ABSTRACT

A mobile ad hoc network (MANET) is a self-organized and adaptive wireless network formed by dynamically gathering mobile nodes. Since the topology of the network is constantly changing, the issue of routing packets and energy conservation become challenging tasks. In this paper, we propose a cross-layer design that jointly considers routing and topology control taking mobility and interference into account for MANETs. We called the proposed protocol as Mobility-aware Routing and Interference-aware Topology control (MRIT) protocol. The main objective of the proposed protocol is to increase the network lifetime, reduce energy consumption, and find stable end-to-end routes for MANETs. We evaluate the performance of the proposed protocol by comprehensively simulating a set of random MANET environments. The results show that the proposed protocol reduces energy consumption rate, end-to-end delay, interference while preserving throughput and network connectivity. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS

cross-layer design; MANETs; optimization; routing; topology control

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1. INTRODUCTION

A mobile ad hoc network (MANET) is a collection of geographically distributed wireless mobile nodes that self-configure to form a network without a predetermined topology. The lack of an infrastructure and the limited battery power in ad hoc networks pose design challenges at all layers of the protocol stack. A MANET requires new technologies for the mobility management, service discovery, and energy efficient information routing of the network. Significant research has been directed towards implementing application-dependent Quality of Service (QoS) requirements (e.g., [1–3]). These researches mainly addressed adaptive techniques in the link layer, interference in the Medium Access Control (MAC) layer, and energy and delay constrained routing in the network layer.

Topology control is the art of coordinating nodes’ decisions regarding their transmitting ranges, in order to generate a network with the desired properties (e.g., connectivity) while reducing node energy consumption and/or increasing network capacity [4]. The energy-efficient design of the wireless transceiver, however, cannot be classified as topology control because it has a node-wide perspective [4]. The same applies to power-control techniques, whose goal is to optimize the choice of the transmit power level for a single wireless transmission, possibly along several hops. The topology of a MANET frequently changes, and thus original data transmission routes can become disabled. In this paper, the desired effect of a topology control is to reduce the energy consumption, and to reduce the MAC layer interference while preserving the network connectivity.

Another essential issue for MANETs is routing protocol design. It is important to find and maintain optimized routes to the destination in a changing topology resulting from mobility or node failure. Routing protocols is classified to proactive routing, reactive routing, and hybrid routing [5]. Proactive methods maintain routes to all nodes, including nodes to which no packets are sent. Such methods periodically exchange topology information to maintain and update routes. Examples of proactive routing protocols are Optimized Link State Routing (OLSR) [6] and Destination Sequenced Distance Vector (DSDV) [7]. Reactive methods are based on data transmission request. Routes between hosts are determined only when they are explicitly needed to forward packets. Reactive methods therefore generate low control traffic and routing overhead. Examples of
reactive routing protocols are Ad-hoc On-demand Distance Vector (AODV) [8] and Dynamic Source Routing (DSR) [9]. Hybrid methods combine proactive and reactive methods to find efficient routes as Zone Routing Protocol (ZRP) [10]. The AODV routing protocol is the most well-known and default standard routing protocol for MANETs.

Recent related work shows that significant performance improvement can be achieved by using a cross-layer design for MANETs [11-14]. Cross-layer design with respect to a reference-layered architecture is the design of algorithms, protocols, or architectures that exploit and provide a set of inter-layer interactions [15]. These interactions are subsets of the standard interfaces provided by the reference-layered architecture. A cross-layer architecture supports comprehensive state variables accessible to all communication layers. Usually, the topology control and routing in wireless ad hoc networks are investigated separately by taking into account some parameters such as interference and bandwidth [16]. Tang et al. [16] separately considered an interference-aware topology control and QoS routing for static networks. They sought a channel assignment where the topology is interference-minimized, and sought routes for QoS connection requests with bandwidth requirements. A cross-layer design for joint topology control and routing for a multi-radio multi-channel wireless mesh network was proposed in Reference [17]. Its main target was to maximize the network throughput by adjusting the channel assignment, the power level of each radio, and the route for the flows. Casasquite and Hwang [18] proposed integrating the power control, scheduling, and routing to find the optimal transmission power satisfying the Signal to Interference plus Noise Ratio (SINR) requirement as well as the required data rate of all nodes for static wireless ad hoc networks.

Interference and mobility are important factors that affect the performance of topology control and routing for MANETs. In this paper, we take interference and mobility parameters into account for the cross-layer design of topology control and routing for MANETs. We propose a novel cross-layer Mobility-aware Routing and Interference-aware Topology control (MRIT) protocol. In the mobility-aware routing, we aim to find a stable and optimal route, in terms of mobility, between each source and destination pair. In addition, for the interference-aware topology control, we aim to reduce the energy consumption and interference while preserving the network connectivity. We use the cross-layer interactions to decrease the communication overhead and achieve better global performance parameters as network lifetime, delay, and energy consumption. The performance evaluation has been extensively conducted by computer simulation. The simulation results show that the proposed cross-layer protocol increase the network lifetime, consumes 30–50% less energy, and reduce the end-to-end delay by 60–90% compared to the AODV routing protocol which is the well-known and default standard reactive routing protocol for MANETs.

The remainder of this paper is organized as follows. Section 2 provides the problem formulation. The proposed cross-layer design is described in Section 3. Section 4 explains the proposed protocol design. Section 5 states the implementation. Performance and simulation results are presented in Section 6. Section 7 concludes the paper.

2. PROBLEM FORMULATION

A MANET is presented as a graph \( G = (N, L) \), where \( N \) is a set of mobile nodes, and \( L \) is a set of all directed links \((i, j)\) where \( i, j \in N \). The link \((i, j)\) exists if the transmission power of node \( i \) to node \( j \), \( p_{ij} \) in watt, is more than or equal to \( \beta d_{ij}^\alpha \), where \( \beta \) is the transmission quality parameter, \( d_{ij} \) is the Euclidean distance between node \( i \) and node \( j \), and \( \alpha \) is the distance-power gradient [19]. For all nodes \( i \in N \), let the initial energy be \( E_i \) in joule. Let \( Q_i^{(c)} \) be the rate at which bits are generated at node \( i \) per second belonging to commodity \( c \in C \), where \( C \) is the set of all commodities. In the multi-commodity flow, different types of flows are assumed to be transmitted from sender to receiver simultaneously (i.e., more than one flow can share the bandwidth capacity simultaneously). Denote the energy for transmitting a bit from node \( i \) to node \( j \) by \( e_{ij} \) in joule. The flow of commodity \( c \) transmitted from node \( i \) to node \( j \) is \( f_{ij}^{(c)} \) in bits per second. The aggregated flow of all commodities \( f_i = \sum_{c \in C} f_{ij}^{(c)} \). Denote for each commodity \( c \), a set of source nodes by \( S^{(c)} \) where the bits are generated (i.e., \( S^{(c)} = \{i | Q_i^{(c)} > 0, i \in N \} \) and a set of destination nodes \( D^{(c)} \). At any node \( i \), which is neither source nor destination, the flow-in should equal to the flow-out. For node \( i \in S^{(c)} \), the flow-out should equal to the flow-in plus the throughput requirement \( Q_i^{(c)} \). For node \( i \in D^{(c)} \), the flow-out should equal to the flow-in minus \( Q_i^{(c)} \). The flow conservation is defined formally as follows:

\[
\sum_{(i,j) \in L} f_{ij}^{(c)} - \sum_{(k,j) \in L} f_{kj}^{(c)} = \begin{cases} Q_i^{(c)}, & \text{if } i \in S^{(c)} \\ -Q_i^{(c)}, & \text{if } i \in D^{(c)}, \forall c \in C \\ 0, & \text{otherwise} \end{cases}
\] (1)

2.1. Maximize the network lifetime

Maximizing network lifetime is the main goal in MANETs for applications (e.g., disaster relief) where the mobile device’s battery is limited. In such applications, the devices used in the field are battery operated. It should be energy conserving, so that the battery lifetime is maximized [20]. In order to maximize the network lifetime, we need to maximize the minimum lifetime for all the nodes in that network. Furthermore, we need to consider the flow conservation separately applied to each commodity [21].

Let the lifetime of node \( i \) be defined as the time it takes for the battery of node \( i \) to drain out. Let \( T_i(F) \) be the lifetime of node \( i \) under flow \( F = \{f_{ij}\} \), where \((i,j) \in L \). \( T_i(F) \) is defined as the ratio between the initial energy at node \( i \) \( E_i \), and the total energy needed to transmit the flow from node \( i \) to its neighbors. The lifetime of node \( i \) is formally defined as:

\[
T_i(F) = \frac{E_i}{\sum_{(i,j) \in L} f_{ij}^{(c)} e_{ij}}
\]
Thus we have the following linear programming problem.

\[ T_{\text{f}}(\mathbf{F}) = \frac{E_i}{\sum_{(i,j) \in L} e_{ij} \sum_{c \in C} f^{(c)}_{ij}} \]  

(2)

The lifetime of the network \( G \) under flow \( \mathbf{F} \) is defined as the minimum battery lifetime over all nodes,

\[ T_{\text{G}}(\mathbf{F}) = \min_{i \in N} T_{\text{f}}(\mathbf{F}) \]

\[ = \min_{i \in N} \frac{E_i}{\sum_{(i,j) \in L} e_{ij} \sum_{c \in C} f^{(c)}_{ij}} \]  

(3)

The maximum network lifetime problem for MANETs is formulated as a non-linear optimization problem as follows:

\[ \text{Maximize} \quad T_{\text{G}}(\mathbf{F}) = \min_{i \in N} \frac{E_i}{\sum_{(i,j) \in L} e_{ij} \sum_{c \in C} f^{(c)}_{ij}} \]

subject to

\[ \sum_{(i,j) \in L} f^{c}_{ij} - \sum_{(i,j) \in L} f^{c}_{ki} = \begin{cases} Q^{(c)}_i, & \text{if } i \in S^{(c)} \\ -Q^{(c)}_i, & \text{if } i \in D^{(c)}, \forall c \in C \\ 0, & \text{otherwise} \end{cases} \] 

\[ f^{c}_{ij} \geq 0, \forall i \in N, \forall (i, j) \in L, \forall c \in C \]  

(4)

This linear programming formulation can be viewed as a variation of the conventional maximum flow problem with node capacities (i.e., \( \sum_{(i,j) \in L} \sum_{c \in C} f^{c}_{ij} \leq E_i/e_i \)) [23], without power control (i.e., the transmission power at each node is fixed, \( e_{ij} = e_i \)). With the linear formulation, the problem can be solved in an efficient way [24,25]. To maximize the network lifetime, it is also important to consider the topology control problem. Transmitting at minimum level of power helps to minimize the interference and prolong the lifetime of a node, and thus, maximize the network lifetime [26,27]. In this paper, the interference-aware topology control is addressed as follows.

### 2.2. Interference-aware topology control problem

Topology control is the art of coordinating nodes’ decisions regarding their transmitting ranges, in order to generate a network with the desired properties (e.g., connectivity) while reducing node energy consumption and/or increasing network capacity [4]. In this paper, we propose a topology control protocol that has the following characteristics:

- It uses the routing control messages to trigger node transmission power updating, and uses the MAC layer to apply the SINR constraint, so there is no overhead messages. Here, we want to ensure a minimum SINR of specific threshold \( \gamma_j \) for successful reception.
- All the network nodes that participate in communication adjust its transmission power to satisfy the interference and connectivity constraints.

The problem with the topology control was defined as Integer Linear Programming (ILP) considering the delay QoS parameter in Reference [28]. In this paper, we define the topology control problem as mixed integer linear programming and consider the SINR QoS parameter as a constraint.

Let \( p_{ij} \) be the transmission power from node \( i \) to node \( j \), and \( p_{ij}/d_{ij}^\alpha \) is the received power at node \( j \). Let \( P_i \) be the maximum allowed transmission power of node \( i \) and \( p_{\text{max}} \) be the maximum transmission power of network nodes. The Boolean variable \( x_{i,j} \) equal to 1 if there is a link from node \( i \) to node \( j \); otherwise equal to 0. The problem is defined as follows:

Minimize \( p_{\text{max}} = \max \{ p_{ij} | 0 \leq i < n \} \), subject to

\[ x_{i,j} = x_{j,i}, \forall i, j \in N \]  

(7)

\[ x_{i,j} \leq x_{i,k}, \text{ if } d_{i,k} \leq d_{i,j}, \forall i, j, k \in N \]  

(8)

\[ P_i \geq p_{ij} \geq \beta d_{ij}^\alpha x_{i,j}, \forall i, j \in N \]  

(9)

\[ \text{SINR}_{ij} = \frac{p_{ij}/d_{ij}^\alpha}{\sum_{(k,j) \in L, k \neq j} p_{kj}/d_{kj}^\alpha + \sigma} \geq \gamma_{ij}, \forall i, j, k \in N \] 

(10)

\[ x_{i,j} = 0, \text{ or } 1, \forall i, j \in N \]

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Constraint in Equation (7) ensures that there is a bidirectional link between node $i$ and node $j$. This constraint overcome the transmission power heterogeneity exists between mobile nodes. Constraint in Equation (8) ensures that nodes have broadcast ability. The transmission by a node can be received by all the nodes within its transmission range. For node $i$, if there is a link to $j$ (i.e., $x(i, j) = 1$), then there must be a link to any node $k$ (i.e., $x(i, k) = 1$) when $d_{i, k} \leq d_{i, j}$. Constraint in Equation (9) ensures transmission power from any node $i$ to node $j$ is less than or equal to the maximum allowed transmission power, and more than or equal to $\beta d_{i,j}^\alpha$, where $\beta$ is the transmission quality parameter, $d_{i,j}$ is the Euclidean distance between node $i$ and node $j$ and $\alpha$ is the distance-power gradient. Let $\sigma$ be the ambient noise power level, and let $k$ be any node simultaneously transmitting with node $i$ at some time instant over a certain channel. Constraint in Equation (10) ensures a minimum SINR of $\gamma_{ij} \geq 1$ is necessary for successful reception at node $j$ from transmitting node $i$ (i.e., received power at node $j$ is more than or equal to commutative interference power plus noise power).

### 2.3. Mobility-aware route selection

In the previous subsection, we defined the network lifetime problem with the objective to maximize it subject to throughput requirement and limited bandwidth and energy. In addition, to maximize the network lifetime, we need an efficient route selection metric to maximize the route lifetime. A routing protocol has already been considered for the network layer [15]. In most of MANETs routing protocols, the shortest-hop metric is used to select the best route [6-9,29]. When the shortest-hop metric is used to select the data route, the same route is used between the same source and destination node. The nodes in this route will die earlier than the nodes belonging to other routes. In this paper, we consider MANETs where all the nodes are expected to frequently change their positions. In such cases, the route should be changed every time any of its nodes change their position. In this section, we will use the speed parameter to choose the best route. The used route will change every time the source node sends to the same destination node as it depends on the route nodes speed. For convenience, we define a route from source node $s$ to the destination node $d$ as follows:

$$ R = \{(i_0, i_1), \ldots, (i_{h-1}, i_h)\}, \forall (i_k, i_{k+1}) \in L $$

where $i_0, i_1, \ldots, i_h$ are distinct nodes, $i_0 = s$, $i_h = d$, and $h$ is the number of hops between source node $s$ and destination node $d$.

Consider there are $m$ number of available routes between source node $s \in S^{(c)}$ and destination node $d \in D^{(c)}$. Let $v_i$ be the speed of node $i$ in meter per second.

The maximum speed of route $r$ is defined as follows:

$$ v_r = \max(v_{i_0}, v_{i_1}, \ldots, v_{i_{h-1}}) $$

### Table I. Formulation parameters.

| $\tau$ | The network lifetime defined as the time it takes for the first node to die. |
| $T_i$ | The lifetime of node $i$. |
| $T_G$ | The lifetime of the network $G$. |
| $p_i$ | The transmission power from node $i$ to node $j$. |
| $P_i$ | The maximum allowed transmission power of node $i$. |
| $P_{\max}$ | The maximum transmission power of network nodes. |
| $E_i$ | The initial energy for node $i \in N$. |
| $\nu_i$ | The energy for transmitting one bit across the link $(i, j) \in L$. |
| $v_i$ | The speed of node $i$ in meter per second. |
| $f_i$ | The flow of commodity $c$ transmitted from node $i$ to node $j$ per second. |
| $f^{(c)}_i$ | The amount of bits of commodity $c$ transmitted from node $i$ to node $j$ in the network lifetime $T$. |
| $Q_i^{(c)}$ | The rate at which bits are generated at node $i$ per second belonging to commodity $c \in C$. |
| $TQ_i^{(c)}$ | The rate at which bits are generated at node $i$ over the network lifetime $T$ belonging to commodity $c \in C$. |
| $\gamma_{ij}$ | The SINR requirement for the transmission from node $i$ to node $j$. |
| $\alpha$ | The distance-power gradient. |
| $\beta$ | The transmission quality parameter. |
| $d_i$ | The Euclidean distance between the nodes $i$ and $j$. |
| $\sigma$ | The ambient noise level. |
| $\nu_r$ | The ambient noise power level. |

The best route $r_{\text{min}}$ is the route with the minimum speed nodes.

We select a route $r_{\text{min}}$ from $m$ available routes as,

$$ r_{\text{min}} = \min(v_1, \ldots, v_m) $$

The notations for the formulation are summarized in Table I for convenience.

### 3. CROSS-LAYER DESIGN

In the previous section, we introduced the formulation for the maximum network lifetime problem using a flow constraint in the transport layer, the route selection in the network layer, and an interference-aware topology control in the MAC layer. In this section, we propose a cross-layer solution for these problems. We introduce a distributed protocol that jointly considers these three problems. The protocol is localized and distributed (i.e., depends only on the first hop information and there is no central processing node). The traditional layering design ignores the overall requirements of the network design, the dependence between the protocol layers, and the dynamic characteristics of ad hoc networks. As a result, the resulting protocols may not be adaptive. As shown in Figure 1(a), a cross-layer design allows information integration between the protocol.
layers, so that the changes could affect more than one layer, and then each layer responds appropriately to the changes in other layers [12].

We propose a cross-layer mobility-aware routing and interference-aware topology control protocol. As shown in Figure 1(b), we consider the SINR constraint Equation (10) in MAC layer and throughput constraint in the application layer. We use the routing protocol control messages to exchange the transmission power and speed information in order to avoid communication overhead. The routing decision is affected by the speed information to satisfy the routing metric in Equation (13).

The AODV routing [8] is one of the most studied routing protocols for MANETs. AODV is a reactive routing protocol. Routes between hosts are determined only when they are explicitly needed to forward packets. Reactive methods therefore generate low control traffic and routing overhead. Another known reactive protocol is the Dynamic Source Routing (DSR). DSR uses source routing. The sender knows the complete hop-by-hop route to the destination. These routes are stored in a route cache. The data packets carry the source route in the packet header. AODV outperforms DSR in higher mobility situations. However, DSR consistently generates less routing load than AODV [30].

In this paper, we present our solution to the mobility-aware routing and interference-aware topology control problem, defined in Section 2, as a mobility and interference-aware extension to the AODV protocol for MANETs. In AODV, when a source node requires a route, it broadcasts a route request message (RREQ). When the desired destination node receives the RREQ messages, it chooses the best route (i.e., the shortest-hop route) and then uses it to send a route reply RREP to the sender node. The sender node then uses this route to send the data [8]. As the shortest-hop route is used in AODV, the nodes in this route will lose their energy and die earlier than other nodes in the longer routes. The network lifetime is decreased extensively when a source sends packets to the same destination more than once.

The proposed MRIT protocol uses routing control messages to avoid extra message overhead. In MRIT, the RREQ message will trigger the topology control. The received nodes adjust their transmission power before forwarding it to the other nodes according to the SINR constraint in Equation (10). Then, this RREQ message will maintain maximum speed. Then, the destination node will receive the RREQ messages with their maximum speed according to Equation (12), and uses the minimum one to send the RREP message as in Equation (13). We assume that the destination node has enough energy to receive the packets, which is a common assumption for wireless ad hoc networks (e.g., [31]).

4. PROPOSED PROTOCOL DESIGN

The proposed protocol is designed to use the well-known AODV protocol. In the proposed protocol, a speed parameter is used to choose the best route, combined with an interference-aware topology control protocol. In the following paragraphs we outline the detailed steps for the proposed MRIT protocol.

INPUT: $m$ available routes from $s \in S^c$ to $d \in D^c$, associated with node’s speed.

OUTPUT: the updated transmission power $p_{ij}$, and the selected data route $r_{ij}$ from $s \in S^c$ to $d \in D^c$.

Procedure: Route-request ($s \in S^c$, $d \in D^c$).

- Step 1: $s$ broadcast RREQ for all neighbor nodes.
- Step 2: $\forall i \in R - s, d$.

(1) Compute-new-power($d_{ij}$): node $i$ will adjust its own transmission power $p_{ij}$ taking into considerations the topology and SINR constraints.
communication complexity as the proposed one does not use between AODV and the proposed MRIT protocol in communication complexity for AODV and the proposed MRIT protocol is $O(n^2)$ steps. The communication complexity for AODV and the proposed MRIT protocol is $O(n^2)$ where $n$ is the total number of nodes. The extra time comes from the transmission power update could be $nb$. If the longest route length is $k$, the AODV routing protocol time complexity is $O(k)$ [8]. If the maximum node degree (number of neighbors) is $nb$, then the time complexity for the proposed MRIT protocol is $O(k \times nb)$. In the worst case, each node may have $n$ neighbors, so the time complexity could be $O(k \times n)$ where $n$ is the total number of nodes. The extra time comes from the transmission power update steps. The communication complexity for AODV and the proposed MRIT protocol is $O(n)$. There is no difference between AODV and the proposed MRIT protocol in communication complexity as the proposed one does not use any extra control messages.

5. IMPLEMENTATION AND SIMULATION SCENARIO

The AODV routing protocol implementation is available in ns-2 network simulator as the default standard routing protocol for MANETs [32]. We implement the proposed MRIT protocol using C++ in ns-2 network simulator. Our code is available in our research group website [33]. In our implementation, we consider the followings:

- We implement the proposed transmission power computation using ns-2 shadowing propagation model [32] with a path loss exponent $\alpha = 3$ and $\beta = 1$ [19,34].
- We use the extended cumulative interference model [35] with the original Mac802.11 implementation in ns-2 to implement the SINR constraint in Equation (10) with $\gamma_j = 1$ (i.e., received power should be more than or equal to noise power and accumulated interference power).

We consider a typical mobile ad hoc network with 100 mobile nodes randomly moved over a $1500 \times 300$ m$^2$ rectangle flat space [36] for 1 h (i.e., 3600 s) as a testing environment. To compare the AODV protocol and the proposed MRIT protocol with identical loads and environmental conditions, each simulation implementation accepts the following scenario files as inputs:

- The first file is the node positions and their initial transmission range. The nodes are uniformly distributed in a $1500 \times 300$ m$^2$ area, and the initial transmission range is uniformly distributed between 250 m and 300 m.
- The second file is the packet sequence originated by each node. The traffic source is a constant bit rate (CBR) with a sending rate of four packets per second. The network contains 32 CBR connections with a packet size of 512 bytes. The connections are started at times uniformly distributed between 0–1600 s to avoid drop packets caused by simulation time end.
- The third file is the nodes mobility scenario. The nodes are moved according to a random trip model. At a trip transition instant, a node picks a trip destination uniformly at random on a rectangular area and samples numeric speed from a uniform distribution. The trip path is the straight line that connects node positions at this and next trip transition instant. Upon reaching the trip destination, the node may pause for a random time drawn from a uniform distribution. This trip selection rule repeats. It used the perfect sampling algorithm implementation from References [37,38]. The proposed protocol and the AODV tested for 0, 600, 1200, 1800, 2400, 3000, and 3600 s pause times and the maximum speed is 20 m/s. A pause time of 0 s means high mobility, and a 3600 s pause time means nodes move once (i.e., low mobility).

This scenario is repeated 20 times using different random mobility patterns, speed and traffic scenarios. The simulation result is presented with 95 percent confidence intervals.

6. PERFORMANCE AND SIMULATION RESULTS

We have conducted a performance evaluation and a comprehensive comparison with AODV as the default standard reactive routing protocol for MANET using the simulation scenario described in Section 5.

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6.1. Performance metrics

We test the proposed protocol to check the energy efficiency by calculating the energy consumption rate [39], and the network lifetime [40]. The throughput and drop ratio are measured to show the effect of less energy consumption on the throughput requirement. The node degree is calculated to measure the nodes interference [41]. The end-to-end delay is calculated to include all the possible delays caused by the routing, MAC, or propagation and transmission time. Our goal of topology control is to reduce network interference while preserving the network connectivity. We measure interference by the physical node degree and we measure the connectivity by the network connectivity ratio [42]. The performance metrics are described in details as follows:

- **Energy consumption rate**: we compute the energy consumed per byte as follows:

\[
\text{Energy consumed per byte} = \frac{\text{Total energy consumed}}{\text{Total throughput}} \tag{14}
\]

The total energy consumed includes the total energy consumed in the receipt and transmission.

- **Average node degree**: to measure the effect of the transmission power updates on interference, we compute the average nodes degree. The physical node degree of any node is the number of nodes within its transmission range.

- **Throughput**: we compute the network throughput as the total number of received bytes per second.

- **Drop ratio**: we compute the packets drop ratio as the ratio between the number of dropped packets to the total packets sent during the simulation time.

- **End-to-end delay**: the time a packet takes to be transmitted across a network from the source to the destination. We compute the average delay for all received packets.

- **Network lifetime**: the network lifetime is defined as the time it takes for the first node to die.

- **Connectivity ratio**: a pair of nodes said to be connected if at least one path exists between them. A network is said to be connected if at least one path exists between any two nodes in the network [4]. We calculate the connectivity ratio as the ratio between number of connected pairs and all possible pairs at every time instance (i.e., every 2 s). We compute the average for the total simulation time.

6.2. Simulation results

In this paper, we take into consideration the mobility degree (i.e., pause time) parameter to test the impact of mobility. The proposed protocol (MRIT) performs better at a higher mobility for the simulated MANET environment described in Section 5. In Figures 2–8, we show the different performance metrics by comparing the proposed MRIT protocol with AODV protocol. These figures show the simulation results for a set of motion pause time from 0 to 3600 (i.e., from high mobility to almost no mobility). Figures 2, 3, and 4 indicate how AODV and the proposed MRIT protocols consume energy. In Figure 2, we show the
energy consumption rate verses pause time. The proposed MRIT protocol decreases the energy consumption rate by 30–50% compared to the AODV. This decrease is due to less retransmission, so that the end-to-end delay is decreased by the proposed MRIT as shown in Figure 6. Furthermore, the network lifetime is increased by the proposed MRIT protocol as shown in Figure 3. While the network lifetime is increased, the network connectivity is increased by the proposed MRIT as shown in Figure 4. This is due to less node failure because of energy. In Figure 5, the proposed MRIT protocol decreases the average physical node degree, which results in lower node interference. The reduction in physical node degree is not so voluminous, so it does not affect the connectivity. As a result of low interference and high connectivity, the proposed MRIT decreases the end-to-end delay by 60–90% compared to the AODV.

As a result of energy efficient and less packet retransmissions, the proposed MRIT protocol increases the throughput and decrease the drop packets ratio as shown in Figures 7 and 8, respectively. However, the energy is decreased, the throughput is increased by the proposed MRIT. This is due to the reduction of energy consumption is not so voluminous, therefore the connectivity and the throughput could be preserved. Furthermore, the property of cross-layer approach is expected to have an overall better performance not only for a single parameter.

In Figures 2–8, we show that the proposed MRIT protocol decrease the energy consumption rate, node degree, and end-to-end delay while preserving network connectivity and throughput in all mobility conditions. In addition, as a result of energy consumption reduction, the proposed MRIT increases the network lifetime.

7. CONCLUSION

We investigate a cross-layer design for routing and topology control taking interference and mobility into account for MANETs. We propose a novel cross-layer MRIT protocol to increase the network lifetime, reduce the energy consumption, and find a stable end-to-end route for all network pairs in the mobile ad hoc network. The interaction between the layers with a global performance target produces better results than dealing with each layer separately. The proposed MRIT protocol is a mobility and interference-aware extension to the AODV as the default standard reactive routing protocol for MANET. We consider the mobility parameter to determine the best route. In addition, we consider the topology control with interference constraint in a cross-layer design to avoid communication overhead. We conduct a comprehensive performance evaluation using ns-2 network simulation and compare the proposed protocol to the AODV protocol. The simulation results show that the proposed MRIT protocol reduces energy consumption rate, end-to-end delay, and interference while preserving throughput and network connectivity. We find that the proposed cross-layer protocol benefits from the interaction between the routing protocol in the network layer and interference-aware topology control in the MAC layer.

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