Self-tuning Network Support for MANETs

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***Abstract*—Rapid and unpredictable topology changes and resource constraints make delivering packets in a MANET (Mobile Ad hoc Network) a challenging task. Routing information has to be updated to reflect the topology changes and maintain the correctness of route selection. On the other hand, the dissemination of control messages has to be optimised for efficient resource usage and to alleviate channel contention problems. To solve this problem, this dissertation focuses on how to automatically tune routing performance for MANETs in terms of packet delivery ratio and control overhead. The impacts of soft state signalling, especially the refresh intervals, are studied under various scenarios. A variety of topology advertisement strategies are presented. Two self-tuning neighbour detection schemes are proposed, the Dynamic Timer algorithm and the Fast Neighbour Handshake algorithm, in order to enhance routing performance.**

I. Introduction

MANETs are self-organising multi-hop wireless networks, consisting of mobile nodes connected by wireless links. Each node can act as a router for traffic from other nodes, as well as a source or destination for traffic. A MANET has three major features: dynamic topology, resource constraints and decentralised infrastructure.

The nodes in MANETs are free to move arbitrarily. Also, the nodes may be unavailable when their power is low or if re-started. Thus, network topology may change randomly and rapidly. So, traffic metrics, closely correlated with network connectivity, are usually dynamic and subject to topology changes. MANET protocols and applications have to be resilient and robust in the presence of frequent topology changes.

Links of a wireless networks typically have lower capacities than those of fixed networks. The available link capacity of a wireless channel is often much less than the channel capacity because of the effects of fading, noise, interference and medium access control (MAC) operation. This makes network congestion more common than in fixed networks. Other resources, such as battery life, are usually limited for a variety of MANET applications, such as sensors and personal devices. Therefore, in order to provide similar services to the fixed network infrastructure, there are increasing demands for MANET protocols to be well-designed to optimise resource usage. Such demands may intensify with the deployment of real-time applications, e.g. multimedia applications, in ad hoc environments such as sensor networks.

Due to their dynamic nature, MANET nodes are self-organised in a decentralised infrastructure. In each network, there is no central control node responsible for packet forwarding and node discovery. Such a design increases the resilience in the presence of node failure. On the other hand, this increases the difficulties in designing effective and efficient protocols and applications. For example, the nodes have to broadcast or flood requests for route or service discovery, which may introduce excessive control overhead and increase channel contention, if not properly configured.

Such characteristics of MANETs bring performance concerns for existing design principles of MANET protocols, specifically protocol configuration, including timers to control generation of control-plane messages to maintain routing state. Due to its *simplicity* and *robustness* [2], [3], a timer-based state maintenance approach has been an attractive choice for a variety of network protocols and applications, especially for dynamic networks such as MANETs.

Generally speaking, MANET protocols use two types of timers: (1) time-out timers, which expire and remove state entries if they are not refreshed within a certain period; and (2) message-sending timers, which declare state validity by propagating periodic messages. The control functions we are concerned with are:

- **Neighbour Detection.** In most MANET routing protocols, either proactive protocols like OLSR (Optimised Link State Routing protocol) [4], DSDV (Destination-Sequenced Distance-Vector Routing) [5]; or reactive protocols, like AODV (Ad hoc On-Demand Distance Vector Routing) [6]; or even hybrid protocols like ZRP (Zone Routing Protocol) [7], periodic HELLO messages are exchanged between neighbouring nodes to detect link dynamics and to maintain node status. For example, nodes running OLSR [4] discover new neighbours and links when receiving the first HELLO message from an *unknown* neighbour. Moreover, obsolete neighbour state (caused by for example link breakage) are removed after state time-out.
- **Topology Advertisements.** Proactive routing protocols like OLSR [4] propagate periodic network-wide *topology update* – or topology control (TC) – messages to advertise topology changes. In addition to initiating new link state in topology repositories of each node, for example, the topology advertisement process in OLSR removes obsolete topology state either implicitly by assigning sequence numbers to topology advertisements, or by state time-out.

Major concerns about timer configuration in MANET protocols include:

- **Manual Configuration.** Administrators of MANETs rely on manual configuration, scripting, or SNMP to configure the timers. The value of the timer intervals is mainly determined based on recommendations of original protocol designers or empirically. Usually there is no careful calculation, solid theoretical studies or experimental research on how to configure the intervals of various soft-state timers, including refresh timers and time-out timers. Moreover, timers may have correlations in configuration. For instance, the timer interval of HELLO messages [4], [5] should be (much) longer than the time-out interval of neighbour entries. Consequently, existing approaches have been found to be expensive in effort for (re-)configuration, unreliable, and incapable of scaling to the needs of large networks. As an arbitrary choice, different timers often use the same (fixed) interval.
- **Unawareness of Network Conditions.** The value of such timer intervals usually remains fixed no matter what the network conditions are (e.g. node velocity, link loss rate). Therefore, several questions may arise as to the configuration of timer intervals: e.g. does the default value of timer intervals work well against all types of link failures under various scenarios? So, given requirements on system consistency, how do we determine the value of the refresh intervals in order to achieve the best balance between performance and overhead?
  For instance, in considering control overhead, topology advertisement intervals of MANET routing protocols are usually set to a relatively large value, e.g. 5s in OLSR. In a high-density network with fast mobility, the change rate of topology is relatively high. However, topology changes are not advertised until the update timer expires. Under such circumstances, topology changes might be too fast to be captured by *periodic* updates.
- **Difficulties in Balancing Throughput and Overhead.** It is commonly believed that a smaller refresh (timer) interval could speed up adaptation to changes at the expense of increased overhead. However, there is no solid study on *how much* it could improve the consistency and the amount of overhead. This question is critical to MANET protocols. On one hand, topology changes require timely signalling (i.e. smaller timer intervals) to maintain routes and so maximise the throughput. On the other hand, the resource constraints of MANETs require minimum control overhead to reduce channel contention and power consumption. With the existing fixed-timer-interval approach, it is very difficult to balance network throughput and control overhead.
- **Excessive Control Overhead.** One contributing factor to lack of scalability for MANET protocols is the potentially excessive routing message overhead caused by the increase of the network population (number of nodes) and node mobility. For example, in a network with population n, topology updates of LS (Link State) protocols generate routing overhead of $O(n^2)$. In large networks with high mobility, the transmission of routing information will ultimately consume a large proportion of the bandwidth and consequently congest the channel, rendering it unfeasible for bandwidth limited wireless ad hoc networks.
  The amount of routing state, i.e. the size of routing tables and topology repositories, is another concern for MANET protocols. In proactive routing protocols, large routing tables or topology repositories imply heavier processing overhead in route calculation, and/or larger control packet size, hence increased control overhead.
  Existing fixed-timer-interval approach propagates periodic update messages irrespective of topology changes. However, in real-world scenarios, the nodes' mobility is more likely to be intermittent. Also, there might be only a fraction of the node population moving during a certain time period. Therefore, keeping a constant refresh rate may lead to unnecessary resource consumption.

This dissertation identifies the essential causes for these concerns from the following two aspects:

- **Lack of clear understanding of soft-state signalling performance in MANETs.** Despite its fundamental importance to proactive MANET routing protocols, the properties of the soft-state approach and the circumstances in which it might best be employed are not fully understood.
- **Fixed timer intervals.** Although simple and robust, existing fixed-timer-interval approaches do not adequately handle the problems of wireless media, such as the trade-off between performance and costs, in the presence of node mobility and resource constraints.

This dissertation addresses these problems by providing self-tuning mechanisms for automated timer configuration, to adjust timer intervals of MANET routing protocols based on network conditions, and therefore ensure both effectiveness and efficiency in delivering data packets in dynamic network environments like MANETs. In particular, the study analyses soft-state signalling performance in two existing proactive MANET routing protocols, OLSR [4] and DSDV [5], and shows the quantitative relationship between routing performance and factors like refresh intervals, node mobility and node density (see Section III). Based on performance analysis, the efficiency of topology control and maintenance strategies is studied to maximise resource usage and reduce channel contention (see Section IV). Two self-tuning neighbour detection schemes are proposed (see Section V), either by adapting automatically the value of refresh intervals to node mobility, or using explicit notification messages in establishing links.

II. Self-Tuning Support for MANETs: Key Issues

In order to provide self-tuning support, the following key issues have been identified in designing MANET routing protocols:

- The *quantitative* relationship between signalling performance and various factors including refresh intervals and node velocity.

- Optimising signalling performance, i.e. improving throughput without introducing excessive control overhead, instead of balancing signalling performance between throughput and control overhead.
- Adaptive signalling in the presence of network heterogeneity. The volume of control messages should be determined by network conditions. The state description should be generic enough to provide additional flexibility in defining the objects carried by signalling messages.
- Incremental implementation and deployment of the proposed methods, which are expected to be *generic* and *independent* of specific routing protocols.

This dissertation adopts a step-by-step performance optimisation approach.

Firstly, this dissertation investigates the impacts of different soft-state updates on the routing (signalling) performance. This study finds that the HELLO interval has a more significant impact on routing performance than the topology update interval. From this we can infer that lowering the rate of topology updates would not downgrade significantly the routing throughput, but could lead to significant reduction of control overhead. Therefore, this finding can be used to optimise control overhead.

Secondly, this dissertation presents an in-depth study of various topology update strategies and their impacts on routing performance. The efficiency of topology advertisements was investigated from two major aspects, namely spatial redundancy (i.e. using extra topology state information in each topology control message) and temporal redundancy (i.e. adjusting the topology update frequency). The results from this study provide useful insights on how to effectively design flooding-based protocols and applications.

Finally, this dissertation proposes the Dynamic Timer algorithm and the Fast Neighbour Handshake algorithm. These two algorithms achieve better data packet delivery performance, while introducing much less control overhead than reducing HELLO intervals. Moreover, the Dynamic Timer algorithm could successfully mitigate the channel contention by dynamically adapting refresh intervals to network conditions.

III. Impact of Timer Configuration on Routing Performance

During the past decades, researchers from both the Internet community [3], [9], [10] and wireless research [4] have advocated soft-state design as a fundamental protocol design principle. As has been discussed, some intuitive and high-level *qualitative* explanations have been provided on why soft state approaches have advantages over hard-state approaches. On the other hand, quantitative studies on signalling performance are limited.

Traditional quantitative studies on soft-state performance are model-based and targeted at signalling in Internet scenarios [2], [3], [10]. For example, in order to evaluate the performance of soft state systems, Raman [10] built a queueing model using open-loop announce/listen process for data transport. Consistency and wasted bandwidth are used as the major metric, with loss rate and announcement death rate as the factors. Ji [2] compared the performance of soft-state and hard-state mechanisms with a continuous time Markov model. The impacts of loss rate, delay, retransmission timer and session length are examined on the performance of these two signalling approaches. Lui [3] evaluated the impact of the refresh timer period on robustness, using channel loss rate and a range of session characteristics as factors.

One drawback of these studies is that the models are too generic to fit into a specific scenario. For example, data packet loss in MANETs can be caused by channel contention (channel loss rate), route unavailability and other reasons. Therefore, loss rate is too general as a factor in analysing MANET signalling performance. In addition, since the analysis is fully based on mathematic models, the accuracy of the analytical results largely depends on the applicability of the models/-methods on the problem space (i.e. signalling performance). This is not fully validated in the previous studies.

The proposed approach in this dissertation is a combination of a model-based analytical method and a simulation-based performance evaluation method. Instead of proposing a general soft-state signalling model, the model in this study is based on a MANET routing process in the presence of link dynamics. Correspondingly, state consistency is analysed under various factors, including node density, node velocity, refresh interval and radio range. It is seen that the impact of soft-state refresh intervals depends on a range of factors, and the intervals of some message types (HELLO messages) have a larger impact on routing performance than other message types. In addition, tuning temporal update rates has a larger impact on routing performance in high-density/high-mobility networks than in low-density/low-mobility networks.

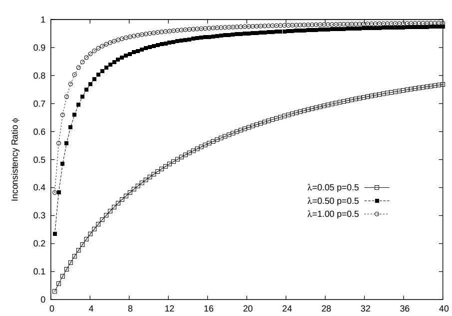
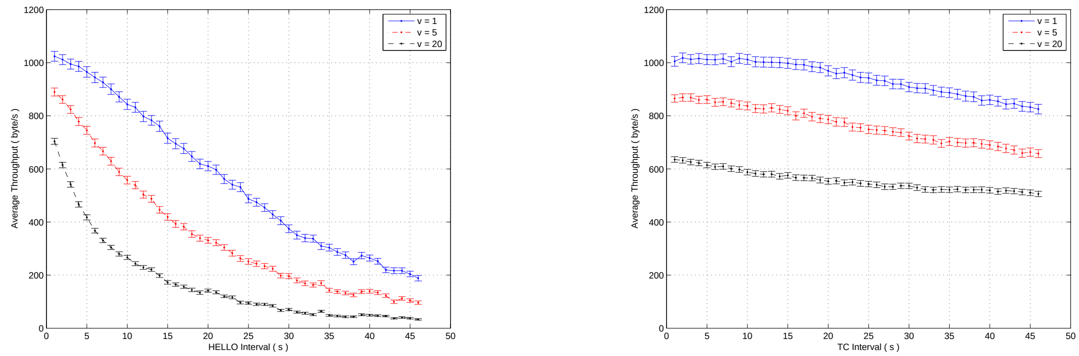


Fig. 1. Inconsistency Ratio vs. Refresh Interval

As expected, state consistency drops as expected when the refresh interval, r (Fig. 1), increases. However, the amount of the decrease depends on the state change rate λ. For example, when the state change rate is relatively low (e.g. $\lambda = 0.05$), the consistency reduces gradually with the increase of refresh interval. In addition, the maximum inconsistency ratio is moderate, 57% in this case. On the other hand, when the state change rate is relatively high (e.g. $\lambda = 0.5$ or 1), the consistency drops sharply to 20% when the refresh interval increases from 1s to 4s; after that, the consistency ratio levels



(a) HELLO Intervals

(b) TC Intervals

Fig. 2. Impact of Timer Intervals on OLSR Throughput

out and increasing refresh interval does not have significant impact on the performance.

The focus on soft-state signalling under a MANET routing scenario facilitates further performance evaluation. This dissertation carries out simulation-based performance evaluations on the impact of refresh intervals under the same factors as in the analytic model. The observations from the simulations provide support for the results obtained from model-based analysis.

For instance, we observe that increasing HELLO intervals has a significant impact on throughput. In particular, when node mobility is relatively low ($v = 1m/s$), the relationship can be approximated with a linear function. When node mobility is relatively high ($v > 5m/s$), the throughput is approximately proportional to the inverse of the refresh intervals (Fig. 2(a)). Increasing topology update rates brings a less significant improvement to throughput (Fig. 2(b)). This is because the average route change rate within a reasonable velocity range is larger than $2s^{-1}$. The impact of refresh intervals is low when the change rate is larger than $2s^{-1}$.

The control overhead drops with the increase of refresh intervals, which can be approximated by an inversely proportional relationship. Because topology update messages are forwarded to each node in the network while temporal update messages are only exchanged locally between neighbouring nodes, topology updates generate more overhead than temporal updates. Consequently, reducing topology update rates has a more beneficial impact on control overhead than reducing temporal update rates.

IV. Topology Maintenance Strategies

This dissertation presents an in-depth study on various topology update strategies and their impacts on routing performance. The efficiency of topology advertisements was investigated from two major aspects, namely spatial redundancy (i.e. using extra topology state information in each topology control message) and temporal redundancy (i.e. adjusting the topology update frequency). The results from this study provide useful insights on how to effectively design flooding-based protocols and applications.

A. Temporal Redundancy

From the aspect of temporal redundancy, it has been observed that the intervals of *proactive* topology updates have no significant impact on routing throughput. Therefore topology update intervals can be maximised within certain value ranges without damaging the performance. This supports the existing studies of topology update strategies [11], [12].

In addition, *reactive* update strategies in the studied MANET routing protocol (OLSR) do not lead to improved throughput while producing a large amount of overhead. In particular, the global reactive update approach introduces excessive control overhead. The localised reactive approach, although introducing the least overhead, has the worst packet delivery performance. This leads to the conclusion that proactive strategies are more suitable for MANET topology updates than the reactive strategies.

B. Spatial Redundancy

From the aspect of spatial redundancy, introducing state redundancy in low-density networks leads to performance improvements due to increased route availability. State redundancy has more impact in moderate- or high-mobility networks. In relatively stable networks, however, no obvious improvement has been observed.

Performance degradation is observed when topology state redundancy is applied to high-density networks. The degradation is particularly strong when full topology information is advertised in high-density networks with cross-layer optimisation. The MAC layer notification mechanism is one of the key contributing factors to the impact of state redundancy on routing performance, especially for performance degradation in high-density networks.

V. Automating Timer Tuning in Neighbour Detection

This dissertation looks at the problem of neighbour detection mechanisms, either by adapting automatically the values of refresh intervals in response to node mobility (i.e. the

Dynamic Timer scheme), or through the use of explicit notification messages in establishing link connections (i.e. the Fast Handshake scheme).

A. Dynamic Timer Approach

In order to mitigate the side effects of the soft update control overheads, we propose a Dynamic Timer algorithm to adjust neighbour detection intervals of proactive routing protocols according to node mobility. Essentially, such an adaptive algorithm is feedback based. The protocol's behaviours (i.e. parameters) are tuned according to the status of hosting environments such as node mobility and channel loss rate, in order to achieve better performance with less control overhead.

Up till now, there have been several adaptive routing approaches for MANETs. Benzaid et al [13] present an approach that adjusts refresh frequency based on node mobility and the mulitpoint relay (MPR) status of its neighbouring nodes. Ramasubramanian et al [14] propose a zone-based hybrid routing algorithm that combines proactive and reactive strategies. Boppana et al [15] propose an adaptive Distance Vector routing algorithm by adopting flexible route update strategies according to conditions. These adaptive approaches have the following potential drawbacks.

- *Dependency on network measurement.* The routing performance of the schemes proposed in [13] and [14] depends primarily on the accuracy of network measurement. Accurate estimates of real-time network/traffic metrics may not be available in practice.
- *Increased complexity.* For example, in [14], the operations in zone maintenance and continuous network monitoring not only introduce extra processing overhead but also increase the complexity in configuration and implementation. The performance of ADV (Adaptive Distance Vector Routing) [15] is determined by *constant trigger thresholds*, which need to be manually configured.
- *Unknown performance bounds.* For example, in ADV [15], the route update frequency increases quickly with node mobility, which brings larger overheads than periodic updates. Also, since only partial route information is maintained, ADV takes longer for a new connection to find a valid route.

In order to address these problems, we propose two dynamic timer algorithms to improve neighbour detection, namely *DT_MIAD* (Dynamic Timer Based on Multiplicative Increase Additive Decrease) and *DT_ODPU* (Dynamic Timer Based on On-Demand Proactive Update).

- **DT_MIAD.** The dynamic timer algorithm based on MIAD is inspired by control-theoretic adaptive mechanisms similar to those widely adopted in the Internet, i.e. Additive Increase Multiplicative Decrease (AIMD) of TCP's congestion window, which is used to adjust sending rates in response to network congestion: the sending rate of TCP in congestion avoidance state is controlled by a congestion window that is halved for every window of data containing a segment drop, and increased by one segment per segment of data acknowledged. Our approach uses a Multiplicative-Increase Additive-Decrease (MIAD) controller to adapt the soft-state refresh rate f to the conditions of node mobility and data traffic.
  Briefly, refresh rate f is multiplied by a factor α ($\alpha > 1$) if node mobility or packet drop rate increases, and otherwise decremented by a factor β. By aggressively increasing f when the packet failure rate and the network change rate increase, the routing algorithm improves link detection performance, which reduces data packet drops and increases link availability. When the link change rate decreases, the routing algorithm lowers the refresh frequency until it finally reaches a steady state.
- **DT_ODPU.** Dynamic Timer Based on On-Demand Proactive Update (*DT_ODPU*) is based on the concept of a *Finite State Machine* (FSM). The status of a node is roughly classified into two states: *dynamic* and *static*. When internal link changes are detected, the node is *dynamic*; correspondingly, it uses a smaller refresh interval h_{min}. Otherwise, the node is *static* and uses a larger refresh interval h_{max}. In this algorithm, the state update is still *proactive* since refresh messages are still exchanged periodically; however, the refresh frequency(or refresh interval) is adjusted *on-demand*.

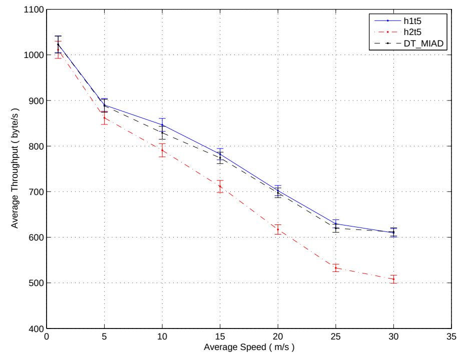
The dynamic timer scheme achieves similar routing throughput as standard protocols with small refresh intervals, but with much less overhead (Fig. 3). This is because the dynamic timer algorithms aggressively increase the refresh rate when there are link changes, but otherwise reduce the refresh frequency. As a result, routing protocols with the dynamic timer algorithms send frequent refresh messages *only* when link changes are detected. This leads to significant control overhead reduction.

Compared to the standard protocols with large refresh intervals, the dynamic timer scheme achieves much better throughput at the expense of extra control overhead. However, in low-density networks with low mobility, the dynamic timer scheme has similar overhead to standard protocols. With increase in mobility, the dynamic timer scheme increases the refresh rate in response to network changes, which leads to an overhead increase. However, the overhead is still much less than that of standard protocols with smaller interval.

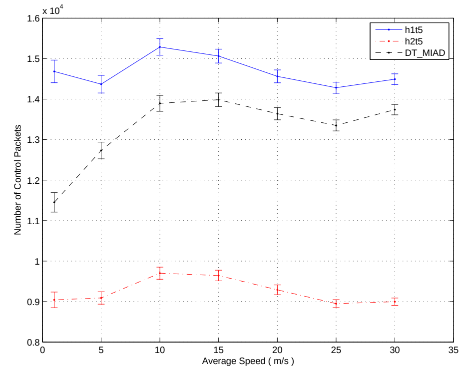
B. Fast Handshake Approach

The neighbour detection latency of HELLO-based routing protocols is caused by the periodic nature of HELLO messages. After receiving the first HELLO message from a neighbouring node, the OLSR node does not respond until it broadcasts the next HELLO message. Essentially, the neighbour handshake process is done *implicitly* through exchanging periodic HELLO messages.

The fast handshake approach uses *explicit* handshake messages to facilitate connectivity detection. More specifically, in addition to periodic HELLO messages, the node sends explicit handshake messages to its neighbours. This approach reduces the neighbour detection latency. With the handshake options, OLSR nodes detect link establishment faster than



(a) Average Throughput



(b) Control Overhead

Fig. 3. Performance of DT_MIAD

the HELLO based approach. This in turn leads to fewer data packet drops and gives a throughput improvement. The performance improvement is more significant in low-density networks with relatively smaller transmission radius, moderate or high mobility, and larger refresh intervals. This is because the link detection improvements are more significant when the link arrival rates are low and the refresh intervals are large.

The main drawback of the fast handshake scheme is an increase in control overhead, which *can* cause channel congestion and lower network performance.

VI. Conclusions

This dissertation focuses on the problem of automatically tuning timer intervals of MANET routing protocols. The key observation is that the impact of timer intervals on routing performance depends on a range of network parameters including node density and node velocity. Accordingly, reducing refresh intervals may not lead to performance improvements. Based on this, a variety of topology advertisement strategies are studied. Two self-tuning neighbour detection schemes are proposed, the Dynamic Timer algorithm and the Fast Neighbour Handshake algorithm, to enhance routing performance.

These efforts have allowed this dissertation to provide a clear insight into various aspects of soft-state signalling performance in dynamic resource-constrained networks, and to provide useful understanding on how to effectively design MANET protocols. In addition, this research proposes a number of original signalling mechanisms to improve routing performance. These are described and evaluated within the dissertation along with recommendations for further study.

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