

Mobility-aware Energy-efficient Protocols  
for Wireless Ad Hoc Networks

Graduate School of Systems and Information Engineering  
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## Abstract

In an infrastructure wireless network, the wireless nodes are connected to access points or base stations within their transmission ranges. In contrast, the Wireless Ad hoc Network (WANET) is self-configured to build a network without any infrastructure support. In recent years, application domains of WANETs get more influence in military and non-military organizations. Such networks are scalable and adaptive. They can be extended to places, which cannot be wired and support mobility. We focus on two fundamental issues in WANET. We, firstly, focus on the topology control. Although mobile devices are becoming increasingly powerful and capable, it still holds true that such devices have a limited (battery) power supply. The topology control protocols concern with nodes' transmission power adjustment to reduce network energy consumption and interference while preserving connectivity and increasing network capacity. Secondly, we focus on routing protocol design as an essential issue for WANETs. In WANET, there is no mobility limitation thus the network topology changes dynamically causing frequent route breaks, thereby requiring the re-establishment of new routes. It is necessary to find and maintain optimized routes to the destination in a changing topology resulting from mobility or node failure due to limited power. For each of these issues, we present novel proposals, which are energy-efficient and can achieve better performance.

This dissertation proposes mobility-aware topology control protocols using the geometric graphs for WANETs with mobile nodes. We use the nodes' speed as an important parameter to update nodes' neighbor and to reduce nodes' transmission power. We propose distributed topology control protocols for updating nodes' transmission power and the dynamic network graphs according to symmetric and cone-based graphs. The proposed topology control protocols are localized in which they depend on collecting information from the one-hop neighbors only. The simulation results indicate that the proposed protocols reduce the average transmission power by more than forty to fifty percent, which result in lower throughput. Moreover, the proposed protocols reduce the average node degree while preserving network connectivity but not the throughput.

In addition, we propose energy and mobility-aware topology control protocols for WANETs with mobile nodes. These topology control protocols depend on using a utility function that considers nodes' residual energy and speed taking the geometric graphs in consideration. Simulation results show that the using of energy and speed parameters improves the preser-

vation of network connectivity and throughput. In addition, the proposed topology control protocols reduce the interference and transmission power along with highly dynamic network. The proposed protocols reduce the average transmission power by forty to fifty percent. The proposed energy and mobility-aware topology control protocols achieve the same network throughput as the maximum power network topology in high mobility network scenarios.

The traditional layering design ignores the overall requirements of the network design, the dependences between the protocol layers, and the dynamic characteristics of WANETs. As a result, the resulting protocol may not be adaptive. In this dissertation, we propose a cross-layer design for energy-efficient routing protocol. We integrate power control and routing protocol to increase the network lifetime, reduce the transmission power, and maintain the throughput requirement. We evaluate the proposed protocol by comprehensively simulating WANET environments. The results show that the proposed protocol increases the network lifetime, reduces the end-to-end delay, and saves the total energy consumption while achieving the throughput requirement.

Furthermore, we propose a cross-layer design that jointly considers routing and topology control taking mobility and interference into account. An efficient protocol called Mobility-aware Routing and Interference-aware Topology control (MRIT) protocol is proposed. The main objective of the proposed protocol is to increase the network lifetime, reduce energy consumption, and find stable end-to-end routes in WANETs with mobile nodes. The simulation results demonstrate that the proposed protocol reduces energy consumption rate, end-to-end delay, interference while preserving throughput and network connectivity.

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# Chapter 1

## Introduction

### 1.1 Wireless Ad hoc Network

A Wireless Ad hoc Network (WANET) is a collection of wireless mobile nodes that communicate with each other without any predetermined topology. In an infrastructure wireless network, the wireless nodes have wired access points or base stations within their transmission range. In contrast, WANET is self-configured to form a network without infrastructure support. Thus, WANETs can be extended to places which cannot be wired and provide mobility and access to information based on physical proximity. However, WANETs suffer from interference due to noise, other radio frequency devices, or obstructions. Communications among nodes are accomplished by forwarding data packets for each other, on a hop-by-hop basis. The features of a typical WANET are as follows [1]:

- Heterogeneity: A typical WANET is composed of heterogeneous nodes which may have different maximum transmission ranges.
- Mobility: In a typical WANET, most of the nodes are mobile.
- Relatively dispersed network: The adoption of the wireless ad hoc networking paradigm is justified when the nodes composing the network are geographically dispersed.

In recent years, application domains of WANETs gain more importance in military and non-military organizations. One of the known applications for high-mobility WANETs is the vehicle-to-vehicle communication. Vehicle-to-vehicle communication has been studied in recent years to improve driving safety [2]. Collision warning, road sign alarms and in-place traffic view will give the driver essential tools to decide the best path along the way. Another

typical application for WANETs is the disaster relief environment. In such networks, the wireless nodes in the field are battery operated and not easy to recharge [3]. As more of such applications emerge, it is critical to have energy-efficient protocols. In this dissertation, we focus on two essential protocols in WANETs. First, the topology control protocols which concern with nodes' transmission power adjustment to reduce network energy consumption and interference while preserving connectivity and increasing network capacity. Second, we focus on routing protocol design to find and maintain optimized routes to the destination in a changing topology resulting from mobility or node failure due to limited power.

## 1.2 Topology Control

Since the topology of a WANET frequently changes, the original data transmission routes can become disabled. The desired effect of a topology control is to reduce the energy consumption and interference while preserving the network connectivity. Topology control protocols concern with nodes' transmission range adjustment to reduce network energy consumption and interference while preserving connectivity and increasing network capacity.

Figure 1.1 shows an example of the connectivity problem in WANETs. As shown in Figure 1.1 (a), at time  $T$ , node  $i$  and node  $j$  communicate with each other. Therefore, node  $i$  communicates with node  $k$  using node  $j$  as a relay. Then, as shown in Figure 1.1 (b), at time  $T + 1$  node  $j$  moves out of node  $i$  transmission range and the link  $i - j$  is disconnected. As a result, node  $i$  cannot communicate with node  $k$  and the route  $i - j - k$  cannot be used. Topology control protocols can be homogeneous or heterogeneous as in Figure 1.2. In the homogeneous topology control, all the network nodes must use the same transmitting range (e.g. [4], [5], [6]). In heterogeneous topology control, nodes can choose different transmitting ranges between the minimum and maximum allowed ranges (e.g. [7], [8]). Several other examples can be found in [1].

Heterogeneous topology control is classified into three categories, depending on the information that is used to compute the topology. In location-based approaches (e.g. [8]), it is assumed that the information about node location is known. This information is either used by a centralized authority, or it is exchanged between nodes and used to compute the topology in a fully distributed approach. In direction-based approaches (e.g. [9]), it is assumed that nodes do not know their positions, but they can estimate the relative direction

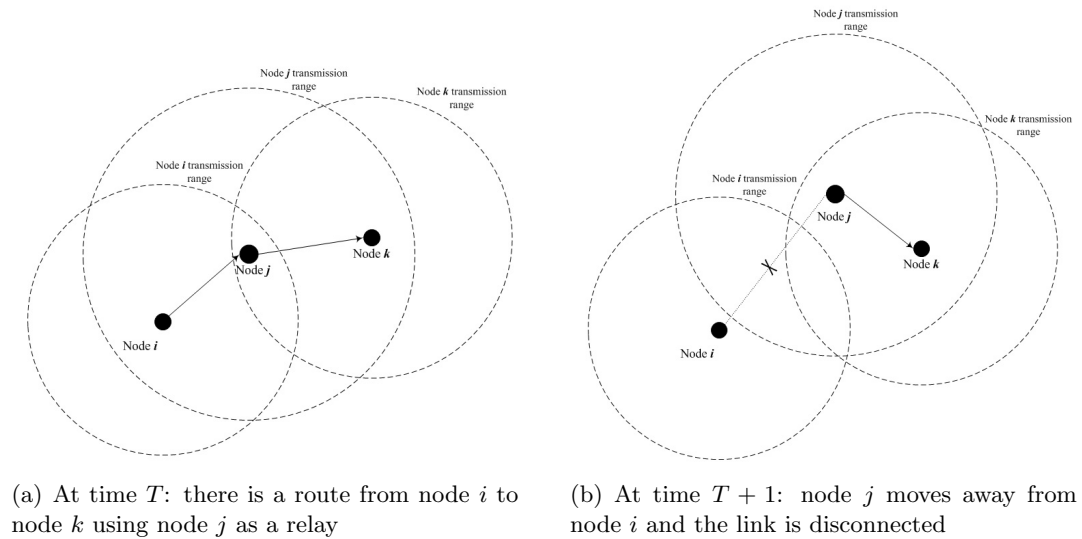


Figure 1.1: An example of connectivity problem

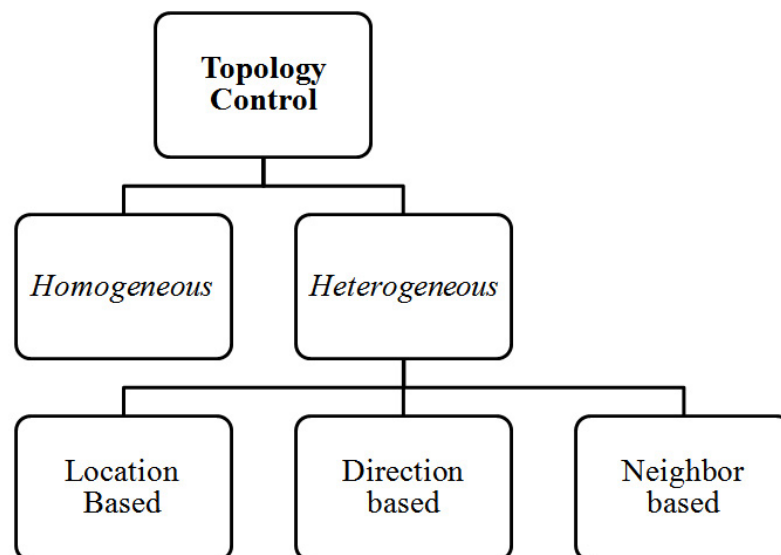


Figure 1.2: Topology control protocols classification

of their neighbors. In neighbor-based techniques (e.g. [10], [11]), nodes are assumed to have access to a minimal amount of information regarding their neighbors, and to order them according to some criterion such as distance, or link quality.

Topology control approaches are also classified according to how often the topology is updated to per-packet and periodical topology control. In the per-packet approach, every node maintains a list of efficient neighbors and the choice of the transmit power to use is done on a per-packet basis. When the packet is destined to a certain neighbor, the relevant power is set, and the packet is transmitted (e.g. [12]). In the periodical topology control approach, every node maintains a list of efficient neighbors. However, differing from per-packet techniques, a node uses a single transmit power to communicate with all the neighbors. This power can be intended as the higher of the transmit powers needed to reach the neighbors in the list. Periodically, the broadcast power level setting used by the node is updated, in response to node mobility and/or neighbor failures (e.g. [13]).

In this dissertation, we propose two distributed heterogeneous topology control protocols for WANETs. In the first one, we consider the mobility parameter and in the second one we consider both mobility and energy parameters in Chapter 3 and Chapter 4 respectively.

### 1.3 Routing Problem

Routing protocol design is an essential issue in WANETs due to energy and mobility constraints. Routing protocols is classified to proactive routing, reactive routing and hybrid routing [14]. This classification is based on how routing information is discovered and maintained by the wireless nodes. Proactive (i.e. table-driven) methods maintain routes to all nodes, including nodes to which no packets are sent. Such methods react to topology changes, even if no traffic is affected by the changes. They periodically exchange topology information to maintain and update routes. Examples of proactive routing protocols are Optimized Link State Routing (OLSR [15]) and Destination Sequenced Distance Vector (DSDV [16]). Reactive (i.e. on-demand) methods are based on demand for data transmission. 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 [17]) and Dynamic Source Routing (DSR [18]). Hybrid methods combine proactive and reactive methods to find more efficient routes, without much control overhead as Zone

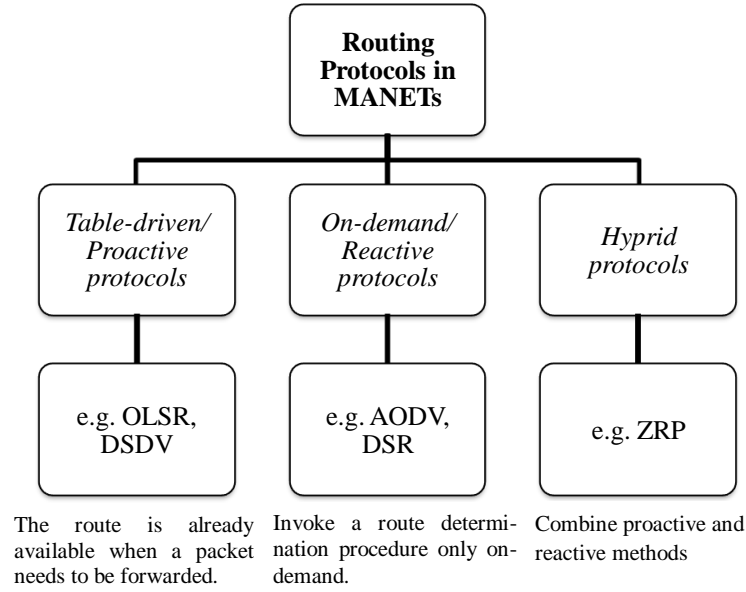


Figure 1.3: Routing protocols for WANETs

Routing Protocol (ZRP [19]). Figure 1.3 summarizes routing types with examples. Some studies [2, 20–23] have been done to evaluate the performance of the proactive and reactive routing protocols. Broch *et al.* [23] report a detailed packet simulation comparative study of AODV, DSR, TORA and DSDV. They show that DSR and AODV achieve good performance at all mobility speeds, whereas DSDV and TORA perform poorly under high speeds and high loads conditions respectively. Mbarushimana and Shahrabi [20] evaluates the performance of reactive (AODV, DSR) and proactive (OLSR) routing protocols for WANETs under Constant Bit Rate (CBR) traffic with mobile nodes and different network conditions. Their results contrarily to previously reported studies conducted on the same routing protocols. They show the superiority of proactive over reactive protocols, in routing such traffic, at a higher load. However, when the offered load to the network and the size of the network increases, a hop-by-hop routing protocol like AODV is more desirable. We choose AODV as a basic routing protocol to implement the proposed protocols and test their performance. In this dissertation, we propose two solutions for energy-efficient routing for WANET with static and mobile nodes. First, we consider routing jointly with power



control. Furthermore, we consider routing jointly with topology control in Chapter 6 and Chapter 7 respectively.

## 1.4 OSI Layered and Cross-layer Models

In the OSI (Open System Interconnections [24]) model, a communication network is divided into seven independent layers. Each ( $N$ )-layer uses the services of the lower ( $N - 1$ )-layer and adds the functionality peculiar to the ( $N$ ) layer to provide service to the ( $N + 1$ )-layer above. Layers can be considered relatively independently. The traditional layering model, however, as shown in Figure 1.4 (a), ignores the overall requirements of the network design, the dependences between protocol layers, and the dynamic characteristics of WANETs. As a result, the resulting protocols may not be adaptive and far from optimal. Recent related work shows that significant performance improvement can be achieved by considering cross-layer design for WANETs [25–28]. Cross-layer design with respect to reference layered architecture is the design of algorithms, protocols, or architectures that exploit and provide a set of interlayer interactions. These interactions are supersets of the standard interfaces provided by the reference layered architecture. Cross-layer architecture supports comprehensive state variables that are accessible to all communication layers. Cross-layer designs of link, multiple access, network, and application layers protocols are imperative to meet emerging application requirements, particularly when energy consumption is a limited resource [29]. As shown in Figure 1.4 (b), cross-layer design allows information integration between protocol layers, so that the changes could affect more than one layer, then each layer responds appropriately to the changes in other layers [30].

## 1.5 Research Contribution

The dissertation makes contributions to the topology control and routing protocols for WANETs in terms of energy-efficiency. We propose four protocols.

1. **Mobility-aware topology control protocols.** We propose mobility-aware geometric graphs for topology control protocols for WANETs with mobile nodes. We use the nodes' speed to update nodes' neighbor set and to reduce nodes' transmission power. The proposed graphs are localized in which they depend on collecting information from the one-hop neighbors only. In

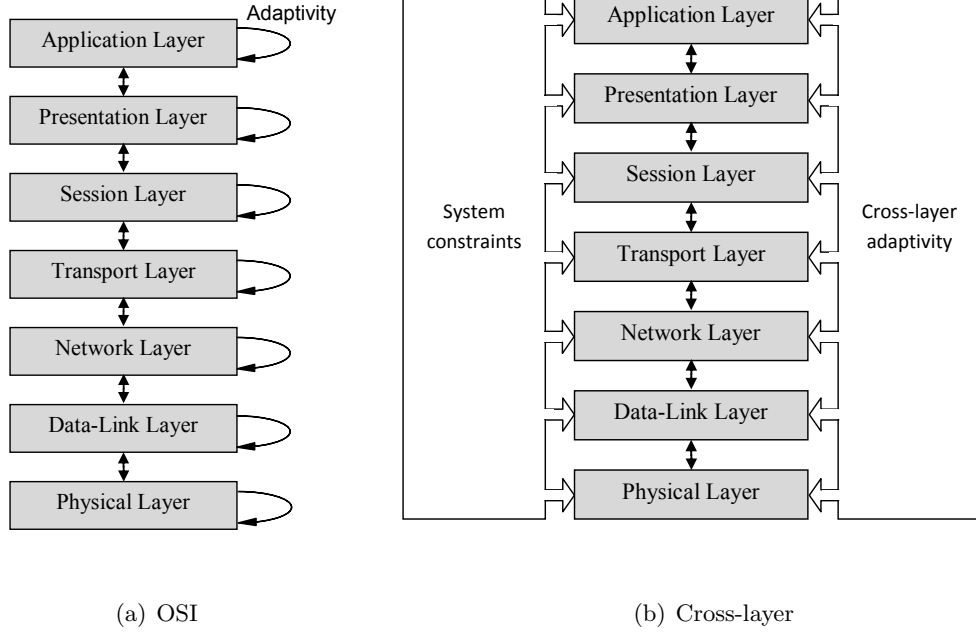


Figure 1.4: OSI model and Adaptive cross-layer model

the proposed graphs, each node transmission power is tuned according to its neighbors moving speeds. Nodes then update their neighbors list according to their updated transmission power. We propose distributed topology control protocols for updating nodes' transmission power and the mobile network graphs according to symmetric and cone-based graphs. The simulation results show that the proposed protocols reduce the average transmission power by more than 40 to 50 percent. This reduction in the transmission range results in less throughput. The proposed protocols reduce the average node degree while preserving network connectivity.

2. **Energy and Mobility-aware topology control protocols.** We propose energy and mobility-aware topology controls for WANETs with mobile nodes. These topology control protocols depend on using a utility function considers nodes' residual energy and speed. Then, the utility function is applied on the symmetric and cone-based geometric graphs. The simulation results show that using the energy and speed parameters improves the preservation of network connectivity and throughput. In addition, the proposed topology control pro-

protocols decrease the interference and transmission power along with highly dynamic network. Consequently, the proposed energy and mobility-aware topology control protocols achieve same but not better network throughput than the maximum power network topology.

3. **Cross-layer design for energy-efficient routing for WANETs.** The main objective of the cross-layer design is to achieve an overall performance. We propose a cross-layer design for energy-efficient routing protocol. The proposed cross-layer integration between power control in link layer and routing protocol in the network layer aims to increase the network lifetime, reduces the transmission power, and maintains the throughput requirement. We evaluate the proposed protocol by comprehensively simulating a set of random WANET environments. The results show that the proposed protocol increases the network lifetime, reduces the end-to-end delay, and saves the total energy consumption while achieving the throughput requirement.
4. **Cross-Layer Design for topology control and routing for WANETs with mobile nodes.** We propose a cross-layer design that jointly considers routing and topology control taking mobility and interference into account. An efficient protocol called Mobility-aware Routing and Interference-aware Topology control (MRIT) protocol is proposed. The main objective of the proposed protocol is to increase the network lifetime, reduce energy consumption, and find stable end-to-end routes for WANETs with mobile nodes. The simulation results show that the proposed protocol reduces energy consumption rate, end-to-end delay, interference while preserving throughput and network connectivity.

## 1.6 Dissertation Organization

The presented dissertation is structured as follows. **Chapter 1** is an introduction that defines the scope of the dissertation. **Chapter 2** presents the preliminaries and formulation used in the research. **Chapter 3** explains the proposed mobility-aware solution for the topology control problem. **Chapter 4** describes the proposed energy and mobility-aware topology control protocol. **Chapter 5** explains cross-layer concepts, motivation, and examples. **Chapter 6** presents the proposed cross-layer design for energy-efficient

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routing protocol for WANETs. **Chapter 7** presents the proposed cross-layer design for interference-aware topology control and mobility-aware routing protocol for WANETs with mobile nodes. **Chapter 8** concludes the dissertation and presents future work.

## Chapter 2

# Preliminaries and Formulation

In this chapter, we introduce a simple but widely accepted communication model of wireless ad hoc network (WANET). WANET is formulated as a graph where the vertexes present the network nodes and the edges between any two nodes presents a link exists between these two nodes. We introduce the geometric graphs that are used in Chapter 3 and Chapter 4. In addition, we give a brief introduction for linear programming formulation that is used in Chapter 6 and Chapter 7.

### 2.1 Communication Model

The WANET topology can be described by a communication graph. That is, the set of wireless links that the nodes can use to communicate with each other. The WANET is presented as a graph  $G = (N, L)$ .  $N$  is a set of wireless devices, and  $L$  is a set of all directed links  $(i, j)$  where  $i, j \in N$ . The existence of a link between two nodes  $i$  and  $j$  in the network depends on [1]:

- the relative distance between  $i$  and  $j$ ,
- the transmit power used to send the data, and
- the surrounding environment.

In the rest of this dissertation, we will model the wireless channel using the log-distance path model, which abstracts many characteristics of the environment. This assumption is standard in research on topology control in WANETs [1]. This model can be seen as a generalization of both the free space and the two-ray ground model, indicates that the average long-distance path loss is proportional to the separation distance between node  $i$

and node  $j$ ,  $d_{ij}$  raised to a certain exponent  $\alpha$ , which is called the path loss exponent, or distance-power gradient. Formally,

$$P_j \propto \frac{P_i}{d_{ij}^\alpha} \quad (2.1)$$

The radio coverage region in this model is a disk of radius proportional to  $\sqrt[\alpha]{P_i}$  centered at the transmitter  $i$  where  $j$  is the receiver. The value of  $\alpha$  depends on the environmental conditions, and it has been experimentally evaluated in many scenarios [1]. Table 2.1 summarizes some of these values. Another parameter that indicates the success of receiving

Table 2.1: Values of path loss exponent parameter

Environment	$\alpha$
Free space	2
Urban area	2.7-3.5
Indoor line of sight	1.6-1.8
Indoor no line of sight	4-6

packets is the Signal to Interference plus Noise Ratio (SINR). SINR is the ratio of the received power of the desired signal to the received power of noise and cumulative interference. The SINR at the receiver node  $j$  from sender node  $i$  formally defined as

$$SINR_{ij} = \frac{P_{ij}/d_{ij}^\alpha}{\sum_{(k,j) \in L} P_{kj}/d_{kj}^\alpha + \sigma} \quad (2.2)$$

where  $k$  is any node interfering with node  $i$  at node  $j$ , and  $\sigma$  is the white Gaussian noise.

## 2.2 Geometric Graphs

The motivation of using the theory of Geometric Random Graphs (GRG) stems from the fact that, a simpler model that abstract away the physical layer details to represent the WANET is graph [14]. The theory of GRG can be seen as an extension to the traditional random graph theory in which the graph is not considered as an abstract entity (set of nodes connected by a number of edges), but as a geometric entity (set of points in the  $d$ -dimensional space, connected based on a proximity relation) In the theory of GRG, points are distributed according to some probability distribution in a certain region. Points are then connected according to some rule [1]. Proximity graphs are a class of graphs introduced in the theory of computational geometry that are based on proximity relationships between

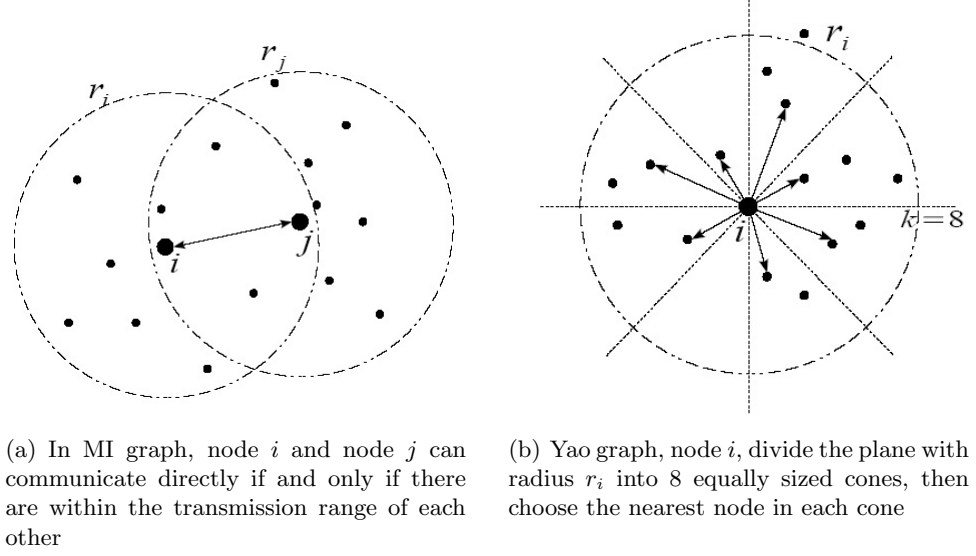


Figure 2.1: MI and Yao graphs

nodes. The following proximity graphs have been considered in this dissertation. The communication model in WANETs is formulated by proximity graphs, where nodes are connected according to the Mutual Inclusion (MI) graph (Figure 2.1(a)) or Yao graph (Figure 2.1(b)). Let  $G$  be a heterogeneous WANET graph,  $G = (N, L)$ , where  $N$  is a set of nodes distributed in 2-dimension plan, with  $|N| = n$  representing the mobile nodes and  $L$  is a set of wireless links, pairs of ordered elements of  $N$ . Each node  $i$  has a transmission range  $r_i$ .

The MI graph could be used to model heterogeneous WANETs, as there is no assumption for equally transmission ranges. The MI graph is defined as follows [7].

**Definition 1.** Mutual Inclusion (MI) graph. In a MI graph, two nodes can communicate directly if and only if they are within transmission range of each other. Formally,  $MI = (N, L)$  is defined as follows. There is a link  $l_{i,j} \in L$  if and only if  $d_{ij} \leq \min(r_i, r_j)$ , where  $d_{ij}$  is the Euclidean distance between nodes  $i$  and  $j$ .

Another basic proximity graph used in topology control problem research work is Yao graph. The basic Yao graph is defined as follows [31].

**Definition 2.** Yao Graph. Given a set of  $N$  nodes in the 2-dimension plane, and an integer  $k \geq 6$ , the Yao Graph of a parameter  $k$  is the directed graph  $Yao_k = (N, L_k)$  defined as follows.

For each node  $i \in N$ , divide the plane with radius  $r_i$  into  $k$  equally sized cones originating at node  $i$ . Denoting the cones for node  $i$  by  $C_i^1, \dots, C_i^c, \dots, C_i^k$ . There is a link between node  $i$  and node  $j$ ,  $l_{i,j} \in L_k$  if and only if node  $j$  is the closest neighbor of node  $i$  in  $C_i^c$ , where  $L_k$  is the set of links generated by Yao graph with parameter  $k$ .

## 2.3 Linear Programming Optimization

Linear programming (LP) is a powerful and remarkably versatile tool which is widely applied in business activities, industry manufacturing, military activities, information techniques, etc. [32]. There are three basic steps in the linear programming model of formulations: 1) determination of the decision variables; 2) formulation of objective; 3) formulation of the constraints [32]. Network optimization problems are a class of important applications of linear programming. Typically, the min-cut max-flow problem, the shortest path problem and the minimum cost-flow problem can be formulated as linear programming problems [32, 33]. In our dissertation, the energy-efficient routing problem in WANETs is defined with LP, where the objective is to maximize the network lifetime. Furthermore, we define the topology control problem with the objective of minimizing the maximum transmission power. The detailed LP formulation and constraints are defined in Chapter 6, and Chapter 7.



## Chapter 3

# Mobility-aware Topology Control in WANETs

In this chapter, we propose topology control algorithms in heterogeneous wireless ad hoc networks with mobile nodes, where mobile nodes have different transmission ranges, and moving speeds. We propose mobility-aware geometric graphs in which the mobility parameter has been used instead of the distance parameter to reduce nodes' transmission power. To study the performance of the proposed protocols, WANET with high mobility nodes has been simulated.

### 3.1 Introduction

A wireless ad hoc network (WANET) is a kind of heterogeneous wireless network formed by a set of mobile nodes in a self-organizing way without the need for a fixed infrastructure. In WANETs all nodes cooperate to achieve certain goal tasks, such as fast traffic information delivery on highways and urban areas, ubiquitous Internet access, and delivery of location-aware information. WANETs raise many challenging research problems as it has some unavoidable limitations as memory, energy, and processing elements. One of the challenges for WANETs is to minimize the energy consumption. Topology control protocols concern with nodes' transmission range coordination to reduce energy consumption and interference while preserving connectivity and/or increasing network capacity. WANETs usually suffer from the topology connectivity problem. Connectivity problem appears when any message sent at one time slot between two connected nodes and one of the nodes moved before

the topology is updated, so the topology will be out of date, and may be disconnected. The localized solution has the advantage that nodes depend on collecting information from the one-hop neighbors only. In WANETs, topology control protocols can be seen as a layer between the routing layer and medium access control (MAC) layer [1]. The topology control protocol sets the new transmission range to the MAC layer, and updates the neighbor-list used for the routing layer.

## 3.2 Related Work

The most prior research on network topology control assumed that WANETs are modeled by unit disk graphs (UDG) [5][6], where nodes are static (i.e. not moving). In UDG, nodes can communicate with each other as long as their Euclidean distances are no more than a constant threshold. UDG cannot be perfectly used with heterogeneous WANETs, in which the maximum transmission range of wireless devices may vary and each node may have its own transmission range. To solve the problem with UDG, the Mutual Inclusion (MI) graph is proposed in which, two nodes can communicate directly if and only if they are within transmission range of each other [7]. Also Yao graph [31] is proposed for topology control in heterogeneous WANET. In Yao graph, each node divides its transmission range to equally size cones then communicate with the nearest neighbor in each cone. Yao graph and its extensions [5] [6] [7] [34] are proven having good characteristics in the topology control in respect of sparseness, bounded node degree, and can be constructed locally in an efficient way. However, nodes in heterogeneous WANETs modeled by MI graph, Yao graph and its extensions are assumed being static in the previous work. Wu *et al.* [11] has studied the topology control for WANETs where nodes may move but have the same maximum transmission ranges. They propose mobility-sensitive extensions for many of the mobility-insensitive topology control protocols that have already been introduced for WANETs. The research depends on solving the problem of inconsistency that emerged from node mobility. This research extends the relative neighborhood graph (RNG), minimum spanning tree (MST), and shortest path tree (SPT) based protocols by two different mechanisms. The first is consistent local views that avoid inconsistent information and delay. The second is the mobility management that tolerates outdated information.

The Directed Relative Neighborhood Graph (DRNG) [10] is a localized topology control algorithm for heterogeneous networks depending on RNG. Song *et al.* [35] propose Ordered

Yao graph (OrdYaoGG) topology control structure applies the ordered Yao structure on Gabriel graph structure. In OrdYaoGG, all nodes have same maximum transmission ranges and uses only 1-hop information. The final topology is a planar graph, whose node degree is bounded. Li *et al.* [7] propose geometric graphs for topology control problem which are based on MI graph. EYG<sub>k</sub> graph, extends the Yao graph with MI initial graph, in which each node  $i$  partitions its transmission region into  $k$  equal-sized cones. In each cone, node  $i$  keeps the closest communication neighbor  $j$ , if the transmission range of  $j$  is more than or equal the transmission range of node  $i$ , preserving bidirectional links. Another extension is EYG<sub>k</sub><sup>\*</sup> graph, which extends EYG<sub>k</sub> graph. It depends on sink structure. It replaces the directed star in a Yao graph consisting of all links toward a node  $j$  by a directed tree  $T(j)$  with  $j$  as sink. Sink node  $j$  constructs a Tree  $T(i)$  rooted at  $i$ , where  $i$  is some in-neighbor of  $j$  in EYG<sub>k</sub> graph. Then it informs the end nodes of the selected links to keep such links if they already exist or add it otherwise. EYG<sub>k</sub> and EYG<sub>k</sub><sup>\*</sup> graphs both are sparse and have constant bounded power and length stretch factors. EYG<sub>k</sub><sup>\*</sup> has a bounded node degree. These extensions assume a static network without mobility in WANETs.

### 3.3 Proposed Proximity Graphs

To deal with the node mobility for WANETs, we here introduce two extensions to MI graph and Yao graph, respectively.

#### 3.3.1 Proposed Mobility-aware Mutual Inclusion Graph

MI graph should be used to model heterogeneous WANETs, as there is no assumption for equally transmission ranges. The Mobility-aware Mutual Inclusion (MMI) proposed graph is a mobility-aware extension to MI graph to deal with motion parameter. MMI graph is defined as follows.

**Definition 1.** Mobility-aware Mutual Inclusion (MMI) graph. Let  $MI_T = (N, L)$  be the maximum power MI graph at time  $T$ , where  $T$  is updated when the node changes its position, and  $MI'_T = (N, L')$  be the sub-graph generated by MMI graph as follows: Each node  $i \in N$ , with transmission range  $r_i$  and speed  $\nu_i$  chooses the slowest neighbor  $j$  that satisfies  $r_j \geq r_i$ , and  $\nu_j \leq \nu_i$ .

Algorithm 1 shows how to construct the MMI graph. From MMI construction steps, we can see that MMI is a localized protocol as it depends only on speed information from only first-hop neighbors.

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**Algorithm 1** *MMI graph construction steps*

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- 1: Each node  $i$ , with transmission range  $r_i$  and speed  $\nu_i$  locally broadcasts a message with  $ID_i$  and its speed  $\nu_i$  to all first-hop neighbors  $Neigh(i)$  in its transmission range.
  - 2: When node  $i$  updates its position:  $i$  checks for all neighbors, and chooses  $j$  as new neighbor if:
    - $j$  has the minimum speed  $\nu_j$  among all neighbors of  $i$ .
    - The transmission range  $r_j \geq r_i$  which ensures bi-directional links, and
    - The speed  $\nu_j \leq \nu_i$  which ensures the connectivity.
  - 3: Each node  $i$  updates its neighbor list, and updates the transmission range according to the new neighbors.
  - 4: MMI graph is the union of all chosen links.
- 

### 3.3.2 Proposed Mobility-aware Yao Graph

The proposed extension for Yao graph, Mobility-aware Yao MYao $_k$  graph, is constructed using MI graph as an initial graph, considering mobility parameter. Yao graph based on MI graph is connected if MI is connected. Yao graph extensions in WANETs [7], have bounded node degree and are energy-efficient. Here we propose a mobility-aware extension for Yao graph to deal with mobility parameters instead of distance parameters. The proposed MYao $_k$  can be defined as follows.

**Definition 2.** Mobility-aware Yao (MYao $_k$ ) graph. Let  $MI_T = (N, l)$  be the maximum power MI graph at time  $T$ , where  $T$  is updated when the node changes its position, and  $MI'_T = (N, L')$  be the sub-graph generated by MYao $_k$  as follows.

Given an integer  $k \geq 7$ , each node  $i \in N$ , with transmission range  $r_i$  and speed  $\nu_i$ , divides its plane into  $k$  equally sized cones  $C_i^1, \dots, C_i^c, \dots, C_i^k$  originating at node  $i$ . In each cone node  $i$  chooses the slowest neighbor  $j$  that satisfies  $r_j \geq r_i$ , and  $\nu_j \leq \nu_i$ . Assuming the network consists of  $N$  nodes and initial topology is MI graph.

Algorithm 2 shows how to construct MYao $_k$  graph. From MYao $_k$  construction steps, we can see that MYao $_k$  is a localized protocol as it depends only on direction and speed information from only first-hop neighbors.

**Algorithm 2** *MYao<sub>k</sub> construction steps*

- 
- 1: Each node  $i$ , with transmission range  $r_i$  divides the disk  $d(i, r_i)$  of  $\pi$  angle around the node, into  $k$  equal sized cones each with angle  $2\pi/k$ . These cones can be represented with its number and center node as  $C_i^1, \dots, C_i^c, \dots, C_i^k$ .
  - 2: Each node  $i$  locally broadcasts a message with  $ID_i$  and its speed  $\nu_i$  to all first-hop neighbors  $Neigh(i)$  in its transmission range.
  - 3: When node  $i$  updates its position:  $i$  checks for all neighbors, and add  $j$  to  $C_i^c$ , if:
    - $j$  is inside the  $c^{th}$  cone,
    - $j$  has the minimum speed  $\nu_j$  among all neighbors of  $i$  in this cone,
    - The transmission range  $r_j \geq r_i$  which ensures bi-directional links, and
    - The speed  $\nu_j \leq \nu_i$  which ensures the connectivity.
  - 4: Each node  $i$  updates its neighbor list, and updates the transmission range according to the new neighbors.
  - 5: MYao<sub>k</sub> graph is the union of all chosen links.
- 

**3.3.3 Proposed Graphs Properties**

To show the benefits of the two proposed graphs for the topology control in WANETs. We study the properties of the proposed graphs in this section.

For  $N$  nodes, Let  $MI_T(N, L)$  be the maximum power MI graph at time  $T$ , and  $MI'_T(N, L')$  be the sub-graph generated by MYao<sub>k</sub> or MMI graphs.

*Property 1:*  $MI'_T(N, L')$  results from MYao<sub>k</sub> have a linear number of links at most  $kn$  links, where  $k$  is a constant represents the number of cones and  $n$  is the number of nodes. For example, when dividing the range around node  $i$  into  $k$  cones, it chooses only one node in each cone. So node  $i$  gets at most  $k$  neighbors. For  $n$  nodes network, links is at most  $kn$ . In the case of MMI, the number of links for each node can reach  $(n - 1)^2$  in the worst case, but in average each node chooses only one logically neighbor node so the number of links can be only  $n$ .

*Property 2:*  $MI'_T(N, L')$  results from MYao<sub>k</sub> or MMI preserves connectivity, if the initial MI graph is connected.

If the nodes are static, the condition  $r_j \geq r_i$  that ensures the bidirectional links can preserve the connectivity condition, as proved in [7].

If the nodes are mobile, the condition  $\nu_j \leq \nu_i$  can preserve the connectivity. As node  $j$  do not change its position before node  $i$ . Each time node  $i$  changes its position it recalls the graph to be updated.

### 3.4 Performance Metrics

Topology control problem aims to reduce the energy consumption and interference while preserving the connectivity. The major performance metrics, for topology control, are node degree, connectivity, transmission power and throughput. Connectivity and throughput parameters measure how the proposed graphs preserve network properties. The graphs are evaluated in terms of the following metrics.

- *Physical Node degree*: Let  $G_P = (N, L_P)$ , the communication graph generated by a certain topology control protocol  $P$ . For a given  $i \in N$ , the physical node degree of  $i$  in  $G_P$  is the number of nodes within  $i$ 's transmission range when it transmits at the broadcast power [1]. To measure the effect of the structures on the interference, average physical node degree is computed.
- *Connectivity*: A Graph  $G = (N, E)$  is connected if for any two nodes  $(i, j) \in E$ , there exists a path from  $i$  to  $j$  in  $G$  [1]. The connectivity ratio is computed as the ratio of all connected pairs to all possible pairs in  $N$ .
- *Transmission power*: average power used for every packet transmission is computed.
- *Throughput*: network throughput is computed as the total number of received bits per second.

### 3.5 Simulation Parameters

The simulation for the proposed graphs has been implemented in C++ using ns-2.30 simulator [36] and our implementation is available at [37]. We implement  $EYG_k$  graph, which uses the distance parameter [7], and the proposed  $MYao_k$  graph both with  $k = 8$ , and the proposed MMI graph. MI graph, the maximum power graph, was tested to indicate the effect of different topology control on the network properties.

The initial position for the nodes and its transmission range are randomly generated. Each graph is updated when node updates its position. The domain, in which 100 mobile nodes are distributed, is a square area  $1000 \times 1000 \text{ m}^2$ . Each node has random initial transmission range uniformly distributed between 200 m~250 m. In our simulation, we assume that the minimum transmission range is 180 m. Nodes move with random speed between 10 to 50 m/sec in 500 sec. The traffic between nodes is generated as constant bit rate

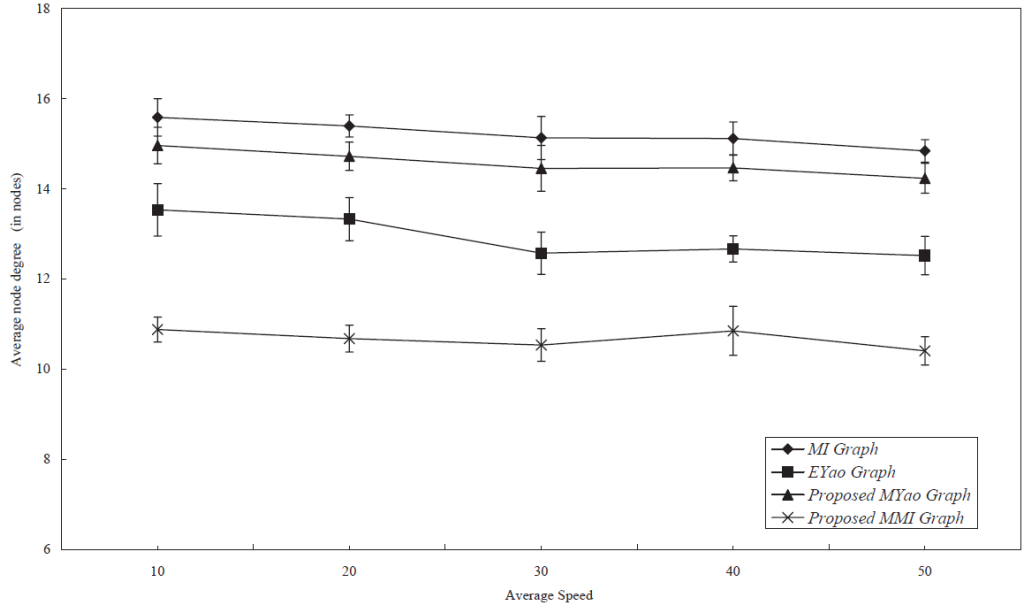


Figure 3.1: Average node degree for 100 nodes

(CBR) with packet size 512 Byte and 60 connections. Each result is repeated 10 times and associated with a 95 percent confidence interval.

## 3.6 Simulation Results

### 3.6.1 Node degree

To measure the effect of the structures on the interference, average physical node degree is computed. Figure 3.1 shows that the proposed MMI graph has the lowest node degree among the others. Although MYao graph is the nearest to the initial graph. From the throughput results, the lower node degree affects the network throughput, so the proposed MYao graph can preserve better throughput ratio than MMI graph.

### 3.6.2 Connectivity

The connectivity ratio is computed as the ratio of all connected pairs to all possible pairs in  $N$ . We compute the average ratio of all connected pairs to all possible pairs in the network. The simulation results show that the proposed graphs preserve connectivity, if the

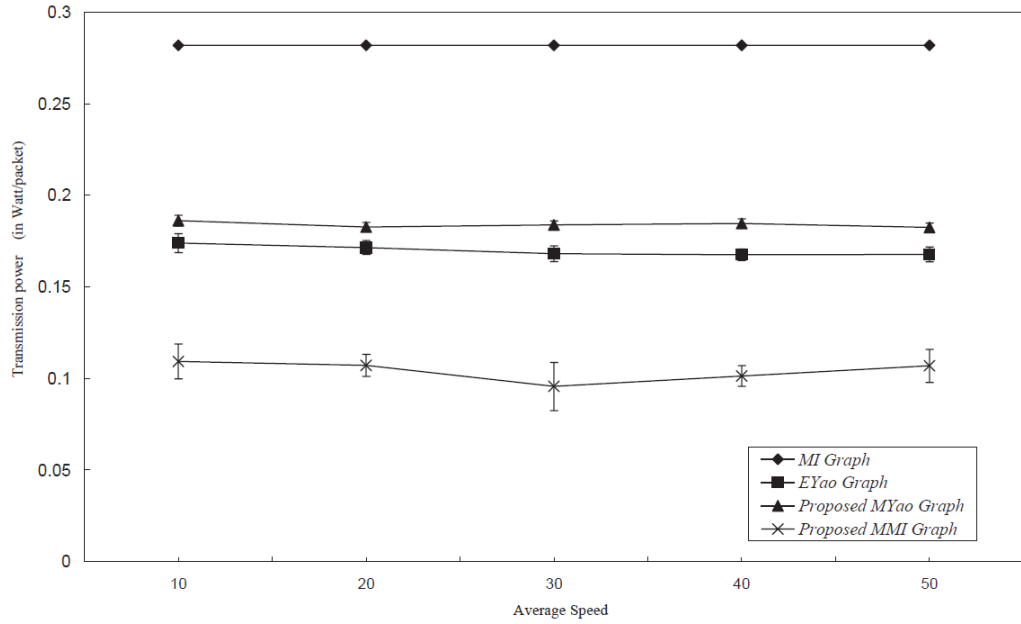


Figure 3.2: Average transmission power for 100 nodes

maximum power MI graph is connected. The connectivity ratio for these graphs may differ than the MI basic graph by 0.01 to 1 percent.

### 3.6.3 Transmission power

Average power used for every packet transmission is computed. As shown in Figure 3.2, The lower value is for the proposed MMI graph. It has the smallest average transmission range. MMI graph reduces the transmission power with more than 50 percent than maximum power MI. MYao<sub>k</sub> graph, and EYG<sub>k</sub> graph, for  $k = 8$ , reduce the transmission power by at least 40 percent than MI graph. The initial MI graph has a constant transmission power as initially defined for the node (the maximum one), as it has no criteria to adjust the transmission power according to nodes distance or speed parameters.

### 3.6.4 Throughput

Network throughput is computed as the total number of received bits per second. Figure 3.3 shows that the throughput (bit/sec) for the maximum power MI graph is maximum. The proposed MMI has the lowest throughput value while MYao has higher throughput than MMI. It is clear that the throughput level is related to transmission power and node



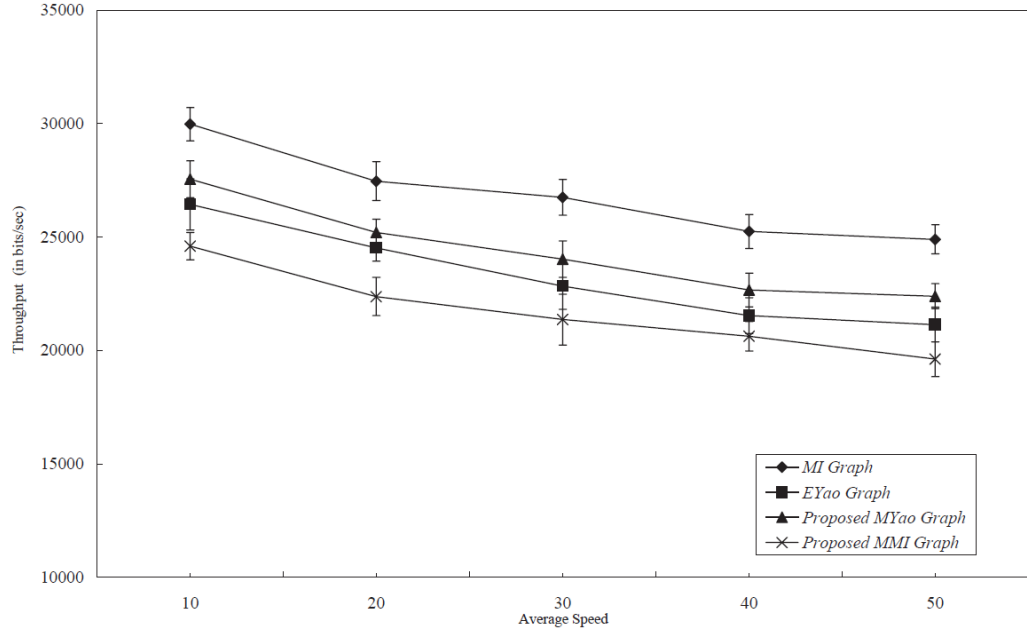


Figure 3.3: Throughput for 100 nodes

degree parameters. As when transmission power is minimized to lower level, the physical node degree is also reduced while the throughput is decreased.

The network throughput is affected by other protocols as the routing protocols and MAC Layer protocols. From this point, we can conclude two things. First, topology control problem can be studied as large scale protocol changing in routing and MAC protocols. Second, it is required to study topology control as optimization problem to minimize the energy consumption while maximizing the network throughput.

### 3.7 Summary

Topology control problem is one of most important issues for WANETs. The main target of topology control is to decrease power consumption and interference while preserving network desired properties as connectivity. Using geometric graphs for this problem proves efficiency along many related works. Most of the related work deal with WANETs in a static state such as the case of sensor networks. In this kind of networks, the main target is to minimize the energy consumed. While in WANETs, the problem of preserving the

connectivity with various node speeds is added. Various transmission ranges and speeds should be considered.

In this Chapter, mobility-aware topology control protocols are proposed. The proposed protocols depend on using the speed parameter instead of only the distance parameter. Using of speed parameter add a new dimension in dealing with the mobile WANETs. It improves the preservation of the connectivity parameter along with highly dynamic network. MYao and MMI are proposed as mobility-aware extensions to Yao graph and symmetric Mutual Inclusion (MI) graph.

The proposed graphs are constructed locally using only first-hop information. The simulation results show that the MMI proposed graph can reduce network interference as it reduces the physical node degree by at least four degrees (in case of 100 nodes) regardless of nodes' speed. The proposed MMI and MYao graph reduce the average transmission power by more than 50 percent and 40 percent respectively while preserving network connectivity.

## Chapter 4

# Energy and Mobility-aware Topology Control in WANETs

In this chapter, we propose energy-efficient and mobility-aware topology control solution for heterogeneous WANETs with mobile nodes. We propose energy and mobility-aware proximity graphs extensions in which a neighbors utility function has been used instead of the distance parameter to choose the new neighbors and update the transmission range. To study the performance of the proposed graphs, WANET with high mobility nodes has been simulated.

### 4.1 Introduction

The lack of an infrastructure and the limited battery power in WANETs pose design challenges at all layers of the protocol stack. Energy-efficient protocols are required for WANETs applications (e.g. disaster relief) where the mobile devices used in the field are battery operated [3]. Topology control has an important role in the design of WANETs. Topology control achieves network desirable characteristics such as sparser connectivity, lower transmission power, and smaller node degree. However, the enforcement of a topology control algorithm in a network may consume more energy and reduce the network operational lifetime. For this reason, in our research we consider topology control as 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. The most basic requirement of a topology is that it be connected. It is re-

quired that any two nodes that are connected in the maximum power network graph are also connected in the network graph after topology control. It is also important that there exist energy-efficient paths between potential source-destination pairs for efficient routing.

## 4.2 Related Work

Energy-efficient topology control and transmission power control has received a lot of attention in the area of WANETs (e.g. [13, 35, 38, 39]). Wattenhofer *et al.* [38] propose a distributed algorithm where each node makes local decisions about its transmission power based on the directional information where the nodes are static. The resulting network topology increases the network lifetime by reducing transmission power and reduces traffic interference by having low node degrees. Song *et al.* [35] propose Ordered Yao graph (OrdYaoGG) topology control structure applies the ordered Yao structure on Gabriel graph structure for static WANETs. The proposed graph is power efficient, planar, and has bounded node degree. In OrdYaoGG, all nodes have same maximum transmission ranges and uses only one-hop information. Blough *et al.* [13] propose a topology control protocol based on the computation of a symmetric subgraph of the  $k$  nearest neighbors graph (called  $k$ -Neigh).  $k$ -Neigh protocol is energy-efficient for static WANET.

## 4.3 Proposed Proximity Graphs

To solve the topology control problem in WANETs, we propose energy and mobility aware extensions for MI graph and Yao graph, respectively. Our proposed protocol has the following characteristics:

- Energy-aware: the proposed protocols use the remaining energy parameter at each node. Each node can updates its neighbor list and transmission power according to the maximum energy level at these nodes.
- Mobility-aware: speed parameter is used; each node can update its neighbor list and transmission power according to minimum speed nodes.

### 4.3.1 Proposed Energy and Mobility-aware Mutual Inclusion Graph

We use the MI graph to represent the initial network communication model, as there is no assumption for equally transmission ranges. The proposed Energy and Mobility-aware

MI (EMMI) graph is energy and mobility-aware extension to MI graph that uses the energy and speed parameter to update its neighbor list then update its transmission range. EMMI graph is defined as follows.

**Definition 1.** Energy and Mobility-aware MI (EMMI) graph. Let  $MI_T(N, L)$  be the maximum power MI graph at time  $T$ , where  $T$  is updated when the node changes its position, and  $MI'_T(N, L')$  be the sub-graph generated by EMMI graph as follows:

Each node  $i \in N$ , with transmission range  $r_i$  and speed  $\nu_i$  chooses the neighbor node  $j$  that has the maximum utility value  $U_j$  and satisfies  $r_j \geq r_i$ , and  $\nu_j \leq \nu_i$ . The utility function for node  $i \in N$ ,  $U_i$  is defined as follows.

$$U_i = w_1 * \frac{E_i}{E_{max}} - w_2 * \frac{\nu_i}{\nu_{max}}. \quad (4.1)$$

Where  $E_i$  is the remaining energy at node  $i$ ,  $E_{max}$  is the maximum energy, and  $\nu_{max}$  is the maximum speed. The parameters  $w_1$  and  $w_2$  are for adjustment, where  $0 \leq w_1, w_2 \leq 1$ , and  $w_1 + w_2 = 1$ .  $w_1$  and  $w_2$  could be adjusted according to the highest priority parameter as follows. If  $w_1 = 1$  and  $w_2 = 0$ , then the neighbor nodes is chosen according to energy parameter only (i.e. the nodes with larger remaining energy value is choose). If  $w_1 = 0$  and  $w_2 = 1$ , then the neighbor nodes is chosen according to speed parameter only (i.e. the nodes with smaller speed value is chosen). If  $w_1 = 0.5$  and  $w_2 = 0.5$ , then the neighbor nodes is chosen according to energy and speed parameter.

Algorithm 1 shows how to construct the EMMI graph. From EMMI construction steps, we can see that EMMI is a localized protocol as it depends only on energy and speed information from first-hop neighbors.

### 4.3.2 Proposed Energy and Mobility-aware Yao Graph

The proposed extension for Yao Graph, Energy and Mobility-aware Yao graph  $EMYao_k$ , is constructed using MI graph as initial graph, considering mobility parameter. Yao graph based on MI graph is connected if MI is connected. Yao graph extensions in WANETs [7], have bounded node degree and energy-efficient. Here we propose an Energy and Mobility-aware extension for Yao graph to deal with energy and speed parameters instead of distance parameters for WANETs. The proposed  $EMYao_k$  is defined as follows.

**Definition 2.** Energy and Mobility-aware Yao ( $EMYao_k$ ) graph. Let  $MI_T(N, L)$  be the maximum power MI graph at time  $T$ , where  $T$  is updated when the node changes its

**Algorithm 3** *Construction steps of the proposed EMMI graph*INPUT: Network graph  $MI = (N, L)$ .

OUTPUT: EMMI graph.

- Each node broadcasts its identification number, its transmission range, and speed to its first-hop neighbors.
- When node  $i$  updates its position
  - 1: Computes the utility value  $U_j$  for each node.
  - 2: Chooses  $j$  as a new neighbor if:
    - node  $j$  has the maximum utility value  $U_j$  among all neighbors in  $Neigh_i$ .
    - The transmission range  $r_j \geq r_i$  which ensures bidirectional links, and
    - The speed  $v_j \leq v_i$  which ensures the connectivity.
  - 3: Node  $i$  updates its neighbor list, and updates the transmission range to cover the new neighbor set.
- EMMI graph is the union of all chosen links.

position, and  $MI'_T(N, L')$  be the sub-graph generated by  $EMYao_k$  as follows.

Given an integer  $k \geq 7$ , each node  $i \in N$ , with transmission range  $r_i$  and speed  $v_i$ , divides its plane into  $k$  equally sized cones  $C_i^1, \dots, C_i^s, \dots, C_i^k$  originating at node  $i$ . For each cone, node  $i \in N$ , chooses the neighbor node  $j$  that has the maximum utility value  $U_j$  and satisfies  $r_j \geq r_i$ , and  $v_j \leq v_i$ . The utility function for node  $i \in N$ ,  $U_i$  is defined as in equation (1).

Algorithm 2 shows how to construct the proposed Energy and Mobility-aware Yao (EMYao) graph. From  $EMYao_k$  construction steps, we can see that  $EMYao_k$  is a localized protocol as it depends only on direction, speed and energy information from only first-hop neighbors.

### 4.3.3 Proposed Graphs Properties

To show the benefits of the two proposed graphs for the topology control in WANETs. We study the properties of the proposed graphs in this section.

For  $N$  nodes, Let  $MI_T = (N, L)$  be the maximum power MI graph at time  $T$ , and  $MI'_T = (N, L')$  be the sub-graph generated by  $EMYao_k$  or EMMI graphs.

*Property 1:*  $MI'_T = (N, L')$  results from  $EMYao_k$  have linear number of links at most  $kn$  links, where  $k$  is a constant represents the number of cones and  $n$  is the number of nodes. For example, when dividing the range around node  $i$  into  $k$  cones, it chooses only one node in each cone. So node  $i$  gets at most  $k$  neighbors. For  $n$  nodes network, links are at most

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**Algorithm 4** *Construction steps of the proposed EMYao graph.*


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INPUT: Network graph  $MI = (N, L)$ , and  $k$ .

OUTPUT: EMYao<sub>k</sub> graph

- Each node broadcasts its identification number, its transmission range, and speed to its first-hop neighbors.
  - When node  $i$  updates its position
    - 1: node  $i$ , with transmission range  $r_i$  divides the disk  $d(u_i, r_i)$  of  $\pi$  angle around the node, into  $k$  equal sized cones each with angle  $2\pi/k$ , as  $C_i^1, \dots, C_i^s, \dots, C_i^k$ .
    - 2: Compute the utility value  $U_j$  for each node.
    - 3: For each cone, chooses  $j$  as a new neighbor if:
      - Node  $j$  has the maximum utility value  $U_j$  among all neighbors in  $Neigh_i$ .
      - The transmission range  $r_j \geq r_i$  which ensures bidirectional links, and
      - The speed  $\nu_j \leq \nu_i$  which ensures the connectivity.
    - 5: Node  $i$  updates its neighbor list, and updates the transmission range to cover the new neighbor set.
  - EMYao<sub>k</sub> graph is the union of all chosen links.
- 

$kn$ .

In the case of EMMI, the number of links for each node can reach  $(n-1)^2$  in the worst case, but in average each node chooses only one logically neighbor node so the number of links can be only  $n$ .

*Property 2:*  $MI'_T = (N, L')$  results from EMYao<sub>k</sub> or EMMI preserves connectivity, if the initial MI graph is connected.

If the nodes are static, the condition  $r_j \geq r_i$  that ensures the bidirectional links can preserve the connectivity condition, as proved in [7]. If the nodes are mobile, the condition  $\nu_j \leq \nu_i$  can preserve the connectivity. As node  $j$  do not change its position before node  $i$ . Each time node  $i$  changes its position it recalls the graph to be updated.

## 4.4 Performance Metrics

Topology control problem aims to reduce the energy consumption and interference while preserving the connectivity. We test most parameters that can be affected by the network topology update. The proposed protocols are evaluated in terms of the following metrics:

- Throughput: network throughput is computed as the total number of received bits per second.
- Transmission power: average transmission power used by all nodes in the network is computed.
- Physical Node degree: let  $G_P = (N, L_P)$ , the communication graph generated by a certain topology control protocol  $P$ . For a given node  $i \in N$ , the physical node degree of  $i$  in  $G_P$  is the number of nodes within  $i$ 's transmission range when it transmits at the broadcast power [1]. To measure the effect of the structures on the interference, average physical node degree is computed.
- Delay: the time taken for a packet to be transmitted across a network from source to destination. The average delay for all received packets is computed.
- Connectivity: a Graph  $G = (N, L)$  is connected. If for any two nodes  $i, j \in L$ , there exists a path from  $i$  to  $j$  in  $G$  [1]. The connectivity ratio is computed as the ratio of all connected pairs to all possible pairs in  $N$ .

## 4.5 Simulation Parameters

The simulation for the proposed graphs has been implemented in C++ using ns-2.33 simulator [36] and our implementation is available at [37]. Our protocol evaluations are based on the simulation of 50 mobile nodes forming a WANET, moving over a rectangle  $1500 \times 300$  m<sup>2</sup> flat space for 900 seconds of simulated time. To make the comparisons between the protocols with identical loads and environment conditions, each run of the simulator accepts as input a scenario file that describes the following:

- Node positions and their initial transmission range: initial transmission range is uniformly distributed between 200 m and 250 m. The nodes initial connections and neighbor list follow the MI graph.
- Motion of each node: nodes move according to random way-point mobility model with maximum speed 20m/sec. The movement is characterized by a pause time. We ran our simulation with movement patterns generated for 7 different pause times: 0, 30, 60, 120, 300, 600, and 900 seconds. A pause time of 0 seconds corresponds to continuous motion, and a pause time of 900 seconds corresponds to no motion.



- The exact sequence of packets originated by each node: the traffic source is constant bit rate (CBR) with sending rate 4 packets per second, network contains 30 CBR sources, and packet size of 512 bytes. Connections are started at times uniformly distributed between 0 and 300 seconds.

## 4.6 Simulation Results

For the simulated WANET environment described in Section 4.5, we test the impact of the mobility and the different values for the weight parameters ( $w_1$ , and  $w_2$ ) in the utility function. Each scenario is repeated ten times with different values and associated with a 95 percent confidence interval.

### 4.6.1 Proposed protocols with different mobility scenarios

We implement the proposed EMYao $_k$  graph with  $k = 8$ , and the proposed EMMI graph using the utility function as defined in equation 4.1 with different values for  $w_1$ , and  $w_2$  as follows.

- Case 1:  $w_1 = 1$ , and  $w_2 = 0$ .
- Case 2:  $w_1 = 0$ , and  $w_2 = 1$ .
- Case 3:  $w_1 = 0.5$ , and  $w_2 = 0.5$ .

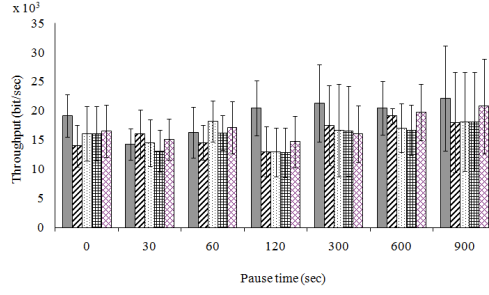
Figure 4.1 shows the performance of the proposed protocols with different mobility scenarios. From simulation results, the proposed EMYao graph performance did not change with different values of  $w_1$ , and  $w_2$  due to the fact that EMYao $_8$  graph selects 8 different neighbors each time. When adjusting the transmission range to satisfy all 8 neighbors the difference between the cases degraded. The results graphs show the performance of EMMI with case 1, case 2, and case 3, and EMYao $_8$ . The base graph for comparison is the initial MI graph with no topology control.

Network throughput is computed as total number of received bits per second. Figure 4.1 (a) shows that the throughput (bit/sec) for the proposed EMMI, case 2 and case 3, has higher throughput than the maximum power MI graph at pause time 30, and 60 sec (i.e. high mobility pattern). The proposed EMYao has a higher throughput at pause time 60 sec. Clearly, the throughput level is related to transmission power and node degree parameters. Lower node degree decrees the collision rate due to lower interference. The proposed EMMI

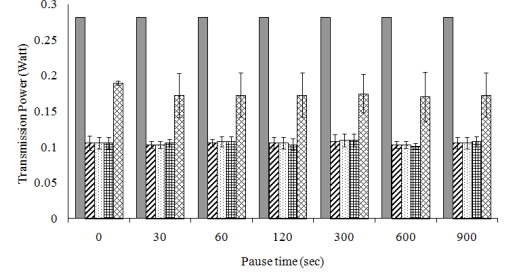
with case 3, which take into consideration the energy and speed parameters, could preserve network throughput with lower transmission power specially with high mobility scenario. Average power used for every packet transmission is computed. As shown in Figure 4.1 (b), the lower value is for the proposed EMMI graph. It has the smallest average transmission range. The EMMI graph reduces the transmission power with more than 50 percent than MI. The EMYao<sub>8</sub> graph reduces the transmission power by at least 40 percent than MI graph. The initial graph MI has a constant transmission power as initially defined for the node (the maximum one), as it has no criteria to adjust the transmission power. To measure the effect of the graphs on interference, average physical node degree is computed. Figure 4.1 (c) shows that the proposed EMMI graph has the lowest node degree than the EMYao graph. Although EMYao graph is similar to the initial graph in the worst case, the throughput results show that the lower node degree affects the network throughput. The proposed EMYao graph can preserve better throughput ratio than EMMI graph. Figure 4.1 (d) shows the effect of the proposed graphs on the average end-to-end delay. All proposed graphs decrease the average delay, even in the worst case EMMI and EMYao graphs have lower delay. The use of energy and speed parameters minimize the need for route updates. On the other hand, lower interference reduces the collision and the probability of packet retransmission. The connectivity ratio is computed as the ratio of all connected pairs to all possible pairs in the network. We compute the average ratio of all connected pairs to all possible pairs in the network. In Figure 4.1 (e), the simulation results show that the proposed protocols preserve connectivity, if the maximum power MI graph is connected. The connectivity ratio for these graphs may differ than the MI basic graph by 0.01 to 1 percent.

#### 4.6.2 Proposed protocols with different values of $w_1$ , and $w_2$

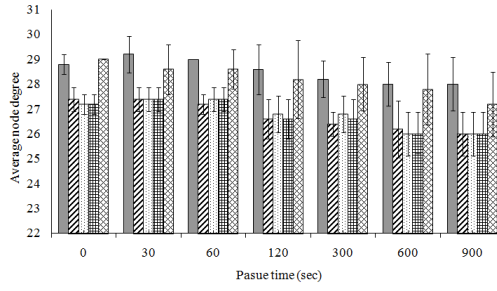
We test the proposed EMMI topology control with maximum speed 20 m/sec and 30sec pause time versus  $w_1$  different values for different random input files. The weight parameter  $w_2$  is set to  $1 - w_1$ . Figure 4.2 shows the performance of the proposed protocols with different mobility scenarios. Figure 4.2 (a) shows that the throughput(Bytes/sec) for the proposed EMMI and the maximum power graph MI. The proposed EMMI preserves the throughput requirement compared to the maximum power MI topology. Figure 4.2 (b) shows that the proposed EMMI decrease the average transmission power by about 50 percent while



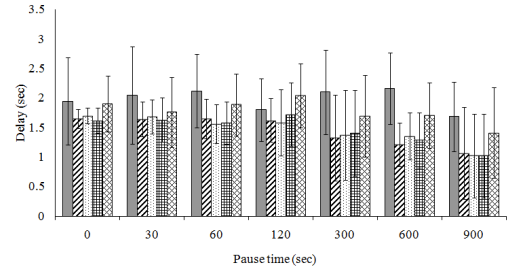
(a) Network throughput (bits/sec)



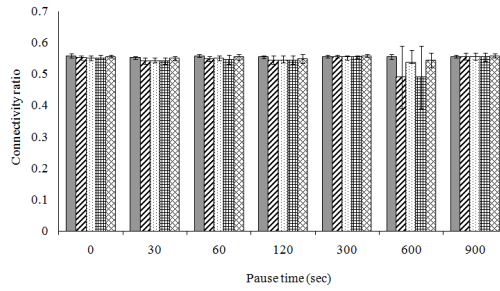
(b) Average transmission power needed for one packet



(c) Average node degree



(d) Average end-to-end delay



(e) Average connectivity ratio

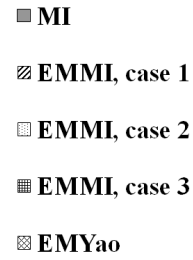
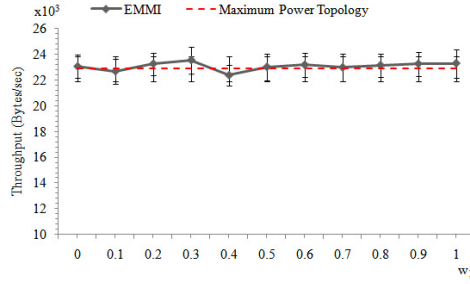
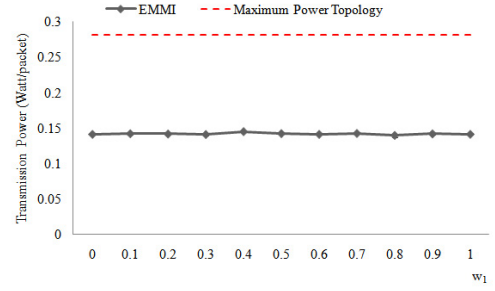


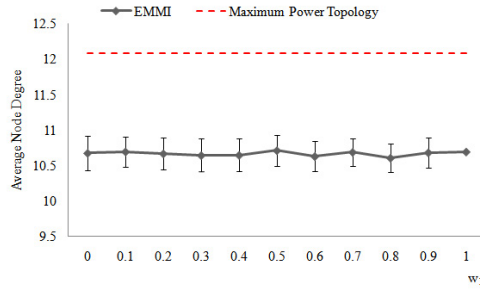
Figure 4.1: Simulation results for the proposed energy and mobility-aware topology control protocols



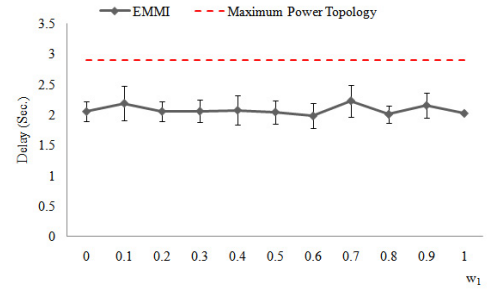
(a) Network throughput (Bytes/sec)



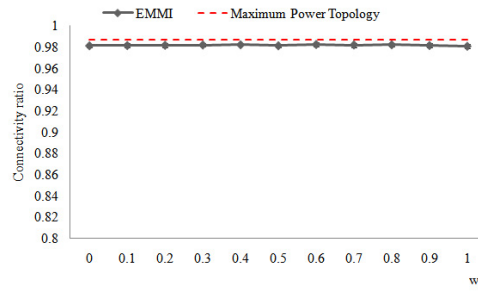
(b) Average transmission power needed for one packet



(c) Average node degree



(d) Average end-to-end delay



(e) Average connectivity ratio

Figure 4.2: Simulation results for the proposed EMMI topology control protocols with different weight parameters

preserving the connectivity as shown in Figure 4.2 (e). There is no much difference between considering the energy, speed or both parameters effect in these scenarios. However, the end-to-end delay in Figure 4.2 (d) shows that considering both parameters archives lower end-to-end delay. The weight parameters are more useful if one of energy or speed parameter is not available.

## 4.7 Summary

Topology control problem is one of most important issues for WANETs. The main target of topology control is to decrease power consumption and interference while preserving network desired properties as connectivity. Using geometric graphs for this problem proves efficiency along many researches. Most of the related work deal with wireless network in static state in the case of sensor network studying. In this kind of networks, the main target is to minimize the energy consumed. While in WANETs, the problem of preserving the connectivity with various node speeds is added. Various transmission ranges and speeds should be considered.

In this Chapter, energy and mobility-aware topology control protocols are proposed. The proposed protocols depend on using a utility function considers the energy and speed parameter instead of only distance parameter. Using of energy and speed parameters improves the preservation of the connectivity parameter and minimize the interference and transmission power along with highly dynamic network. EMYao and EMMI are proposed as energy and mobility-aware extensions to Yao graph and symmetric Mutual Inclusion (MI) graph.

The proposed graphs are constructed locally using only first-hop information. The simulation results show that the EMMI and EMYao proposed graphs can reduce network interference and end-to-end delay as it reduce the physical node degree and node's transmission power. The proposed EMMI and EMYao graphs reduce the average transmission power by more than 50 percent and 40 percent respectively while preserving network connectivity property. The proposed EMMI and EMYao graphs achieve same throughput as the maximum power topology but not better.

## Chapter 5

# Cross-layer Design

### 5.1 Introduction

Traditional layered communication approaches typically separate communication tasks into several layers. In a layered communication stack, interaction among layers occurs through well-defined standardized interfaces that connect only adjacent layers in the stack. Each layer makes use of the services provided by the layer directly below it, and also provides service to the layer directly above it. In contrast, cross-layer approaches attempt to exploit a richer interaction among communication layers to achieve performance gains.

Jurdak [40] have proposed the following definition for cross-layer design: Cross-layer design with respect to a reference layered architecture is the design of algorithms, protocols, or architectures that exploit or provide a set of interlayer interactions that is a superset of the standard interfaces provided by the reference layered architecture. The layered communication approach simplifies design and implementation. In wireless communications and networking the information is exchanged between different protocol layers dynamically. The suitability of the layered protocol architecture is coming under close scrutiny from the research community. It is repeatedly argued that although layered architectures have served well for wired networks, they are not suitable for WANETs [41].

In Figure 5.1, we show an example for cross-layer possible interactions in WANET. The physical layer, the data link layer, and the network layer together contend for the network resource. Transmission power and rate in the physical layer affects Medium Access Control (MAC) in the data link layer and routing decisions in the network layer. The MAC sub-layer is responsible for scheduling and allocating the wireless channel, which finally will determine

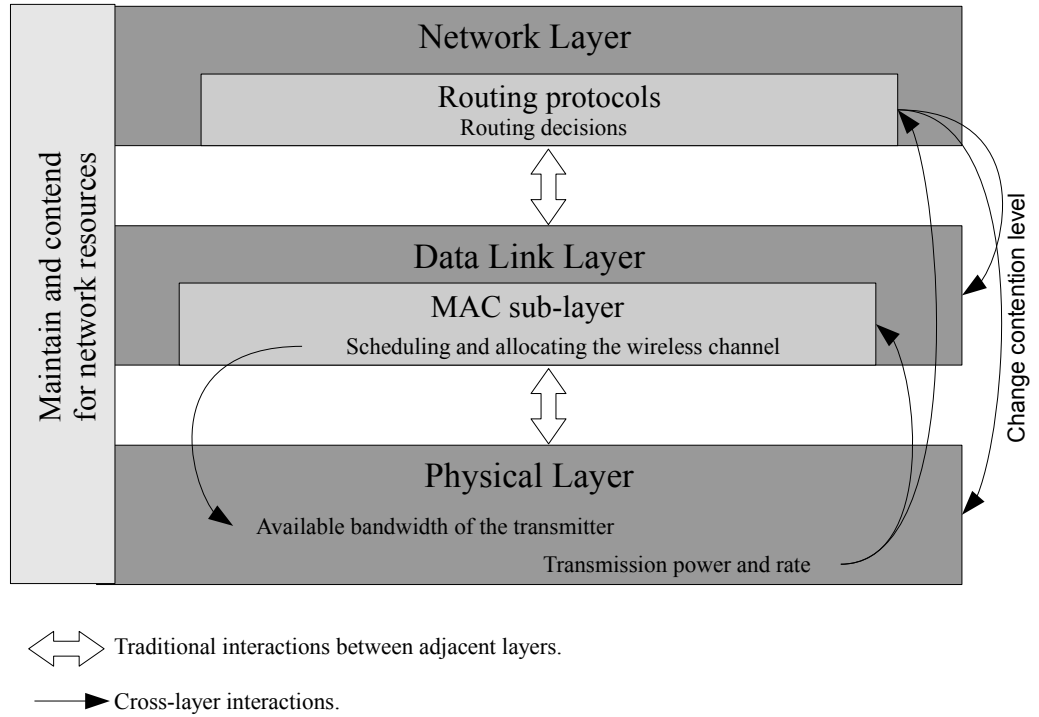


Figure 5.1: Example for cross-layer interactions

the available bandwidth of the transmitter and the packet delay [42]. This bandwidth and packet delay also can affect the decision at the routing in network layer to select the best link. The routing protocol chooses the wireless links to relay the packets to the destination. The routing decision will change the contention level at the MAC sub-layer, and accordingly the physical layer parameters.

## 5.2 Cross-layer Design Motivation

Why does the presence of wireless links in the network motivate designers to violate the layered architectures? The motivating factors for cross-layer design for WANETs are as follows [40].

1. Cross-layer aspects. For instance, both medium access and routing decisions have a significant impact on power consumption, and the joint consideration of both can yield more efficient power consumption.

2. **Distributed state.** The network state in WANETs is distributed across the nodes. Distributed algorithms can utilize a cross-layer design to enable each node to perform fine-grained optimizations locally whenever it detects changes in the state.
3. **Mobility.** Mobility introduces an additional challenge for WANET design. Routing protocols would have to cope with this mobility by constantly adapting routing state to the changing router positions. Mobility management poses an additional challenge to the battery-powered nodes in WANETs, which have to adapt their behavior to the changing node locations. Mobility causes changes for the physical layer (e.g. interference levels), the data link layer (e.g. link schedules), the routing layer (e.g. new neighbors), and the transport layer (e.g. connection timeouts). As such, a cross-layer design enhances a nodes capability to manage its resources in mobile environments.
4. **Inherent layer dependencies.** Several interlayer dependencies motivate cross-layer design for WANETs. The data link and routing layers in WANETs exhibit both variable and algorithmic interaction, suggesting the need for design coupling of these layers.
5. **Resource-constrained nodes.** The battery-powered nodes should interact, in an ultra-efficient manner, to maximize the lifetime of the battery. Cross-layer design approaches can expose power related variables at various layers, enabling nodes to utilize their energy resources efficiently.

### 5.3 Cross-layer Design

In this section, we give examples of how the layers can be coupled. In other words, what kind of architecture violation has taken place in cross-layer designs. The layered architecture can be violated in the following basic ways [41]. Most cross-layer design proposals in the literature fit into one of these basic categories.

- **Creation of new interfaces**

- **Upward:** From lower layer to a higher layer. A higher-layer protocol that requires some information from the lower layer(s) at runtime results in the creation of a new interface from the lower layer(s) to the higher layer e.g.([43]), as shown in Figure 5.2(a).



- **Downward:** From higher layer(s) to a lower layer. Some cross-layer design proposals rely on setting parameters on the lower layer of the stack at runtime using a direct interface from some higher layer, as illustrated in Figure 5.2(b). As an example, applications can inform the link layer about their delay requirements, and the link layer can then treat packets from delay-sensitive applications with priority e.g.([44]).
- **Back and forth:** Iterative flow between two layers. Two layers, performing different tasks, can collaborate with each other at runtime. Often, this manifests in an iterative loop between the two layers, with information flowing back and forth between them as highlighted in Figure 5.2(c). A back and forth information flow between layers is seen in proposals performing joint scheduling and power control in wireless ad hoc networks e.g.([45]). In chapter 6 and 7, our proposed cross-layer protocols consider the back and forth collaboration between network layer and physical layer.
- **Merging of adjacent layers** Figure 5.2(d). Another way to do cross-layer design is to design two or more adjacent layers together such that the service provided by the new super-layer is the union of the services provided by the constituent layers. This does not require any new interfaces to be created in the stack. The super-layer can be interfaced with the rest of the stack using the interfaces that already exist in the original architecture.
- **Design coupling without new interfaces.** Cross-layer design couple two or more layers at design time without creating any extra interfaces for information sharing at runtime e.g.([46]). It may not be possible to replace one layer without making corresponding changes to another layer, which cause a higher maintenance cost.
- **Vertical calibration across layers.** This refers to adjusting parameters that span across layers. The performance seen at the level of the application is a function of the parameters at all the layers below it. Hence, it is conceivable that joint tuning can help to achieve better performance than individual settings of parameters e.g.([47]).

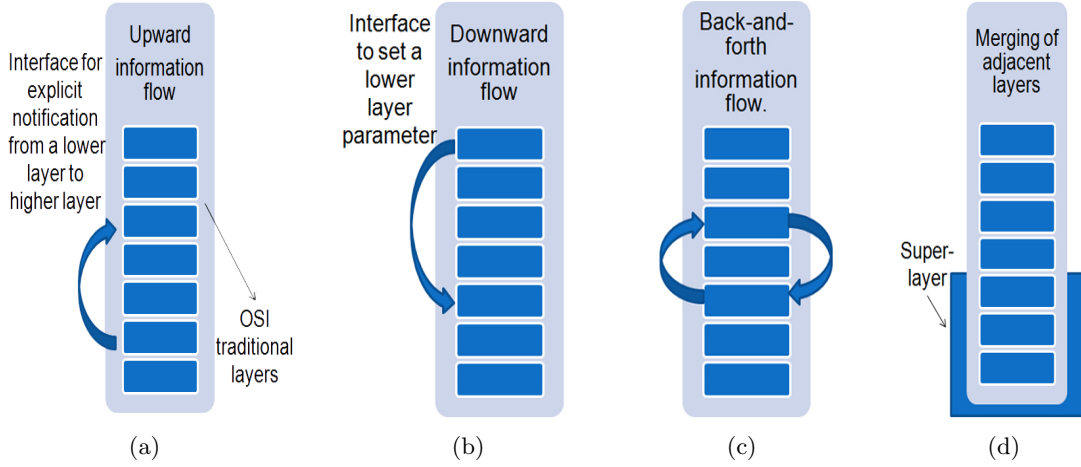


Figure 5.2: Illustrating the different kinds of cross-layer design proposals

## 5.4 Literature Review

There have been countless proposals and research papers applying some sort of cross-layer design. They address various problems and issues of different kinds of wireless networks. In this section, we show some cross-layer design proposals from the literature based on the layers that are coupled. Weiss *et al.* [25] propose a combined data link and network layers control loop, which allows prediction of link breakage in WANETs. The method monitors the physical layer transmission mode according to the link quality on data link layer and exploits the gained knowledge at the network layer layer. Gong *et al.* [48] propose a distributed channel assignment protocol that is based on a cross-layer approach. They combine channel assignment in data link layer with routing protocol in the network layer. The proposed channel assignment protocol is shown to require fewer channels and exhibit lower communication, computation, and storage complexity. Romdhani and Bonnet [27] jointly study the routing protocol and power control for WANETs in order to determine the optimal route with low energy consumption rate. Casaquite and Hwang [49] propose an integration among power control in physical layer, scheduling in data link layer, and routing in network layer in order to find an optimal transmission power satisfying the Signal to Interference plus Noise Ratio (SINR) requirement as well as the required data rate of all nodes for WANETs. Chafekar *et al.* [50] jointly study the power control, scheduling, and routing in order to minimize latency with a centralized way for WANETs. Kozat *et al.* [28] present a framework for cross-layer design between the physical and data link layers. They

address the joint problem of power control and scheduling with the objective of minimizing the total transmit power subject to bandwidth and bit error rate requirements. Zhang *et al.* [51] incorporate the power control and scheduling in the routing decision in order to find the concurrent packets relay paths associated with the exact relay instants, which can minimize the system-wide energy consumption at all nodes with the deterministic mobility pattern, traffic load, and channel conditions.

## Chapter 6

# Cross-layer Energy-efficient Routing in WANETs

In this chapter, we propose a cross-layer integration approach for power efficient routing protocol. The proposed cross-layer integration between power control in link layer and routing protocol in network layer aims to maximize the network lifetime. We implement our proposed protocols as extension to AODV routing protocol. The performance of the proposed protocols was studied by simulating a set of random WANET environments.

### 6.1 Introduction

A wireless ad hoc network (WANET) is a collection of geographically distributed nodes that can be self-configured to form a network without predetermined topology [29]. The lack of infrastructure and the limited battery power in WANETs requires new technologies for mobility management, service discovery, and energy-efficient information routing, and poses design challenges at all layers of the protocol stack. Significant research has been directed towards implementing application dependent Quality of Service (QoS) requirements (e.g., [52–55]) and has addressed power control, coding, adaptive techniques at the link layer, scheduling in the Medium Access Control (MAC) layer, and energy and delay constrained routing in the network layer. In WANETs, it is important to find and maintain correct routes to the destination in a changing topology resulting from node failure or mobility. Different routing protocols use one or more metrics to determine optimal routes. The most widely used routing protocols are the Ad-hoc On-demand Distance Vector

(AODV [17]), the Dynamic Source Routing (DSR [18]), the Destination Sequenced Distance Vector (DSDV [16]) and the Temporally-Ordered Routing Algorithm (TORA [56]). All these routing protocols use the shortest-hop metric to choose the best route.

## 6.2 Related Work

### 6.2.1 Energy-efficient Routing Protocols

The problem of energy-efficient routing is addressed in many works such as [3, 57, 58]. These works deal with each layer individually. Singh et.al [3] propose five different metrics based on battery power consumption at node. They show that using these metrics in a shortest-cost routing algorithm reduces the cost/packet of routing packets. Li et.al [57] seek to find a broadcast tree such that the energy cost of the broadcast tree is minimized. They propose heuristic algorithms to solve this problem. Chang and Tassiulas [58] show that in order to maximize the lifetime, the traffic should be routed such that the energy consumption is balanced among the nodes. These researches did not investigate the effect of power cost reduction on the network throughput.

### 6.2.2 Cross-layer Approaches

Recent related works show that significant performance improvement can be achieved by using a cross-layer design in WANETs (e.g., [25–28]). Cross-layer design with respect to reference layered architecture is the design of protocols that provide a set of interlayer interactions. These interactions are supersets of the standard interfaces provided by the reference layered architecture [29]. Transmission power control is a cross-layer design problem that affects all layers of the protocol stack from physical layer to transport layer and affects throughput, delay, and energy consumption [59]. Chen et.al [26] propose a cross-layer design for joint topology control and routing for a multi-radio multi-channel wireless mesh network. The research main target is to maximize the network throughput by adjusting the channel assignment, the power level of each radio, and the route for flows. Casaquite and Hwang [49] propose 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 WANETs.

### 6.3 Problem Formulation

The WANET is presented as a graph  $G = (N, L)$ .  $N$  is a set of wireless devices, 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  $\beta \cdot d_{ij}^\alpha$  (i.e.,  $P_{ij} \geq \beta \cdot d_{ij}^\alpha$ ), 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 [60]. For all nodes  $i \in N$ , let the initial energy be  $E_i$  and the residual energy be  $\underline{E}_i$  in joule. Let  $Q_i^{(c)}$  be the rate at which bits per second are generated at node  $i$  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  $c$  is transmitted from node  $i$  to node  $j$  in bits per second and denoted by  $f_{ij}^{(c)}$ . The aggregated flow of all commodities  $f_{ij} = \sum_{c \in C} f_{ij}^{(c)}$ . 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 conservative of flow is defined formally as follows.

$$\sum_{(i,j) \in L} f_{ij}^{(c)} - \sum_{(k,i) \in L} f_{ki}^{(c)} = \begin{cases} Q_i^{(c)} & \text{if } i \in S^{(c)}, \\ -Q_i^{(c)} & \text{if } i \in D^{(c)}, \forall c \in C, \\ 0 & \text{otherwise.} \end{cases} \quad (6.1)$$

#### 6.3.1 Maximizing the Network Lifetime

For WANETs, the nodes are power-limited and recharging may not be available, consequently we need to maximize the network lifetime. It is considered for WANETs in data link layer. In order to maximize the network lifetime, we need to maximize the minimum lifetime for all nodes in that network. Furthermore, we need to consider the flow conserva-

tion separately applied to each commodity [58].

Let the lifetime of node  $i$  defined as the time it takes for the battery of node  $i$  to drain out. Let  $T_i(\mathbf{F})$  be the lifetime of node  $i$  under flow  $\mathbf{F} = \{f_{ij}\}$ , where  $(i, j) \in L$ .  $T_i(\mathbf{F})$  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 for node  $i$  is formally defined as follows.

$$T_i(\mathbf{F}) = \frac{E_i}{\sum_{\substack{\forall j \in N, \\ (i,j) \in L}} e_{ij} \sum_{c \in C} f_{ij}^{(c)}}. \quad (6.2)$$

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

$$\begin{aligned} T_G(\mathbf{F}) &= \min_{i \in N} T_i(\mathbf{F}) \\ &= \min_{i \in N} \frac{E_i}{\sum_{\substack{\forall j \in N, \\ (i,j) \in L}} e_{ij} \sum_{c \in C} f_{ij}^{(c)}}. \end{aligned} \quad (6.3)$$

The maximum network lifetime problem for WANETs is formulated as a non-linear optimization problem as follows.

$$\text{Maximize}_{\mathbf{F}} \quad T_G(\mathbf{F}) = \min_{i \in N} \frac{E_i}{\sum_{\substack{\forall j \in N, \\ (i,j) \in L}} e_{ij} \sum_{c \in C} f_{ij}^{(c)}},$$

Subject to

$$\begin{aligned} \sum_{(i,j) \in L} f_{ij}^{(c)} - \sum_{(k,i) \in L} f_{ki}^{(c)} &= \begin{cases} Q_i^{(c)} & \text{if } i \in S^{(c)}, \\ -Q_i^{(c)} & \text{if } i \in D^{(c)}, \forall c \in C, \\ 0 & \text{otherwise.} \end{cases} \\ f_{ij}^{(c)} &\geq 0, \quad \forall i \in N, \forall (i, j) \in L, \forall c \in C. \end{aligned} \quad (6.4)$$

Similar to [58], the above maximum network lifetime problem can be formulated as the following linear programming problem with some proper manipulation. Note that  $T$  is the network lifetime which is defined as the time it takes the first node to die. Denote by  $\hat{f}_{ij}$ , the amount of bits transmitted from node  $i$  to node  $j$  in the network lifetime  $T$ , i.e.  $\hat{f}_{ij}^{(c)} = T f_{ij}^{(c)}$ . Thus we have the linear programming problem.

Maximize  $T$

Subject to

$$\sum_{(i,j) \in L} e_{ij} - \sum_{c \in C} \hat{f}_{ij}^{(c)} \leq E_i, \forall i, j \in N, \quad (6.5)$$

$$\begin{aligned} \sum_{(i,j) \in L} \hat{f}_{ij}^{(c)} - \sum_{(k,i) \in L} \hat{f}_{ki}^{(c)} = \\ \begin{cases} TQ_i^{(c)} & \text{if } i \in S^{(c)}, \\ -TQ_i^{(c)} & \text{if } i \in D^{(c)}, \forall c \in C, \\ 0 & \text{otherwise.} \end{cases} \end{aligned} \quad (6.6)$$

$$\hat{f}_{ij}^{(c)} \geq 0, \quad \forall (i, j) \in L, \forall c \in C,$$

$$E_i > 0, \quad \forall i \in N.$$

The linear programming formulation given above can be viewed as a variation of the conventional maximum flow problem with node capacities (i.e.,  $\sum_{(i,j) \in L} \sum_{c \in C} \hat{f}_{ij}^{(c)} \leq E_i/e_i$ ) [61], 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 [62]. To maximize the network lifetime, it is also important to consider the power control problem. Transmitting at minimum power helps to prolong the lifetime of a node and thus the network lifetime [59, 63]. In this Chapter, the power control is addressed with the maximum network lifetime problem as in the following subsection.

### 6.3.2 Transmission Power Control

For WANETs, to maximize the network lifetime and minimize the intra-network interference, we need to minimize the transmission power for all network nodes. We assume the selfish behavior for network nodes which is reasonable in a real WANET (e.g., [64]). Therefore we need to minimize each node transmission power. While minimizing transmission power at link layer [29], we need to consider the connectivity constraint and the Signal to



Interference plus Noise ratio, SINR, constraint. We can preserve network connectivity, if the transmission power from node  $i$  to node  $j$  ( $P_{ij}$ ) is more than or equal to  $d_{ij}^\alpha$  multiplied by the transmission quality parameter  $\beta$  for all  $(i, j) \in L$ . Also  $P_{ij}$  should be more than zero as far as the flow  $f_{ij}$  is more than zero and less than or equal to  $P_{max}$ , the maximum transmission power. In order to satisfy the SINR constraint, the received power at node  $j$  should be more than the interference power plus noise multiplied by the SINR requirement parameter,  $\gamma_{ij}$ . The problem of minimizing the transmission power in WANETs is formulated as a linear optimization problem as follows.

Minimize  $P_{ij}$

Subject to

$$P_{ij} \geq \beta \cdot d_{ij}^\alpha, \quad (6.7)$$

$$SINR_{ij} = \frac{P_{ij}/d_{ij}^\alpha}{\sum_{(k,j) \in L} P_{kj}/d_{kj}^\alpha + \sigma} \geq \gamma_{ij}, \quad (6.8)$$

$$P_{max} \geq P_{ij} \geq 0, \forall i \in N, \forall (i, j) \in L.$$

### 6.3.3 Energy-aware Route Selection

In the previous subsection, we propose to minimize the transmission power which is an important parameter affecting the nodes lifetime. In addition to maximize the network lifetime, we need an efficient route selection metric. Routing protocol is considered in the network layer [29]. In the basic routing protocols [16–18, 56], the shortest-hop metric is used to select the best route. When the shortest-hop metric is used to select the data route, the same route is used between the same source and destination nodes. The nodes in this route will die earlier than nodes belonging to other routes. In this Chapter, we define the residual energy to be the metric to choose the best route. The used route is changed every time the source node sends to the same destination node as it depends on the residual energy which is dynamically changed. For convenience, we define a route from source node  $s$  to destination  $d$  as follows:

$$R = \{(i_0, i_1), \dots, (i_{h-1}, i_h)\}, \forall (i_k, i_{k+1}) \in L, \quad (6.9)$$

where  $i_0, i_1, \dots, i_h$  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 is a number of  $m$  available routes

between source node  $s \in S^{(c)}$  and destination node  $d \in D^{(c)}$ . The residual energy of route  $r$ , with the intermediate nodes  $i_1, \dots, i_h - 1$ , source node  $i_0 = s$ , and destination node  $i_h = d$  is defined as follows.

$$\underline{E}_r = \text{Min}(\underline{E}_{i_0}, \underline{E}_{i_1}, \dots, \underline{E}_{i_h-1}). \quad (6.10)$$

The best route  $r_{max}$  is the route with the maximum residual energy node. We select a route  $r_{max}$  from  $m$  available routes as,

$$r_{max} = \text{Max}(\underline{E}_{r_1}, \dots, \underline{E}_{r_m}). \quad (6.11)$$

The notations for the formulation are summarized in Table 6.1, for convenience.

Table 6.1: Formulation parameters

$T$	The network lifetime defined as the time it takes for the first node to die.
$T_i$	The time it takes for the battery of node $i$ to drain out.
$T_G$	The lifetime of the network $G$ .
$P_{ij}$	The transmission power required by node $i$ to transmit data to node $j$ .
$E_i$	The initial energy for node $i \in N$ .
$\underline{E}_i$	The residual energy at node $i \in N$ .
$e_{ij}$	The energy for transmitting one bit across the link $(i, j) \in L$ .
$f_{ij}^{(c)}$	The rate at which bits of commodity $c$ are transmitted across the link $(i, j)$ per second, $\forall c \in C$ .
$\hat{f}_{ij}^{(c)}$	The total number of bits of commodity $c$ for link $(i, j)$ transmitted from node $i$ to node $j$ over $T$ , $\forall c \in C$ .
$Q_i^{(c)}$	The throughput requirements, i.e., the number of bits that should be routed between source $s \in S^{(c)}$ and destination $d \in D^{(c)}$ nodes per second, $\forall c \in C$ .
$TQ_i^{(c)}$	The number of bits transmitted over $T$ , at the source node $s \in S^{(c)}$ for $d \in D^{(c)}$ , $\forall c \in C$ .
$SINR_{ij}$	The Signal to Interference with Noise Ratio requirement at the receiver node $j$ from sender node $i$ .
$\alpha \geq 2$	The distance-power gradient.
$\beta \geq 1$	The transmission quality parameter.
$d_{ij}$	The Euclidean distance between the nodes $i$ and $j$ .
$\sigma$	The ambient noise power level.
$\gamma_{ij} \geq 1$	The SINR requirement for the transmission from node $i$ to node $j$ .

## 6.4 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 power control in the link layer, and the route selection in the network layer. In this section, we introduce a cross-layer design that jointly considers the three problems. The protocol solves the problem locally

depends only on the first hop information and in distributed way, i.e. there is no central processing node.

The traditional layering design ignores the overall requirements of the network design, the dependences between protocol layers, and the dynamic characteristics of WANETs. As a result, the resulting protocols may not be adaptive and far from optimal. As shown in Figure 6.1(a), cross-layer design allows information integration between protocol layers, so that the changes could affect more than one layer, then each layer responds appropriately to changes in other layers [30].

We propose cross-layer integration between routing and power control to maximize the network lifetime. In Figure 6.1(b), the routing decision is affected by the residual energy information to satisfy the routing metric in equation 6.11. Routing protocol control messages is used to trigger network node to update their transmission power level according to the connectivity and SINR constraints.

We design the proposed routing protocol as an extension for AODV protocol [17]. The protocol use the AODV routing protocol control messages to avoid extra message overhead. In AODV, a route request message (RREQ) is used to send a route request from the source node by broadcasting it. When the desired destination node receives the RREQ messages, it chooses the best route, i.e. the shortest-hop route, then uses it to send route reply RREP to the sender node. The sender node then uses this route to send the data [17]. 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.

In the proposed protocol, the RREQ message triggers the received nodes to adjust their transmission power before forwarding it to other nodes. Then each relay node adds in this RREQ message its residual energy. Then, the destination node receives the RREQ messages with their minimum residual energy according to equation (6.10), and uses the maximum one to send the RREP message as in equation 6.11. We assume that the destination node has enough energy to receive the packets which is a common assumption for WANETs (e.g., [14]).

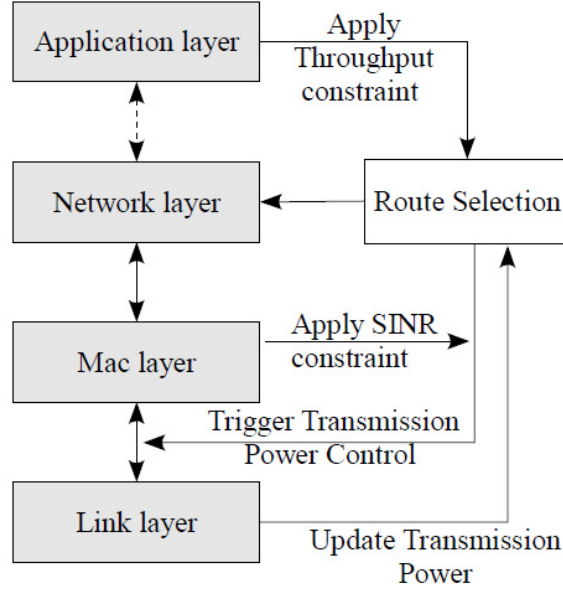


Figure 6.1: The proposed cross-layer design for power control and routing protocols

## 6.5 Proposed Protocol

The proposed protocol is designed as an extension to the well-known AODV protocol. The proposed protocol design allows the user in application layer to choose between them according to the application requirements. In the proposed protocol, a residual energy parameter is used to choose the best route, combined with power control in MAC layer, or both. Thus, we have the following three variations of the proposed protocol as the AODV extensions.

- **ER-AODV:** *Energy-efficient and maximum Residual energy route selection over AODV.* It implements the proposed cross-layer protocol in section 3. It implements the power control at MAC layer which updates the transmission power according to connectivity and SINR constraints as in equation 6.7 and equation 6.8. The destination node chooses the maximum remaining energy route to send the RREP message as in equation 6.10 and equation 6.11.
- **E-AODV:** *Energy-aware AODV.* It implements the power control using routing control messages. Each node updates its transmission power according to connectivity and SINR constraints as in equation 6.7 and equation 6.8.

- **R-AODV:** maximum Residual energy-aware route selection over AODV. The destination node chooses the maximum residual energy route to send the RREP message as in equation 6.10 and equation 6.11.

In the following we show the detailed steps for ER-AODV proposed protocol.

*INPUT:*  $m$  available routes from a source node  $s \in S^{(c)}$  to a destination node  $d \in D^{(c)}$ , associated with node's energy level.

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

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

- Step 1: The source node  $s$  broadcasts RREQ for all its neighbor nodes.
- Step 2: For each node  $i$  which receives the RREQ message:
  1. Node  $i$  adjusts its own transmission power  $P_{ij}$  to the minimum according to the connectivity and SINR constraints as in equation 6.7 and equation 6.8 respectively.
  2. Keep the minimum residual energy  $\underline{E}_r$  in the RREQ message. The minimum residual energy is computed as in equation 6.10.
  3. Forward the RREQ message using the updated  $P_{ij}$  to its neighbors.
- Step 3: The destination node  $d$  chooses route  $r_{max}$  with the maximum residual energy according to (11) and uses it to send the RREP to source node  $s$ .

The protocol takes as an input the network topology and the set of available routes between each source and destination. Step 2 implements the connectivity and SINR constraints in equation 6.7 and equation 6.8 respectively. Every relay node  $i$  belonging to the route from source  $s \in S^{(c)}$  to destination  $d \in D^{(c)}$  minimizes its transmission range to satisfy the connectivity constraint in equation 6.7, and the SINR constraint in equation 6.8. In Step 3, the destination node  $d$  selects the RREP route according to the routing metric in equation 6.10 and equation 6.11. The flow conservation is satisfied as there is no assumption for unlimited bandwidth.

In the proposed E-AODV, Step 3 is not considered, and the shortest-hop metric is used. In the proposed R-AODV, Step 2.1 is not considered and the default transmission power is used. If the longest route length is  $k$ , the AODV routing protocol time complexity is  $O(2k)$  [17]. If the maximum node degree (number of neighbors) is  $nb$ , then the time

complexity for the proposed ER-AODV and E-AODV is  $O(2k * nb)$ . In the worst case each node may have  $n$  neighbors, so the time complexity could be  $O(2k * n)$ . The extra time comes from the transmission power control step, so the time complexity for R-AODV is the same as AODV. The communication complexity for AODV and the proposed routing protocol is  $O(2n)$ . There is no difference between AODV and the proposed routing protocol in communication complexity as the proposed protocol does not impose any extra control messages.

## 6.6 Implementation and Simulation Scenario

We must consider the following in order to implement the proposed protocol in ns-2.33 [36] network simulator.

- The new transmission power calculation depends on the distance between the sender node and its first hop neighbors using a shadowing propagation model with a path loss exponent  $\alpha = 3$  [60, 65].
- We use the extended cumulative interference model [66] with the original 802.11 MAC code in ns-2 to implement the SINR constraint in equation 6.8.
- Simultaneous connections are considered to show the effect of multi-commodity flows.

We consider a typical WANET with 100 wireless nodes randomly located over a  $1500 \times 300 \text{ m}^2$  rectangular flat space [23]. We use identical loads and environmental conditions to compare the AODV with the proposed protocol variations. Each simulated run accepts the following scenario files as input.

- Nodes position and their initial transmission range: the nodes are uniformly distributed in a  $1500 \times 300 \text{ m}^2$  area, and the initial transmission range is uniformly distributed between 200 and 250m.
- 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 2, 4, 8, 16, 32, and 64 CBR connections with a packet size of 512 bytes. The connections are started at times uniformly distributed between 0 to 300 seconds. For multi-commodity flows, 2, 4, 8, and 16 simultaneous connections are considered with maximum 32 CBR connections.

This scenario is repeated twenty times using different random values, and the average result was presented with a 95 percent confidence interval.

## 6.7 Performance Metrics

We have conducted a performance evaluation and made a comprehensive comparison with the well-known AODV using a computer simulation. The simulation was implemented using ns-2.33 [37] and the results are analyzed to get different six major performance metrics which are described in details as follows.

- Total energy consumption rate: the energy consumed per byte [67] is computed as follows.

$$\frac{\text{Total energy consumed}}{\text{Total throughput}} \quad (6.12)$$

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 the interference, we computed the average node degree. The node degree of any node is the number of nodes within its transmission range.
- Throughput: we computed the network throughput as the total number of received bytes per second.
- Drop ratio: we computed the packet drop ratio as the ratio between the dropped packets to total packets sent during the simulation time.
- End-to-end delay: the time a packet takes to be transmitted across a network from source to destination. We computed 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.

## 6.8 Simulation Results

In this Chapter, we took into consideration only static nodes with no mobility model. For the simulated WANET environment described in Section 6.6, we test the impact of the numbers of CBR connections and the simultaneous connections.

### 6.8.1 Impact of the number of connections

In Figures 6.2-6.7, we show the different performance comparison of the variations of the proposed protocol (i.e., ER-AODV, R-AODV, AND E-AODV) with the AODV protocol. This figure presents the simulation results in which the number of CBR connections changes. For this scenario there is one connection at a time. From Figures 6.2-6.7, the proposed ER-AODV and E-AODV have better performance than AODV and the proposed R-AODV. Figure 6.2 shows the energy consumption rate. The proposed ER-AODV and E-AODV with power control decrease the total energy consumption rate by 20 to 30 percent compared to the AODV and the proposed R-AODV (i.e. no power control). As the number of connections increased, the proposed ER-AODV and E-AODV decrease the average physical node degree as shown in Figure 6.3 which results in lower nodes interference. Figure 6.4 shows the network throughput. The proposed ER-AODV and E-AODV preserve the throughput in 2, 4, 8, and 16 connections and increase it at 32 and 64 connections. This is due to less interference and low drop ratio. The drop ratio is shown in Figure 6.5. The end-to-end delay is decreased by the proposed protocol as shown in Figure 6.6. R-AODV has lower delay and ER-AODV and E-AODV has the minimum delay. It is clear at the 32 connections. Lower interference leads to decreasing the energy consumption and maximizing the network lifetime while preserving the throughput and the packet drop ratio. The network lifetime is shown in Figure 6.7. The proposed protocol shows better performance with 32 and 64 connections, which indicates good performance with higher network load.

### 6.8.2 Impact of multi-commodity flow

Figures 6.8-6.13 shows the relative performance of AODV and the variations of the proposed routing protocol if we consider the multi-commodity flow (i.e. simultaneous connections). Total energy consumption rate is shown in Figure 6.8 which shows that the proposed protocol with power control (i.e., ER-AODV and E-AODV) consumes 10 to 20 percent less energy than AODV. This is due to the reduction of the overall interference. The



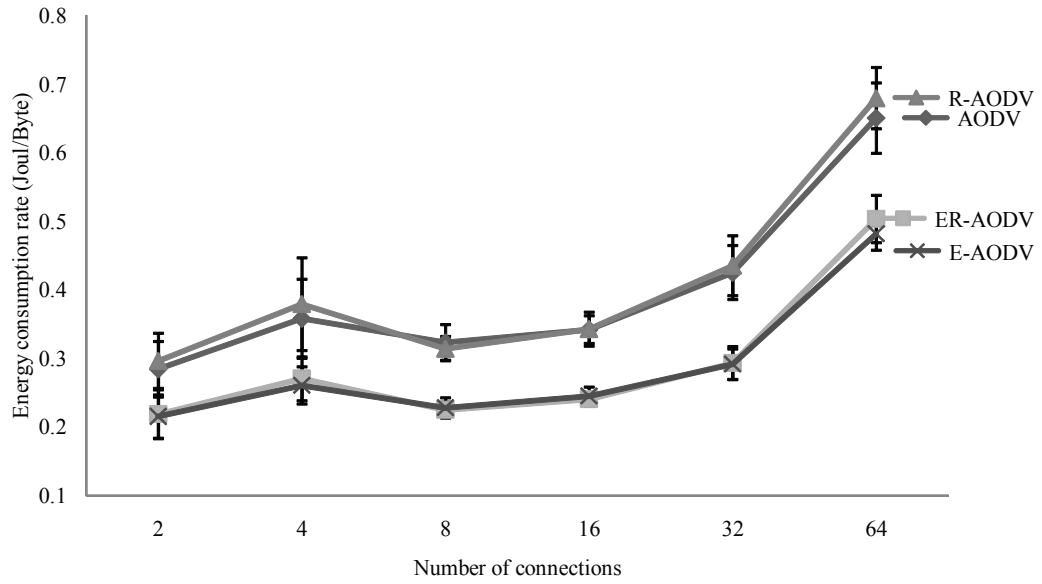


Figure 6.2: Energy consumption rate with various number of connections.

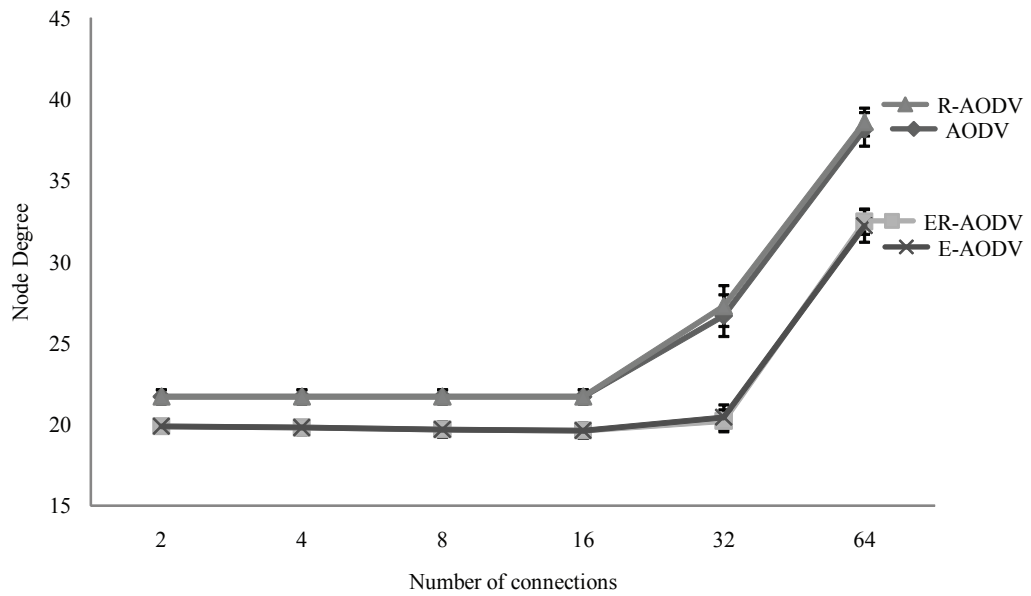


Figure 6.3: Node degree with various number of connections.

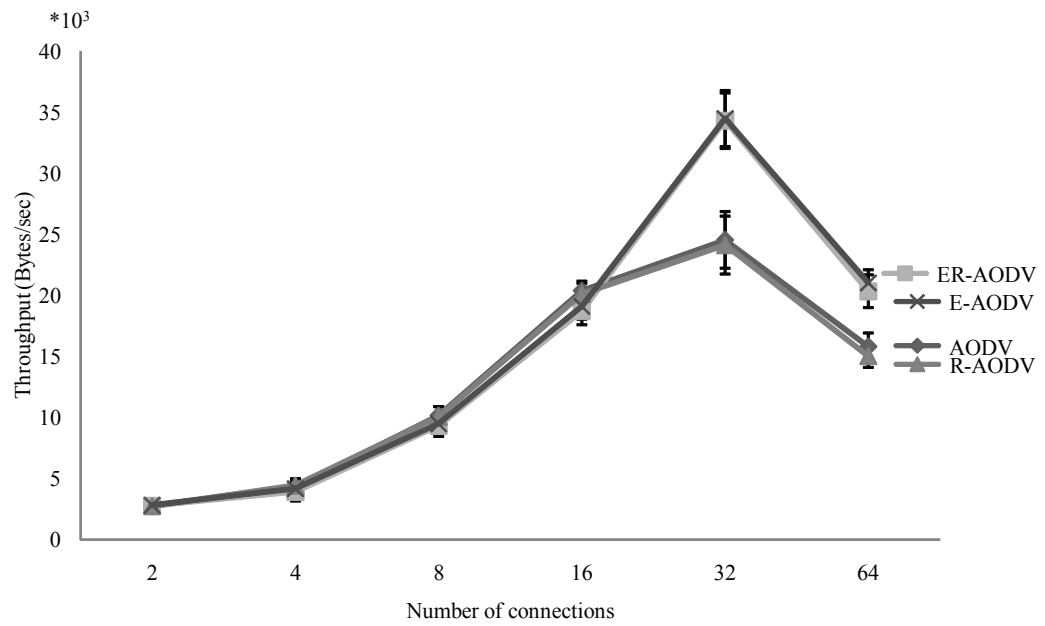


Figure 6.4: Network throughput with various number of connections.

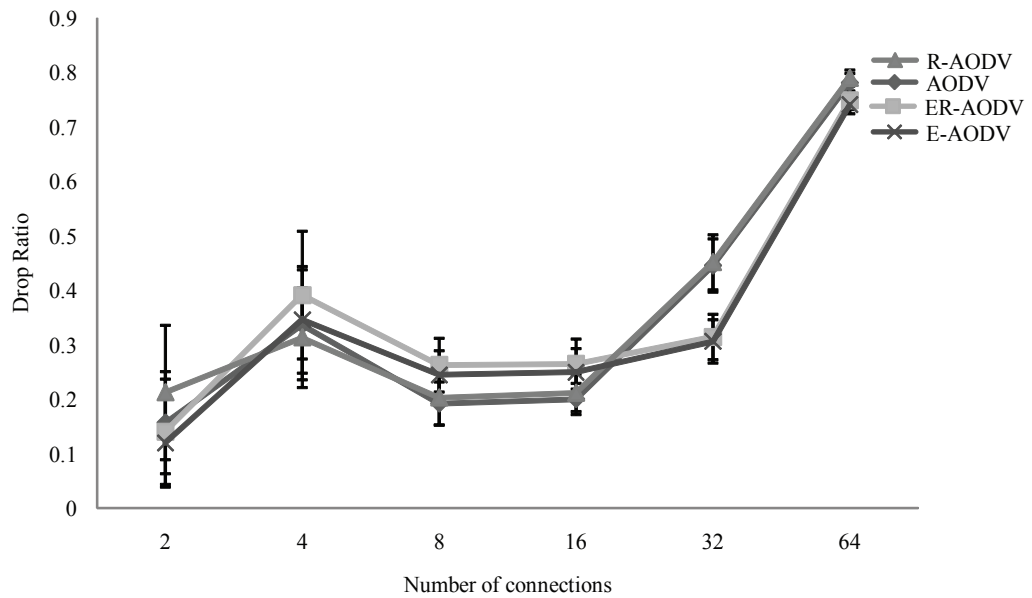


Figure 6.5: Packets drop ratio with various number of connections.

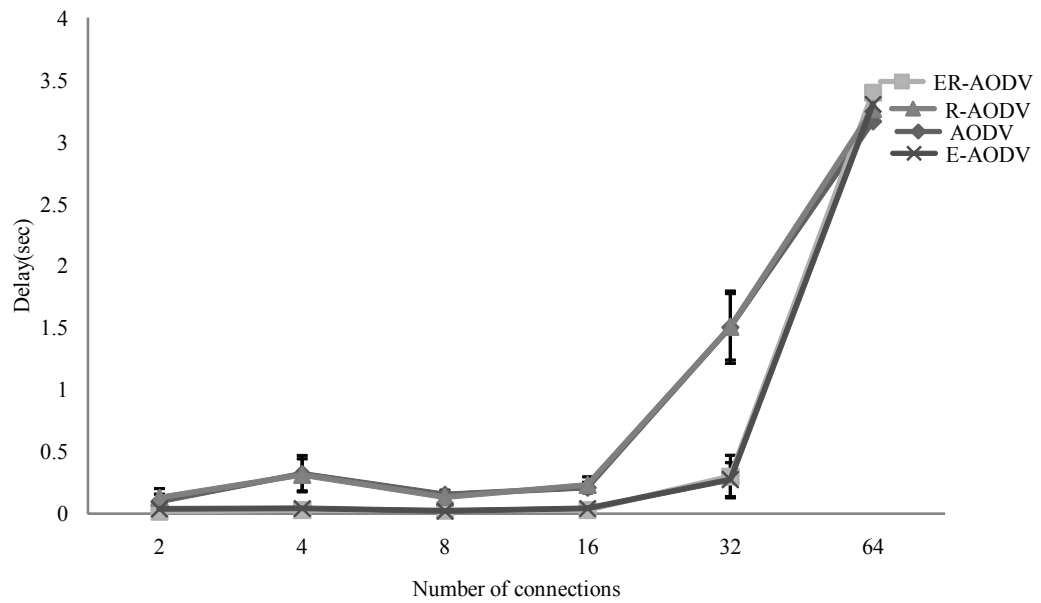


Figure 6.6: End-to-end delay with various number of connections

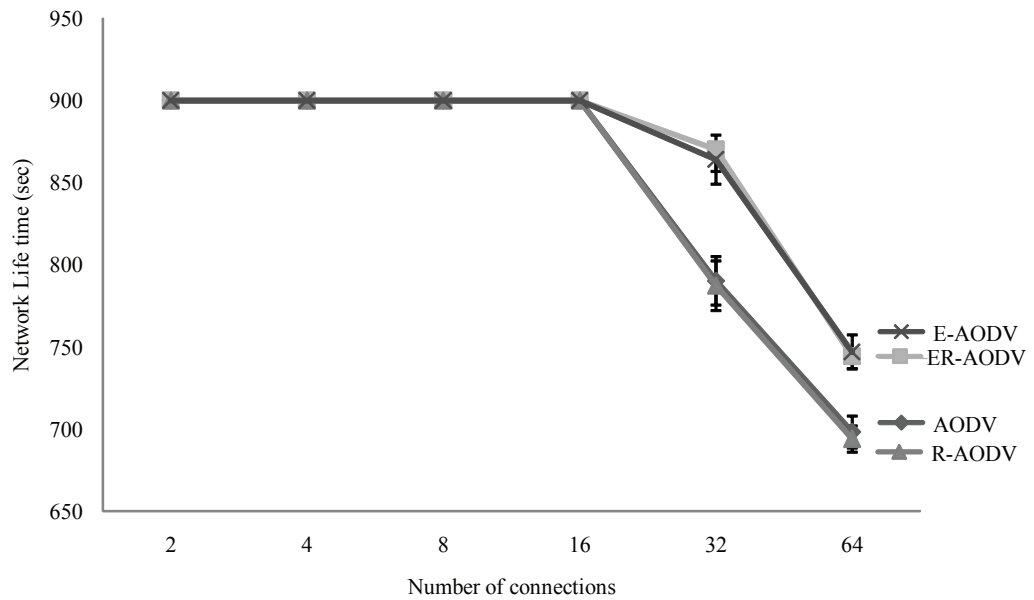


Figure 6.7: Network lifetime with various number of connections

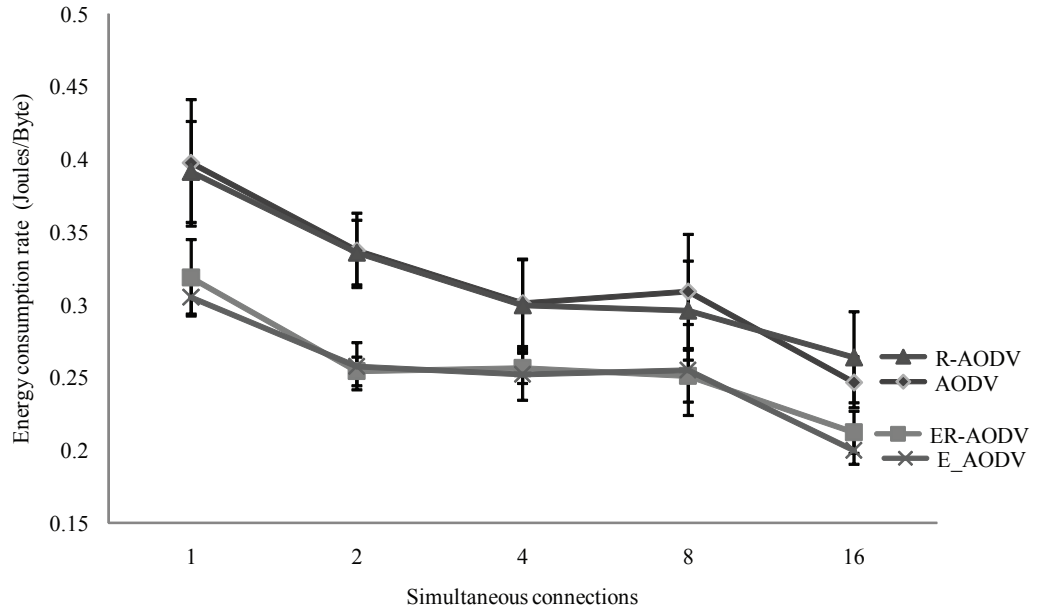


Figure 6.8: Energy consumption rate with multi-commodity flow.

reduction of the overall interference is shown in Figure 6.9 where the average physical node degree is decreased. ER-AODV and E-AODV have the minimum average node degree. The throughput each protocol is able to achieve is shown in Figure 6.10. ER-AODV achieves better throughput than AODV. This is due to less interference and less drop ratio. The drop ratio is shown in Figure 6.11. ER-AODV reduces the average end-to-end delay by 40 to 50 percent relatively to AODV protocol with 1, and 2 simultaneous connections (Figure 6.12). R-AODV has the highest delay among the AODV, E-AODV, and ER-AODV. The network lifetime of the ER-AODV is better than AODV with one and two simultaneous connections as shown in Figure 6.13.

The simulation results show that ER-AODV gets the average overall performance from E-AODV and R-AODV. E-AODV and ER-AODV results show that power control has more effect on the performance than the route metric change.

## 6.9 Summary

We investigate the energy-efficient routing for WANETs using cross-layer design. The interaction among the layers with a global performance target can produce better results

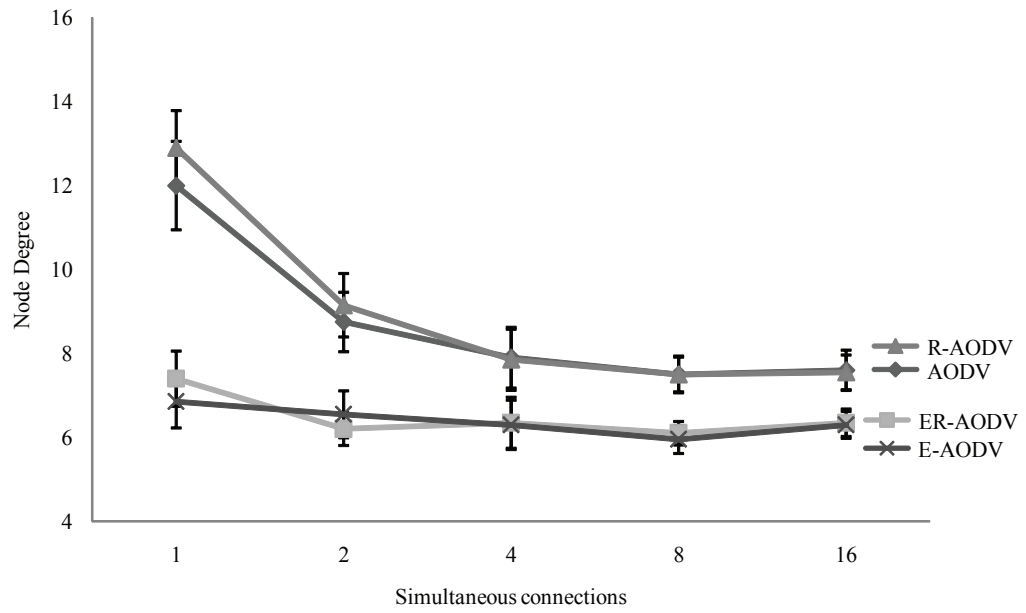


Figure 6.9: Node degree with multi-commodity flow.

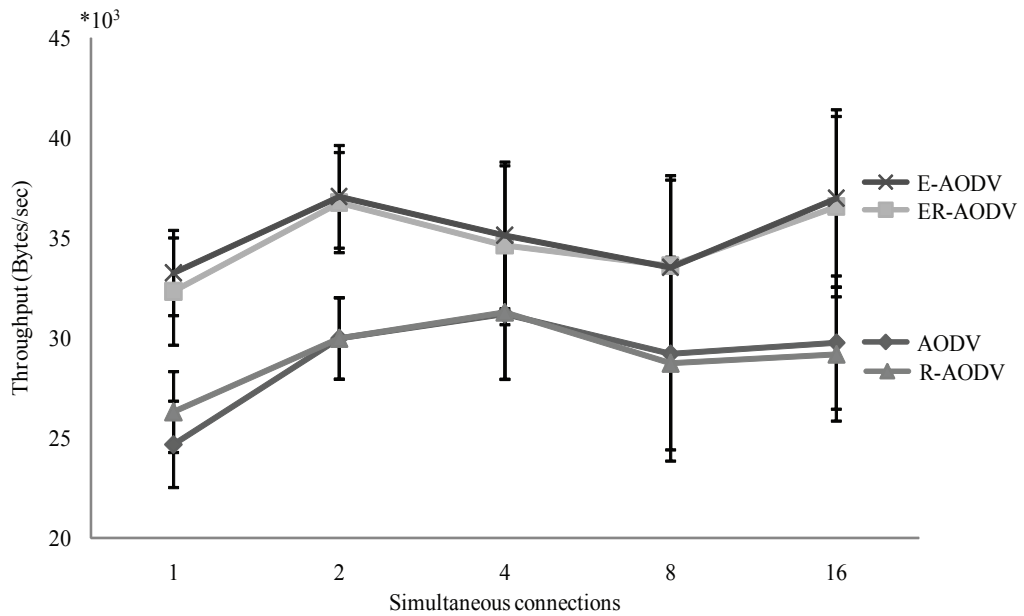


Figure 6.10: Network throughput with multi-commodity flow.

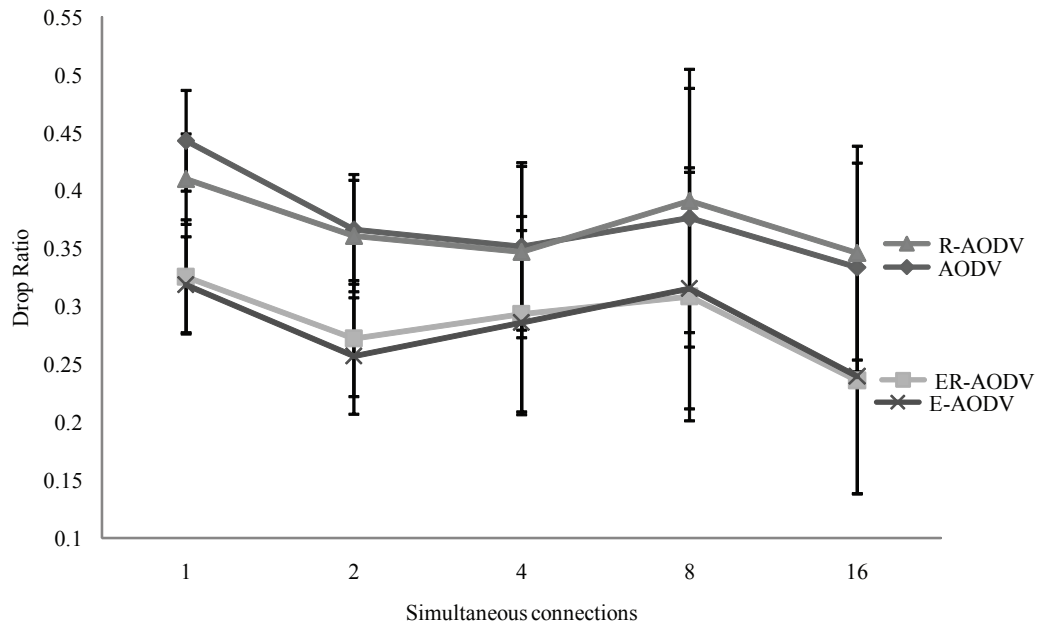


Figure 6.11: Packets drop ratio with multi-commodity flow.

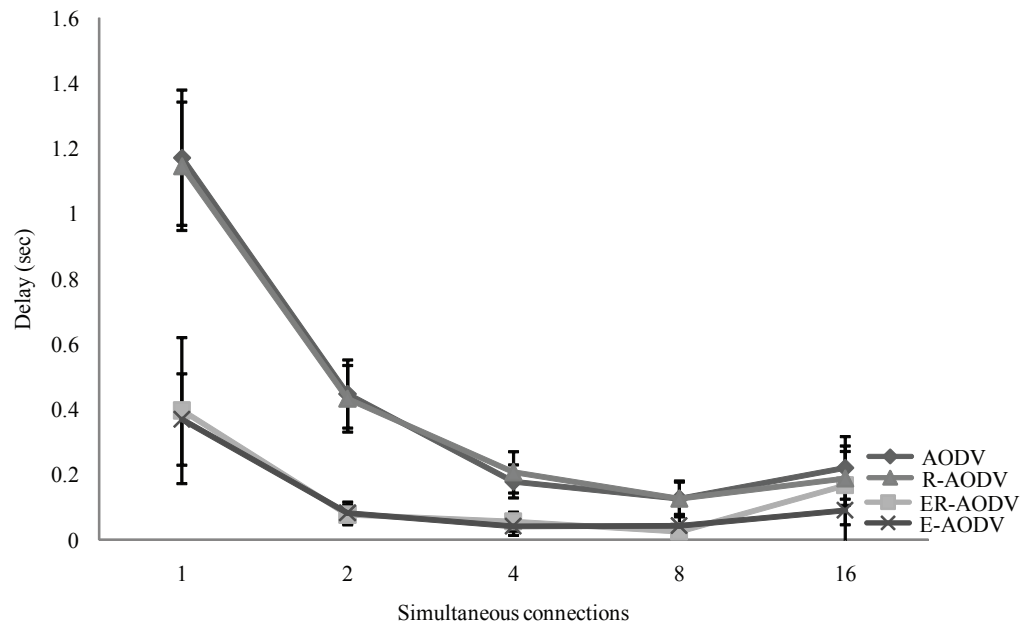


Figure 6.12: End-to-end delay with multi-commodity flow.

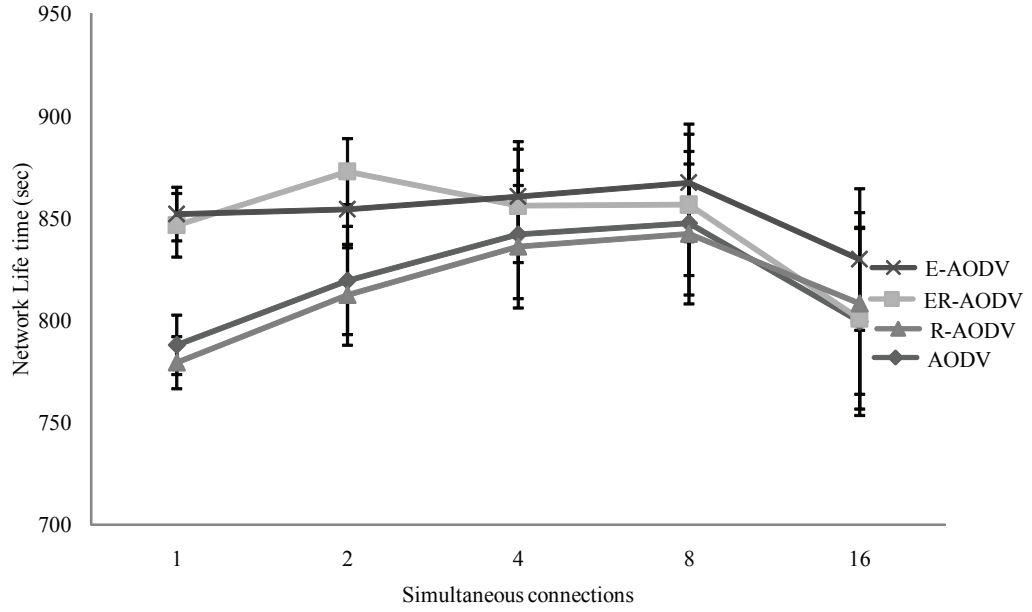


Figure 6.13: Network lifetime with multi-commodity flow.

than dealing with each layer individually. We develop a cross-layer energy-efficient routing approach as an extension to the well-known AODV routing protocol with three variations (i.e., ER-AODV, E-AODV, and R-AODV). We conduct a comprehensive performance evaluation using a network simulation. It is shown that the ER-AODV gets the benefit of the cross-layer interaction between power control and routing protocol. It increases the network lifetime, reduces the end-to-end delay and saves the total energy consumption. The E-AODV implements the power control using the routing protocol messages. The R-AODV uses routing protocol with residual energy criteria to choose the best route.

## Chapter 7

# Cross-Layer Design for Topology Control and Routing in WANETs

In this chapter, we propose a cross-layer design that jointly consider routing and topology control taking mobility and interference into account for WANETs. 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 WANETs. We evaluate the performance of the proposed protocol by comprehensively simulating a set of random WANET environments with high-mobility nodes.

### 7.1 Introduction

A WANET 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., [68–70]). These researches have 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 [1]. The energy-efficient design of the wireless transceiver, however, cannot be classified as topology control



because it has a node-wide perspective [1]. 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 WANET frequently changes, and thus original data transmission routes can become disabled. Another essential issue for WANETs 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 [22]. 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 OLSR (Optimized Link State Routing [15]) and DSDV (Destination Sequenced Distance Vector [16]). 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 AODV (Ad-hoc On-demand Distance Vector [17]) and DSR (Dynamic Source Routing [18]). Hybrid methods combine proactive and reactive methods to find efficient routes as ZRP (Zone Routing Protocol [19]). 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 in WANETs [25, 27, 28, 30]. 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 [29]. These interactions are supersets 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 networks are investigated separately by taking into account some parameters such as interference and bandwidth [71].

## 7.2 Related Work

There are some related works that have been conducted for the cross-layer design of topology control, and the routing for WANETs with static and mobile nodes. Casaquite and Hwang [49] propose 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 WANETs. Chafekar *et al.* [50] jointly study the power control, scheduling, and routing to minimize the latency in a centralized way for WANETs. Romdhani and Bonnet [27] jointly study the routing protocol and power control for MANETs to determine the optimal route with a low energy consumption rate. Li *et al.* [72] seek to find a topology that can meet the energy-efficient QoS requirements and to ensure the maximum transmitting power of the nodes is minimized. They consider the topology control problem separately assuming there are collision-free MANETs. Wu *et al.* [11] propose mobility-sensitive extensions for many of the mobility-insensitive topology control protocols that have already been introduced for WANETs. Two mechanisms had been introduced. One is the consistent local views that avoid inconsistent information and delay. The other is the mobility management tolerating outdated information. They do not consider any layer interactions. Tang *et al.* [71] separately consider an interference-aware topology control and QoS routing for static networks. They seek a channel assignment where the topology is interference-minimized, and sought routes for QoS connection requests with bandwidth requirements.

### 7.3 Problem Formulation

A WANET is presented as a graph  $G = (N, L)$ .  $N$  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  $\beta \cdot d_{ij}^\alpha$  (i.e.,  $p_{ij} \geq \beta \cdot d_{ij}^\alpha$ ), 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 [60]. 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  $f_{ij} = \sum_{c \in C} f_{ij}^{(c)}$ . 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:

$$\sum_{(i,j) \in L} f_{ij}^{(c)} - \sum_{(k,i) \in L} f_{ki}^{(c)} = \begin{cases} Q_i^{(c)}, & \text{if } i \in S^{(c)}, \\ -Q_i^{(c)}, & \text{if } i \in D^{(c)}, \forall c \in C, \\ 0, & \text{otherwise.} \end{cases} \quad (7.1)$$

### 7.3.1 Maximize the Network Lifetime

Maximizing network life time is the main goal in WANETs 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 [3]. 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 [58].

Let the lifetime of node  $i$  be defined as the time it takes for the battery of node  $i$  to drain out. Let  $T_i(\mathbf{F})$  be the lifetime of node  $i$  under flow  $\mathbf{F} = \{f_{ij}\}$ , where  $(i, j) \in L$ .  $T_i(\mathbf{F})$  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 for node  $i$  is formally defined as follows:

$$T_i(\mathbf{F}) = \frac{E_i}{\sum_{\substack{\forall j \in N, \\ (i,j) \in L}} e_{ij} \sum_{c \in C} f_{ij}^{(c)}}. \quad (7.2)$$

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

$$\begin{aligned} T_G(\mathbf{F}) &= \min_{i \in N} T_i(\mathbf{F}) \\ &= \min_{i \in N} \frac{E_i}{\sum_{\substack{\forall j \in N, \\ (i,j) \in L}} e_{ij} \sum_{c \in C} f_{ij}^{(c)}}. \end{aligned} \quad (7.3)$$

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

$$\text{Maximize}_{\mathbf{F}} \quad T_G(\mathbf{F}) = \min_{i \in N} \frac{E_i}{\sum_{\substack{\forall j \in N, \\ (i,j) \in L}} e_{ij} \sum_{c \in C} f_{ij}^{(c)}},$$

subject to

$$\begin{aligned} \sum_{(i,j) \in L} f_{ij}^{(c)} - \sum_{(k,i) \in L} f_{ki}^{(c)} = & \begin{cases} Q_i^{(c)}, & \text{if } i \in S^{(c)}, \\ -Q_i^{(c)}, & \text{if } i \in D^{(c)}, \forall c \in C, \\ 0, & \text{otherwise.} \end{cases} \quad (7.4) \\ f_{ij}^{(c)} \geq 0, & \forall i \in N, \forall (i,j) \in L, \forall c \in C. \end{aligned}$$

Similar to [58], the above maximum network lifetime problem can be formulated as the following linear programming problem with some proper manipulation. Note that  $T$  is the network lifetime which is defined as the time it takes the first node to die (e.g. [58, 73]). Denote by  $\hat{f}_{ij}$ , the amount of bits transmitted from node  $i$  to node  $j$  in the network lifetime  $T$ , i.e.  $\hat{f}_{ij}^{(c)} = T f_{ij}^{(c)}$ . Thus we have the linear programming problem.

Maximize  $T$

subject to

$$\sum_{(i,j) \in L} e_{ij} \sum_{c \in C} \hat{f}_{ij}^{(c)} \leq E_i, \quad \forall i, j \in N, \quad (7.5)$$

$$\begin{aligned} \sum_{(i,j) \in L} \hat{f}_{ij}^{(c)} - \sum_{(k,i) \in L} \hat{f}_{ki}^{(c)} = & \begin{cases} TQ_i^{(c)}, & \text{if } i \in S^{(c)}, \\ -TQ_i^{(c)}, & \text{if } i \in D^{(c)}, \forall c \in C, \\ 0, & \text{otherwise.} \end{cases} \quad (7.6) \end{aligned}$$

$$\hat{f}_{ij}^{(c)} \geq 0, \quad \forall (i,j) \in L, \forall c \in C,$$

$$E_i > 0, \quad \forall i \in N.$$

This linear programming formulation can be viewed as a variation of the conventional maximum flow problem with node capacities (i.e.,  $\sum_{\forall(i,j) \in L} \sum_{c \in C} \hat{f}_{ij}^{(c)} \leq E_i/e_i$ ) [61], 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 [62, 74]. To maximize the network lifetime, it is also important to consider the topology control problem. Transmitting at minimum level of power helps to prolong the lifetime of a node, and thus, the network lifetime [59, 63]. The interference-aware topology control is addressed as follows.

### 7.3.2 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 [1]. In this chapter, 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  $\gamma_{ij}$  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 is defined as Integer Linear Programming (ILP) considering the delay QoS parameter in [72]. In this chapter 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  $p_{max}$  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  $\{p_{max} = \text{Max } \{p_{ij} | 0 \leq i < n\}\}$ ,  
 subject to

$$x_{i,j} = x_{j,i} \quad \forall i, j \in N, \quad (7.7)$$

$$x_{i,j} \leq x_{i,k}, \quad \text{if } d_{ik} \leq d_{ij} \quad \forall i, j, k \in N, \quad (7.8)$$

$$P_i \geq p_{ij} \geq \beta \cdot d_{ij}^\alpha \cdot x_{i,j}, \quad \forall i, j \in N, \quad (7.9)$$

$$\begin{aligned} SINR_{ij} = \frac{p_{ij}/d_{ij}^\alpha}{\sum_{(k,j) \in L, k \neq i} p_{kj}/d_{kj}^\alpha + \sigma} \geq \gamma_{ij}, \\ \forall i, j, k \in N, \\ x_{i,j} = 0, \text{ or } 1, \quad \forall i, j \in N. \end{aligned} \quad (7.10)$$

Constraint in equation (7) ensures that there is a bidirectional link between node  $i$  and node  $j$ . We need this constraint to deal with the transmission power heterogeneity exists between mobile nodes. Constraint in equation (8) ensures that nodes have broadcast ability. That is, the transmission by a node can be received by all the nodes within its transmission range. This feature can be represented as 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  $d_{ik} \leq d_{ij}$ . Constraint (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  $\beta \cdot d_{ij}^\alpha$ , 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. 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 (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).

### 7.3.3 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 [29]. In most of WANETs routing protocols, the shortest-hop metric is used to select the best route [15–18, 56]. 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 chapter, we consider WANETs, 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 use the speed parameter to choose the best route. The route used is changed 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  $d$  as follows:

$$R = \{(i_0, i_1), \dots, (i_{h-1}, i_h)\}, \forall (i_k, i_{k+1}) \in L, \quad (7.11)$$

where  $i_0, i_1, \dots, i_h$  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  $\nu_i$  be the speed of node  $i$  in meter per second.

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

$$\nu_r = \text{Max}(\nu_{i_0}, \nu_{i_1}, \dots, \nu_{i_{h-1}}). \quad (7.12)$$

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

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

$$r_{min} = \text{Min}(\nu_{r_1}, \dots, \nu_{r_m}). \quad (7.13)$$

The notations for the formulation are summarized in Table 7.1, for convenience.

## 7.4 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., de-

Table 7.1: Formulation parameters

$T$	The network lifetime defined as the time it takes for the first node to die.
$T_i$	The time it takes for the battery of node $i$ to drain out.
$T_G$	The life time of the network $G$ .
$p_{ij}$	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 $i \in N$ .
$e_{ij}$	The energy for transmitting one bit across the link $(i, j) \in L$ .
$\nu_i$	The speed of node $i$ in meter per second.
$f_{ij}^{(c)}$	The rate at which bits of commodity $c$ are transmitted across the link $(i, j)$ per second, $\forall c \in C$ .
$\hat{f}_{ij}^{(c)}$	The total number of bits of commodity $c$ for link $(i, j)$ transmitted from node $i$ to node $j$ over $T$ , $\forall c \in C$ .
$Q_i^{(c)}$	The throughput requirements, i.e., the number of bits that should be routed between source $s \in S^{(c)}$ and destination $d \in D^{(c)}$ nodes per second, $\forall c \in C$ .
$TQ_i^{(c)}$	The number of bits transmitted over $T$ , at the source node $s \in S^{(c)}$ for $d \in D^{(c)}$ , $\forall c \in C$ .
$SINR_{ij}$	The Signal to Interference with Noise Ratio requirement at the receiver node $j$ from sender node $i$ .
$\alpha \geq 2$	The distance-power gradient.
$\beta \geq 1$	The transmission quality parameter.
$d_{ij}$	The Euclidean distance between the nodes $i$ and $j$ .
$\sigma$	The ambient noise power level.
$\gamma_{ij} \geq 1$	The SINR requirement for the transmission from node $i$ to node $j$ .
$x_{i,j}$	A boolean variable, =1 if there is a link from node $i$ to node $j$ ; otherwise =0 .

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 dependences between the protocol layers, and the dynamic characteristics of WANETs. As a result, the resulting protocols may not be adaptive. As shown in Figure 7.1(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 [30].



We propose a cross-layer mobility-aware routing and interference-aware topology control protocol. As shown in Figure 7.1(b), we consider the SINR constraint equation (7.10) 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 (7.13).

The Ad-hoc On-demand Distance Vector routing (AODV) [17] is one of the well-known routing protocols for WANETs. 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. DSR, however, consistently generates less routing load than AODV [75].

In this chapter, 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 WANETs. 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 [17]. 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 triggers the topology control. The received nodes adjust their transmission power before forwarding it to the other nodes according to the SINR constraint in equation (7.10). Then, this RREQ message maintains the maximum speed. The destination node receives the RREQ messages with their maximum speed according to equation (7.12), and uses the minimum one to send the RREP message as in equation (7.13). We assume that the destination node has enough energy to receive the packets, which is a common assumption in WANETs (e.g., [14]).

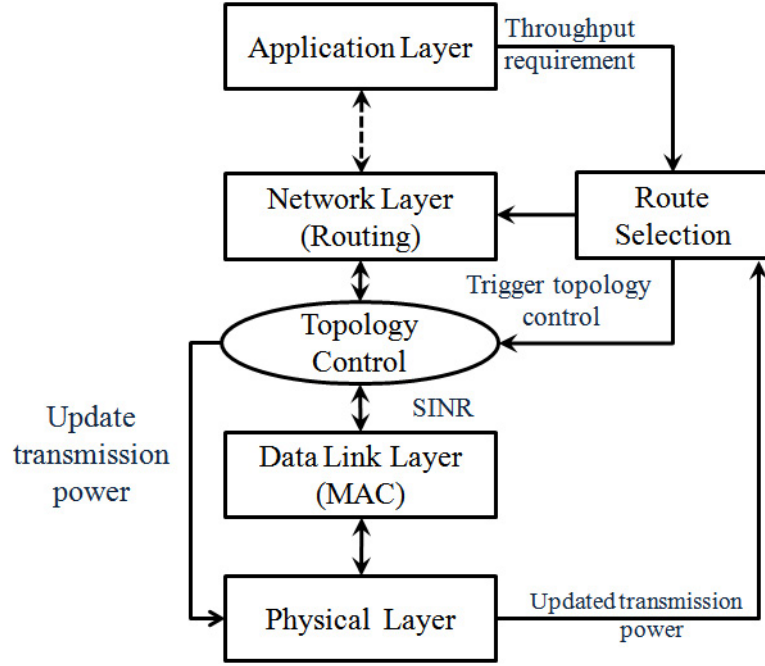


Figure 7.1: The proposed cross-layer design for topology control and routing protocols

## 7.5 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  $r_{min}$  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:  $\forall i_k \in R - s, d$ .
  1. Compute-new-power( $d_{ij}$ ): node  $i$  adjusts its own transmission power  $p_{ij}$  taking into considerations the topology and SINR constraints.
  2. keep the maximum  $\nu_i$  in the RREQ message.
  3. Forward the RREQ message using the updated  $p_{ij}$  to its neighbors.

- Step 3:  $d$  choose route  $r_{min}$ ; the RREQ messages from source node  $s$  that has the minimum speed nodes as equation (7.13).

- Send the RREP to source node  $s$  using route  $r_{min}$ .

The protocol takes as an input the initial network topology and the set of available routes between each source and destination. Step 2 implements the topology, and the SINR constraints in equation (7.9), and equation (7.10) respectively. Every relay node  $i$  belongs to the route from the source  $s \in S^{(c)}$  to the destination  $d \in D^{(c)}$  adjust its transmission range as follows.

*INPUT:*  $d_{ij}$ , the Euclidean distance from node  $i$  to node  $j$ , path loss exponent  $\alpha$ , transmission quality parameter  $\beta$  and SINR requirement  $\gamma_{ij}$ .

*OUTPUT:* Updated  $p_{ij}$ , nodes  $i$  transmission power to node  $j$ .

*Procedure:* Compute-new-power( $d_{ij}$ )

- Before sending the message:  $p_{ij} = \beta \cdot d_{ij}^\alpha + a$ , where  $a$  is a constant initially equal to 0. In implementation the actual calculation of  $p_{ij}$  depends on the propagation model.
- While sending the message: if SINR is more than or equal to  $\gamma_{ij}$ , do nothing. If SINR is less than  $\gamma_{ij}$ : increase the constant  $a$  by a random variable more than 0 and less than 1 until  $SINR \geq \gamma_{ij}$  or message lifetime ends.

In step 3, the destination node  $d$  selects the RREP route according to the routing metrics in equation (7.12), and equation (7.13). The flow conservation is satisfied as there is no assumption for an unlimited bandwidth.

If the longest route length is  $k$ , the AODV routing protocol time complexity is  $O(k)$  [17]. If the maximum node degree (number of neighbors) is  $nb$ , then the time complexity for the proposed MRIT protocol is  $O(k*nb)$ . In the worst case, each node may have  $n$  neighbors, so the time complexity could be  $O(k*n)$  where  $n$  is the total number of nodes. The extra time comes from the topology control step. 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.

## 7.6 Implementation and Simulation Scenario

The AODV routing protocol implementation is available in ns-2 network simulator as the default standard routing protocol for WANETs [36]. We implement the proposed MRIT protocol using C++ in ns-2 network simulator. Our code is available in our research group website [37]. In our implementation, we consider the followings:

- We implement the proposed transmission power computation using ns-2 shadowing propagation model [36] with a path loss exponent  $\alpha = 3$  and  $\beta = 1$  [60, 65].
- We use the extended cumulative interference model [66] with the original *Mac802.11* implementation in ns-2 to implement the SINR constraint in equation (7.10) with  $\gamma_{ij} = 1$  (i.e. received power should be more than or equal to noise power and accumulated interference power).

We consider a typical WANET with 100 mobile nodes randomly moved over a  $1500 \times 300 \text{ m}^2$  rectangle flat space [23] for one hour (i.e. 3600 sec). 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  $1500 \times 300 \text{ m}^2$  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 seconds 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 [76, 77]. The proposed protocol and the AODV tested for 0, 600, 1200, 1800, 2400, 3000 and 3600 sec pause times and the maximum speed is 20

meter/sec. A pause time of zero sec means high mobility, and a 3600 sec pause time means nodes move once (i.e. low mobility).

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

## 7.7 Performance Metrics

We have conducted a performance evaluation and a comprehensive comparison with AODV as the default standard reactive routing protocol for WANET using the simulation scenario described in Section 7.6. We test the proposed protocol to check the energy efficiency by calculating the energy consumption rate [67], and the network lifetime [78]. 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 [72]. 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 [11]. The performance metrics are described in details as follows:

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

$$\frac{\text{Total energy consumed}}{\text{Total throughput}} \quad (7.14)$$

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 [1]. We calculate the connectivity ratio as the ratio between number of connected pairs and all possible pairs at every time instance (i.e. every two seconds). We compute the average for the total simulation time.

## 7.8 Simulation Results

In this chapter, 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 WANET environment described in Section 5.1. In Figures 7.2-7.8, 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 7.2, 7.3, and 7.4 indicates how AODV and the proposed MRIT protocols consume energy. In Figure 7.2, we show the energy consumption rate verses pause time. The proposed MRIT protocol decreases the energy consumption rate by 30 to 50 percent 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 7.6. Furthermore, the network lifetime is increased by the proposed MRIT protocol as shown in Figure 7.3. While the network lifetime is increased, the network connectivity is increased by the proposed MRIT as shown in Figure 7.4. This is due to less node failure because of energy. In Figure 7.5, 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 to 90 percent compared to the AODV. As a result of energy-efficient and less packet retransmissions, the proposed MRIT protocol increases the throughput and

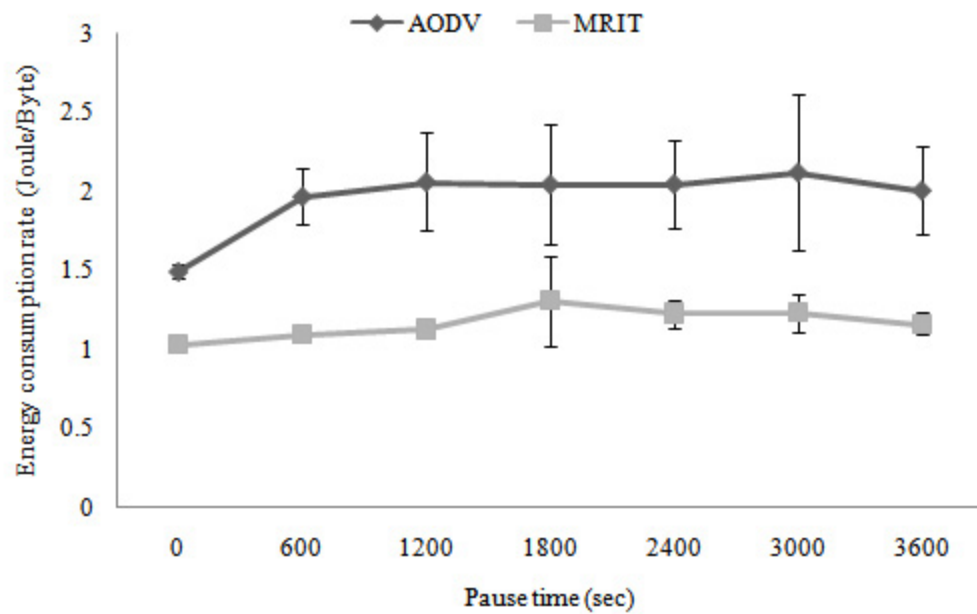


Figure 7.2: Energy consumption rate.

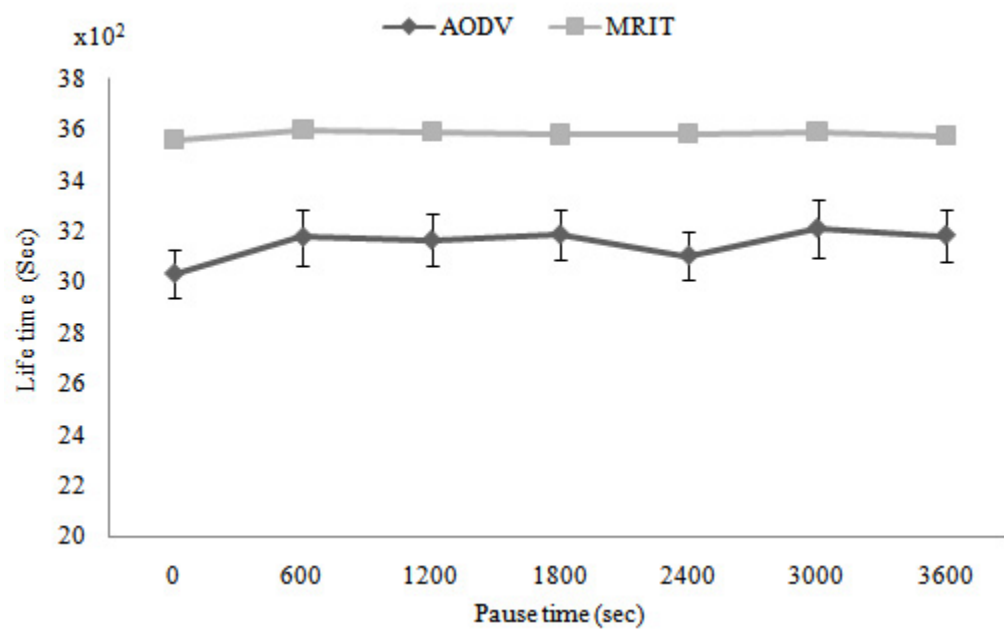


Figure 7.3: Network lifetime.

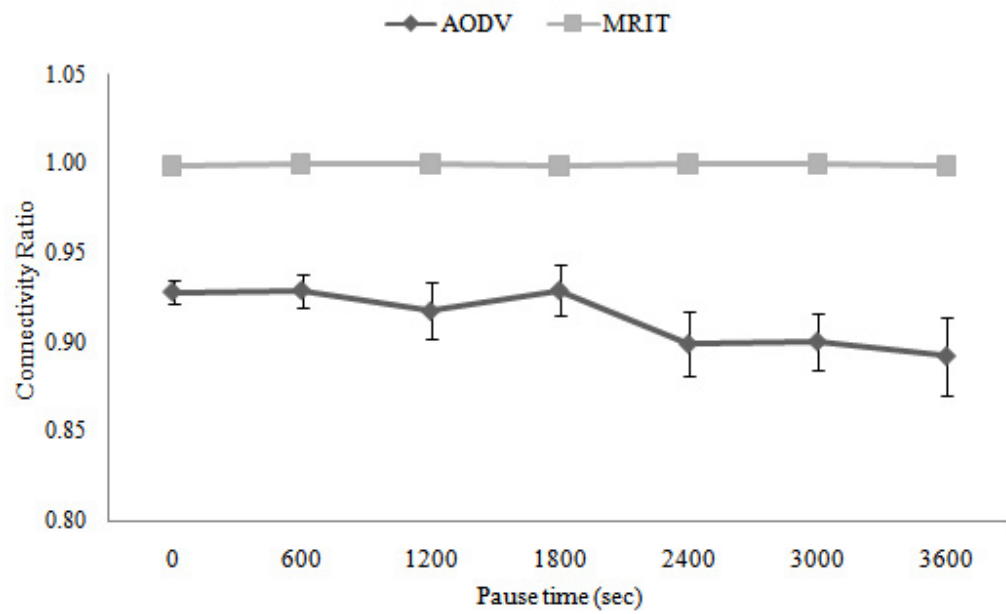


Figure 7.4: Network connectivity ratio.

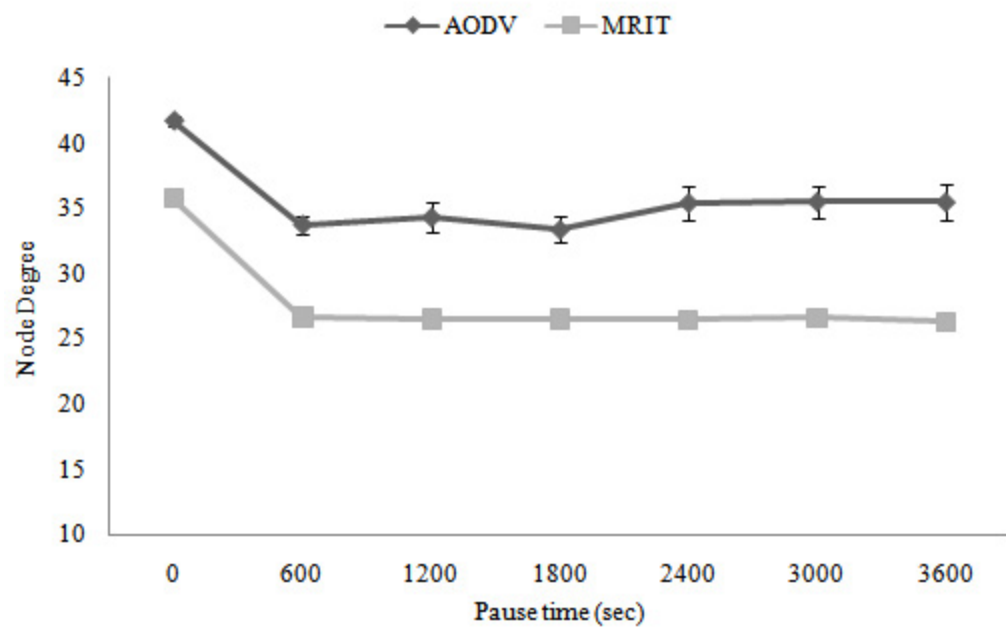


Figure 7.5: Node degree.



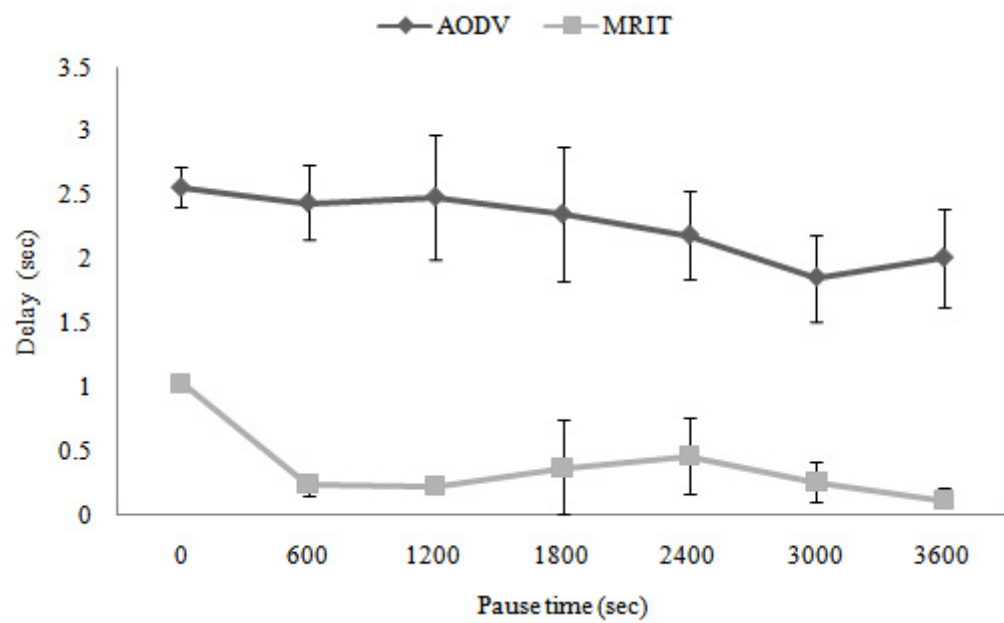


Figure 7.6: End-to-end delay.

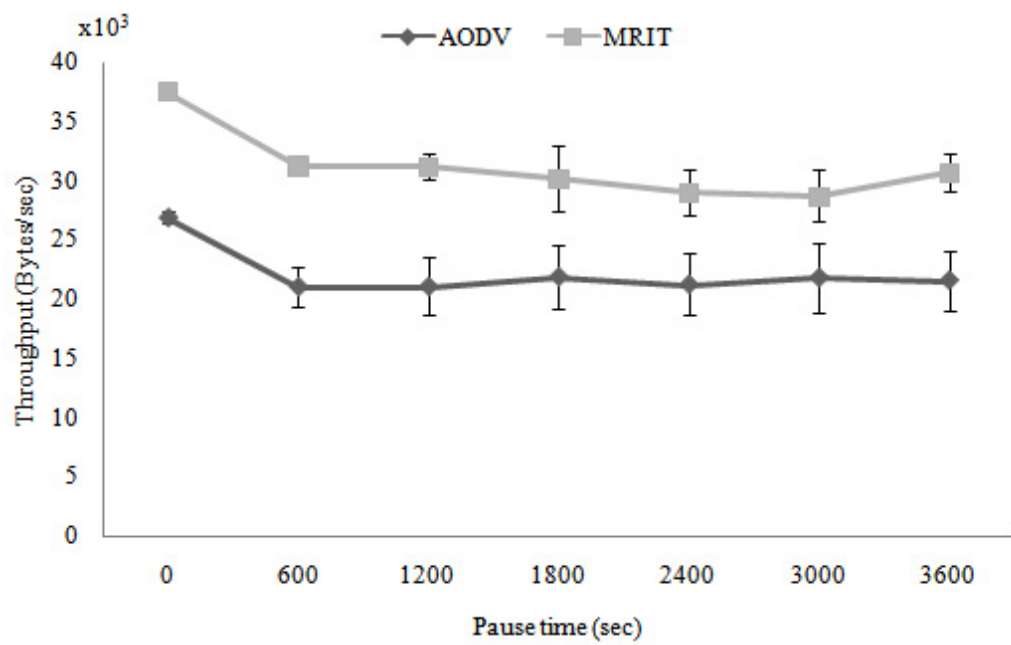


Figure 7.7: Throughput.

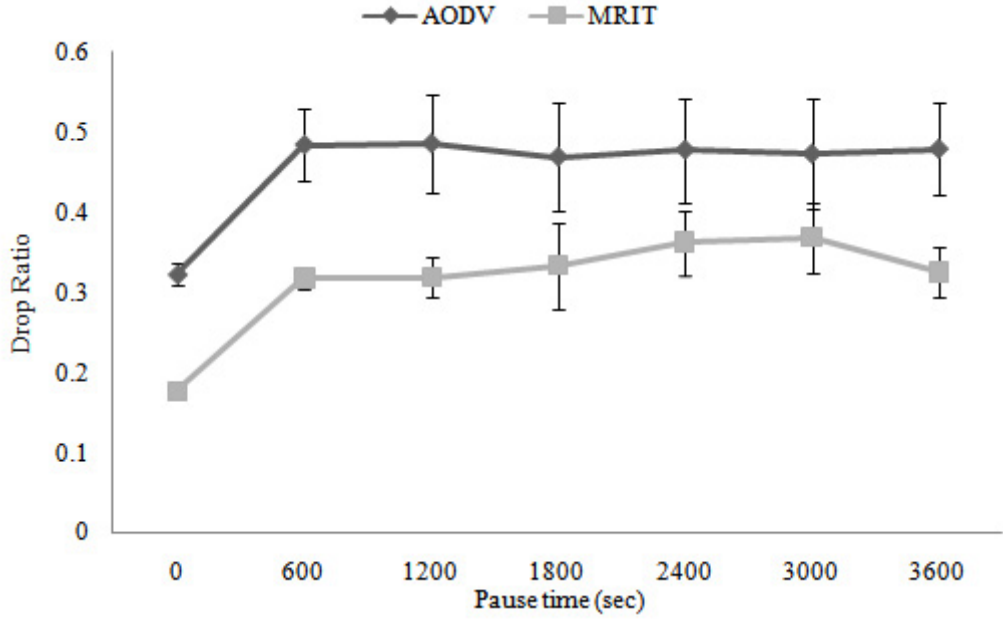


Figure 7.8: Packets drop ratio.

decrease the drop packets ratio as shown in Figure 7.7 and 7.8 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 7.2-7.8, 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.

## 7.9 Summary

We investigate a cross-layer design for routing and topology control taking interference and mobility into account for WANETs. We propose a novel cross-layer Mobility-aware Routing and Interference-aware Topology control (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 WANET with high-mobility nodes. 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.

## Chapter 8

# Conclusion and Future work

A wireless ad hoc network (WANET) is composed of stationary or mobile nodes without predetermined infrastructure. Communication among nodes is accomplished by forwarding data packets for each other, on a hop-by-hop basis.

First, in this dissertation, we consider the topology control problem using speed parameter to minimize the nodes' transmission range while preserving the network connectivity with high-mobility. Topology control problem is one of the most crucial issues for WANETs. The main objective of topology control is to reduce power consumption and interference while preserving network desired properties as connectivity. Using geometric graphs for this problem proves efficiency along various related work. Most of the related work deal with WANETs in a static state in the case of sensor network studying. In this class of networks, the main target is to reduce the energy consumed. While in WANETs, the problem of preserving the connectivity with different node speeds is added. Various transmission ranges and speeds should be considered. In Chapter 3, mobility-aware topology control protocols are proposed. It depends on using the speed parameter instead of only distance parameter. Using of speed parameter add a new dimension in dealing with the mobile networks. It improves the preservation of the connectivity parameter along with highly dynamic network. MYao and MMI are proposed as mobility-aware extensions to Yao graph and symmetric Mutual Inclusion (MI) graph. The proposed graphs are constructed locally using only first-hop information. The simulation results show that the MMI proposed graph can reduce network interference as it reduces the physical node degree by at least four degrees (in case of 100 nodes) regardless of nodes' speed. The proposed topology control protocols reduce

the average transmission power by more than 50 percent and 40 percent respectively while preserving network connectivity property.

Furthermore, we consider topology control using a weight utility function which combines the speed and energy parameters to minimize the nodes' transmission power. In Chapter 4, energy and mobility-aware topology control protocols are proposed. It depends on using a utility function considers the energy and speed parameter instead of only distance parameter. Using of energy and speed parameters improves the preservation of the connectivity parameter and minimizes the interference and transmission power along with highly dynamic network. EMYao and EMMI are proposed as energy and mobility-aware extensions to Yao graph and Mutual Inclusion (MI) graph.

The proposed graphs are constructed locally using only first-hop information. The simulation results show that the EMMI and EMYao proposed graphs can reduce network interference and end-to-end delay. This is result from the decrease in the physical node degree and node's transmission power. The proposed EMMI and EMYao graphs reduce the average transmission power by more than 50 percent and 40 percent respectively while preserving network connectivity property. In addition, the simulation results show that the proposed protocols achieves the same throughput as the maximum power topology. We observe that, to consider a single protocol cannot achieve an overall performance goal.

In Chapter 6, we propose an energy-efficient routing for WANETs using cross-layer design. The interaction among the layers with an overall performance target can provide better results than dealing with each layer individually. We develop a cross-layer energy-efficient routing approach as an extension to the well-known AODV routing protocol with three variations (i.e., ER-AODV, E-AODV, and R-AODV). We conducted a comprehensive performance evaluation using a network simulation. It is shown that the ER-AODV gets the benefit of the cross-layer interaction between power control and routing protocol. It increases the network lifetime, reduces the end-to-end delay and saves the total energy consumption. The E-AODV implements the power control using the routing protocol messages. The R-AODV uses a routing protocol with residual energy criteria to choose the best route. We evaluate the proposed protocol performance using ns-2 simulation [36]. The simulation results show that the proposed cross-layer routing protocol consumes 20 to 30 percent less energy, and minimizes the end-to-end delay by 10 to 40 percent in comparison to the well-known AODV routing protocol.

In addition, in Chapter 7, we propose a novel cross-layer Mobility-aware Routing and Interference-aware Topology control (MRIT) protocol to increase the network lifetime, reduce the maximum transmission power, and find a reliable end-to-end route for WANETs with high-mobility conditions. The proposed MRIT protocol is designed as an extension to the well-known AODV routing protocol. We used the mobility parameter to determine the best route. Also, we used the topology control with interference constraint to minimize the maximum transmission power. A comprehensive performance evaluation is conducted using ns-2 network simulation. We found that the proposed cross-layer protocol benefits from the interaction between the routing protocol in the network layer and the interference-aware topology control. The simulation results show that the proposed cross-layer protocol increases the network lifetime, consumes 30 to 40 percent less energy, and reduces the end-to-end delay by 50 to 80 percent in comparison to the well-known AODV routing protocol.

As future work, we can consider more challenging WANETs problems. In recent years, vehicle-to-vehicle communication has been studied to improve drive safety. Collision warning, road sign alarms and in-place traffic view will provide the driver the essential tools to determine the best path along the way [79]. As more of such applications emerge, it is challenging that the protocols employed are capable of efficiently coping with high-mobility. We want to investigate more protocols that could be efficiently applied in vehicular networks (also known as VANETs) with high-mobility situations.

# Appendix A

## Detailed Simulation Parameters

In this dissertation we use ns-2 network simulator [36] for performance evaluation. Each chapter contains the main simulation parameters definition. In this Appendix, we state all the parameters define in the simulation however its default or defined by us.

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Signal frequency <sup>1</sup>	914e+6 Hz
Receive power threshold	3.652e-10 watt
Carrier sense threshold	1.559e-11 watt
Receive power	0.2818 watt
Default Transmission power <sup>2</sup>	0.2818 watt
Sensing range	550.0 meter
Propagation model	Two-ray ground model used in Chapter 3 and 4 Shadowing model used in Chapter 6 and 7
Shadowing model path loss exponent	3.0
Shadowing model reference distance	30.0 meter
Shadowing model deviation	4 decibels
Antenna	Omnidirectional antenna
Antenna hight	1.5 meter
Antenna transmit gain	1.0
Antenna receive gain	1.0
Interface queue length	150
Mac Protocol	IEEE 802.11
Bandwidth	2 Mbps
Traffic	Constant Bit Rate (CBR)
Packet size	512 Byte
Packet rate	4 packets/sec

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<sup>1</sup>It work like the 914MHz Lucent WaveLAN DSSS radio interface.

<sup>2</sup>Changed with different values by the proposed protocols.

# Appendix B

## List of Acronyms

<b>AODV</b>	Ad hoc On-demand Distance Vector routing protocol
<b>CBR</b>	Constant Bit Rate
<b>DSDV</b>	Destination Sequenced Distance Vector
<b>DSR</b>	Dynamic Source Routing protocol
<b>GRG</b>	Geometric Random Graphs
<b>Hz</b>	Hertz
<b>MAC</b>	Medium Access Control
<b>Mbps</b>	Mega bite per second
<b>MI</b>	Mutual Inclusion graph
<b>MRIT</b>	Mobility-aware Routing and Interference-aware Topology control proposed protocol
<b>MST</b>	Minimum Spanning Tree
<b>OLSR</b>	Optimized Link State Routing protocol
<b>OSI</b>	Open System Interconnections
<b>RNG</b>	Relative Neighborhood Graph
<b>SPT</b>	Shortest Path Tree



**SINR**     Signal to Interference plus Noise Ratio

**UDG**     Unit Disk Graph

**WANET**   Wireless Ad hoc Network

**ZRP**     Zone Routing Protocol

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## List of Publications

### Journals

Khoriba Ghada, Jie Li, and Yusheng Ji. Cross-Layer Design for Topology Control and Routing in MANETs. *Accepted for publication in Wireless Communications and Mobile Computing Journal, Wiley InterScience 2009.*

Khoriba Ghada, Jie Li, and Yusheng Ji. Energy and mobility-aware topology control in heterogeneous mobile ad hoc networks. *Accepted for publication in International Journal of Computational Science and Engineering (IJCSE), Special Issue on Information Interchange 2009.*

### Conference proceedings

Khoriba Ghada, Jie Li, Yusheng Ji, and Guojun Wang, "Cross-layer approach for energy efficient routing in WANETs," *Proceedings of the IEEE sixth International Conference on Mobile Ad hoc and Sensor Systems (MASS 2009)*, pp.393-402, 12-15 Oct. 2009.

Khoriba Ghada, Jie Li, and Yusheng Ji. Localized Mobility-Aware Geometric Graphs for Topology Control in Heterogeneous Mobile Ad Hoc Networks. *Proceedings of 5th International Workshop on Databases in Networked Information Systems (DNIS2007) Lecture Notes in Computer Science (LNCS)*, Vol. 4777, pp. 178-188, 2007.

Khoriba Ghada, and Jie Li. Cross-Layer Design for Power Efficient Wireless Ad Hoc Networks. *The First Egypt-Japan International Symposium on Science and Technology (EJISST2008)*. June 8 10, 2008, WASEDA University, Tokyo, Japan. (Abstract)