is taken in protocols such as DARPA packet radio network project [10], Intra-zone Routing Protocol (IARP) [8] [9], and Fisheye State Routing protocol (FSR) [15], where TRULS is not performed at all.

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 control traffic and the consistency of route information. To address this, another class of proactive protocols has been proposed, which does not perform PUR and performs only TRULS for maintaining fresh routes. Unlike the PP+BTP, these protocols do not rely on destination initiated sequence numbers in maintaining fresh loop-free routes. Examples include Source Tree Adaptive Routing (STAR) [4], Wireless Routing Protocol (WRP) [13], and Optimized Link State Routing (OLSR) [3].

4. Proactive Protocols with PMLS (PP+B) A different class of distributed routing protocols has been proposed which do not require 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 Self-Stabilizing Shortest Path Spanning Tree (SS-SPST) [7] [21], Energy-aware SS-SPST (SS-SPST-E) [12] and Breadth First Spanning Tree (BFST) [6] [5] protocols. Although these protocols may reduce the volume of control messages, they may incur higher end-to-end delay due to diffusion of local changes across the network.

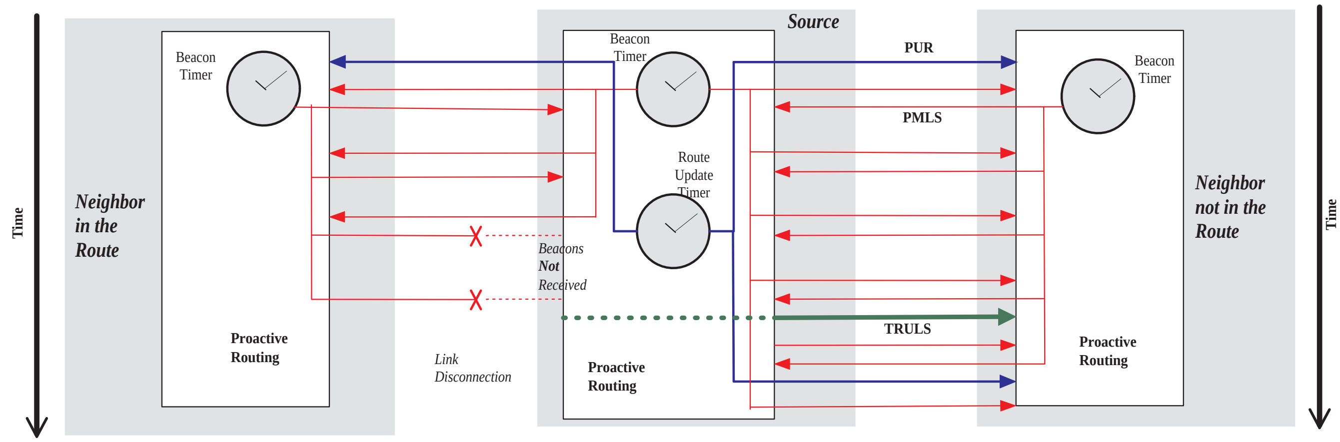


Figure 2: Periodic messages exchanged in proactive routing for MANETs

Table 1: Control operations in proactive protocols

Proactive Protocols	PMLS	TRULS	PUR
PP+BTP (DSDV [16], TBRPF [2])	✓	✓	✓
PP+BP (FSR [15], IARP [8])	✓	✗	✓
PP+BT (WRP [13], OLSR [3])	✓	✓	✗
PP+B (BFST [5], SS-SPST [21])	✓	✗	✗

Table 1 summarizes the operations employed in the aforementioned approaches. 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) 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 destinations as well (as in DSDV [16]).

The following subsection motivates for timer period optimization and presents different parameters impacting the optimization.

2.2 Timer Period Optimization

The control traffic of a proactive protocol depends on which class of protocols they belong to. Increasing the timer periods is necessary to reduce the control traffic. However, this increase may result in stale routing structure due to infrequent update of routes. Decreasing the period, on the other hand, results in high control overhead. Proper determination of the timer periods is therefore mandatory to minimize the control traffic without hindering the performance of the proactive protocols. We conclude this section with a discussion on the factors that will influence this determination.

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

Application data arrival rate: The data traffic determines the requirement of routes between source-destination pairs. For very little or no traffic, the requirement for maintaining fresh routes can be relaxed compared to high data traffic, which requires 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 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 generated 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 packet transmission in the proactive protocols. For low bandwidth, it may be infeasible to perform fresh route maintenance even with high rate of link changes.

3. 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, application 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 control traffic in proactive protocols. The required reliability and the channel capacity provides the constraints in achieving this goal.

3.1 System Model

3.1.1 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. A link can break if the corresponding nodes get out of each other's communication range. The average number of neighbor 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. A node in the MANET moves with a constant velocity i.e. the velocity does not change with time. Further, the velocity has a value within certain limits. The degree of mobility in a given application can be taken into account by appropriately choosing the limits of node speed. Nodes' speed, direction of motion and their location are mutually independent. Under the same network model, it has been proved that the time between consecutive link-changes is exponentially distributed [19]. We denote the mean, the average rate of any single link change, to be μ.

Each node periodically transmits *beacon* messages (with β being the average beacon interval in seconds, i.e. the average 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 neighbor 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 source to the destination. It is further assumed that there is single source-destination pair in the network. The analysis can be however extended to multiple source destination pairs. For protocols employing PUR (PP+BTP, and PP+BP), *route update* timers are maintained at the sources (or destinations depending on the specific protocol), with φ being the average route update interval.

3.1.2 Node Energy Consumption

When there is no on-going transmission, nodes are in the sleep state. MAC protocols with perfect wake-up scheme are employed to make sure that only the intended receiver is brought back to the active state, thus eliminating unnecessary energy consumption in listening. There are three major types of energy consumptions at each node: (1) when a node is in sleep state it consumes e_s Joules per unit time, (2) when in active mode, the energy consumption for reception is e_{rx} Joules per bit received, and (3) transmission energy consumption e_{tx} in transmitting one bit by a node to all the nodes in the communication range.

3.1.3 Application Model

We assume Bulk Poisson traffic generation model [19] [1] 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 military applications, disaster rescue missions etc. Further, these applications can tolerate packet losses within a threshold [20].

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

PDR gives the average probability of successful packet delivery from the source to destination. It is an effective measure to characterize the reliability of MANETs [20]. We assume that, on average, a PDR of Γ is required by the application.

3.1.4 Problem Statement

The goal is to calculate the optimum beacon interval β_{opt} and the optimum route update interval φ_{opt} to minimize control overhead in the proactive protocols as a function of the network and application parameters – average link change rate (μ), number of nodes (N) in the network, average message arrival rate (λ), and average PDR (Γ) required for the application – i.e. $\boldsymbol{\beta_{opt} = f(\mu, \lambda, \Gamma, N)}$, and $\boldsymbol{\varphi_{opt} = g(\mu, \lambda, \Gamma, N)}$.

3.2 Overhead Energy Consumption

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

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

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 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:

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

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 energy consumption per unit time as,

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

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

3.3 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 average probability of successful delivery of data packets from the source to destination (Definition 1). If η_p denotes the probability of packet loss for single link failure in the route, then probability of successful packet delivery from the source to destination is given by $(1 - \eta_p)^D$, D being the average network diameter in number of hops (Section 3.1). If Γ is the PDR required by the application then we have the following constraint:

$$(1 - \eta_p)^D \geq \Gamma \quad (4)$$

Note here that η_p is dependent on the rate of link change 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 for any application. 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 exponential message arrival. Under the same traffic model it has been proved in [1] that if, on average, there are α packets per message where the arrival of messages is distributed exponentially with 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,

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

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

$$\eta_p = \Omega\delta \quad (6)$$

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) Link-change rate is less than or equal to packet generation rate ($\mu \le \Lambda$): There are multiple packets between consecutive link disconnections. As not all the packets are lost, $\delta < 1/\mu$. The number of packets, not get delivered during the time δ is $\delta\Lambda$ as Λ is the rate of packet arrival. Moreover, between two consecutive route disconnections there are Λ/μ number of packets from the source. Let us assume that the total number of packets transmitted is t'. There is a total of $\mu t'/\Lambda$ number of route disconnections during the period in which t' packets are transmitted. So, the total number of packets lost is $(\mu t'/\Lambda)(\delta\Lambda)$. The probability of packet loss is

$$\eta_1 = \frac{\frac{\mu t'}{\Lambda}(\delta\Lambda)}{t'} = \mu\delta. \quad (7)$$

(II) Link change rate is greater than packet generation rate ($\mu > \Lambda$): There are multiple link failures between consecutive data packets. As not all the packets are lost, $\delta < 1/\Lambda$. Similar argument as Case I would give the probability of packet loss as,

$$\eta_2 = \frac{t'\Lambda\delta}{t'} = \Lambda\delta. \quad (8)$$

The probability of link change rate being greater than packet generation rate (Case II), under same set of assumptions, have been calculated in [1], and is given by:

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

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

$$\eta_p = (1-P_m)\eta_1 + P_m\eta_2 \quad (10)$$

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

3.4 Optimization for PP+BTP

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

$$E_{ov} = E_{PMLS} + E_{TRULS} + E_{PUR}. \quad (11)$$

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

3.4.1 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) end-to-end delay to propagate the update across the network. The detection of any change in link status is performed after non-reception of k beacon messages, leading to a detection delay of $k\beta$. Although TRULS updates routes whenever a change in the link-status is detected, it does not affect the worst case delay. As explained in Section 2, it is possible in PP+BTP protocols that TRULS may generate invalid routes with one or more cycles. The 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. Replacing this in Equation 6 and taking δ to the left hand side of Equation 4 we get,

$$k\beta + \varphi + d_{rec} \le \frac{1-\Gamma^{\frac{1}{D}}}{\Omega}. \quad (12)$$

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.

3.4.2 Channel Capacity Constraint

The data and control traffic can never exceed the capacity of the channel. First, we describe the 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 3.1, 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 3.2). If the channel capacity is C (in $bits/second$) and a data packet has d bits on an average, we have the following constraint:

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

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

3.4.3 Optimization

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 PDR requirement of the application.

Therefore, given the 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:

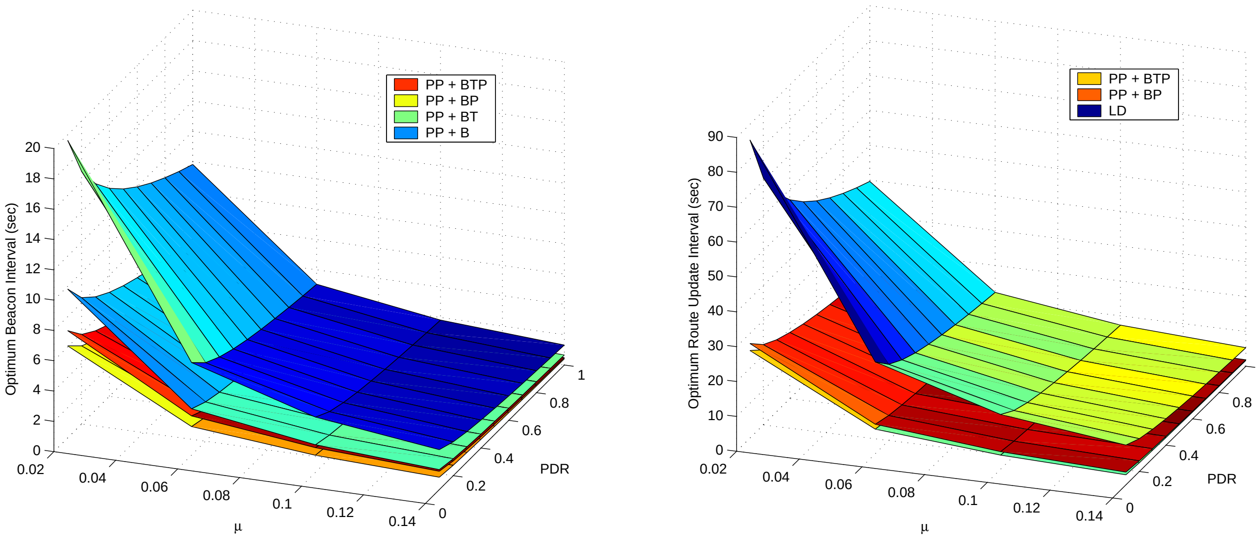
$$\infty > \beta_{opt} \ge \frac{\frac{1-\Gamma^{\frac{1}{D}}}{\lambda\alpha+\Lambda} - d_{rec}}{k}\left(1 + \sqrt{\frac{N}{k+ND}}\right)^{-1}, \quad (14)$$

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

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.

3.5 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 con-



(a) Optimum Beacon Interval

(b) Optimum Route Update Interval

Figure 3: 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

Table 2: 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}	$\frac{1-\Gamma^{\frac{1}{D}}}{\Omega\sqrt{k}\left(\sqrt{N}+\sqrt{k}\right)}$	$\frac{1-\Gamma^{\frac{1}{D}}}{\Omega k}$	$\frac{1-\Gamma^{\frac{1}{D}}}{\left(k+\sum_{i=0}^{D} c^i\right)\Omega}$

straint are determined by the operations employed in these protocols (Table 1). PP+BTP leads to the worst case situation in terms of overhead and channel usage because of the employment of all the three operations. The problem becomes simpler for the other protocols. 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 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 $\beta \sum_{i=0}^{i=D-1} c^i$ [21], 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 2 presents the β_{opt} and φ_{opt} for PP+BP, PP+BT, and PP+B.

4. EVALUATION

This section evaluates the optimal beacon interval and route update interval with different parameters. First, we compare the proposed model with Link Dynamics (LD) based optimization [19].

4.1 Comparison with LD

LD performs optimization based only on the rate of change in the link-status in the MANETs and does not consider rate of traffic and achievable PDR for the proactive protocols. We enhance the LD model with our packet loss analysis (Section 3.3) for performing fair comparison with respect to application parameters. However, LD only optimizes the route update interval (φ) and does not address the optimization of β (Table 3).

LD assumes the detection of change in the link-status as an instantaneous process. This can only be achieved through infinite beacon frequency, leading to infinite overhead ($E_{PMLS} \rightarrow \infty$, $E_{TRULS} \rightarrow \infty$), which is clearly infeasible in MANETs. The proposed analytical model, on the other hand, optimizes both β and φ. It should be noted here that LD leads to high φ_{opt} (Figures 3 and 4) than the proposed optimization because of the implicit assumption of no delay in the detection of the changes in link-status. This assumption results in increasing the value of φ while meeting the constraints in Equation 12, as $\beta = 0$.

4.2 Effect of Link Change, Traffic, and PDR

Figures 3 and 4 show the optimum update intervals (both β_{opt} and φ_{opt}) for different values of PDR (Γ), rate of change in the link-status (μ) and application message arrival rate (λ). As shown in Figure 3, when μ is higher, lower intervals (i.e. higher update frequencies) are required in order to provide a specific PDR to the application. Similarly, Figure 4 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 arrival increases, the requirement of maintaining fresh routes also increases. Table 5 summarizes these trends.

4.2.1 *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 3 and 4). This phenomenon is attributed to the fact that both PP+BTP and PP+BP have same worst case delay in terms of route update. It is better to increase β_{opt} for PP+BTP in order to reduce control traffic due to TRULS. However, to maintain the worst case delay constraints, φ_{opt} has to be reduced.

Table 3: 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 4: 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	

4.2.2 *Optimum Beacon Intervals*

Both PP+BTP and PP+BP have low β_{opt} compared to PP+BT and PP+B (Figures 3 and 4). 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 higher delay compared to PP+BT. This is because PP+B requires possibly 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 4 summarizes the results.

4.3 Effect of Number of Nodes

Figures 5(a) and 5(b) compare the effect of number of network nodes (with same node density) to β_{opt} and φ_{opt}. The constant node density leads to constant value for the network diameter D. 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 5(a) and 5(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 broadcast. Note here that LD does not change the route broadcast interval with the increase in number of nodes. Although PP+BT employs triggered broadcast, it can not increase β_{opt}, which is already maximum.

4.4 Effect of Network Diameter

Figures 5(c) and 5(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 node number variation in Figure 5. 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.

5. CONCLUSIONS

Proactive routing protocols have been categorized into four different classes − PP+BTP, PP+BP, PP+BT, and PP+B − based on the link and route maintenance operations performed. Optimization of the periods of the maintenance operations for all 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 application required PDR. The proposed optimization leads to significant reduction of control traffic in proactive protocols for low data traffic intensity. Further, it allows higher scalability of the proactive protocols with increased network size.

Table 5: Variation of β_{opt} and φ_{opt} ('$\uparrow$', '$\downarrow$', 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}
$\uparrow \mu, \lambda, \Gamma$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
$\uparrow N$	$\downarrow$	$\uparrow$	$\downarrow$	$\uparrow$	$-$	$-$
$\uparrow D$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$

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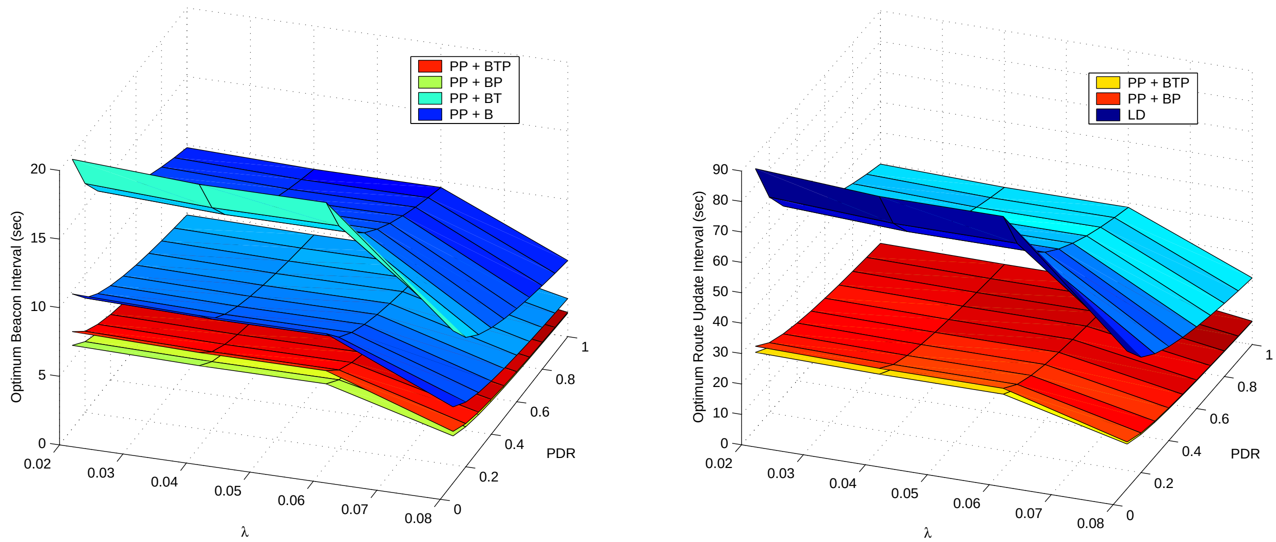
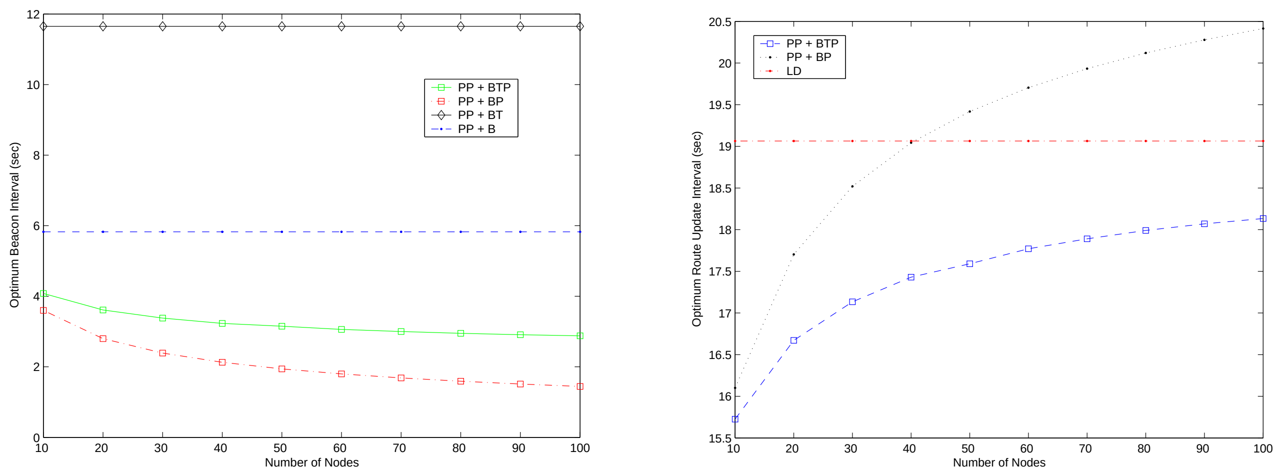


(a) Optimum Beacon Interval

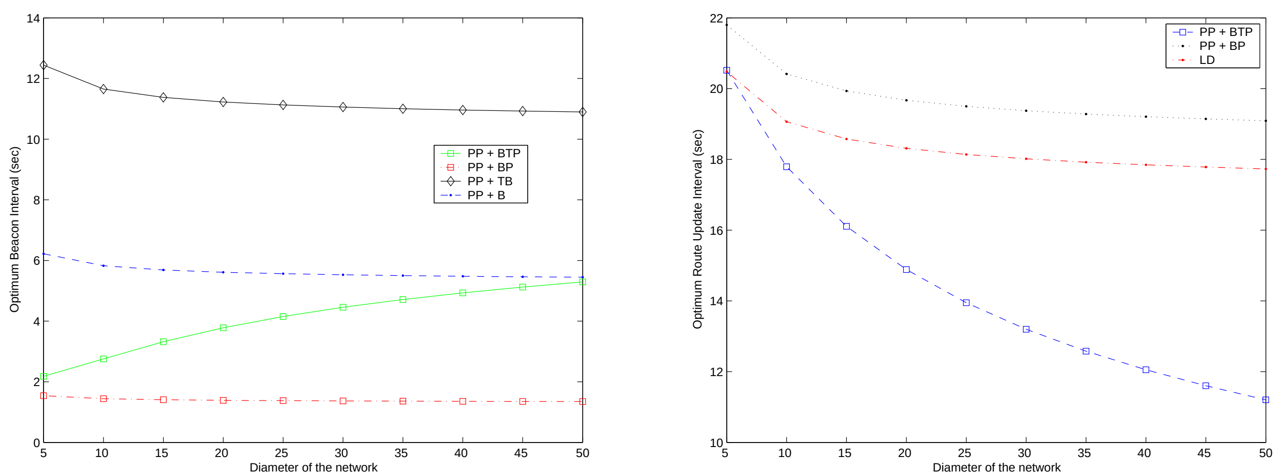
(b) Optimum Route Update Interval

Figure 4: 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 5: β_{opt} and φ_{opt} with respect to network size. Here $k = 2$, $\mu = 0.02$, $\lambda = 0.02$, $\alpha = 100$, $\tau = .01$ sec.