Cross-layer Approach for Energy Efficient Routing in WANETs

Khoriba Ghada*, Jie Li*, Yusheng Ji† and Guojun Wang‡
* Graduate School of Systems and Information Engineering
University of Tsukuba, Tsukuba Science City, Ibaraki, Japan 305-8573
Email: khoriba@osdp.cs.tsukuba.ac.jp, and lijie@cs.tsukuba.ac.jp
† National Institute of Informatics
The Graduate University for Advanced Studies
Tokyo, Japan 101-8430
Email: kei@nii.ac.jp
‡ School of Information Science and Engineering
Central South University
Changsha, Hunan Province, P. R. China, 410083
Email: csgjwang@mail.csu.edu.cn

Abstract

A wireless ad hoc network (WANET) is a collection of wireless terminals that communicate with each other without predetermined topology. Since WANET devices are power-limited, network protocols should be designed to prolong the battery lifetime of these devices. In this paper, 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 protocol as an extension to AODV routing protocol. We evaluated the proposed protocol by comprehensively simulating a set of random WANET environments. We simulated six different metrics comparing our proposed protocol with AODV protocol. The results showed that the proposed protocol maximizes the network lifetime, reduces the end-to-end delay, and saves the total energy consumption while achieving the throughput requirement.

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 [1]. The lack of infrastructure and the limited battery power in ad hoc networks 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., [2], [3], [4], [5]) 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 [6]), the Dynamic Source Routing (DSR [7]), the Destination Sequenced Distance Vector (DSDV [8]) and the Temporally-Ordered Routing Algorithm (TORA [9]). All these routing protocols use the shortest-hop metric to choose the best route. The problem of energy efficient routing is addressed in many works such as [10], [11], [12], [13]. These works deal with each layer individually. Recent related works show that significant performance improvement can be achieved by using a cross-layer design in ad hoc networks (e.g., [14], [15], [16], [17]). Cross-layer design with respect to reference

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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 [1]. 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 [18]. A cross-layer design for joint topology control and routing for a multi-radio multi-channel wireless mesh network is proposed in [15]. Its main target is to maximize the network throughput by adjusting the channel assignment, the power level of each radio, and the route for flows. In [19], power control, scheduling, and routing are integrated 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.

To the best of our knowledge, the problem of maximizing network lifetime and power control has not been jointly studied for routing protocols in WANETs. In this paper, we introduce a solution for how to bring together ways of controlling data routes over WANETs as well as with minimizing the intra-network interference and maximizing the network lifetime. We jointly integrate power control and route selection in a distributed way assuming selfish behavior exists among those nodes. It means that each node will change its transmission power regardless of other nodes status or decision. The simulation results show that the proposed cross-layer routing protocol maximizes the network lifetime, consumes 20 to 30% less energy, and minimizes the end-to-end delay by 10 to 40% compared to the well-known AODV routing protocol.

The remaining of the paper is organized as follows. Section 2 introduces the problem formulation. The proposed cross-layer interaction is described in section 3. Section 4 explains the detailed design of the proposed protocol. Section 5 states the implementation assumptions and the simulation scenario. Performance and simulation results are presented in Section 6, and Section 7 concludes the paper.

2. 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 $\beta.d_{ij}^{\alpha}$ (i.e., $P_{ij} \geq \beta.d_{ij}^{\alpha}$), where β is the transmission quality parameter, d_{ij} is the Euclidean distance between node i and node j, and α is the distance-power gradient [20]. 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 a set of source nodes by $S^{(c)}$ where the bits are generated for each commodity c, 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 follow.

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

2.1. 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 the network. Furthermore, we need to consider the flow conservation separately applied to each commodity [12].

Let node i lifetime 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.

$$T_i(\mathbf{F}) = \frac{E_i}{\sum\limits_{\substack{\forall j \in N,\\(i,j)\in L}} e_{ij} \sum\limits_{c\in C} f_{ij}^{(c)}}. \tag{2}$$

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

$$\begin{aligned} T_G(\mathbf{F}) &= Min_{i\in N}\, T_i(\mathbf{F}) \\ &= Min_{i\in N} \frac{E_i}{\sum\limits_{\substack{\forall j \in N,\\(i,j)\in L}} e_{ij} \sum\limits_{c\in C} f_{ij}^{(c)}}. \end{aligned} \tag{3}$$

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

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

Subject to

$$\sum_{(i,j)\in L} f_{ij}^{(c)} - \sum_{(k,i)\in L} f_{ki}^{(c)} = \begin{cases} Q_i^{(c)} & \text{if } i \in S^{(c)}, \\ -Q_i^{(c)} & \text{if } i \in D^{(c)}, \forall c \in C, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

$$f_{ij}^{(c)} \geq 0, \quad \forall i \in N, \forall (i,j) \in L,\ \forall c \in C.$$

Similar to [12], 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 programing problem.

Maximize T

Subject to

$$\sum_{(i,j)\in L} e_{ij} \sum_{c\in C} \hat{f}_{ij}^{(c)} \leq E_i, \forall i,j \in N, \tag{5}$$

$$\sum_{(i,j)\in L} \hat{f}_{ij}^{(c)} - \sum_{(k,i)\in L} \hat{f}_{ki}^{(c)} = \begin{cases} TQ_i^{(c)} & \text{if } i \in S^{(c)}, \\ -TQ_i^{(c)} & \text{if } i \in D^{(c)}, \forall c \in C, \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

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

The linear programming formulation given above can be viewed as a variation of the conventional maximum flow problem with node capacities (i.e, $\sum_{\forall (i,j)\in L} \sum_{c\in C} \hat{f}_{ij}^{(c)} \leq E_i/e_i$) [21], 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 [13], [22]. 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 [18], [23]. In this paper, the power control is addressed with the maximum network lifetime problem as in the following subsection.

2.2. 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., [24]). Therefore, we need to minimize each node transmission power. While minimizing transmission power at link layer [1], we need to consider the connectivity constraint and the Signal to Interference plus Noise ratio, SINR, constraint. We can preserve the network connectivity, if the transmission power from node i to node j (P_{ij}) is more than or equal to d_{ij}^{α} multiplied by the transmission quality parameter β 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 the noise multiplied by the SINR requirement parameter, γ_{ij}. The problem of minimizing the transmission power in WANETs is formulated as a linear optimization problem as follows.
Minimize P_{ij}

Subject to

$$P_{ij} \geq \beta . d_{ij}^{\alpha}, \tag{7}$$

$$SINR_{ij} = \frac{P_{ij}/d_{ij}^{\alpha}}{\sum\limits_{(k,j)\in L} P_{kj}/d_{kj}^{\alpha} + \sigma} \geq \gamma_{ij}, \tag{8}$$

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

2.3. 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 [1]. In the basic routing protocols [6], [7], [8], [9], 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 paper, we define the residual energy to be the metric to choose the best route. The used route will change every time the source node sends to the same destination node as it depends on the residual energy which is dynamically changed. For convenience, we define a route from source node s to destination d as follows:

$$R = \{(i_0, i_1), \ldots, (i_{h-1}, i_h)\}, \ \forall (i_k, i_{k+1}) \in L, \tag{9}$$

where $i_0, i_1, \cdots, i_h$ 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 $i_1, ..., i_h - 1$, source node $i_0 = s$, and destination node $i_h = d$ is defined as follows.

$$\underline{E}_r = Min(\underline{E}_{i_0}, \underline{E}_{i_1}, \cdots, \underline{E}_{i_{h-1}}). \tag{10}$$

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,

$$r_{max} = Max(\underline{E}_{r_1}, \cdots, \underline{E}_{r_m}). \tag{11}$$

The notations for the formulation are summarized in Table 1, for convenience.

3. Cross-layer Design

In the previous section, we introduced the formulation for the maximum network lifetime problem using a flow constraint in the transport layer, the 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 ad hoc networks. As a result, the resulting protocols may not be adaptive and far from optimal. As shown in Fig. 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 [25].

We propose the cross-layer integration between

TABLE 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 $(i, j) \in L$.
$\hat{f}_{ij}^{(c)}$	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.
σ	The ambient noise power level.
$\gamma_{ij} \geq 1$	The SINR requirement for the transmission from node i to node j.

routing and power control to maximize the network lifetime. In Fig. 1(b), the routing decision is affected by the residual energy information to satisfy the routing metric in (11). Routing protocol control messages will be 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 [6]. The protocol will make use of 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 [6].

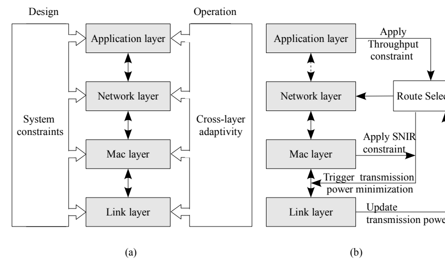

Fig. 1. (a) Adaptive cross-layer design [1], (b) Layers interactions in the proposed cross-layer design.

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 will trigger the received nodes to adjust their transmission power before forwarding it to other nodes. Then, each relay node will add its residual energy into this RREQ message. Then, the destination node will receive the RREQ messages with their minimum residual energy according to (10), and uses the maximum one to send the RREP message as in (11). We assume that the destination node has enough energy to receive the packets which is a common assumption for wireless ad hoc networks (e.g., [26]).

4. Proposed Protocol

The proposed protocol is designed as an extension to the well-known AODV protocol. The proposed protocol design allows a user in application layer to choose between three variations 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:** *E*nergy efficient and maximum *R*esidual 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 (7) and (8). The destination node chooses the maximum remaining energy route to send the RREP message as in (10) and (11).

- **E-AODV:** *E*nergy-aware AODV. It implements the power control using the routing control messages. Each node updates its transmission power according to connectivity and SINR constraints as in (7) and (8).
- **R-AODV:** maximum *R*esidual energy-aware route selection over AODV. The destination node chooses the maximum residual energy route to send the RREP message as in (10) and (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 will adjust its own transmission power P_{ij} to the minimum according to the connectivity and SINR constraints as in (7) and (8) respectively.
    2) Keep the minimum residual energy $\underline{E}_r$ in the RREQ message. The minimum residual energy is computed as in (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 (7) and (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 (7), and the SINR constraint in (8). In Step 3, the destination node d selects the RREP route according to the routing metric in (10) and (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 $O(2k)$ [6]. 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.

5. Implementation

We consider the following in order to implement the proposed protocol in ns-2.33 [27] 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 $\alpha = 3$ [20], [28].
- We use the extended cumulative interference model [29] with the original 802.11 MAC code in ns-2 to implement the SINR constraint in (8).

- Simultaneous connections are considered to show the effect of multi-commodity flows.

5.1. Simulation Scenario

We consider a typical wireless ad hoc network with 100 wireless nodes randomly located over a 1500m x 300m rectangular flat space [30]. We use identical loads and environmental conditions to compare 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 1500m x 300m area, and the initial transmission range is uniformly distributed between 200m 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 at most 32 CBR connections.

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

6. Performance Evaluation

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 [31] and the results are analyzed to get different six major performance metrics which are described in details as follows.

6.1. Performance Metrics

For the performance evaluation, we have the following major performance metrics.

- Total energy consumption rate: the energy consumed per byte [32] is computed as follows.

$$\frac{\text{Total energy consumed}}{\text{Total throughput}} \tag{12}$$

  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.

6.2. Simulation Results

In this paper, we took into consideration only static nodes with no mobility model. For the simulated WANET environment described in Section 5.1, we test the impact of the numbers of CBR connections and the simultaneous connections.

6.2.1. Impact of the Number of Connections

In Fig. 2, 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 Fig. 2, the proposed ER-AODV and E-AODV have better performance than AODV and the proposed R-AODV. Fig. 2(a) 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 increases, the average physical node degree of the proposed ER-AODV and E-AODV decreases as shown in Fig. 2(b), which results in lower nodes interference. Fig. 2(c) 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 Fig. 2(d). The end-to-end delay decreases as shown in Fig. 2(e). R-AODV has a 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 Fig. 2(f). The proposed protocol shows better performance with 32 and 64 connections, which indicates good performance with a higher network load.

6.2.2. Impact of Multi-commodity Flow

Fig. 3 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 Fig. 3(a) which shows that the proposed protocol with power control (i.e., ER-AODV and E-AODV) consumes 10 to 20% less energy than AODV. This is due to the reduction of the overall interference. The reduction of the overall interference is shown in Fig. 3(b) where the average physical node degree decreases. ER-AODV and E-AODV have the minimum average node degree. The throughput each protocol is able to achieve is shown in Fig. 3(c). ER-AODV achieves better throughput than AODV. This is due to less interference and less drop ratio. The drop ratio is shown in Fig. 3(d). ER-AODV reduces the average end-to-end delay by 40 to 50% compared to AODV protocol with 1, and 2 simultaneous connections (Fig. 3(e)). R-AODV has the highst 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 Fig. 3(f).

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.

7. Conclusion

We investigated the energy efficient routing for WANETs using cross-layer design. The interaction among the layers with a global performance target can produce 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 maximizes the network lifetime, minimizes 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. As future work, we will consider mobility parameters and more layers interaction for routing protocol design.

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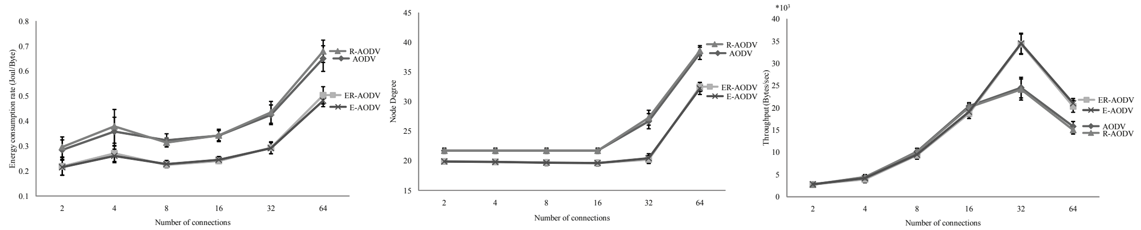
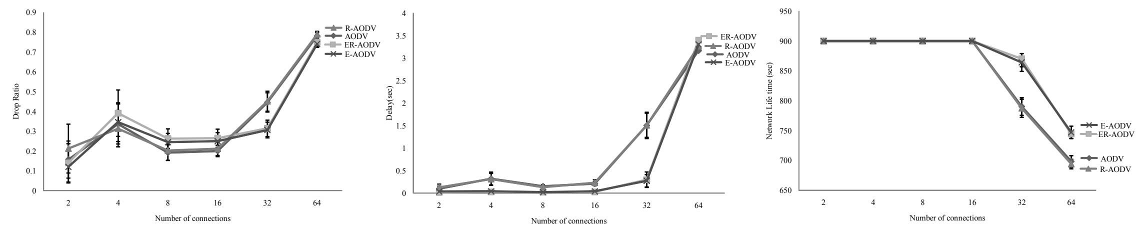
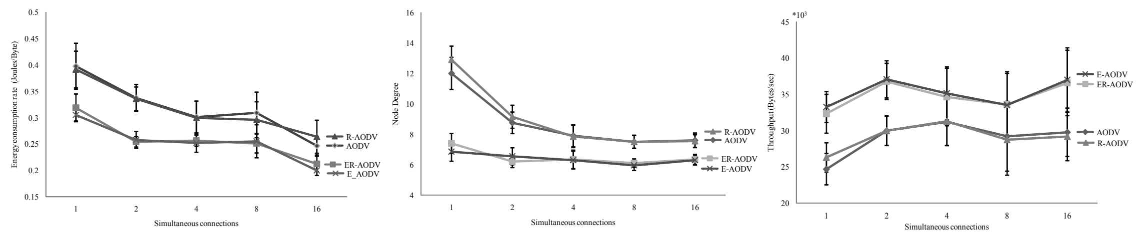


(a) Energy consumption rate (b) Node degree (c) Throughput

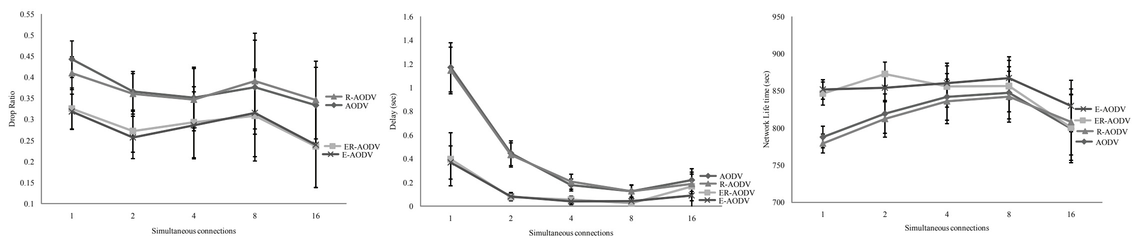


(d) Drop ratio (e) Delay (f) Network lifetime

Fig. 2. Impact of the number of connections



(a) Energy consumption rate (b) Node degree (c) Throughput



(d) Drop ratio (e) Delay (f) Network lifetime

Fig. 3. Impact of multi-commodity flow

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