Energy-efficient Routing in MIMO-based Mobile Ad hoc Networks with Multiplexing and Diversity Gains

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Abstract

It is critical to design energy-efficient routing protocols for battery-limited mobile ad hoc networks, especially in which the energy-consuming MIMO techniques are employed. However, there are several challenges in such a design: first, it is difficult to characterize the energy consumption of a MIMO-based link; second, without a careful design, the broadcasted RREP packets, which are used in most energy-efficient routing protocols, could flood over the networks, and the destination node cannot decide when to reply the communication request; third, due to node mobility and persistent channel degradation, the selected route paths would break down frequently and hence the protocol overhead is increased further. To address these issues, in this paper, a novel Greedy Energy-Efficient Routing (GEER) protocol is proposed: (a) a generalized energy consumption model for the MIMO-based link, considering the trade-off between multiplexing and diversity gains, is derived to minimize link energy consumption and obtain the optimal transmit model; (b) a simple greedy route discovery algorithm and a novel adaptive reply strategy are adopted to speed up path setup with a reduced establishment overhead; (c) a lightweight route maintenance mechanism is introduced to adaptively rebuild the broken links. Extensive simulation results show that, in comparison with the conventional solutions, the proposed GEER protocol can significantly reduce the energy consumption by up to 68.74%.

Keywords: energy efficient, routing protocol, MIMO links, mobile ad hoc networks

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1. Introduction

As an important component of the mobile Internet, Mobile Ad hoc Networks (MANETs) potentially enable any-time and any-where networking, connect wireless devices to each other without the need of infrastructural administration or maintenance, and allow wireless devices to share data and access distributed services in a seamless and easy way. Such decentralized networks are highly suitable for many military and commercial applications, e.g., military battle field communication, emergency disaster relief, environmental monitoring, and so on [1].

Recently, as the proliferation of wireless devices (smart phones, pads, notebooks, etc), there is a significant increase transmission demand for data intensive services and applications, such as multimedia streaming, voice over IP, online social and gaming. To meet the high data rate requirements, more and more wireless devices are equipped with multiple antennas. Hence, Multiple-Input Multiple-Output (MIMO) has emerged as an important technology to improve the communication efficiency in MANETs. In general, MIMO takes advantage of spatial multiplexing by transmitting multiple data streams concurrently to increase data rate, and spatial diversity by combining the signals from various different transmission streams to increase transmission reliability and range [2]. MIMO has been a de-facto component in several mainstream wireless standards, such as 802.11n [3], LTE [4] and the ongoing 802.11 ac [5].

However, a higher network throughput usually requires higher energy consumption, which is a big challenge or even unaffordable for battery-limited MANETs. Hence, it is an urgent task to reduce energy consumption while satisfying throughput requirements in MANETs. Specific to MIMO techniques, although they boost the transmission capabilities (rate or range), energy consumption could also increase: the MIMO transmission requires more circuit energy consumption including the energy consumed by all the circuit blocks along the signal path; moreover, more time or frequency resources are spent on signaling overhead for the MIMO transmission [6]. Some preliminary results have shown that only when the transmission range exceeds a certain distance, MIMO links are more energy-efficient than SISO (Single-Input Single-Output) links for the same throughput [7].

In this paper, we address the issue of the energy-efficient routing design in MIMO-based MANETs, to minimize transmission energy consumption by considering the trade-off between multiplexing and diversity gains. As energy consumption characterization is very critical in energy-efficient routing protocols, we firstly derive a generalized energy consumption model to obtain the optimal transmit model for the MIMO-based link. Aiming to reduce the protocol overhead of the energy-efficient routing in MIMO-based MANETs, a novel Greedy Energy-Efficient Routing (GEER) protocol is proposed to speed up path setup while adaptively adjusting the routing path selection and maintenance. Extensive simulation results show that, compared to the existing solutions, GEER protocol can significantly enhance the performance of transmission energy consumption.

The rest of this paper is organized as follows. Section 2 discusses the related work, and section 3 presents the system model and the derived energy consumption model. Section 4 details the proposed GEER routing protocol. In Section 5, we evaluate the performance of GEER protocol over a comprehensive set of network scenarios. Finally, conclusions are summarized in Section 6.

2. Related Work

The routing protocol design for MANETs with MIMO links becomes an emerging topic that attracts many researchers' attentions. The main research direction is sourced from the work on the characterization of MIMO links, and the application of this knowledge to MANETs in an efficient manner [8]. Although there are a few existing contributions to provide first insights into the topic, generally speaking, the effort is still in its infancy.

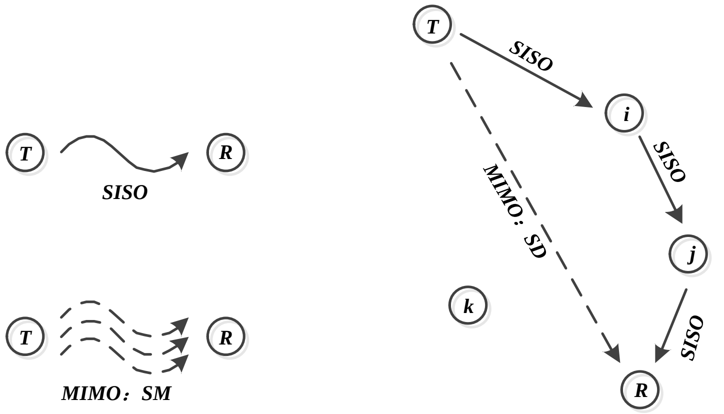
The early work to explore the utility of MIMO techniques for MAC and routing design in MANETs can be found in [9]. The authors devise a MIMO MAC protocol to exploit spatial diversity, study the impact of MAC on routing, and characterize the optimal hop distance that minimizes the end-to-end delay. In [10, 11], a routing protocol called MIR for ad hoc networks with MIMO links is proposed. This protocol leverages the various characteristics of MIMO links, including density, mobility and link quality, to improve the network performance. The work in [12], based on a joint power control and routing, investigates the optimum link scheduling that carries flows in a multi-hop network at the requested rate, under throughput feasibility and minimum power constraints. In [13], the authors focus on the allocation of channel bandwidth to each node on a multi-hop path, when using orthogonal channels for each active link. In [14], the authors study the effects of different routing choices in a MIMO ad hoc network, and provide a cross-layer design to track the receive capabilities of eligible forwarders so as to avoid that they become overloaded and unable to de-multiplex super-imposed waveforms. In [15], the authors propose a power-controlled channel access protocol for MIMO-capable wireless LANs with two antennas per node, called E-BASIC, and incorporate E-BASIC in the design of a power-aware routing (PAR) scheme that selects minimum-energy end-to-end paths.

Most of the existing studies [9-14] are throughput-oriented, which means that, the primary design motivation is to increase the network throughput, e.g., by supporting a larger number of concurrent transmissions. An exception is [15], where a special case with up to two antennas at the transceiver is considered for the energy-efficient routing. Besides, the PAR protocol in [15] is a proactive routing based on the centralized Dijkstra's algorithm, which is not appropriate for distributed MANETs. In this paper, we consider a fully distributed routing design in the network where a node can have an arbitrary number of antennas.

3. System Model and Energy Consumption Model

3.1 System Model

We consider a mobile ad hoc network consisting of nodes with multiple embedded antennas. As shown in **Fig. 1**, two operation modes are provided to take advantage of MIMO links to improve the energy efficiency: (*i*) in a rich scattering environment where the transmission channels for different streams are differentiable and independent, i.e., orthogonal, by means of *Spatial Multiplexing* (SM), the receiver can separate and decode its received data streams based on their unique spatial signatures, therefore a linear increase (along with the number of antenna elements) in the asymptotic link capacity is provided; (*ii*) since the transmission quality of multiple transmission paths could be very different, by making use of *Spatial Diversity* (SD), the same data stream is transmitted in multiple transmission paths, and the corresponding transmission reliability or range maybe significantly improved. In other words, the multiplexing gain could enhance transmission energy efficiency by reducing the transmission time required for a data packet, whereas the diversity gain could enhance the transmission energy efficiency by reducing the signal-to-noise ratio (SNR) required for certain bit error rate (BER).



(a) Spatial Multiplexing (SM) (b) Spatial Diversity (SD)

Fig. 1. Two operation modes are provided to take advantage of MIMO links

Considering a MIMO link with M_t transmit antenna elements and M_r receive antenna elements. Denote the multiplexing gain and the diversity gain by r and d_r, respectively. As descripted in [2],

$$r = lim_{\overline{SNR}\to\infty} \frac{R_b(\overline{SNR})}{log\overline{SNR}}, \quad (1)$$

$$d_r = -lim_{\overline{SNR}\to\infty} \frac{logB_e(\overline{SNR})}{log\overline{SNR}}, \quad (2)$$

where B_e is the bit error rate (BER), R_b is the transmission bit rate, and $\overline{SNR}$ is the average SNR at each receive antenna. Here, we consider that the channel only experiences a square-law path loss, then

$$\overline{SNR} = P_t/(A_0\, d^2 N), \quad (3)$$

where P_t is the average transmission power, A_0 is a parameter that depends on the transmitter, receiver antenna gains and the transmission wavelength, d is the distance between the transmitter and the receiver, N is the noise power spectral density [16].

Note that, in this paper we try an approximate analysis where the received SNR is sufficiently high and the specific coding issue has not been considered, that means, $R_b = rlog\overline{SNR}$ and $B_e = \overline{SNR}^{-d_r}$ are assumed. Considering that the optimal coding scheme is used, the relationship between the multiplexing gain and the diversity gain is given by [2],

$$d_r \le (M_t - r)(M_r - r), r = 1,2,\dots, min(M_t, M_r), \quad (4)$$

and it's known that SISO can be thought as the special case of MIMO with $r = 1$ and $d_r = 0$. Here, we do not consider the cases with $r = 0$, in which data transmits at a fixed rate.

3.2 MIMO-based Link Energy Consumption Model

In this section, the energy consumption model for the MIMO link from node i_1 to node i_2, denoted by l_{i_1,i_2}, is derived while both energy consumption for circuitry and transmission are considered. The resulting signal paths on the transmitter and receiver sides are shown in **Fig. 2**, and the frequency synthesizer (LO) is assumed to be shared among all the signal paths.

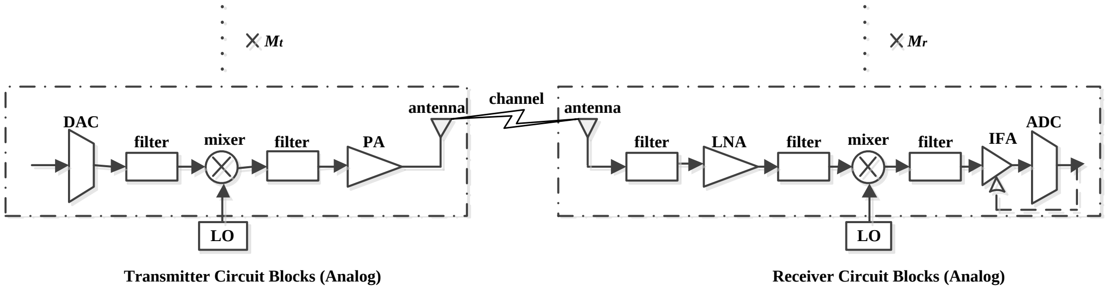


Fig. 2. Illustration of a signal path [7]

From [7], the total energy consumption per bit can be expressed as

$$E_{i_1,i_2}^{bt} = \left(\frac{\xi}{\eta}\right) \times \overline{E_b} \times \frac{(4\pi d_{i_1,i_2})^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c}{R_b}, \tag{5}$$

where $\overline{E_b}$ is the required energy per bit at the receiver for a given BER requirement $B_e \leq B_e^{max}$, d_{i_1,i_2} is the transmission distance between node i_1 and node i_2, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the carrier wavelength, M_l is the link margin, N_f is the receiver noise figure given by $N_f = N_r/N_0$ (N_0 is the single-sided thermal noise power spectral density, $N_r = N$ is the power spectral density of the total effective noise at the receiver input), η is the drain efficiency of the RF power amplifier, ξ is the peak-to-average ratio and P_c is the circuit power consumption of the link, which is given by

$$\begin{aligned} P_c = {} & (r + m_t)\big(P_{DAC} + P_{mix} + P_{filt}\big) + 2P_{syn} \\ & + (r + m_r)\big(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC}\big), \end{aligned} \tag{6}$$

where P_{DAC}, P_{mix},P_{LNA}, P_{IFA}, P_{filt}, P_{filr}, P_{ADC}, P_{syn} are the power consumption values for the DAC, the mixer, the low-noise amplifier (LNA), the intermediate frequency amplifier (IFA), the active filters at the transmitter side, the active filters at the receiver side, the ADC and the frequency synthesizer, respectively, and m_t $(0 \leq m_t \leq M_t - r)$, m_r $(0 \leq m_r \leq M_r - r)$ are the number of antenna elements used for space diversity $d_r = m_t m_r$ at the transmitter and receiver, respectively.

According to the Chernoff bound [17] (in the high SNR regime)

$$B_e \leq \left(\frac{\overline{E_b}}{(r+m_t)N_o}\right)^{-d_r}, \tag{7}$$

then we can derive an upper bound for the required energy per bit

$$\overline{E_b} \leq \frac{(r+m_t)N_o}{{B_e}^{-d_r}}. \tag{8}$$

Given the configuration of MIMO link l_{i_1,i_2} as (r, m_t, m_r), by approximating the bound as an equality, we can calculate the total energy consumption per bit of the MIMO-based link l_{i_1,i_2} as

$$\begin{aligned} & E_{i_1,i_2}^{bt}(r, m_t, m_r) = \\ & \left(\frac{\xi}{\eta}\right) \times \frac{(r+m_t)N_o}{{B_e}^{-m_t m_r}} \times \frac{\left(4\pi d_{i_1,i_2}\right)^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c}{r log \overline{SNR}_{i_1,i_2}}. \end{aligned} \tag{9}$$

Denote packet error rate (PER) of the MIMO link l_{i_1,i_2} as $P^e_{i_1,i_2}(r, m_t, m_r)$, given the bit error rate $B^e_{i_1,i_2}(r, m_t, m_r) = \overline{SNR}_{i_1,i_2}^{\;-m_t m_r} \le B_e^{max}$, then we can calculate the packet error rate as

$$P^e_{i_1,i_2}(r, m_t, m_r) = 1 - \left(1 - B^e_{i_1,i_2}(r, m_t, m_r)\right)^L, \tag{10}$$

where L is the size of the packet in bits. Denote the energy consumption metric for the link l_{i_1,i_2} with the MIMO configuration (r, m_t, m_r) by $E^l_{i_1,i_2}(r, m_t, m_r)$, i.e., the total energy consumption per bit for a successful packet transmission. Denote the optimal energy consumption metric for the link l_{i_1,i_2} by $E^l_{i_1,i_2}$. Then we have

$$E^l_{i_1,i_2}(r, m_t, m_r) = \frac{E^{bt}_{i_1,i_2}(r, m_t, m_r)}{1 - P^e_{i_1,i_2}(r, m_t, m_r)}, \tag{11}$$

$$E^l_{i_1,i_2} = \min_{\substack{r=1,2,\ldots,M \\ 0 \le m_t \le M_t - r, 0 \le m_r \le M_r - r}} E^l_{i_1,i_2}(r, m_t, m_r), \tag{12}$$

and the optimal MIMO configuration of link l_{i_1,i_2} is

$$\left(r_{i_1,i_2}, m^t_{i_1,i_2}, m^r_{i_1,i_2}\right) = arg \min_{\substack{r=1,2,\ldots,M \\ 0 \le m_t \le M_t - r, 0 \le m_r \le M_r - r}} E^l_{i_1,i_2}. \tag{13}$$

4. The Proposed GEER Routing Protocol

4.1 Design Challenges

Routing protocols in MANETs can be roughly divided into two categories: table-driven proactive routings, which keep real-time routing tables as in wired networks, and on-demand reactive routings, which try to create a route only when a communication request happens. Generally, the reactive routing protocols are more suited for the mobile networks: reactive routings allow mobile nodes to obtain routes quickly for new destinations and do not require mobile nodes to maintain routes to destinations that are not in active communication, moreover, it also allows mobile nodes to respond to situations associated with broken link and changes in network topology in a timely manner [18].

In the conventional reactive routing protocols such as AODV [19], a source node initials a route discovery process when a packet is going to be delivered to a new destination: the source node first broadcasts a route request (RREQ) packet and then waits for the route reply (RREP) packet from the destination node; the intermediate route nodes receiving the RREQ packet will rebroadcast it to help to connect the source with the destination. To cut down the broadcast overhead, any nodes, including the destination and intermediate route nodes, are supposed to respond to the first received RREQ packet and discard the other duplicate ones.

While routing strategies in MIMO-based energy-efficient routing protocols are quite different. First, the duplicate RREQ packets cannot be discarded simply as every possible RREQ packet could come from a more energy-efficient route path. Therefore, the intermediate route nodes may need to broadcast the RREQ packet from the same source node many times, and the destination could not tell which route paths is the best until it receives all possible RREQ packets. Based on the Bellman-Ford algorithm [20], it's seen that the routing overhead for minimum energy efficient routing protocols is $O(n^2)$, the complex of which increases dramatically with the network size n. Second, it is very critical for the network layer to be aware of the specific characteristics of MIMO links and make more wise and intelligent routing decisions. According to the features of MIMO link configurations, the array of antennas in each node pair can be grouped to form different MIMO channels, with different energy consumption and different achievable transmission capacities (range and rate).

Here, we present the MIMO routing protocol, named as GEER, which is a reactive routing protocol. The goal of GEER is to exploit the benefits of MIMO links in an optimal manner to find an energy-efficient routing path, furthermore, GEER protocol is supposed to speed up path establishment while adjusting the routing path to various network conditions with reasonable overhead. The main idea of GEER protocol is to find a route path close to the optimal one quickly through a simple greedy algorithm and a novel adaptive reply strategy, besides a lightweight maintenance mechanism is employed to respond the environment changes.

4.2 Route Establishment Process

4.2.1 Neighbor Discovery (ND)

As spatial diversity techniques can enhance the transmission range, the different MIMO link configurations might result in different neighbor sets of the transmitter. To this end, we require the bit error rate (BER) B_e to satisfy a decoding threshold, i.e., $B_e \leq 0.001$. Then from section 3, the maximum transmission range of the MIMO link is fixed to a distance threshold, denoted by d_{max}, and all the nodes inside the maximum transmission range are the potential route neighbors of the transmitter, denoted by $\mathcal{N}$.

4.2.2 Route Discovery (RD)

In this section, we introduce the route discovery process of GEER protocol based on a simple energy-greedy algorithm. Denote the set of route paths between source S and destination D by G, and denote a route path with intermediate route nodes $i_1, i_2, \ldots, i_{h-1}$ $(i_{j+1} \in \mathcal{N}_{i_j}, j = 1,2,\ldots,h-1, i_1 \in \mathcal{N}_S, D \in \mathcal{N}_{i_{h-1}})$ by g $(g \in G)$. Then the total energy consumption for the route path g can be expressed as

$$E_{S,D}^{g} = E_{S,i_1}^{l} + \sum_{j=1}^{h-2} E_{i_j,i_{j+1}}^{l} + E_{i_{h-1},D}^{l}. \tag{14}$$

The goal of energy-efficient routing is to find the route path g^{opt} with the minimum energy consumption,

$$g^{opt} = arg\,min\, E_{S,D}^{g},\ \ g \in G. \tag{15}$$

To speed up the route path establishment, GEER adopts a simple energy-greedy strategy: for every transmission hop, pick the neighboring node with the minimum energy consumption as the next route node. To implement this greedy discovery algorithm, the route request packet is supposed to carry three pieces of information: the route node list $\mathcal{L}_{rn}$, the MIMO link configuration list $\mathcal{L}_{Mc}$, total energy consumption metric E_c. The source node first broadcasts the RREQ packet with $\mathcal{L}_{rn}$, $\mathcal{L}_{Mc}$ set to null, and E_c set to 0, respectively. Once an intermediate node j receives a RREQ packet from the previous route node i, it first updates the RREQ information: $\mathcal{L}_{rn} = \mathcal{L}_{rn} \cup \{j\}$, $\mathcal{L}_{Mc} = \mathcal{L}_{Mc} \cup \{(r_{i,j}, m_{i,j}^{t}, m_{i,j}^{r})\}$ and $E_c = E_c + E_{i,j}^{l}$. The intermediate node will rebroadcast such RREQ packet only if it has not received such a RREQ packet from the same transmission request before or the RREQ packet comes with a more energy-efficient route path, i.e., the total energy consumption metric is the least among the all received RREQ packets.

In energy-efficient routings, the destination node may not be able to make the decision as it does not know that, when is the best time to reply the RREQ packet. GEER employs an adaptive reply strategy in which the destination node sets up a timer after it firstly receives a new RREQ packet. Before the timer decreases to 0, if the destination receives another RREQ packet with a more energy-efficient route path from the same source, it will reset the timer. Otherwise, it will select the best path found before the timer goes off and reply the source with a route reply (RREP) packet containing all the route information. In general, our reply strategy can adapt to the number of arriving RREQ packets: if there are only a few RREQ packets arriving at the destination, the destination can reply the source quickly to shorten the route setup time; otherwise, it can wait for a small proportion of time for a better route path with less energy consumption.

Example: As shown in **Fig. 3**, we consider a full connected mini-network consisting of three nodes X, Y, Z, all equipped with two antennas. A data packet is dedicated to be transmitted from node X to node Z. There are five MIMO link configurations for each neighboring node pairs: (1, 1, 1), (1, 1, 0), (1, 0, 1), (1, 0, 0) and (2, 0, 0), each of which is of different energy consumption metric (the MIMO-based link configuration (r, m_t, m_r) is defined in section 3). It's seen that as node Z is a little far from node X, the direct transmission from node X to node Z costs more energy than route relaying through node Y, i.e., $E^l_{X,Y} + E^l_{Y,Z} < E^l_{X,Z}$, and therefore the destination node Z will reply the optimal route path XYZ with route information $\mathcal{L}_{rn} = \{Y, Z\}$, $\mathcal{L}_{Mc} = \{(1,0,1), (1,0,0)\}$ and $E_c = 3.8 + 3 = 6.8$ to the source node X.

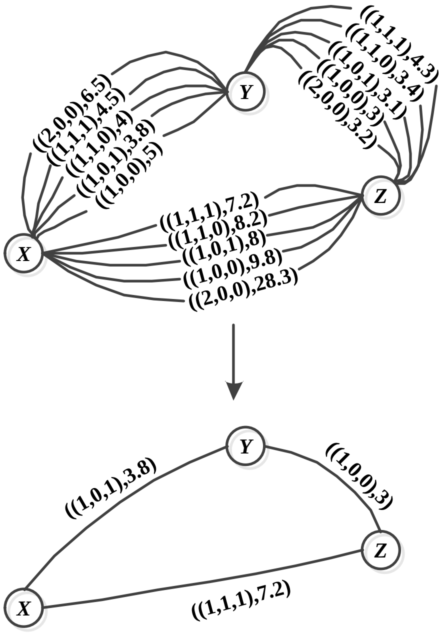


Fig. 3. An Example of the route discovery operation in the GEER routing protocol

4.3 Route Maintenance (RM)

Due to node mobility or persistent channel degradation, the selected route path may break down frequently. If we initial a new route discovery process every time a link along the route path is interrupted, the route protocol overhead would make the network overloaded and few data transmissions can be carried on. Therefore, the route maintenance mechanism is very critical for routing designs in MANETs.

Given a route path g obtained in the above route discovery process, with source node i_0 (or S), destination node i_h (or D) and intermediate route nodes i_1, i_2, …, i_{h-1}. If a link $l_{i_j,i_{j+1}}$ $(0 \leq j \leq h-1)$ on the path g breaks down (node i_j has not received Hello packet from node i_{j+1} for a period of time), the maintenance mechanism in GEER protocol will try to find a substitutive link $l_{i'_j,i'_{j+1}}$ to retain the established path firstly, while not find a brand-new route path directly. The process of repairing the link $l_{i_j,i_{j+1}}$ $(0 \leq j \leq h-2)$ is equivalent to find a new route node i'_{j+1} between node i_j and node i_{j+2}, and the selection strategy is to minimize the sum energy of link $l_{i_j,i'_{j+1}}$ and link $l_{i'_{j+1},i_{j+2}}$. If there exists such a route node i'_{j+1}, then we replace node i_{j+1} in path g by node i'_{j+1}, and refresh the corresponding MIMO link configuration information and energy consumption metric; otherwise, we consider that the route path g cannot be repaired easily and a new route path discovery process is supposed to be initialed. Note that, the process of repairing the link l_{i_{h-1},i_h} is a litter different as we can not to replace the destination node i_h, thus we turn to find a new route node i'_{h-1} between node i_{h-2} and node i_h to replace the node i_{h-1} on the path g.

5. Performance Evaluation

In this section, extensive simulations are performed in NS-2 [21] to evaluate the performance of the proposed MIMO-based routing protocols. To implement GEER protocol in NS-2, we modified the AODV implementation [22] to search for the minimum energy consumption path using the new MIMO-based link energy consumption model derived in Section 3. The network in the simulation is $1200m \times 1200m$ and the nodes are randomly distributed in the network. The route sessions are initialed between two randomly selected nodes, and the session arrival rate follows Poisson distribution with parameter λ_p and the session duration follows Exponential Distribution with parameter λ_e. The application protocol is Constant Bit Rate (CBR) with parameter R_c, and the node mobility follows the Random Waypoint Model with minimal speed rate s_{min}, maximal speed rate s_{max} and 30 second pause time. The path loss and collision rate are estimated using method in [23]. Each simulation result is averaged by 5 runs with different time-seeds, and the time for each simulation run is 4 hours. The other important default simulation parameters are listed in following Table 1, where the most simulation parameters about the MIMO link are sourced from the reference paper [7].

Table 1. Simulation parameters

$f_c = 2.5\ GHz$	$P_{filt} = P_{filr} = 2.5mW$
$B = 10\ kHz$	$P_{mix} = 30.3mW$
$G_tG_r = 5\ dBi$	$P_{sys} = 50\ mW$
$M_l = 40\ dB$	$P_{LNA} = 20\ mW$
$N_f = 10\ dB$	$P_{ADC} = P_{DAC} = 35mW$
$P_t = 30mW$	$P_{IFA} = 15\ mW$
$A_0 = (4\pi f_c)^2 M_l N_f / G_t G_r$	$\xi = 0.51, \eta = 0.35$
$N_0 = -348\ dBm/Hz$	$L_{RREQ} = 40\ bytes$
$N = BN_0$	$L_{RREP} = 50\ bytes$
$L_{data} = 500\ bytes$	$P_e^{max} = 0.001$
$n = 60$	$R_c = 6\ packet/second$
$\lambda_p = 30\ sessions/hour$	$s_{min} = 0.5\ m/s$
$\lambda_e = 6\ minutes$	$s_{max} = 5\ m/s$

The existing work most closest to ours, reference paper [15], is a proactive protocol based on the centralized Dijkstra's algorithm, which is different from our distributed routing strategy and very hard to be implemented in NS-2, and the other existing work [9-14] depart from the design principle of energy efficient. Hence, in this paper, we turn to a widely accepted reactive protocol in NS-2, AODV (or AODV-SISO), as a performance comparison, and for a fair comparison, we modify AODV-SISO to adopt the proposed MIMO link energy consumption model, named as AODV-MIMO. By comparing with AODV-SISO and AODV-MIMO, the advantages of the derived MIMO link energy-consumption model and the proposed routing strategies can be presented clearly. The performance metrics used in the simulation are defined as follows:

(a) *Energy consumption per packet*: it is defined by the total energy consumption divided by the total number of data packets received. The calculation of this energy metric is based on the equation (14), which illustrates the energy consumed along the selected route path g per bit. Note that, during a session duration, node mobility would change some route nodes on the route path g, thus the energy metric need to be refreshed timely;

(b) *Transmission hops per packet*: it is defined by the total transmission hops for relaying data packets along route paths divided by the total number of data packets received;

(c) *Protocol overhead per packet*: it is defined by the total number of packets delivered in the network, including all the RREQ, RREP, data packets and retransmissions, divided by the total number of data packets received at the destinations.

The above three performance metrics of GEER, AODV-SISO and AODV-MIMO protocols are compared by varying two impact factors: network size n, and maximal node speed s_{max}. The simulation results are shown in **Fig. 4-5**.

Fig. 4. Impact of varying density.
(a) Energy consumption vs. Density.
(b) Transmission hops vs. Density.
(c) Protocol overhead vs. Density.

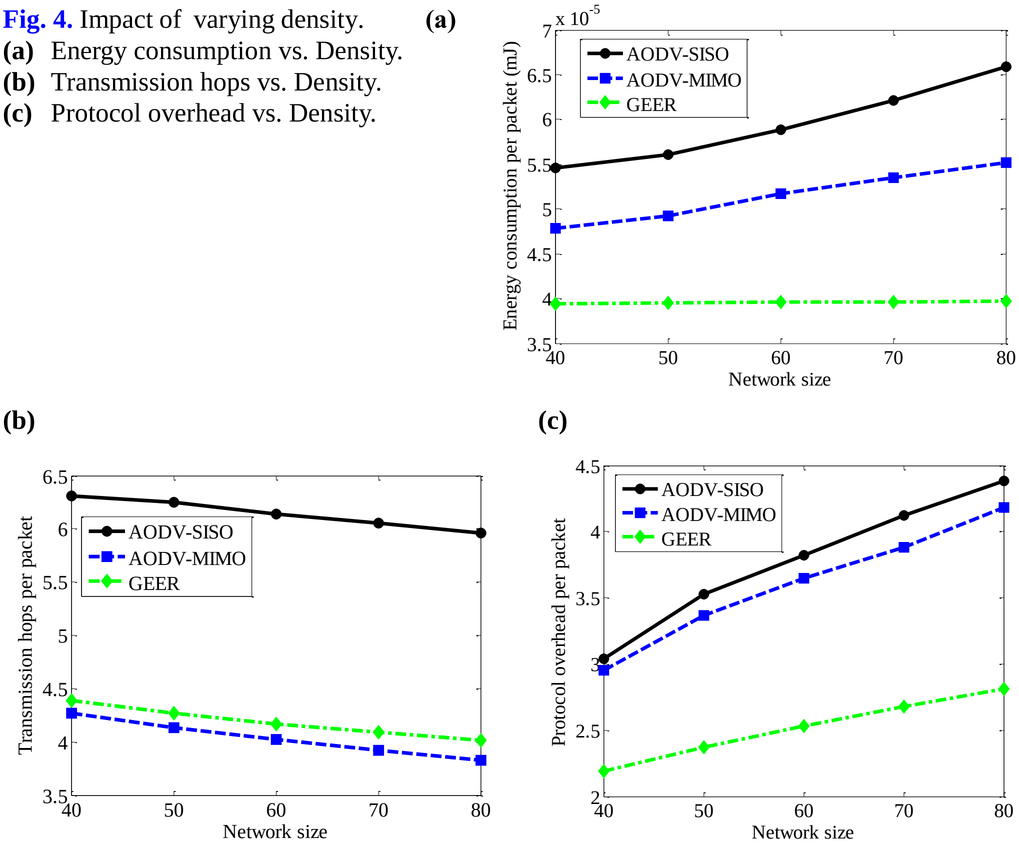
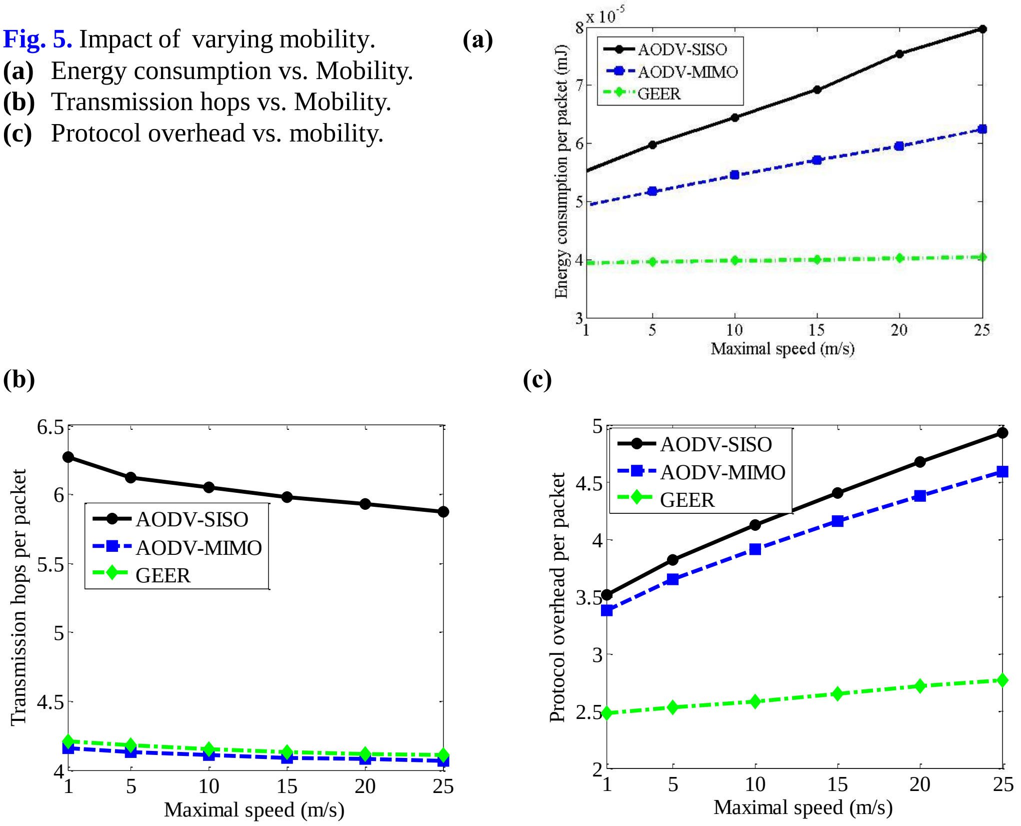


Fig. 5. Impact of varying mobility.
(a) Energy consumption vs. Mobility.
(b) Transmission hops vs. Mobility.
(c) Protocol overhead vs. mobility.



(1) *Varying density*: Fig. 4(a), (b) and (c) present the results for varying density, where performance metrics of the different strategies are recorded as functions of network size n. It can be seen that, on one hand, since the overhead increases dramatically as the increase of network size n, energy consumption increases with node density for all protocol; on the other hand, as more nodes provide more potential route relay opportunities, the average transmission hops in all protocols decrease with node density. Generally, the influence to protocol overhand play the completely dominant role. While irrespective of node density, the proposed GEER protocol performs much better than AODV-SISO and AODV-MIMO protocols in terms of the energy consumption, and the average performance gains are up to 50.40% and 30.13%, respectively..

(2) *Varying mobility*: Fig. 5(a), (b) and (c) present the results for varying mobility, where performance metrics of the different strategies are recorded as functions of maximal speed s_{max}. Generally speaking, the situation is almost the same with the case of varying density. The reason is that, as the same as higher node density, higher node mobility could also provide more potential route relay opportunities, while it also produces much more route overhead as the selected route paths are broken down much more frequently. In comparison with the AODV-SISO and AODV-MIMO protocols, the average energy performance gains of GEER protocol are up to 68.74% and 29.08%, respectively.

There are several reasons that GEER performs better in terms of energy consumption. First, as spatial diversity could enhance the transmission range of MIMO-based links, the average transmission hops in a route path in the MIMO-based protocols, GEER and AODV-MIMO, are largely shortened. Second, GEER and AODV-MIMO employ a novel MIMO link energy consumption model, and can search for a more energy efficient route path and transmit mode for MIMO-based links. Third, the routing establishment strategies in GEER significantly decrease the control packets in the process of creating a new route path than AODV-based protocols, just sometimes at the cost of finding a sub-optimal but acceptable route path. Finally, GEER protocol can adapt to the environment change quickly, and better maintain an energy efficient path by adopting a lightweight routing maintenance mechanism.

In summary, the derived MIMO link energy consumption model accurately characterizes the impact of MIMO techniques, offering a guide for selecting the optimal relaying nodes and the corresponding transmission configurations of MIMO links. The routing mechanisms in GEER protocols are capable to establish and maintain route paths smartly with reasonable overhead. Therefore, the proposed GEER protocol provides significant performance gain over the referencing AODV-based protocols.

6. Conclusions

It is critical to design energy-efficient routing protocols for battery-limited mobile ad hoc networks. In this paper, a new Greedy Energy-Efficient Routing (GEER) protocol is proposed to address the issue of the energy-efficient routing design in MIMO-based MANETs. We firstly derive a generalized MIMO-based link energy consumption model to minimize link energy consumption by taking trade-off between spatial multiplexing and spatial diversity. Then aim to reduce the protocol overhead, a novel greedy route discovery algorithm, adaptive reply mechanism and lightweight route maintenance mechanism are introduced in succession. Finally, extensive simulation results show that, in comparison with the conventional solutions, the proposed GEER protocol can significantly reduce energy consumption.

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