Dynamic power budget distribution schemes that optimize connection lifetimes in MANETS

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Abstract:
We present new dynamic schemes that continuously redistribute a fixed power budget among a set of mobile wireless nodes participating in a multi-hop wireless connection. The schemes operate with the objective of maximizing the expected lifetime of the connection. First, we evaluate performance gains obtained by the proposed schemes and quantify their sensitivity to various system parameters, including connection size, node density, power budget size, and mean node velocities. Second, we compare the efficacy of our schemes in enhancing connection lifetime by comparing their performance against a scheme which distributes the connection power budget uniformly among nodes. Our simulations indicate that the proposed power budget distribution scheme yields a significant increase in connection lifetime. Third, we compare the proposed schemes against a scheme which distributes the connection power budget dynamically with the objective of minimizing end-to-end bit error rate (BER). In making this comparison we obtain quantifiable evidence of the inherent oppositions and tradeoffs between the objectives of BER minimization and lifetime maximization. Finally, we conduct a simulation-based analysis of control traffic incurred by the schemes in order to obtain a description of the relationships between control overhead and expected gains in connection lifetime, and an understanding of the influence of various system parameters (e.g. connection size, node density, and power budget size) on this relationship.

Keywords: Power distribution, connection lifetime, MANET

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1 Introduction

Historically, reconciling the gap between power availability and power supply in MANETs has involve addressing the following issues: (i) improving the power *efficiency* in the system; and (ii) preventing the system deconstruction due to un*fair* power usage [16]. In our earlier work [2, 3], we proposed a budgeted power model [2] to address these concerns. The budgeted power model normalizing the measurement of "efficiency" and "fairness" by using a model in which every connection is assigned a fixed power utilization budget. In practice, the magnitude of the budget reflects the connection's priority, or equivalently, the benefit that the system derives by maintaining the connection.

In consumer MANETS, for example, this benefit might be based on financial incentives provided by a satisfied customer who will continue to pay for the connection service. In military MANETs the benefit might reflect the extent to which the connection is essential to achieving a positive outcome in some coordinated systemic mission objective. In [9], the authors considered the opportunities afforded by such a model vis-a-vis minimizing connection bit error rate (BER), and presented a distributed scheme which successfully minimize a the BER of a connection by continuously reapportioning its fixed power budget among the constituent (static) nodes of the connection.

This work diverges and extends the earlier investigations of the authors [9] in two very significant ways: First, this paper considers *mobile* nodes instead of merely a static snapshots of a dynamic network. Second, our objective is to leverage the ability to dynamically distribute a connection's power budget to *maximize expected connection lifetime*, rather than to minimize connection BER as was the focus in our earlier work [9]. We will compare our proposed lifetime-maximizing schemes with the connection lifetimes exhibited under the BER-minimizing power distribution scheme developed in [9]. By doing so we shall quantify the extent to which the two objectives (lifetime maximization and BER minimization) are in opposition. Finally, we will refine our simulation-based analysis to consider *the traffic required in operating the control protocols themselves.*

2 Related Work

Efficient power management for MANETs has been investigated in prior research at several protocol layers (see e.g. [16]). As an objective, lifetime maximization has been interpreted in one of two ways: network lifetime maximization, and connection lifetime maximization.

Network Lifetime. The lifetime of a network is most frequently defined as the time interval for which the network is a connected graph. Broadly speaking, the network may partition (becoming disconnected) when one of two events occurs: (i) the autonomous movement of a node causes some of its incident link(s) to fail due to a shortage of transmission power, or (ii) some node exhausts its energy supply sufficiently so that some of its incident links fail. Most prior research on network lifetime attempts to delay the onset of these two types of events—the most frequent emphasis being on event type (ii), see e.g. [1, 10]—by extending the network routing protocol to make it energy-aware and using a route selection strategy that facilitates optimization with respect to the network's lifetime.

Connection Lifetime. Somewhat analogously, a connection's lifetime is typically taken to be the time interval during which all of the connection's constituent links are operational. A link in a connection ceases to be operational when one of two events occurs: (a) the autonomous movement of one of the link's endpoints causes it to fall out of transmission range of the other endpoint, or (b) one of the two endpoints exhausts its energy supply, causing the other endpoint fall out of transmission range. Most prior research on connection lifetime attempts to delay the onset of these two types of events—the most frequent emphasis being on events of type (a), see e.g. [7, 15, 8, 5, 11]. The main approach has been (as was the case in research on network lifetime) to extend the network routing protocol by making it energy-aware, and then to make route selection sensitive to connection lifetime maximization. In [7, 15, 8, 5], for example, the authors proposed new routing protocol extensions based on finding the path which probably has longest lifetime among many possible paths from source to destination. In these studies, the route selection process was based on the received signal strength at each of the nodes [7, 8], transmission range and the relative speed of the nodes [15], or recent changes in signal strength [11].

3 Problem Definition

The prior research described in the preceding section addresses those situations in which there is a very limited amount of energy available at each node, as is the case for example, in sensor networks or networks consisting of small mobile devices. Additionally, the strategies adopted in the prior research have centered on the routing layer, vis-a-vis energy-aware path selection. In contrast, we consider a model in which each connection's power requirements are modest compared to battery capacities, and where there are many connections which have been prioritized relative to each other by assigning each connection its own fixed *power budget* (i.e. a cumulative energy utilization rate). Our model better reflects the realities of battlefield settings in which the MANET nodes are unmanned autonomous vehicles [12, 4].

We presume that energy supplies at the nodes are renewable. Notice that we are not trying to increase spatial reuse nor energy efficiency. Specifically, we assume that each connection in a network has a certain ***power consumption budget*** which can be distributed among the nodes on the connection [2, 3]. We describe new power budget distribution schemes which seek to increase connection robustness in mobile environments.

This work thus begins at the point where the research efforts on energy-aware routing end. We assume throughout that the problem of route selection has been resolved in some manner, e.g. by one of the schemes cited in the previous section. Because all schemes we compare implicitly make use of the (unspecified) underlying routing protocol *in the same manner*, the effects of any inefficiencies in routing are reflected identically across the schemes. We make the idealized assumption that node mobility is insignificant when compared to routing convergence times. In reality of course this is not always true, but our conclusions regarding the *relative* lifetime enhancing merits of the variouspower distribution schemes are not influenced by the assumption. Because our study takes routing for granted, we do not investigate on the possibility of extending the lifetime of a connection post link failure through routing-level connection recovery processes. Rather, we restrict ourselves to maximizing expected connection lifetime by minimizing the probability of link breakage.

Link breakage due to node mobility is a severe problem in wireless ad hoc networking. Such disconnections on active routes generally increase traffic overhead in the network layer, and cause packet losses in the link layer. In this study, we exploit the transmission power control in order to prevent link disconnections, and thus maximize of connection(path) lifetime against node mobility. We take connection lifetime to be the time during which its constituent links are operational. A link ceases to be operational when the autonomous movement of one of the link's endpoints causes it to fall out of transmission range of the other endpoint.

We describe dynamic schemes that continuously redistributes the power budget assigned to a connection among its constituent nodes, with the objective of postponing events of type (a), thereby maximizing the connection's expected lifetime in the face of node mobility. We assume—as other similar investigations have, that each node is able to send with dynamically tunable transmission power [13, 3, 2, 9]. Each connection's power requirements are assumed to be modest relative to energy availability at the nodes, and connections are prioritized relative to one another by means of their power budgets. The proposed dynamic power distribution protocol is implemented on top of a routing protocol that is responsible for providing a multi-hop path between s and t, within total power budget constraints.

Consider a single connection between a source node s and a destination node t, and assume that a transmission power budget P has been specified for this connection. The **Fundamental Questions** to be answered are:

Q1. Can one design a lifetime-maximizing power distribution scheme(s) which will dynamically distribute the connection's power budget among the constituent nodes?

Q2. How do these lifetime-maximizing power distribution scheme(s) perform relative to a scheme which simply allocates power in a uniform static manner among the constituent nodes?

Q3. How do these lifetime-maximizing power distribution scheme(s) perform relative to a scheme which dynamically distributes power with the objective of minimizing end to end connection bit error rate? Are BER minimization and lifetime maximization two competing objectives?

Q4. What is the control traffic overhead of these lifetime-maximizing power distribution scheme(s), or more precisely, how do their performance depend on the parameters which govern their control traffic overhead? Answering this question requires us to again compare the relative increases achieved in expected connection lifetimes (Q1,Q2,Q3), but under the additional requirement that all schemes use comparable resources for control traffic.

4 Network Model

We consider a wireless ad-hoc network consisting of N nodes equipped with omni-directional antennas that can dynamically adjust their transmission power. We model this network as a geometric graph $G = (V, E)$, where V is the set of nodes and E is the set of edges. Each node is assigned a unique ID i in $\{1, \ldots, |V|\}$, and node i can send data with a dynamically tunable transmission power.

Wireless propagation suffers severe attenuation [6]. If node i transmits with power $P_t(i)$, the power of the signal received by node j is given by $P_{rcv}(j) = \frac{P_t(i)}{c \times d_{ij}^{\alpha}}$, where d_{ij} is the distance between nodes i and j, and α, c are both constants, and usually $2 \leq \alpha \leq 4$ (See [6]). In order to correctly decode the signal at the receiver side, it is required that $P_{rcv}(j) \geqslant \beta_0 \times N_0$, where β_0 is the required signal to noise ratio (SNR) and N_0 is the strength of the ambient noise. We denote the minimum signal power at which node i is able to decode the received signal as $P_{min} = \beta_0 \times N_0$.

5 Power Distribution Schemes

The following sequence of observations are the intuitive foundation for the power distribution scheme we propose:

1. When a multi-hop connection fails, it does so because at least one of its constituent links has failed.

2. Consider the point in time T when the first link failure occurs. Suppose that one link L_1 of the connection has failed at T while another link L_2 still survives. Then the power budget must have been distributed suboptimally, since giving L_2's endpoints (infinitesimally) less power, and L_1's endpoints (infinitesimally) more power would have yielded a longer lifetime for the connection.

3. Thus, for connection lifetime to be maximized, power must be distributed in such a manner that at the point in time when the connection fails, *all* of its constituent links fail simultaneously.

4. If all nodes have the same sensitivity threshold P_{min} then item (3) implies that the power budget must be distributed in such a manner that the received signal power at each node in the connection is the same.

5. Suppose the connection has power budget P and the distance between nodes j and $j+1$ of the connection is d_j (for $j = 1, \ldots, N-1$). If node j transmits with power $P \cdot d_j^2 / \sum_{i=1}^{N-1} d_i^2$, then all nodes will receive the transmission from their upstream neighbor at the same power level, thus satisfying the conclusion of item (4). Additionally, the total power consumption attributable to the connection will be precisely P.

In what follows, we will refer to the dynamic power redistribution scheme deduced above as the *Sqr* scheme:

5.1 Sqr Scheme

Under this power distribution scheme, the power is allocated based on the square of the distance to the next hop along the path towards the destination node. Specifically, given a connection between nodes s and t with length $N-1$ hops and a total power budget P, each node j will be allocated

$$P_{sqr}(j) = P \cdot d_j^2 / \sum_{i=1}^{N-1} d_i^2,$$

where d_j is the distance from node j to node $j+1$ along the path. We compare the performance of *Sqr* with two existing well-known power distribution schemes:

Power is allocated based on the square of the distance to the next hop along the path towards the destination node. In a connection between nodes s and t with length $N-1$ hops and a total power budget P, each node j will be allocated

$$P_{sqr}(j) = P \cdot d_j^2 / \sum_{i=1}^{N-1} d_i^2,$$

where d_j is the distance from node j to node $j+1$ along the path. The protocol runs continuously to keep power values updated in light of node mobility. The protocol strives to keep received signal power at each node identical, thereby ensuring all links have the same stability. The implementation is as follows:

In phase 1, the source node initiates a control message including its Tx power information and sends it to the next hop towards the destination node. At the next hop the receiver deduces the distance to the sender by comparing Tx and Rx levels, then inserts its own Tx level into the message, updates the cumulative square-distance field, and forwards it to the next hop. This process repeats; when the message is delivered to the destination, $\sum d_i^2$ is known. In phase 2, the destination initiates another control message containing $\sum d_i^2$ and sends it to the source node, allowing all transit nodes to learn the value. In order to prevent budget violations, only reductions of power are carried out in phase 2; increases are carried out in a third phase, in reaction to a control message from the source to the destination.

In theory all links should break simultaneously for the *Sqr* scheme. In practice, however, because the control protocol takes time to converge, shorter links have a smaller radius of safety, which are more sensitive to node mobility, and so break earlier than longer links. This leads us to the next scheme.

5.2 Uniform Scheme

Given an N-node connection between nodes s and t having total power budget P, the *Uniform* power distribution scheme allocates power uniformly to each of the $N-1$ nodes (excluding the destination node) $P_{unif}(j) = \frac{P}{N-1}$.

5.3 MinBER Scheme

This power budget distribution protocol was originally described by the authors in [9]. The protocol operates on *all* (overlapping) consecutive triplets of nodes within the connection (s, t). Within each triplet, we denote the nodes as the upstream node, the central node, and the downstream node—this naming convention is illustrated in Figure 1.

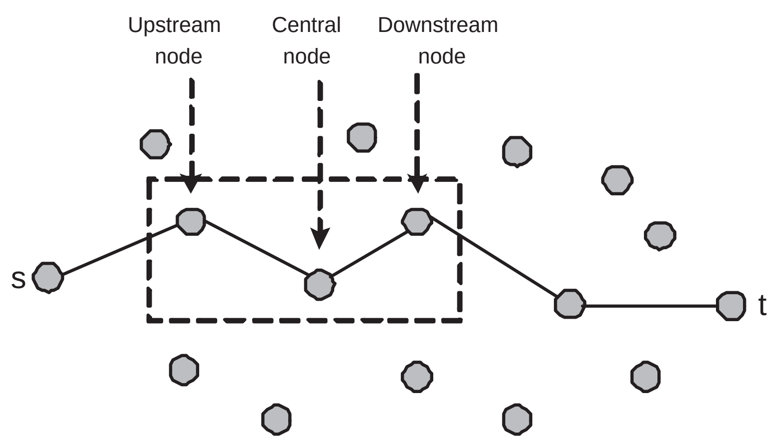

Figure 1 Multi-hop path description

A node enters the protocol by simultaneously sending an Update message to its upstream and downstream neighbors. The Update message describes its present transmission strength. A node receiving an update uses its contents and the actual received signal strength to deduce an estimate of the distance to the sender of the Update. Thus each node (viewed in its central role) maintains estimates of distance to upstream and downstream nodes. When the central node receives an Update message informing it of the transmission power and (implicitly) distance to a neighbor, it determines the optimal redistribution of power between itself and the upstream node. This local optimization is computed using the analytic model of BER model presented in [9]. In effect the central node acts greedily to minimize the BER of the two hop sub-path from its upstream neighbor to its downstream neighbor. If the local optimization shows that a significant redistribution of power is required, and this redistribution will not cause the received signal strength to drop below P_{min} at any node, then the central node is able to draw power downstream or push power upstream. The power reallocation process is negotiated concurrently between all (overlapping) triplets of nodes via a distributed protocol. The protocol is said to "converge" when the total power exchanged drops below a specified threshold. Since we are interested in comparing the quality of power distribution decisions of various schemes, we assume that the *minBER* algorithm converges in timeframes significantly shorter than those involved in node mobility and routing; we denote the resulting power distribution at node j as $P_{BER}(j)$.

5.4 Safe Scheme

The power budget is distributed among the nodes so that the safe distance of every node is equal, where safe distance is defined as the minimum distance for a node to go out of the coverage area of its upstream neighbor (see Figure 2).

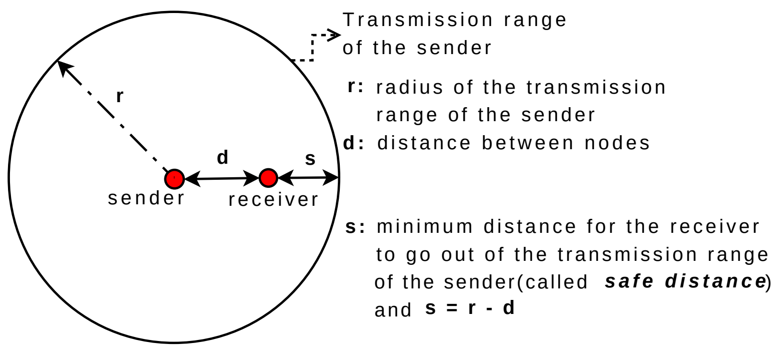

Figure 2 Safe scheme description

Implementation of this protocol is similar to *Sqr* scheme's implementation, however because computing the safe distance of each node requires all distance values between nodes to be known (not just their cumulative value as in *Sqr* scheme), the message initiated by the source node in phase 1 keeps a distance vector rather than just one cumulative value. This makes the resulting message grow linearly in size as it traverses the connection. In addition, in phase 2, the destination must inform each node individually about its new power Tx values. Because of these reasons, control message traffic is higher and convergence time is longer than for *Sqr*.

5.5 ModSqr Scheme

This scheme is a modification of the *Sqr* scheme with the following power distribution formula.

$$P_{sqr}(j) = P \cdot (d_j + c)^2 / \sum_{i=1}^{N-1} (d_i + c)^2,$$

where c is a constant (taken as 3 meters in this study), d_j is the distance from node j to node $j+1$ along the path. Note that *ModSqr* is a continuous parametric family spanning the *Sqr* ($c=0$) and *Uniform* ($c=\infty$). The control traffic required to implement *ModSqr* is comparable to that of *Sqr* since only a cumulative value needs to be conveyed.

6 Experimental Setup

Initial network design. In our simulations, we consider connections where the nodes were placed randomly according to the following inductive process: If node j is located at (x_j, y_j), then node $j+1$ is located at $(x_{j+1}, y_{j+1}) = (x_j + d_x, y_j + d_y)$ where d_x, d_y are uniformly distributed in the interval $[0, D]$. For most experiments (except when considering the effect of node density) we took $D = 100$ meters.

Mobility model. Nodes are allowed to move according to a Cartesian random walk mobility model [14]. Each node has five possible directions in which to move at each time step, of which one is selected uniformly at random: it may go north, south, east, or west with velocity v, or to stay at the current position until next time step. For instance, movement frequency = 100 means that the nodes move after every 100 packets handled at a node.

Performance measures. Starting with an initial network, we generate a movement sequence for the nodes. Then we simulate this movement sequence under each of the three power distribution schemes and note the time at which the connection fails (i.e. one of the constituent links fails) for each of the schemes. We denote these times as T_{Unif}, T_{Sqr}, T_{BER} and compute the advantage or "gain" enjoyed by the *Sqr* scheme over the *Unif* scheme as

$$\mathrm{G}ain_{Unif} = T_{Sqr}/T_{Unif}$$

, and the gain over the *minBER* scheme as

$$\mathrm{G}ain_{BER} = T_{Sqr}/T_{BER}$$

. The preceding experiment is carried out repeatedly, in 10^4 independent trials, where each trial begins with a different random initial network and movement sequence. The aggregate performance metrics are computed as averages over 10^4 trials:

$$\text{Expected Gain over Uniform} = E[T_{Sqr}/T_{Unif}]$$

$$\text{Expected Gain over minBER} = E[T_{Sqr}/T_{BER}].$$

System and environmental parameters. We explored the impact of the following situational parameters on the above two performance metrics:

- *Number of nodes N:* We vary the number of nodes on the path ranging from few (5) to many (25) nodes.
- *Power budget P:* We consider connection power budgets ranging from small (2.0 Watts) to large (10.0 Watts).

- *Initial node density δ:* We vary node density in the initial network from sparse (0.15 nodes/m) to dense (0.4 nodes/m). This is achieved by taking $N = 500 * \delta$ and scaling the network geometry proportionally so that the initial network is bounded by the 500 meter square.
- *Mean node velocity v:* We consider velocity of the nodes ranging from slow (0.5 meters/sec; 1.1 miles/hr) to rapid (4.0 meters/sec; 9 miles/hr).
- *Signal attenuation exponent α* is taken as 2, appropriate to our connection distance scales in free space.
- P_{min}, the minimum signal power at which a receiver is able to decode a signal is taken as 10 mW.

7 Simulation Results and Analysis

We conducted experiments to quantify the influence of the number of nodes N, connection power budget P, initial node density δ, and mean node velocity v, on the expected gain of *Sqr* over the *Uniform* and *minBER* schemes. The error bars on each graph below show the width of (plus/minus) one standard deviation from the expected values of the gains.

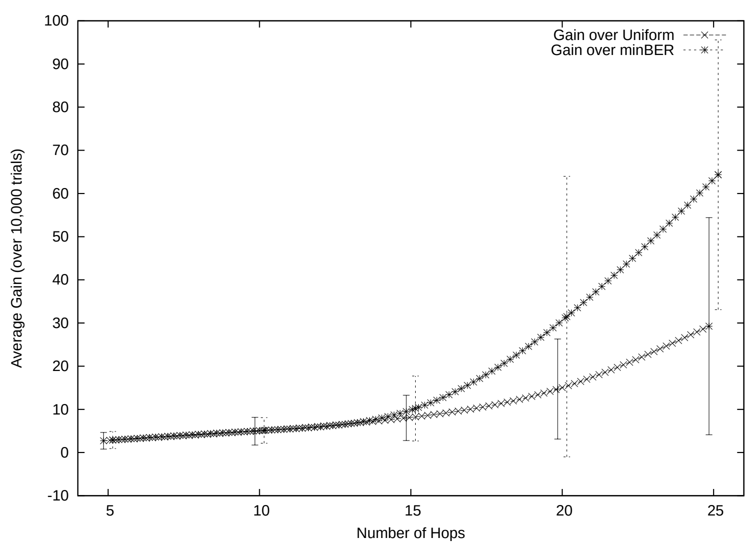

Figure 3 The Influence of Number of Hops on Gain

Varying the connection size. In the first set of experiments, we varied the connection size from 5 to 25 nodes, while keeping all other variables fixed: the power budget (P) was fixed at 5.0W, the mean velocity of the nodes (v) was fixed at 1.0 m/sec, and the initial mean node density was one node every 50m. As can be seen in Figure 3, *Sqr* enjoys a linearly growing gain over both *Uniform* and *minBER* for small connections sizes (i.e. when $N < 15$), outperforming them both by a factor of 2.7 when $N = 5$, a factor of 4.9 when $N = 10$ and a factor of 8.5 when $N = 15$. As connection size grows beyond this threshold, the minBER scheme's power allocation decisions deviate significantly from the lifetime maximization scheme, and the rate at which the latter's gains increase begins to grow super-linearly. The reason for this divergence is explainable as follows. Since we are holding the connection's power budget constant while increasing N, when N becomes sufficiently large energy becomes scarce, and the power distribution which minimizes BER is markedly different from the power distribution which maximizes connection lifetime.

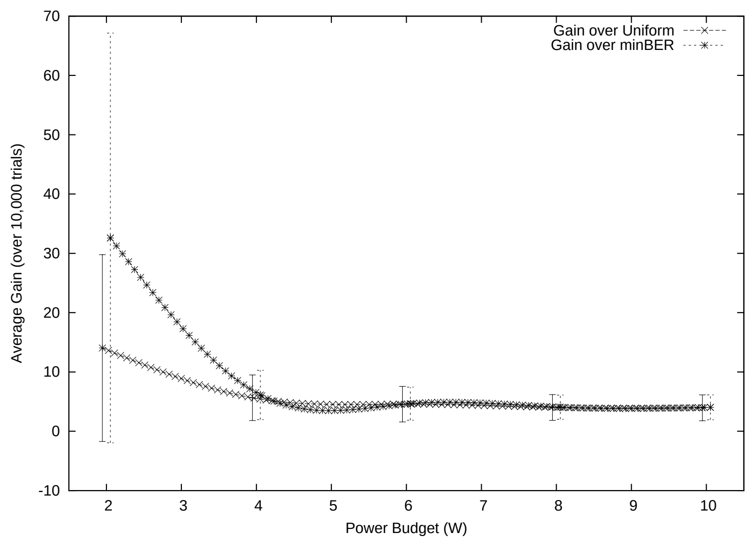

Figure 4 The Influence of Power Budget on Gain

Varying the power budget. In the second set of experiments, we varied the connection's power budget from 2.0W to 10.0W, while keeping all other variables fixed: the number of nodes (N) was fixed at 10, the mean velocity of the nodes (v) was fixed at 1.0 m/sec, and the initial mean node density was one node every 50m. As can be seen in Figure 4, the *Sqr* echeme enjoys a very significant (factor of 32) gain over *minBER* and factor of 14 gain over the *Uniform* scheme in low power budget settings (2.0W). As power budgets increase, the gain that *Sqr* enjoys over both schemes declines near-linearly. Once the power budget exceeds a threshold of 4.0W, any further increases of the power budget do not appear to separate *Sqr*'s factor of 3.9 advantage over *Uniform* and *minBER*.

Varying the node density. In the third set of experiments, we varied the node density from one node every 66m ($\delta = 0.15$ nodes/meter) to one node every 25m ($\delta = 0.40$ nodes/meter), while keeping all other variables fixed: the power budget (P) was fixed at 5.0W, the mean velocity of the nodes (v) was fixed at 1.0 m/sec. The number of nodes N was taken to be $500/\delta$, and the initial configuration was rescaled proportionately so that it was bounded by a 500m by 500m square. As can be seen in Figure 5, *Sqr* enjoys a significant gain in connection lifetime (a factor of 4.1) over both *Uniform* and *minBER*, although as node density increases,

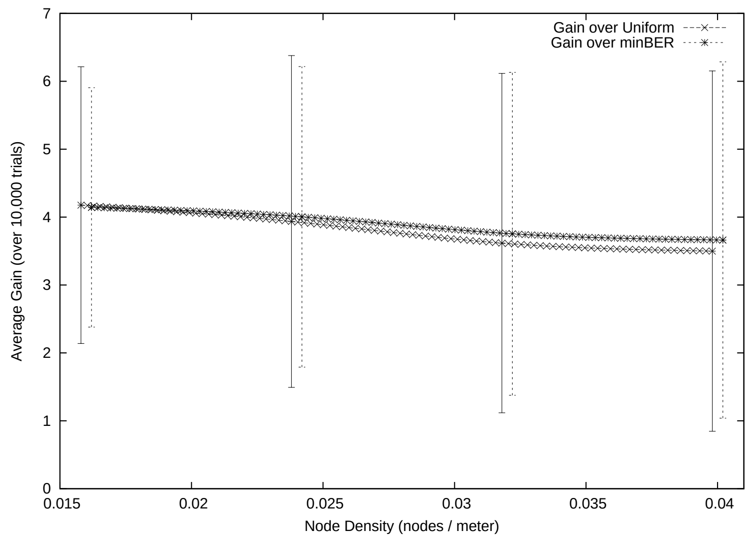

Figure 5 The Influence of Node Density on Gain

the gain is gradually reduced, becoming only a factor of 3.5 when the node density reaches $\delta = 0.4$ nodes per meter. Altering node density does not appear to separate *Sqr*'s advantage over *Uniform* from *Sqr*'s advantage over *minBER*.

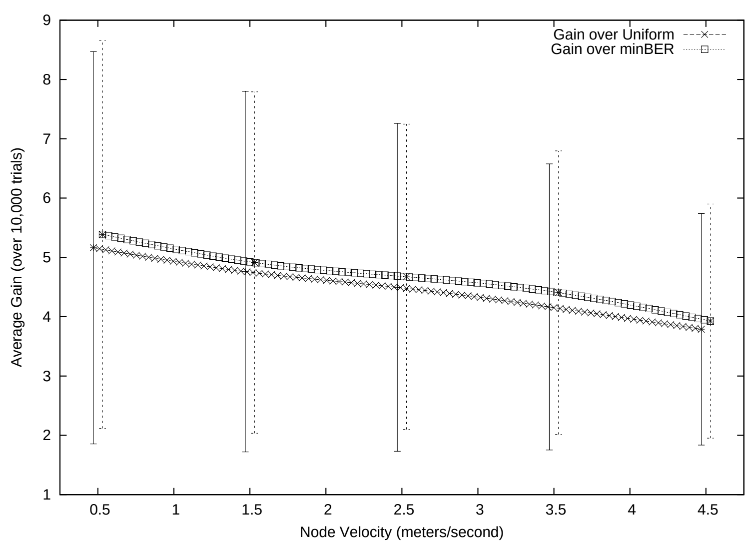

Figure 6 The Influence of Node Velocity on Gain

Varying the node velocity. In the final set of experiments, we varied the mean node velocity from 0.5 meters/sec to 4.5 meters/sec, while keeping all other variables fixed: the power budget (P) was fixed at 5.0W, and the initial mean node density was one node every 50m. As can be seen in Figure 6, *Sqr* enjoys a significant factor of 5.2 gain in connection lifetime over both *Uniform* and *minBER*, although as node velocity increases, the gain is gradually reduced, becoming only a factor of 3.8 when the node velocity reaches 4.5 meters/sec. Altering node velocity does not appear to separate *Sqr*'s advantage over *Uniform* from *Sqr*'s advantage over *minBER*.

8 Control Traffic Overhead

8.1 Experimental Setup

Initial network design. The simulation is realized at packet level such that each node handles one either data or control packet at each simulation step, assuming that there is spatial reuse. We considered two different lower layer implementations in these experiments:

- *Soft TDM (Time Division Multiplexing) Mode:* There are an ε fraction of the time slots assigned to carry control traffic, but these slots can be used for data traffic if there is no control packet to be forwarded.
- *Hard TDM Mode:* As above, except control slots cannot be reallocated to carry data packets.

Performance measures. As performance, we take the number of data packets received by the destination node before the connection breaks. The gain of a power distribution scheme is calculated by comparing its performance against that of the *Uniform* scheme. We conduct 10^3 independent trials, each trial beginning with a different random initial network and movement sequence; aggregate metrics are then computed as averages over the trials:

$$\text{Gain}^*_A = E[\frac{\text{Number of the data messages of Scheme A}}{\text{Number of the data messages of Unif}}]$$

System and environmental parameters. We explore the impact of these situational parameters on gain of each scheme:

- *Initial node density δ:* We vary node density in the initial network from sparse (0.01 nodes/m) to dense (0.05 nodes/m). This is achieved by taking $N = 500 * \delta$ and scaling the network geometry proportionally so that the initial network is bounded by the 500 meter square.
- *Control time slots percentage ϵ:* This parameter determines what percentage of total time slots are assigned for control traffic, ranging from 0 to 100. We fixed this value as 0.2 (20%) for all experiments except the last experiment, gain vs ϵ.

Fixed parameters. We consider *movement frequency* to be fixed, at one movement every 200 packet transmissions, for each node. The *Signal attenuation exponent* α was taken as 2, appropriate to our connection distance scales in free space. The minimum signal power at which a receiver is able to decode a signal is taken as $P_{min} = 10$ mW.

8.2 Simulation Results and Analysis

We conducted experiments to quantify the influence of the number of nodes N, connection power budget P, initial node density δ, and control traffic overhead ϵ, on the expected gain of the schemes over the *Uniform* scheme.

Note: In cases where pairs of curves in our graphs lie within one standard deviation of each other's points, we provide the ***correlation coefficient*** between the per-trial gains of the two schemes, so as to justify any conclusions based on the relative geometry of the two curves.

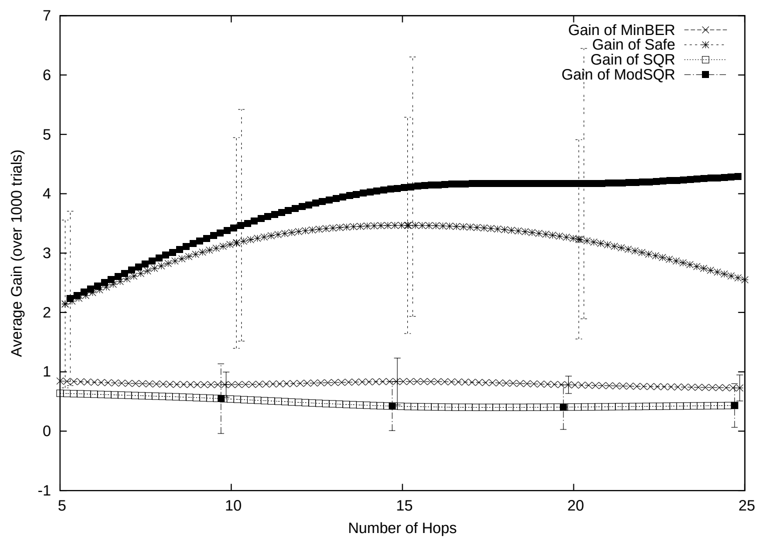

Figure 7 The Influence of Number of Hops on Gain in Soft TDM Mode

A. Varying the connection size. In the first set of experiments, we varied the connection size from 5 to 25 nodes, while keeping all other variables fixed: the power budget (P) was fixed at 10.0W, and the initial mean node density was one node every 100m.

There are three significant factors (which depend on the number of hops) that affect gain: (i) the collective resources available to the nodes to compensate for weak links, (ii) the convergence time of the control protocol (especially for end-to-end operations), and (iii) control traffic overhead of the schemes. For *ModSqr* scheme, as the number of hops increases, the factor (i) increases faster than (ii), while (iii) is remains constant per node. *ModSqr* enjoys a linearly growing gain up to the connection size of 15, after which the first two factors balance each other, and the curve becomes flat as in Figure 7 and 8. For *Safe* scheme, factor (ii) begins to dominate factor (i) because increased message complexity causes the convergence time of *Safe* scheme to grow quadratically in connection size. The correlation between *ModSqr* and *Safe* was (0.98), showing that the former genuinely outperforms the latter, in spite of the fact that the two curves lie within each other's error bars. The gain of *Minber* is independent of the connection size because it works within triplets and it does not use an end-to-end protocol. Finally,

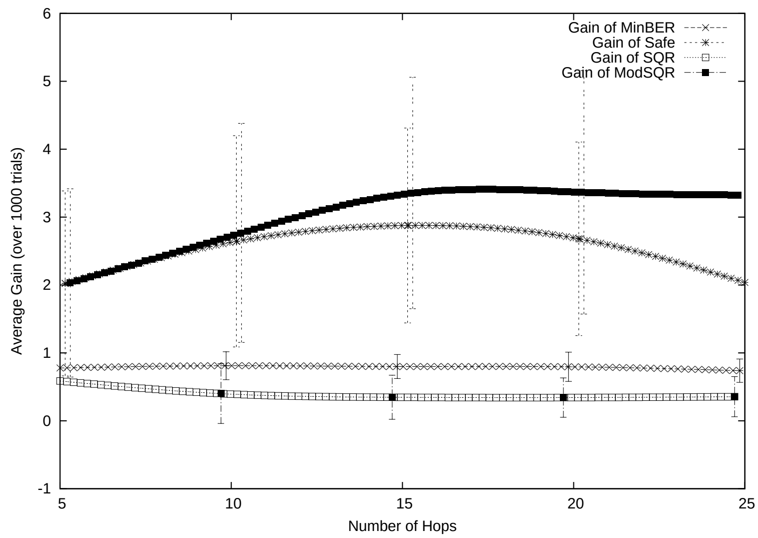

Figure 8 The Influence of Number of Hops on Gain in Hard TDM Mode

Sqr and *minBER* were the worst scheme in terms of gain as seen in the figures. *Sqr* performs poorly because it leaves short connection links disproportionately vulnerable to endpoint mobility. *minBER* performs poorly because its objective is orthogonal to expected longevity. The correlation between *MinBER* and *Sqr* was (0.21) indicating that the schemes cannot be compared to each other, as they lie within each other's error bars.

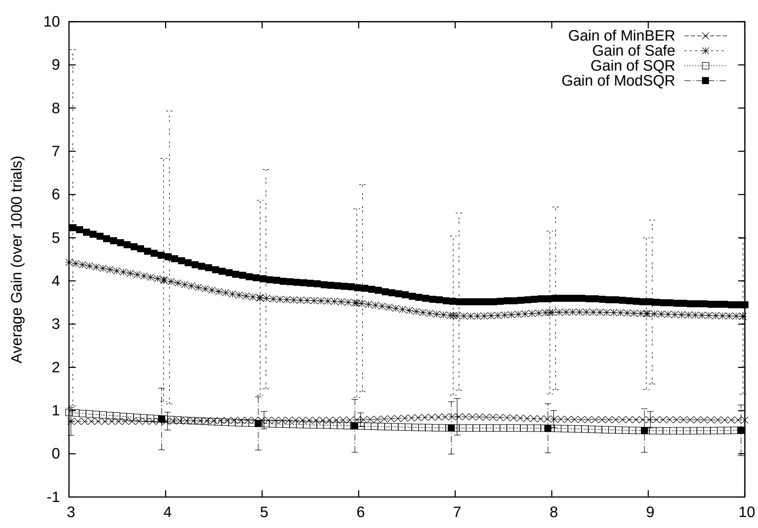

Figure 9 The Influence of Power Budget on Gain in Soft TDM Mode

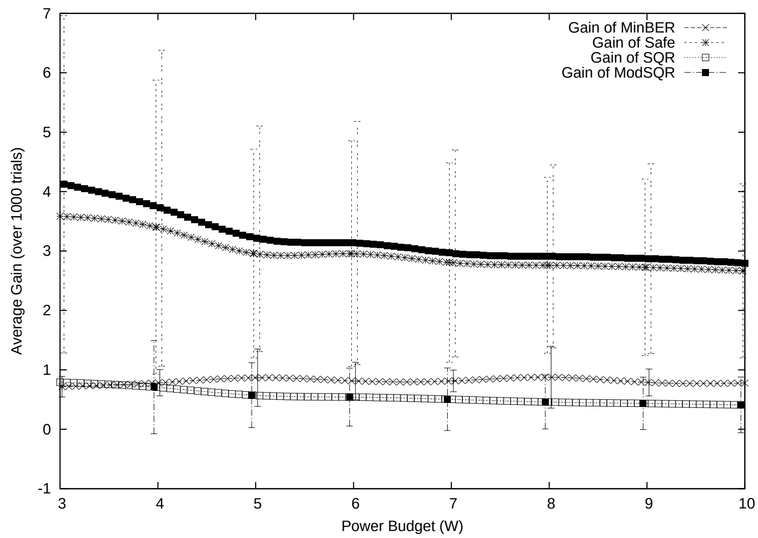

Figure 10 The Influence of Power Budget on Gain in Hard TDM Mode

B. Varying the power budget. In the second set of experiments, we varied the connection's power budget from 3.0W to 10.0W, while keeping all other variables fixed: the number of nodes (N) was fixed at 10, and mean node density was one node every 100m.

Clearly the gains of the schemes should approach 1 as the power budget goes to infinity. This intuition is born out in Figures 9 and 10. In spite of this, ModSqr and Safe schemes outperform the Sqr and minBER schemes, providing a gain of over 300% even for very high power budgets.

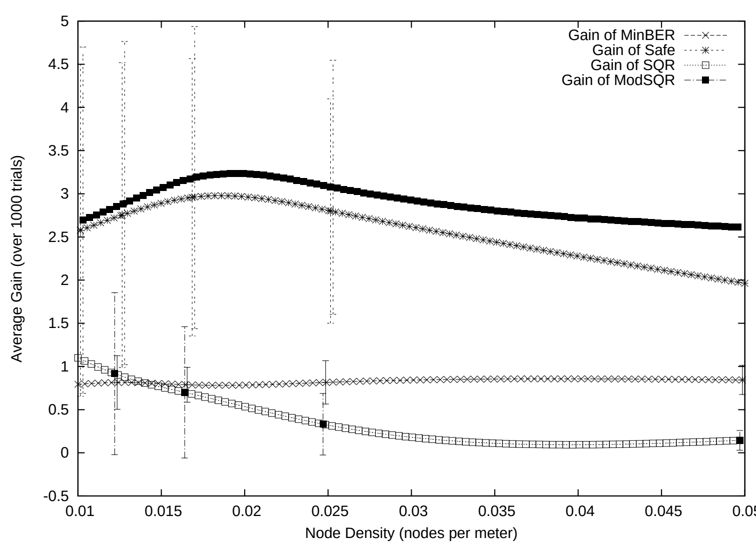

Figure 11 The Influence of Node Density on Gain in Soft TDM Mode

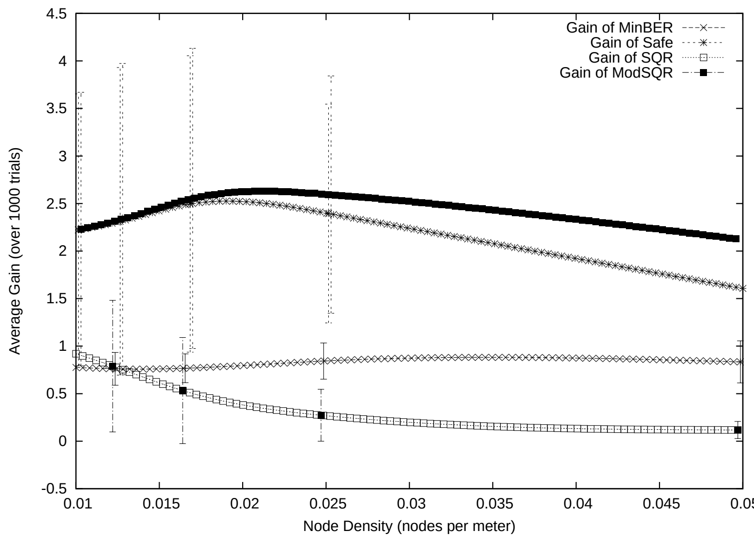

Figure 12 The Influence of Node Density on Gain in Hard TDM Mode

C. Varying the node density. In the third set of experiments, we varied the node density from one node every 100m ($\delta = 0.01$ nodes/meter) to one node every 20m ($\delta = 0.05$ nodes/meter), while keeping all other variables fixed with the power budget (P) of 10.0W. The number of nodes N was taken to be 500δ, and the initial configuration was rescaled proportionately so that it was bounded by a 500m by 500m square.

This experiment is closely related to the investigations of hop size since changing node density implies changing hop size of a connection. The results of both experiments thus look similar (Figure 11 and 12) and the interpretations made in the hop-size experiment are also valid here. The correlation between *ModSqr* and *Safe* was (0.95), showing that the former genuinely outperforms the latter, in spite of the fact that the two curves lie within each other's error bars. The *Sqr* scheme exhibits better performance when node density is low since when the nodes are denser the probability of having short links gets higher. As noted earlier, *Sqr* causes nodes with short links to adjust their power level so that receiver nodes are at the precipice of the transmission radius (i.e. their safe distance is very small); this yields early disconnections of short links.

D. Varying the control traffic overhead. In the final set of the experiments, we varied the control traffic overhead by changing fraction of slots (ε) allocated to control traffic, while keeping other variables fixed: power budget (P) was fixed at 10.0W, the number of nodes (N) was fixed at 10 , and the mean node density was one node every 100m.

Figure 13 shows the effect of *Epsilon* on the gain in Soft TDM mode. *ModSqr* and *Safe* show similar response herein, but *ModSqr*'s gain is higher than *Safe*'s gain since *Safe* has higher control traffic (and hence longer convergence times) than *ModSqr*. Note that the correlation between *ModSqr* and *Safe* was (0.97), showing that the former genuinely outperforms the latter, in spite of the fact that the two curves lie within each other's error bars. Both curves initially rise

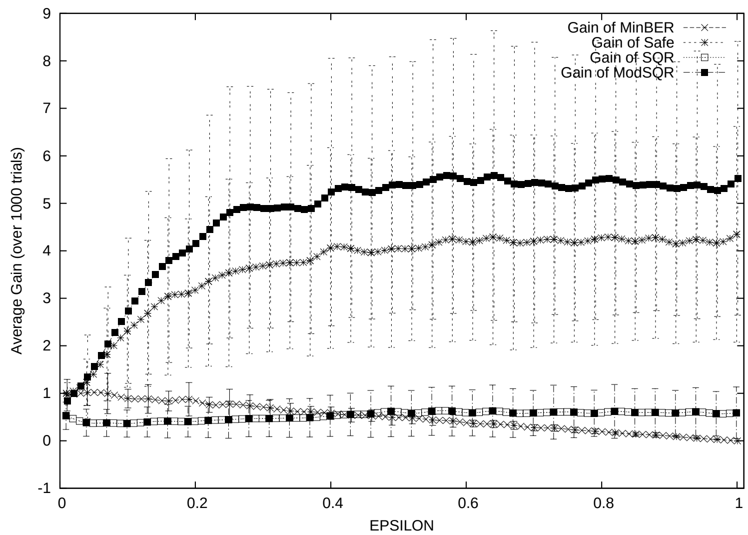

Figure 13 The Influence of Control Traffic on Gain in Soft TDM Mode

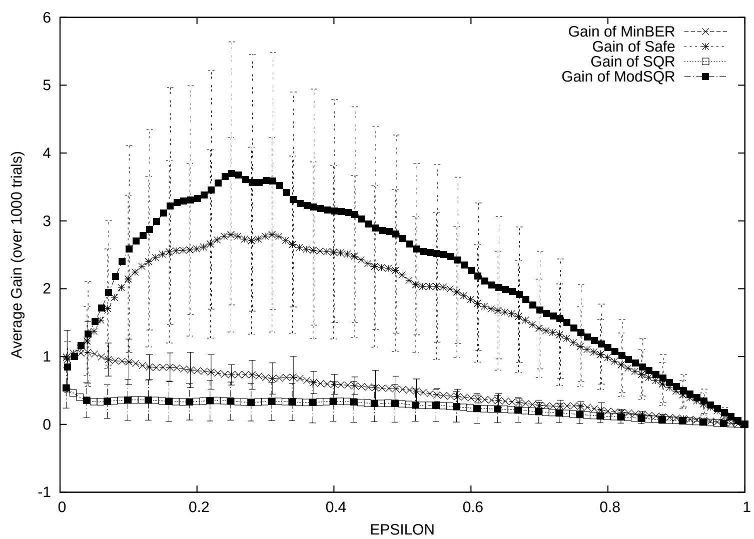

Figure 14 The Influence of Control Traffic on Gain in Hard TDM Mode

linearly up to around ε=0.25, then remain flat. When the ε is too small, there are few control time slots and the schemes run and converge slower than the side effects of node mobility, resulting in lower performance. Once the percentage of control time slots reaches a reasonable value (at about ε=0.25) the schemes obtain maximum gain level and increasing ε beyond this yields nothing in terms of the gain. Assigning too large an ε is both useless and *harmless* due to fact that the schemes is already converged and the nodes are allowed to handle data packets in the absence of control packets respectively in Soft TDM. In the same figure, the gain of *MinBER* decreases linearly as ε increases, and when ε=1.0 its gain becomes zero; this is understandable since in *minBER* the nodes always have control messages to send and will thus swamp out data if given the opportunity. The correlation between *minBER* and *Sqr* was low (0.13), indicating that the two schemes are incomparable, since their curves lie within each other's error bars. Figure 14 considers the effect of varying ε in Hard TDM mode. The correlation between *ModSqr* and *Safe* was (0.99). According to the figure, there are tradeoffs for *ModSqr* and *Safe* schemes such that they reach their maximum gain values when ε=1/4. As ε increases to 1.0 the gains of the all schemes decrease linearly and approach 0, since in Hard TDM control slots will swamp out data slots if ε is set too high.

9 Conclusion

The proposed *Sqr* scheme is able to distribute a fixed power budget among the nodes of a connection, and yields significantly longer expected connection lifetimes relative to the uniform power budget distribution and the BER-minimizing power distribution schemes. The observed gains range from a factor of 3 to a factor of 30, depending on the particular values of system and environmental parameters. The expected gain is seen to be most sensitive to power budget and connection size, and relatively insensitive to initial node density and mean node velocity.

The objectives of BER minimization and lifetime maximization are most starkly in opposition in settings where the total power budget is low or, equivalently, where the size of the connection is large. It is in these settings that the distribution of power is most sensitive to the particular choice of objective, for in such settings, distributing power in a manner that achieves minimum end-to-end connection BER is very different from distributing power in a manner that seeks to maximize expected connection lifetime. The net impact of this tradeoff is that connections which are declared low priority (and hence assigned low power budgets) cannot expect to simultaneously optimize their power distributions with respect to both BER and expected lifetime, since the two criteria are seen to be in opposition. High-priority connections, on the other hand can "have their cake and eat it too", since with large power budgets, the relative advantage of *Sqr* over *minBER* (with respect to lifetime) is diminished.

The *Sqr* scheme equalizes received power levels at all nodes, and so is theoretically optimal in settings where the power distribution protocols operate instantaneously. In practice, however, it is seen to perform poorly when convergence time take into consideration. This realization motivated the design of the *Safe* scheme, which seeks to equalize the safe distances of nodes–that is, the distance that any node can move without breaking the connection. While the *Safe* scheme computes an optimal solution, it is crippled by its high communication complexity (and hence slow convergence in TDM implementations); this motivated the development of the *ModSqr* scheme, which captures the gains of *Safe* without incurring the high communication costs. We have implemented all schemes with two different lower layer assumptions: (i) *Soft TDM mode*, that is, there are control time slots for control traffic, and these time slots can be used on behalf of data traffic if there is no control packet to be forwarded at the nodes. (ii) *Hard TDM* *mode*, that is, there are again control time slots assigned for control traffic, but this time the nodes are not allowed to handle data packets if there is no control packets in the control time slots.The investigations demonstrate that taking control traffic overhead and convergence time of protocols play a critical role in the analysis of the proposed schemes.

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