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Power Adjusting Algorithm: A New Cross-Layer Power Saving Mechanism for Mobile Ad-Hoc Networks

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Abstract Power saving is one of the key issues in Mobile Ad-Hoc Networks (MANETs). It can be realized in Medium Access Control (MAC) layer and network layer. However, previous attentions were mainly paid to MAC layer or network layer with the aim of improving the channel utilization by adopting variable-range transmission power control. In this paper we focus on the power saving in both MAC layer and network layer, and propose a Power Adjusting Algorithm (PAA). In the presence of host's mobility, PAA is designed to conserve energy by adjusting the transmission power to maintain the route's connectivity and restarting the route discovery periodically to find a new route with better energy efficiency dynamically. After analyzing the operations of PAA, we find that the length of route discovery restarting period is a critical argument which will affect power saving, and an energy consumption model is abstracted to find the optimal value of the restarting period by analyzing the energy consumption of this algorithm. PAA can handle the mobility of MANET by adjusting the transmission power and in the meantime save energy by restarting route discovery periodically to balance the energy consumption on route discovery and packet delivering. Simulation results show that, PAA saves nearly 40% energy compared with Dynamic Source Routing protocol when the maximum speed of mobile hosts is larger than 8 m/s.

Keywords mobile ad-hoc networks, mobility control, power control, power efficiency

1 Introduction

Mobile ad-hoc network (MANET) is a kind of wireless networks with mobile hosts (MHs). It is deployed without any fixed routers, and all MHs are capable of movement and can be connected dynamically in an arbitrary manner. Two MHs can communicate with each other either directly or indirectly. MHs in MANET operate not only as hosts but also as routers. Such network is highly self-configured, and MHs in this network automatically establish and maintain connectivity with other MHs. Some or all of the MHs in a MANET may rely on batteries or other exhaustible energy resources. As such, one of the most important system design requirements in MANETs is power saving[1].

With the proliferation of portable mobile devices such as cell phones, laptops and handheld digital devices, MANET has attracted significant attentions in recent years as a method to provide data communications among these devices without any infrastructure. Fundamental characteristics[2-7] of mobile ad-hoc networks include:

Multi-Hop Routing. No default router available, every MH acts as a router and forwards each other packets to enable information sharing between MHs.

Dynamical Network Topologies. In MANET, because MHs can move arbitrarily, the network topology, which is typically multi-hop, can be changed frequently and unpredictably, resulting in route changes, frequent network partitions, and possibly packet losses.

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Energy Constrained Operation. Because batteries carried by MHs have limited power supply, processing power is limited, which in turn limits services and applications that can be supported by MHs. This becomes a bigger issue in mobile ad-hoc networks. As MHs must act as both an end system and a router, additional energy is required to forward packets to other MHs.

Considering the above three specific characters together, this paper presents a novel power saving routing protocol, PAA, to conserve energy for MANET. In Medium Access Control (MAC) layer, a variable-range transmission power control[8-9] is used to handle the mobility and maintain network connectivity, and in network layer, periodical route discovery restarting is used to balance the energy consumption on route discovery and packets delivering. With the aid of variable-range transmission power control supported by MAC layer, PAA is designed to conserve energy in both MAC layer and network layer, and the main contributions of PAA are listed as below:

1) adjusting transmission power in the presence of MHs' mobility to keep the route's connectivity when the packets are transmitted on this route.

2) conserving energy in routing protocol, including the power consumed on both route discovery and data transmission.

3) restarting the route discovery after an appropriate period to find a new more energy efficient route for data transmission.

PAA is essentially a period schedule which introduces the adjustable transmission power control mechanism, and periodically restarts the route discovery to find a more energy efficient route. The length of this period used to balance the energy consumption in route discovery and packets delivering can be further calculated out by the energy consumption model. We analyze this algorithm theoretically and detail its parameter settings. Its merits are displayed by simulations. In our simulations, PAA saves nearly 40% energy compared with the Dynamic Source Routing protocol (DSR), when the maximum speed of MHs exceeds 8 m/s.

The remainder of this paper is organized as follows. Research background on energy saving routing protocols is presented in Section 2. In Section 3, the propagation model, mobility model, and network assumptions used in this paper are introduced. Section 4 proposes and describes PAA. Section 5 discusses the parameters of PAA, where we propose an energy model to obtain the desired parameters for PAA in order to minimize the energy consumption. In Section 6, we implement PAA and perform simulations to analyze and compare PAA and DSR on their power saving performance. Finally, the conclusions are drawn in Section 7.

2 Research Background

Various studies on MANET have recently been published on multi-hop routing, mobility control and power-saving. This section briefly reviews these protocols in MAC layer and network layer, and discusses their solutions and advantages on their power saving trial in MANETs.

2.1 Power-Saving in MAC Layer

In MAC protocol, energy saving research is limited in peer to peer communication. The standardized IEEE 802.11 Distributed Coordination Function (DCF)[10] is an example of the contention-based protocol in ad-hoc networks, and is mainly built on the MACAW[11]. It is widely used in ad-hoc networks because of its simplicity and robustness to the hidden terminal problem. However the energy consumption used in the MAC layer is very high.

In order to reduce the waste of energy from collision, overhearing, idle listening and control packet overhead, S-MAC[12] induces a duty cycle into the 802.11 protocol, and uses virtual clustering, message passing, collision avoidance, and overhearing avoidance to save more energy. As this MAC protocol must predetermine the length of active part, which could not adjust to the network with variable load, T-MAC[13] was proposed to dynamically adjust to the variable load by inducing the TA threshold which determines the minimal amount of idle listening per frame. To dynamically balance the energy usage and guarantee network throughput, PH-MAC 14] was proposed to make a trade-off by allocating timeslots effectively in the contention period.

Energy saving in MAC layer for MANETs using variable-range transmission power control is initially discussed in [15-16]. By introducing the appropriate distributed active-sleep schedule for each MH, the authors of [15] proposed an efficient energy saving MAC protocol for multi-hop mobile ad-hoc networks called p-MANET, which avoids power consumption by activating mobile nodes during one beacon interval for every n intervals, where n is the size of a super frame. The authors of [16] proposed an on-demand power management framework for ad-hoc networks. In this framework nodes that are not involved in delivering may go to sleep in order to adapt to the traffic load, which will save energy in the ad-hoc network. Whereas these two algorithms are both energy-saving schemes adapting to traffic load.

2.2 Power-Saving in Network Layer

As we mentioned in Section 1, multi-hop routing, dynamical network topology, and energy constrain are three main challenging issues in MANETs. Detailed discussion of previous work will be divided into three aspects: multi-hop routing, network mobility control, and energy conserving routing.

2.2.1 *Multi-Hop Routing*

Multi-hop routing can be classified into two routing methodologies. One approach is proactive routing protocol, which is also called as "table-driven" protocols. Examples of reactive routing protocols are Optimized Link State Routing protocol (OLSR)[17] and Dynamic Destination-Sequenced Distance-Vector protocol (DSDV)[18]. In the proactive routing protocol, nodes continuously exchange route information with all reachable nodes and attempt to maintain consistent, up-todate routing information. Therefore, the source node can get a routing path immediately if it needs one.

An approach different from the proactive routing is the reactive routing, which is also called as "on-demand" routing protocol. Examples of reactive routing protocols are Dynamic Source Routing protocol (DSR)[19] and Ad-Hoc on Demand Distance Vector protocol (AODV)[20]. In DSR, all the routing information is maintained and updated at MHs. DSR has two major phases, namely route discovery and route maintenance. These two phases work together and can dynamically help each source host discover and maintain a route to any other host in the network. The source broadcasts a route request (RREQ) message to find a route, a route reply (RREP) is then generated if the message has reached the intended destination node. Along the RREP message a transmission route is fixed. AODV builds routes using a route request & route reply query cycle. When a source host desires a route to a destination for which it does not have a route, it broadcasts an RREQ packet across the network. A host receiving the RREQ may unicasts an RREP back to its source or rebroadcasts the RREQ depending on whether it is the destination or not. Hosts keep track of the RREQ's source IP address and broadcast ID. As RREP propagates back to the source, nodes set up forward pointers to the destination. Once the source node receives the RREP, it may begin to forward data packets to the destination.

Reactive routing protocols create routes only when desired by the source node. When a node requires a routing to a destination, it initiates a routing discovery to find a routing path. However routes may be disconnected due to MHs' mobility. Therefore, route maintenance is an important operation of reactive routing protocols. Compared with proactive routing protocols, less control overhead and better scalability is the main strength of reactive routing protocols. But both DSR and AODV do not include the power saving issues in their design.

2.2.2 *Mobility Models*

Researches on routing protocols for changing network topologies are mainly focused on mobility model of MHs[21-23] and route recover methods[19-20].

The mobility model, evaluating the performance of mobile wireless systems and the algorithms and protocols at the basis of them, is one of the most critical and, at the same time, difficult aspects of the simulation of applications and systems designed for mobile environments. According to different kinds of dependencies and restrictions, mobility models can be classified into random-based, temporal dependencies, spatial dependencies, geographic restorations, and hybrid characteristics[21-22]. Whereas the most widely used one is random-based one called random walk model, and in this paper this model is used to evaluate the performance of PAA[23].

Route recover aims to recover the broken routes due to the mobility of MHs. DSR recovers the broken route by restarting routing discovery process, whereas in AODV, some periodic hello messages can be used to ensure symmetric links, as well as to detect link failures. Once the next hop becomes unreachable, the node upstream of the break first repairs the failed link locally, and if it fails then the node will propagate an unsolicited RREP to all active upstream nodes. Upon receiving notification of a broken link, the source node can restart the discovery process if it still requires a route to the destination.

2.2.3 *Energy Conserving Routing*

To conserve energy, energy-efficient routing protocols can be divided into two categories, one is minimum energy routing[24-26] and the other one is maximum network lifetime routing[27-28].

Minimum energy routing protocols[24-26] search a route to minimize the energy consumed to forward a packet from the source to the destination, while maximum network lifetime routing, for the general case, selects routes and adjusts the corresponding power levels which can closely achieve the optimal lifetime. Since minimum energy routing scheme is also an important part in most recent maximum network lifetime routing protocols such as Conditional Max-Min Battery Capacity Routing (CMMBCR)[27] and Conditional Maximum Residual Packet Capacity (CMRPC) routing[28], we focus on developing efficient minimum energy routing protocols in this paper.

3 Research Background

We first introduce the propagation model and mobility model used in this paper, and then some network assumptions and notations are listed which will help us simplify the problems and models.

3.1 Propagation Model

Here we use free space propagation model to forecast the power level of the sender and receiver within line of sight. Let P_t and P_r be the power level when the packet is transmitted at the sender and received at the receiver respectively. Let the distance between the sender and receiver be d. Then, the power level of the receiver is given by Friis formula[29]:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, \tag{1}$$

where λ is the carrier wavelength, L is the system wastage factor, and G_t and G_r are the antenna gains at the sender and receiver respectively. Note that λ, L, G_t and G_r are constants in this formula.

In the free space we let the path loss exponent be 2, and then the power consumed on the transmitter side by sending one unit of data is:

$$P_t = \varepsilon_{11} + \varepsilon_2 d^2. \tag{2}$$

And the power consumed on the receiver side by receiving one unit of data is

$$P_r = \varepsilon_{12}. \tag{3}$$

Here ε_{11} is the power to run the transmitter circuitry, ε_{12} is the power to run the receiver circuitry, and ε_2 is the power for the transmit amplifier to achieve an acceptable SNR (signal to noise ratio).

Then the power consumed by the network to forward one unit of data can be calculated as below:

$$P_f = P_t + P_r = \varepsilon_1 + \varepsilon_2 d^2. \tag{4}$$

Here we let $\varepsilon_1 = \varepsilon_{11} + \varepsilon_{12}$.

As the power consumption on computation is less than the energy for radio transmission by order of magnitude, we ignore the power consumption on computation in this paper.

3.2 Mobility Model

Random walk model is selected to evaluate our work in this paper. In the random walk model, an MH moves from its current location to a new location by randomly choosing a direction and speed in which to travel. The new speed and direction are both chosen from pre-defined ranges, $[0, maxspeed]$ and $[0, 2\pi]$ respectively. Each movement in the random walk model occurs in a constant time interval t, at the end of which a new direction and speed are calculated. If an MH which moves according to this model reaches a simulation boundary, it "bounces" off the simulation border with an angle determined by the incoming direction. The MH then continues along this new path. Fig.1 cited from [19] shows an example of the movement observed from this 2-D model. The MH begins its movement in the center of the 300 m×600 m simulation area or position (150, 300). At each point, the MH randomly chooses a direction between 0 and 2π and a speed between 0 and 10 m/s. The MH is allowed to travel for 60 seconds before changing direction and speed.

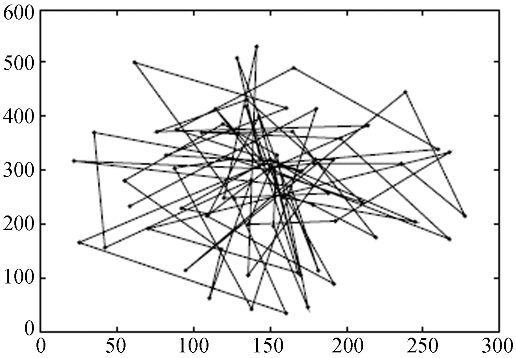


Fig.1. Traveling pattern of MHs using the 2-D random walk mobility model.

3.3 Network Assumptions

Without sacrificing the generality, we make the following assumptions:

1) There are N MHs uniformly displayed in an area with radius R.

2) We adapt the random walk mobility model as our MH's mobility model.

3) The optimal transmission radius of the MH, which minimizes the power consumption in the multi-hop adhoc network, is characteristic distance[30], denoted as r_{char}, where $r_{\text{char}} = \sqrt{\frac{\varepsilon_1}{\varepsilon_2}}$.

4) We also make sure that r_{char} and N satisfy $\pi r_{\text{char}}^2 \geqslant \frac{\log N + c(N)}{N}$, which will keep network being connected[31].

5) The MH's maximum speed is set to be v_m in the random walk model.

6) The data rate of the flow through the network is r_f packets/s.

7) The length of the message RREQ, RREP, DATA is L_{RREQ}, L_{RREP}, L_{DATA} respectively.

8) The main cause to the break of route is the mobility of the MHs, which means that when the receiver moves out of the sender's transmission range, a link break will happen, and this will cause the route break. We ignore the result of host failure, unreliable

channel, and network congestion in this paper.

4 Power Adjusting Algorithm Design

In this section we present PAA, which can be embedded in the existing reactive routing protocols, such as DSR for power conserving. We present the description of PAA and its implementations in real networks.

4.1 Description of PAA

For a flow with data rate r_f originating from MH s and route to MH d, as PAA constructs a periodic schedule on packet transmission, we simply let the time of sending every k packets to be one period T, where $T=\frac{k}{r_f}$, then after one period of sending k packets, the old route may not be energy efficient due to the mobility of hosts, then the new route needs to be found, so route discovery is restarted to find a new route to the destination to replace the old one. Fig.2(a) shows a route from MH 2 to MH 6 constructed by route discovery. After a period of T this route becomes less energy efficient as shown in Fig.2(b). Finally, as shown in Fig.2(c), we have found a new and more energy efficient route (2, 8, 1, 5, 6) by restarting route discovery.

We firstly describe the algorithm of PAA as below:

Step 1. The source of this flow will start route discovery to find a route $(n_0, n_1, \ldots, n_l)$ to the destination, where $n_0 = s$, $n_l = d$. In order to save power, we use the characteristic distance r_{char} as the transmission radius of the RREQ and RREP messages.

Step 2. By analyzing the power level of RREQ and RREP messages received by the host, every host on the route path, will compute out the distance to its adjacent hosts. We denote the distance between adjacent MHs n_i and n_j on the route path to be d_{ij}^0.

Step 3. Every $\frac{1}{r_f}$ seconds, one packet will be transmitted along this route. Let us say that it is the t-th $(1 \leqslant t \leqslant l)$ packet on the fly, we forward it with the transmission radius of $(d_{ij}^{t-1}+2\frac{v_m}{r_f})$ from n_i to n_j, where d_{ij}^{t-1} is the distance which is estimated when the $(t-1)$-th packet passed through the adjacent hosts n_i and n_j on the route path.

Step 4. If there are no more packets to sent, the flow should be canceled from the network.

Step 5. For every period of $T=\frac{k}{r_f}$ seconds, after sending every k packets, we restart the route discovery to find a new route $(n_0, n_1, \ldots, n_l)$ to the destination host, and then go to step 2 to continue.

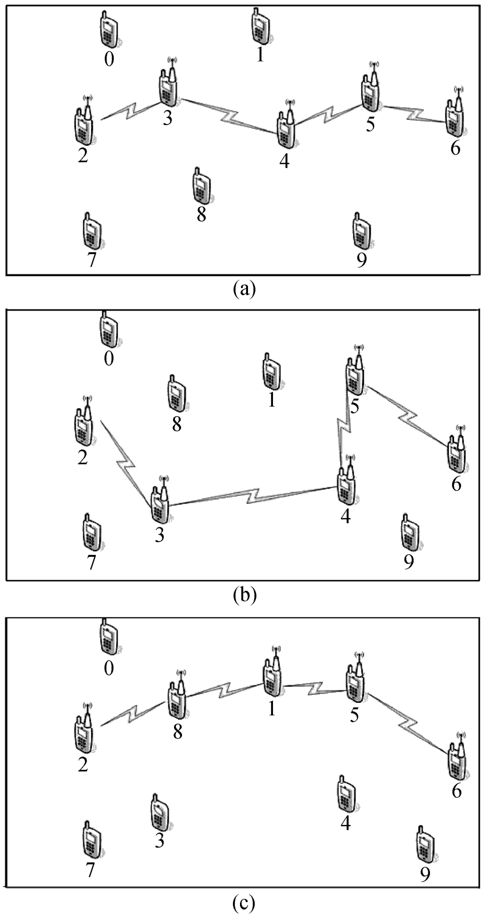


Fig.2. Changing route caused by the mobility of the MHs. (a) A route (2, 3, 4, 5, 6) constructed by route discovery. (b) The route (2, 3, 4, 5, 6) changes its position when the MHs are moving around. (c) A new energy efficient route (2, 8, 1, 5, 6) was found by restarting the route discovery.

4.2 Analysis of PAA

In step 1, the source broadcasts the RREQ messages to find the destination. After receiving the RREQ messages the destination will reply the source by sending an RREP message to construct a route $(n_0, n_1, \ldots, n_l)$ from the source to the destination. By setting the transmission power to be $P_t = \varepsilon_1 + \varepsilon_2 r_{\text{char}}^2$, the transmission radius of RREQ and RREP messages will be r_{char}, then a route $(n_0, n_1, \ldots, n_l)$ from the source to the destination is constructed by route discovery.

In step 2, every host i on the route path needs to calculate the distance d_{ui}^0 from the upstream host u (except the source) and the distance d_{iv}^0 to the downstream host v (except the destination) by analyzing the power level of the received RREQ and RREP messages. The calculation on how the distance can be computed from transmitted power level P_t and received power level P_r will be discussed in next subsection.

In step 3, k data packets can be delivered to the destination within a period $T=\frac{k}{r_f}$ seconds, in every $\frac{1}{r_f}$ seconds one packet will pass through the route. When the t-th packet passes through this route, we can estimate the distance d_{ij}^t between hosts n_i and n_j from the distance d_{ij}^{t-1} which is the distance when the $(t-1)$-th packet pass through $(t \geqslant 1)$. Due to the maximum speed of the MH host is v_m, the distance d_{ij}^t will satisfy:

$$d_{ij}^{t-1} - 2\frac{v_m}{r_f} \leqslant d_{ij}^t \leqslant d_{ij}^{t-1} + 2\frac{v_m}{r_f}. \tag{5}$$

In order to make sure that packet t can be successfully delivered to the host n_j from host n_i, we just let the host n_i's RF power level cover a transmission distance of $d_{ij}^{t-1} + 2\frac{v_m}{r_f}$. Then after the transmission of packet t, we can estimate the distance d_{ij}^t from the transmitted power level P_t and the received power level P_r. Subsequently this updated distance d_{ij}^t can be used to estimate the transmission range of the packet $t+1$.

In step 4, when the flow has no packet to send, the network needs to cancel this flow.

In step 5, when the final packet (packet k) is delivered along this route, the source will restart route discovery to find new route, which will find a new energy efficient one compared with the current one according to the current position of the MH in the network. Next we will further discuss the parameter setting of k in a period in Section 5.

4.3 Method of Distance Estimation

4.3.1 Estimating Initial Distance

The initial distance d_{ij}^0 for the adjacent MHs n_i and n_j on the route path $(n_0, n_1, \ldots, n_l)$ needs to be first estimated. In step 1 of PAA, the power level P_{ij}^i of the RREQ or RREP packet transmitted by the sender n_i is:

$$P_{ij}^i = \varepsilon_1 + \varepsilon_2 r_{\mathrm{char}}^2. \tag{6}$$

The power level P_{ij}^j of the RREQ or RREP packet received by the receiver n_j can be got from the receiver side. As the transmitted power level P_{ij}^i and the received power level P_{ij}^j satisfy (1), which is our propagation model, the distance d_{ij}^0 between the adjacent host sender n_i and receiver n_j on the route path $(n_0, n_1, \ldots, n_l)$ can be calculated from (1) as follows:

$$d_{ij}^0 = \frac{\lambda}{4\pi}\sqrt[n]{\frac{P_{ij}^i G_t G_r}{P_{ij}^j L}}. \tag{7}$$

4.3.2 Estimating Subsequent Distance

With the initial distance, the method on estimating d_{ij}^t from the preceding distance d_{ij}^{t-1} of the adjacent sender n_i and receiver n_j on the route path $(n_0, n_1, \ldots, n_l)$, where $1 \leqslant t \leqslant k$ is present here.

As in step 3 of PAA, the power level P_{ij}^i at the sender side used to transmit packet t will cover a transmission radius of $d_{ij}^{t-1} + 2\frac{v_m}{r_f}$, and it can be calculated as follows:

$$P_{ij}^i = \varepsilon_1 + \varepsilon_2\Big(d_{ij}^{t-1} + 2\frac{v_m}{r_f}\Big)^2. \tag{8}$$

The power level P_{ij}^j at which the receiver receives the packet t will be got from the receiver side, and then the distance d_{ij}^t when packet t passes through sender n_i and receiver n_j can be calculated as follows:

$$d_{ij}^t = \frac{\lambda}{4\pi}\sqrt{\frac{P_{ij}^i G_t G_r}{P_{ij}^j L}}. \tag{9}$$

When a packet comes to the sender n_i, the sender will forward the data packet with the transmission radius $(d_{ij}^{t-1} + 2\frac{v_m}{r_f})$ to ensure the reception of the data packet on the receiver n_j, and the receiver will reply an ack packet with the same transmission radius $(d_{ij}^{t-1} + 2\frac{v_m}{r_f})$ to the sender, finally the sender and the receiver will estimate the current distance d_{ij}^t between them. And this new estimated distance will be used for the transmission of the next packet.

The algorithm of PAA together with distance estimation method will ensure the successful packet transmission under our assumption. The periodic schedule of route recovery is used to adjust the route energy state for power saving.

5 Parameters Setting of PAA

The length of a period is vital in this algorithm. On the one hand, if the period is too short, route discovery is restarted too frequently, which will waste more energy on route discovery. On the other hand if the period is too long, the link state of the route (e.g., Fig.2(b)) will become worse as the MH moves around in the network area. This will also waste much energy on delivering the packet along this energy inefficient route. This motivates us to find an appropriate length of period for route discovery. We will find this parameter based on the consideration that, if the energy wasted on the current route becomes unacceptable, the restarted route discovery will find a new better route to save as much energy as possible on delivering the packets.

Before finding the optimal length of the period, we need first analyze the average distance of the MHs displayed in the network, then the energy consumption of the route discovery, and finally the distance variety between adjacent hosts on the route path in the present of MH's mobility.

5.1 Method of Distance Estimation

Concerning the average distance of any two MHs, we now present the following theorem.

Theorem 1. *If two vectors* $\boldsymbol{v}_1(r_1,\theta_1)$*,* $\boldsymbol{v}_2(r_2,\theta_2)$*, where* $0 \leqslant r_1,\ r_2 \leqslant R$*,* $0 \leqslant \theta_1,\theta_2 \leqslant 2\pi$*, are uniformly distributed in a circle with radius R. By denoting the sum of them as* $\boldsymbol{v}(r,\theta) = \boldsymbol{v}_1 + \boldsymbol{v}_2$*, the probability of* $\boldsymbol{v}$ *locating at* (r,θ) *(where* $0 \leqslant r \leqslant R$*,* $0 \leqslant \theta \leqslant 2\pi$*) is:*

$$P(r,\theta,R) = \frac{1}{\pi^2 R^2}\Big(2\mathrm{arc}\cos\frac{r}{2R} - \frac{r}{R}\sqrt{1-\Big(\frac{r}{2R}\Big)^2}\Big). \tag{10}$$

Proof. Fig.3 displays the two vectors $\boldsymbol{v}_1(r_1,\theta_1)$, $\boldsymbol{v}_2(r_2,\theta_2)$ and their sum $\boldsymbol{v}(r,\theta)$, where the vector $\boldsymbol{v}(r,\theta)$ located in a circle with radius $2R$, two small circles with radius R are centered at the start point and the end point of the vector $\boldsymbol{v}(r,\theta)$. All the possible position of vector $\boldsymbol{v}_1$ should be located in the overlapped regions of the two small circles. Then the area of the overlapped regions of the two small circles is

$$\begin{aligned} A &= R^2(\theta - \sin\theta) \\ &= R^2\Big(2\mathrm{arc}\cos\frac{r}{2R} - \frac{r}{R}\sqrt{1-\Big(\frac{r}{2R}\Big)^2}\Big). \end{aligned} \tag{11}$$

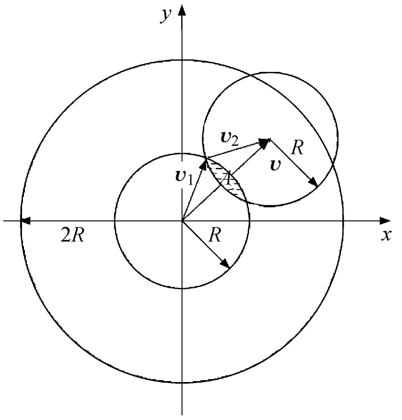


Fig.3. Two vector $\boldsymbol{v}_1(r_1,\theta_1)$, $\boldsymbol{v}_2(r_2,\theta_2)$ and their sum $\boldsymbol{v}(r,\theta)$.

The variable area of the vector $\boldsymbol{v}_1(r_1,\theta_1)$ or $\boldsymbol{v}_2(r_2,\theta_2)$ is πR^2, so the probability of the sum of two vectors $\boldsymbol{v}$ to locate at (r,θ) is:

$$\begin{aligned} P(r,\theta,R) = \frac{A}{\pi R^2 \pi R^2} - \frac{1}{\pi^2 R^2}\Big(2\mathrm{arc}\cos\frac{r}{2R} - \\ \frac{r}{R}\sqrt{1-\Big(\frac{r}{2R}\Big)^2}\Big). \end{aligned} \tag{12}$$ □

Now for any two hosts uniformly displayed in the network with radius R, the locations of the two hosts are $\boldsymbol{v}_1(r_1,\theta_1)$, $\boldsymbol{v}_2(r_2,\theta_2)$ respectively, where $0 \leqslant r_1$, $r_2 \leqslant R$, $0 \leqslant \theta_1$, $\theta_2 \leqslant 2\pi$. This can be seen in Fig.4. Then the average distance l of these two MHs will be:

$$E(l) = \int_0^{2R}\int_0^{2\pi} P(r,\theta,R) r \times r\mathrm{d}\theta\mathrm{d}r = \frac{128}{45\pi}. \tag{13}$$

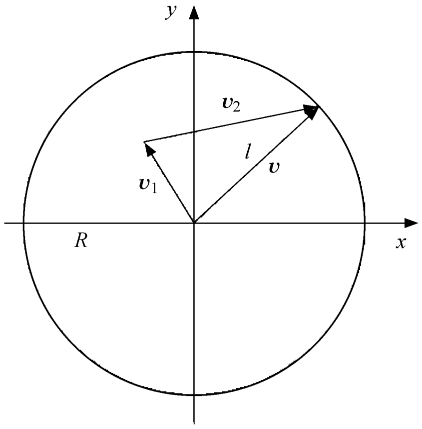


Fig.4. Position of two MHs $\boldsymbol{v}_1(r_1,\theta_1)$, $\boldsymbol{v}_2(r_2,\theta_2)$, and their distance l.

Therefore, for any two hosts which are uniformly located in a network area with radius R, their average distance is $\frac{128}{45\pi}R$.

5.2 Energy Consumption on Route Discovery

In a network with N MHs located in, the energy consumption of route discovery is mainly consumed by broadcasting the RREQ messages and unicasting the RREP messages, which means:

$$E_{\text{restart}} = E_{\text{RREQ}} + E_{\text{RREP}}. \tag{14}$$

The source host broadcasting an RREQ message and this message will flood the whole network, so nearly every host will receive an RREQ message and it will rebroadcast the RREQ message to its neighbors. As the transmission range of the broadcasting is r_{char} which is suggested in PAA, the energy consumption on broadcasting the RREQ message can be calculated approximately as follows:

$$E_{\text{RREQ}} = NL_{\text{RREQ}}(\varepsilon_1 + \varepsilon_2 r_{\text{char}}^2). \tag{15}$$

The destination host will reply an RREP message after receiving an RREQ message. This RREP message will be unicasted back to the source, and all hosts who relay the RREP message will form a route $(n_0, n_1, \ldots, n_l)$ from the source to the destination. As the routing protocol selects the route with minimum number of hops to be the final route, the average number of hops of the active route $(n_0, n_1, \ldots, n_l)$ will be

$$L = \Big\lceil \frac{E(l)}{r_{\text{char}}} \Big\rceil = \Big\lceil \frac{128R}{45\pi r_{\text{char}}} \Big\rceil. \tag{16}$$

Then the energy consumption of unicasting the RREP message can be calculated approximately as follows:

$$\begin{aligned}E_{\mathrm{RREP}} &= LL_{\mathrm{RREP}}(\varepsilon_1+\varepsilon_2 r_{\mathrm{char}}^2)\\ &= \left\lceil \frac{128R}{45\pi r_{\mathrm{char}}}\right\rceil L_{\mathrm{RREP}}(\varepsilon_1+\varepsilon_2 r_{\mathrm{char}}^2).\end{aligned} \tag{17}$$

Finally the energy consumption of the route discovery is:

$$E_{\mathrm{restart}} = \Big(NL_{\mathrm{RREQ}}+\left\lceil \frac{128R}{45\pi r_{\mathrm{char}}}\right\rceil L_{\mathrm{RREP}}\Big)(\varepsilon_1+\varepsilon_2 r_{\mathrm{char}}^2). \tag{18}$$

5.3 Distance Variety Between Adjacent MHs on the Routing Path

For any two objects randomly moving in the space, the distance between them will become larger and larger. This phenomenon is called diffusion in physics. Here we will estimate the distance variety of two adjacent MHs on the routing path. This result will be used to build the energy consumption model of PAA in the next subsection, and then the optimal length of the period can be calculated out from this model.

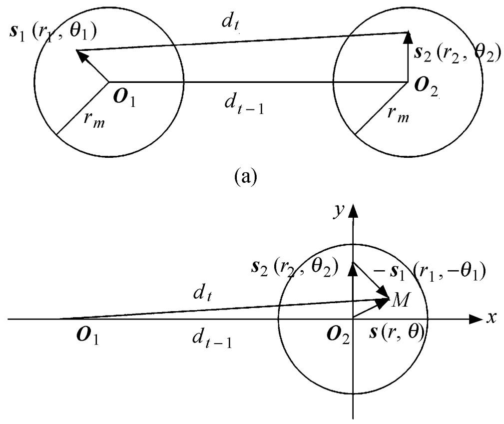
The average distance of any two adjacent hosts n_i and n_j along the route path $(n_0, n_1, \ldots, n_l)$ when packet $t-1$ and packet t come are set to be d_{t-1}, d_t respectively. We define the distance variety to be $\Delta d = d_t^2 - d_{t-1}^2$. As the routing protocol selects the route with minimum number of hops to be the final route, the preliminary distance between any two adjacent hosts along the route path just after the route discovery is restarted is nearly r_{char}, we just set $d_0 = r_{\mathrm{char}}$ for simplicity.

As we have assumed that the flow rate is r_f, the time between any two consecutive packets is $\frac{1}{r_f}$, and the MH's maximum speed in their random walk mobility model is set to be v_m, so the maximum distance that the MHs can move during the interim of two continuous packets is $r_m = \dfrac{v_m}{r_f}$.

The displacement of the two MHs n_i and n_j during the interim of two packets is denoted as $\boldsymbol{s}_1(r_1, \theta_1)$, $\boldsymbol{s}_2(r_2, \theta_2)$ respectively, where $0 \leqslant r_1$, $r_2 \leqslant r_m$, $0 \leqslant \theta_1$, $\theta_2 \leqslant 2\pi$. The movement of the two hosts n_i and n_j is displayed in Fig.5(a), and from the viewpoint of host n_i, the movement of host n_j can be seen in Fig.5(b). The length of $\boldsymbol{O}_1\boldsymbol{O}_2$ is d_{t-1}, the length of $\boldsymbol{O}_1\boldsymbol{M}$ is d_i. Then we can estimate distance variety Δd as follows:

$$\begin{aligned}\Delta d =& d_t^2 - d_{t-1}^2\\ =& \int_0^{2r_m}\int_0^{2\pi} P(r,\theta,r_m)\times\\ & (d_{t-1}^2 + \boldsymbol{s}^2 + 2d_{t-1}r\cos\theta - d_{t-1}^2) r\mathrm{d}r\mathrm{d}\theta,\end{aligned} \tag{19}$$

where $P(r,\theta,r_m)$ is the probability of the final position of the MH n_j located at $\boldsymbol{s}(r,\theta)$ from the viewpoint of MH n_i, where $\boldsymbol{s} = (-\boldsymbol{s}_1) + \boldsymbol{s}_2$, and $\sqrt{d_{t-1}^2 + r^2 + 2d_{t-1}r\cos\theta}$ is the length of vector $\boldsymbol{O}_1\boldsymbol{M}$, which is the final distance of the two host.



(a)

(b)

Fig.5. Movement of two adjacent MHs n_i and n_j. (a) Movement of host n_i and host n_j. (b) Movement of host n_j from the view of host n_i.

By some mathematical manipulations (19) is reduced to:

$$\Delta d = d_t^2 - d_{t-1}^2 = r_m^2, \tag{20}$$

which means that the distance variety Δd of two adjacent MHs n_i and n_j is the square of the maximum distance that MHs can move during the interval of two continuous packets.

5.4 Finding the Optimal Length of the Period

In a period T, we let that k packets can be transmitted along the route, and then the problem of finding optimal period T is translated to find optimal number of packets which can be transmitted in a period, and the data rate r_f of the flow is constant here.

After the route discovery, a route path $(n_0, n_1, \ldots, n_l)$ from the source to the destination is constructed. As in step 3 of PAA, the energy of delivering t-th packet on this route path can be calculated as

$$E(t) = \sum_{i=1}^{l} L_{\mathrm{DATA}}(\varepsilon_1 + \varepsilon_2 d_t^2) = LL_{\mathrm{DATA}}(\varepsilon_1 + \varepsilon_2 d_t^2), \tag{21}$$

where $1 \leqslant t \leqslant k$.

Then the energy of delivering k packets in a period on an active route $(n_0, n_1, \ldots, n_l)$ should be:

$$E_p = \sum_{t=1}^{k} E(t) = LL_{\mathrm{DATA}}\Big(k\varepsilon_1 + \varepsilon_2\sum_{t=1}^{k} d_t^2\Big). \tag{22}$$

Now we need to minimize the average energy consumption on delivering one packet in a period, so this problem can be modeled as follows:

$$\text{minimize}: \frac{1}{k}(E_p + E_{\text{restart}}), \tag{23}$$

subjected to:

$$d_0 = r_{\text{char}}, \tag{24}$$

$$d_1 = d_0 + 2v_m, \tag{25}$$

$$d_t^2 = d_{t-1}^2 + v_m^2, \quad 2 \leqslant t \leqslant k, \tag{26}$$

where E_{restart} is the energy cost on route discovery, (23) means that we need to minimize the average energy consumption on delivering one packet. The conditions (25) is derived from step 3 of PAA, and (26) is derived from (20).

Now by substituting (26) into the object function (23) we will get,

$$E(k) = \frac{LL_{\text{DATA}}\varepsilon_2 r_m^2}{2}k + \Big(\frac{LL_{\text{DATA}}\varepsilon_2 r_m^2}{2} + E_{\text{restart}}\Big)\frac{1}{k} + LL_{\text{DATA}}\big(\varepsilon_1 + \varepsilon_2(d_0 + 2v_m)^2 - \frac{3}{2}\varepsilon_2 r_m^2\big). \tag{27}$$

In order to get the optimal length of a period, we need to minimize the energy consumption (27), to make the energy on delivering packet in the period minimized. So we can get the first order derivative of function (25) and then get the optimal number of packets delivering in one period

$$k_{\text{opt}} = \sqrt{1 + \frac{2E_{\text{restart}}}{LL_{\text{DATA}}\varepsilon_2 r_m^2}}. \tag{28}$$

When all the parameters are determined, combining (16), (18), we obtain the optimal number of packet. Then the length of the period in this network to restart the route discovery schedule will be $T = \dfrac{k_{\text{opt}}}{r_f}$.

6 Simulation Results

We have implemented the routing protocol PAA and DSR in C++ language. The parameter setting of these simulations is listed in Table 1. In the simulation, 100 flows are randomly selected in a MONET, and every flow needs to deliver 1 000 packets through the network. First we verify the optimal number of packets which can be sent in a period, and then compare the number of route discovery, the average energy consumption on delivering one packet, and the total energy consumption between PAA and DSR by changing the MH's maximum speed on the random walk mobility model. These results demonstrate that the algorithm of PAA balances the energy consumed on route discovery and data delivering, which help the routing protocol PAA conserve energy in the presence of different mobile speeds.

Table 1. Parameter Settingg in Simulation

N	1000
R	1000 m
ε_1	180.00 pJ/bit/m^2
ε_2	10 pJ/bit/m^2
L_{RREQ}	16 bytes
L_{RREP}	16 bytes
L_{DATA}	512 bytes
r_f	1 packet/s

In Fig.6, as the number of packets k changes from 1 to 200, the average energy consumption on delivering one packet is plotted, here the maximum speed of the MH is set to 10 m/s. From this picture, one observes that, when the number of packet k is in the range of [20, 60], more energy will be conserved on packet delivering. According to (28), the optimal value that is theoretically computed from our energy consumption model is 57. Therefore, we have verified that this theoretical value agrees with the simulation results in the algorithm PAA.

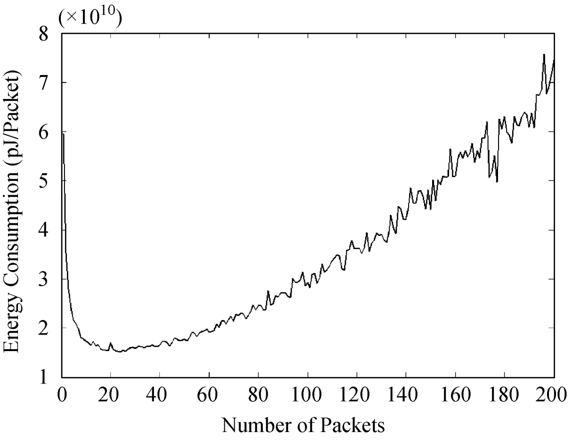


Fig.6. Verify the optimal length of period.

When the maximum speed of MHs increases from 1 m/s to 20 m/s in the mobility model, the optimal number of packets k transmitted in one period is listed in Table 2. PAA will restart the route discovery after sending every k packets, and this is the key strategy for PAA to keep the route energy efficient. Mobility speed is the largest cause of route broken, in Table 2, one can see a clear trend that, the length of period is decreasing when the maximum speed of MHs increases. In return the decreasing length of period will directly increase the number of route discovery to keep the route connect and energy efficient. This is the main strategy for PAA to handle the mobility for MONET.

With the optimal number of packets (k_{opt}) listed in Table 2, the number of restarted route discovery per flow, and the average energy consumption on delivering one packet for DSR and PAA are plotted in Fig.7 and

Table 2. Optimal Number of Packets Transmitte in One Period

Speed	k_{opt}	Speed	k_{opt}
1	86	11	54
2	85	12	52
3	82	13	49
4	79	14	47
5	75	15	44
6	71	16	42
7	68	17	40
8	64	18	39
9	61	19	37
10	57	20	35

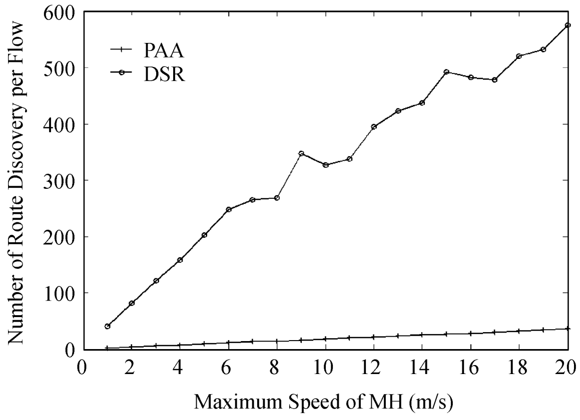


Fig.7. Number of restarted route discovery per flow on delivering 1 000 packets.

Fig.8 respectively. In Fig.7, the number of route discovery restarted increases greatly in DSR compared with PAA. That is because the increasing maximum speed will enlarge the possibility of link break along the route path caused by MH's mobility in DSR, whereas this number increases slowly in PAA. In PAA, the number of route discovery restarted is significantly decreased by adjusting the transmission power dynamically to adapt to the mobility of MHs.

Fig.8 demonstrates the route energy state on delivering packets. In this figure, the route energy state of DSR is always stable at 1.25×10^{10} pJ, while the route energy state of PAA increases as the MH's maximum speed increases. So the route energy state of DSR is maintained in good state, and the route energy state of PAA is becoming worse as the maximum speed increasing. As it is shown in Fig.7, this good state maintained by DSR is at the cost of much larger amount of restarted route discovery, while PAA is aimed to reach a global balance not only in energy consumption on restarting route discovery but also on maintaining route energy consumption state on packet delivering. Clearly smaller amount of route discovery leads to slightly more energy consumption on packet delivering, here the amount of route discovery should be selected carefully in PAA to minimize the total energy consumption.

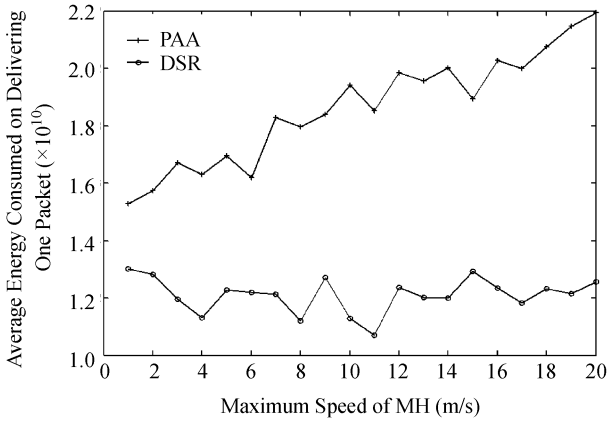


Fig.8. Average consumption on delivering one packet.

The simulation result about the total energy consumption of the two protocols is plotted in Fig.9. From the figure, one can see that 40% of the energy consumed in DSR is saved in the protocol PAA when the maximum speed is becoming high. In the presence of mobility of MH, the protocol DSR always restarts the route discovery when a link break happens. It suffers from the mobility of MHs. While in the protocol PAA, the mobility of MH is under the control of PAA. Furthermore, with the appropriate setting of the length of the restarted period, the route discovery is restarted to adjust the route path, which always balances the energy consumed on route discovery and packets delivering to reach a global power saving effect. In this simulation 40% energy is saved by using PAA to control the mobility of MH.

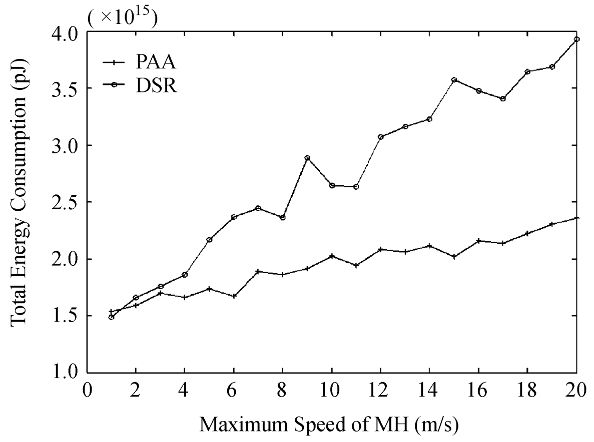


Fig.9. Total energy consumption on delivering 1 000 packets.

7 Conclusions

In this paper, we proposed PAA which can save power in the network layer. The algorithm of PAA introduces the adjustable transmission power control to control the mobility of MHs. By properly setting the length of period to restart the route discovery, PAA has the capability of balancing the energy consumption on route discovery and packets delivering to save energy in network layer. By theoretical analysis and simulations, we first established how the optimal length of period can be calculated from our model, and then by investigating the amount of restarted route discovery and the route energy state, we verified that PAA has indeed balanced the energy consumption on route discovery and packets delivering. Finally the simulation results of total energy consumption shows that the routing protocol PAA saves nearly 40% energy consumption when the maximum speed of MHs is larger than 8 m/s.

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