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Power Controlled and Stability-based Routing Protocol for Wireless Ad Hoc Networks

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In the building of smart city, mobile Ad hoc network (MANET) has shown tremendous application potential because of its flexibility, distributivity, on-demand and self-organization. High-speed mobility and heavy-load traffic in MANET may lead to the existence of frequently interrupted flows and prematurely drained energy, which degrades the performance of routing protocols. In this paper, a novel routing algorithm called as power controlled and stability-based routing protocol (PCSR) is proposed, aiming to improve the energy efficiency and route stability. In PCSR, a local connectivity table is firstly constructed at MAC layer without extra control packets, which is utilized to decide stable forwarding path at network layer. In addition, for the purpose of saving energy, the power for transmitting both control packets and datagrams is reduced in PCSR. Extensive simulations demonstrate that compared with existing routing protocols, our proposed PCSR consumes less energy and prolongs network lifetime with guaranteed packet delivery.

Keywords: wireless ad hoc networks, routing protocols, power controlled, energy efficiency, route stability

1. INTRODUCTION

As a system engineering project for urban residents or industry users, the construction of smart city rising in recent years is intended to use advanced information and communication technologies (ICT) to change the citizens' lives. Smart city allocates resource more reasonable and makes communication more efficient. As we know, mobile ad hoc network (MANET) is formed by a collection of wireless mobile nodes without centralized administration [1]. Based on the features of distributivity, flexibility and self-

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organization, MANET is playing an increasingly important role in many fields of smart city, such as emergency rescue, intelligent transportation and vehicular networking. However, because of the inherently limited factors in MANET, such as nodal mobility, limited battery energy, and heavy traffic load, route breaks continually [2]. Solutions for such issue could be classified into stable routing [3-7] and power control [8-11], both of which have been studied deeply. However, these research results did not simultaneously take the two aspects into account. In this paper, the integration of energy efficiency and route stability across multiple layers is considered.

In combination with power control, there have been several stable routing algorithms proposed previously [12-15]. The authors of [12-14] analyzed the practicability of such joint consideration: on one hand, limiting the power of sending control packets has significant influence on path selection since it can effectively reduce the number of next-hop candidates during route discovery [12]. On the other hand, it was observed that data transmission power control and stable routing can be integrated for achieving better connectivity and energy conservation [13, 14]. Following this motivation, a physical-layeroriented routing was presented in [13], which considers bit error rate as a metric for route selection and adopts one of ten possible transmitted power levels to send data packets. However, such careless power control ignores future interference taking place in its vicinity [11], which can easily result in smaller SINR and discarding packet by mistake. Considering heterogeneity of mobile devices, a relaying framework was put forward in [14], which constructs route and controls transmitted power based on node device-energy-load behavior. Extensive simulations showed that it indeed strikes a balance between energy efficiency and other network performance metrics. Nevertheless, such framework is employed for heterogeneous networks whereas this paper focuses on MANETs where all nodes are treated identical, which differentiates our results with that of [14]. In [15], a Protocol for Energy-Efficient Routing (PEER) was proposed, associated with a collision/interference-based energy consumption model and a corresponding power control mechanism. In order to calculate packet error rate in route maintenance, PEER constantly overhears neighbors' data transmission, which costs much energy necessarily. In addition, the minimum transmitted power in PEER may no longer be enough to maintain the connectivity on condition that the sender and receiver move apart relatively far [10].

In view of the above-discussed issues, the goal of this paper is to devise improved on-demand routing algorithm so as to find stable path and save energy. Along such idea, a novel power controlled and stability-based routing protocol, named PCSR, is presented for MANET. In PCSR, a local connectivity table (LCT) is firstly established at MAC layer to estimate link stability using information such as interference/collision, residual energy and load level. Afterwards, based on the accurate and latest parameters in LCT, a local-state-aware routing algorithm with a particular power control scheme is designed, aiming to enhance route stability.

The rest of this paper is organized as follows. In Section 2, an overview of PCSR is given, followed by detailed description in Section 3. Simulation results are presented in Section 4. Finally, Section 5 summarizes this paper.

2. OVERVIEW OF PCSR PROTOCOL

PCSR is an on-demand unicast routing algorithm and is implemented similar to an existing Ad hoc On-demand Distance Vector (AODV) protocol [16] for MANET. Differently, AODV selects forwarding path based on hop counts whereas PCSR considers route stability and power control. PCSR mainly consists of the following two stages.

Stage 1: Construction of local connectivity table (LCT). In this stage, according to various information such as interference, noise, received power obtained from physical layer and collision/load level from MAC layer, an LCT is created for each node. It is worth noting that the LCT construction does not require adding any additional control packet so as not to bring extra overhead.

Stage 2: Find stable paths. Based on the local state recorded in LCT, the detailed route construction is implemented at MAC layer and network layer, including power control and stable routing. For power control, considering link stability, the transmitted power of route request (RREQ) is adjusted in order to effectively control the number of next-hop candidates during route discovery process. Besides, in data transmission process, datagrams are transmitted at an optimal power to save energy and maintain connectivity. For stable routing, forwarding paths are found and set up based on a routing cost metric during route discovery. Fig. 1 shows the implementation structure of the proposed PCSR.

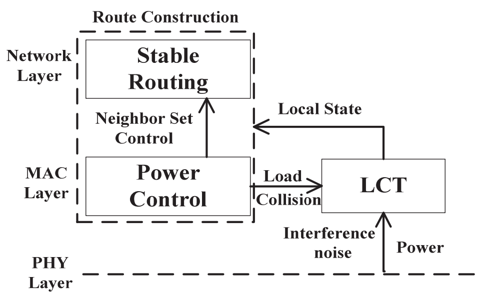


Fig. 1. Structure diagram of PCSR.

As we can see from Fig. 1, information exchange occurs between different layers. Therefore, PCSR is actually a cross-layer scheme across physical layer, MAC layer, and network layer.

3. PCSR PROTOCOL

3.1 Construction of LCT

Compared with the famous AODV protocol for MANET, PCSR keeps an extra LCT for each wireless node in addition to maintaining the neighbor set list, route table and reverse route table. For reflecting the local information including interference/noise, collision/load level, and neighbors' energy, LCT is constructed and maintained employing the request to send (RTS)/clear to send (CTS) overhearing mechanism of IEEE MAC 802.11 without using extra control packets. The structure of LCT is demonstrated in Table 1.

Table 1. The LCT of node *j*.

Address	Behavior Level	Minimum Power	Packet Error Rate	Timestamp
Neighbor 1	$b^{(1)}$	$P_{T\text{-}min}{}^{(1,j)}$	$p_e{}^{(1,j)}$	$t^{(1)}$
Neighbor 2	$b^{(2)}$	$P_{T\text{-}min}{}^{(2,j)}$	$p_e{}^{(2,j)}$	$t^{(2)}$
Neighbor *i*	$b^{(i)}$	$P_{T\text{-}min}{}^{(i,j)}$	$p_e{}^{(i,j)}$	$t^{(i)}$

Without loss of generality, we take one node j and its neighbor i for analysis, and denote the link between i and j by (i, j). In Table 1, $p_e{}^{(i,j)}$ (initialized to be 0) is packet error rate on link (i, j), which is a function of interference, noise and collision [15]. Physical layer can monitor the interference and noise level in the case that the channel is free. The collision could be estimated from the MAC layer for 802.11 [17]. Define $t^{(i)}$ as the timestamp of neighbor i's entry recording the time when the entry is established. If the difference value between current time and $t^{(i)}$ is greater than a maximum survival lifetime T_{life}, this entry will be deleted from LCT to prevent local state from being out of date. In order to timely reflect network situation, T_{life} should not be too high, here T_{life} is set to be 10s in our simulation. Here we use $b^{(i)}$ to denote the behavior level of neighbor i, which represents nodal residual energy and load level. $P_{T\text{-}min}{}^{(i,j)}$ is the minimum power needed to transmit packet from node i to j. Either $p_e{}^{(i,j)}$, $b^{(i)}$ or $P_{T\text{-}min}{}^{(i,j)}$ is calculated by node j as soon as j receives RTS intended for it or overhears such packet intended for other neighbors of sender i. In detail, the definition and calculation of $b^{(i)}$ and $P_{T\text{-}min}{}^{(i,j)}$ are introduced as follows:

(A) Node behavior level $b^{(i)}$

In ad hoc networks, behavior of each node depends on its own residual energy and load state and differentiates with other nodes. Based on this consideration, in PCSR, for the purpose of selecting high-performance node as intermediate station to forward data as far as possible, all nodes are classified into intending and potential categories according to their current energy and load level. Take one node i for example and denote i's energy/load behavior level by $b^{(i)}$, if i is determined as intending node, $b^{(i)}$ will be marked as boolean value 1; otherwise, $b^{(i)} = 0$ if i is a potential node. Node i appends $b^{(i)}$ to RTS message to inform i's neighbors. Specifically, $b^{(i)}$ is defined as

$$b^{(i)} = \begin{cases} 1 & \text{if } a^{(i)} > 0 \\ 0 & \text{if } a^{(i)} \le 0. \end{cases} \tag{1}$$

In Eq. (1), $a^{(i)} = (E^{(i)} - \varphi^{(i)}L^{(i)})/E_{total}{}^{(i)}$ [14], where $E^{(i)}$, $E_{total}{}^{(i)}$ and $L^{(i)}$ indicate the remaining energy level, the initial energy level, queue length of node i respectively, and $\varphi^{(i)}$ is an estimated parameter standing for the energy consumption per transmitting one byte of data. Note that our node classification is self-adaptive, *i.e.*, one node will move from potential to intending category if its load level gets low. Conversely, when the load gets high, intending node could be converted to be potential.

(B) Minimum power $P_{T\text{-}min}{}^{(i,j)}$

Denote the minimum necessary received power that ensures receiving packet successfully by $P_{R\text{-}th}$, and node j's received power of packets from node i by $P_R{}^{(i,j)}$. Assume that both RTS and CTS are transmitted at maximum power $P_{T\text{-}max}$, as in [8], $P_{T\text{-}min}^{(i,j)}$ is given by

$$P_{T-min}^{(i,j)} = \frac{P_{R-th} \cdot P_{T-max}}{P_R^{(i,j)}}. \tag{2}$$

Hence, all parameters maintained in LCT have been introduced and described, which will be utilized for controlling the power and deciding the forwarding path.

3.2 Power Control

Power efficiency should be taken into full account, which enables our proposed scheme to meet the requirement of energy conservation in the construction of smart city. In PCSR, power control mechanism targets at effectively reducing the transmitted power of both control packets and datagrams. Here we make a simple assumption that each wireless node in MANET is able to dynamically adjust the transmitted power according to our scheme.

(A) Power control in RREQ broadcasting

Similarly as AODV protocol, PCSR also establish the route via broadcasting RREQ and receiving route reply (RREP). Differently, in order to reasonably control the optimal set of the candidate next-hop nodes based on link stability, RREQ in PCSR can be transmitted at a properly lower power instead of always the maximum power, which should satisfy the following two rules:

Rule 1: If one node has adequate number of intending neighbors, then its neighbor set can be controlled by broadcasting RREQs at a reduced power.

Rule 2: If the number of intending neighbors is less than a threshold value, RREQ will be transmitted at the maximum power. This rule represents that such node will not find sufficient number of intending neighbors if we still restrict the transmitted power of the source of RREQ.

Based on the rules above, and considering the structure of LCT which records potential next-hop nodes, the transmitted power broadcasting RREQ of node j, denoted by $P_{T\text{-}RREQ}^{(j)}$, is then obtained as

$$P_{T-RREQ}^{(j)} = \begin{cases} \max\limits_{k \in N_I^{(j)}} P_{T-min}^{(k,j)} & \text{if } \left|N_I^{(j)}\right| > m\left|N^{(j)}\right| \\ P_{T-max} & \text{if } \left|N_I^{(j)}\right| \le m\left|N^{(j)}\right|, \end{cases} \tag{3}$$

where $N^{(j)}$, $N_I^{(j)}$ represent the set of node j's neighbors and intending neighbors in LCT respectively, and $|\cdot|$ indicates the total number of elements in the set. Moreover, m is a coefficient with value $0 \le m \le 1$. If $m = 1$, node adopts the maximum transmitted power to broadcast RREQ all time. And if $m = 0$, node will certainly reduce the transmitted power as long as it has at least one intending neighbor. When $0 < m < 1$, RREQ is then broadcast at a reduced power only if the number of intending neighbors is greater than the threshold $m|N^{(j)}|$. Obviously, the smaller value of m we set, the higher the probability that the transmitted power is reduced and the smaller of the area that RREQ covers.

(B) Power control in data transmission

The results of [11] showed that the optimal data transmission power from sender i to receiver j, defined as $P_{T\text{-}data}^{(i,j)}$, is given as

$$P_{T-data}^{(i,j)} = \alpha^{(i,j)} \cdot P_{T-min}^{(i,j)} \tag{4}$$

where $\alpha^{(i,j)}$ is an amplified coefficient for transmission on link (i, j) satisfying

$$\alpha_{max}^{(j)} = \max_{\forall k \in N^{(j)}} \alpha^{(k,j)} = P_{T-max} \Big/ P_{T-RREQ}^{(j)}$$
$$s.t. \qquad 1 \le \alpha^{(i,j)} \le \alpha_{max}^{(j)}.$$

However, $\alpha^{(i,j)}$ in [11] only considers sender's residual energy. In fact for MANET, channel situation is quite complex due to the existence of interference, noise and collision. Therefore, interference, noise and collision should also be taken into account to decide the optimal data transmission power.

If a sender-receiver pair suffers interference, noise or collision with low probability, it is not necessary to transmit data at too high power level; whereas the sender-receiver pair with poor channel conditions is expected to transmit packets at a high power level. At the same time, nodes with low energy level are not expected to transmit datagrams in order to avoid energy exhausting. Based on such intentions, energy level and channel situation are jointly considered in our power control mechanism for data transmission. When receiver j receives RTS from sender i, j can obtain i's node behavior level $b^{(i)}$ and estimate packet error rate $p_e^{(i,j)}$. In IEEE MAC 802.11, the time period between receiving RTS and data is relatively small [18]. Thus, without loss of reasonability, it is further assumed that the packet error rate remains unchanged in this time period. Having these two local state parameters, receiver j calculates $\alpha^{(i,j)}$ as the following equation:

$$\alpha^{(i,j)} = \begin{cases} \max\left\{ 1, \alpha_{max}^{(j)} \; p_e^{(i,j)} \right\} & \text{if } b^{(i)} = 1 \\ 1 & \text{if } b^{(i)} = 0. \end{cases} \tag{5}$$

Afterwards, $P_{T\text{-}data}^{(i,j)}$ is computed according to Eqs. (4) and (5). Receiver j appends this value to CTS to provide sender i with a referred power. After sender i receiving CTS from j and obtaining this power level, datagrams will be transmitted to j at this power.

3.3 Stable Routing

In MANET, a stable route should consist of high-performance intermediate nodes and robust wireless links. Thus, in route discovery of PCSR, only intending nodes within RREQ's broadcasting range are chosen as intermediate nodes because of their higher node behavior levels. Besides, considering the packet error rate in LCT as a reflection of channel condition, the link cost of (i, j) calculated by intending node j is then given by

$$cost^{(i,j)} = p_e^{(i,j)}. \tag{6}$$

As mentioned above, $P_e^{(i,j)}$ can reflect the interference, noise and collision level of the link. Then the route cost, denoted by $cost^{path}$, is defined as the sum of the link cost along a forwarding path, *i.e.*, $cost^{path} = \sum_{(i,j)\in path} cost^{(i,j)}$. This metric should be appended to the route table and routing packets of RREQ/RREP. Based on the route cost, route discovery process of PCSR is executed as follows, which is similar to AODV.

Route discovery process: If source node has data conversation request and its route table has active route to destination node, data packets will be sent at the power calculated according to Eqs. (4) and (5); Or else, RREQ will be broadcast at the power calculated according to (3) with route cost initialized to 0. Afterwards, if intermediate intending node which receives this RREQ hasn't received the corresponding duplicates before or the route cost in RREQ is smaller than that in its own reverse route table, RREQ will be broadcast at the power estimated based on (3) after updating routing information both in RREQ and reverse route table; Otherwise, RREQ will be discarded. Finally, when destination node receives RREQs from alternate paths, it selects the optimal path whose route cost is the minimum and then RREP is sent to source node along this selected path. When the source receives RREP, data packets are forwarded along this established route at the power computed according to (4) and (5). Hence, the completed routing process of PCSR is implemented. An illustration is given in Fig. 2 to describe the process.

As depicted in Fig. 2, there exist two paths between source and destination and the numerical value below solid line represents the $cost^{(i,j)}$ calculated by receiver of RREQ. Table 2 shows the route costs of the two paths.

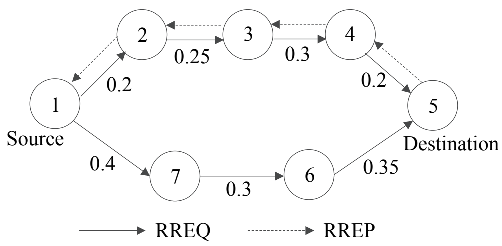


Fig. 2. Route discovery process of PCSR.

Table 2. Comparison of candidate paths.

Path	Routing	Route Cost
Path 1	1→2→3→4→5	0.95
Path 2	1→7→6→5	1.05

It is clearly that PCSR will select Path 1 to forward data even though Path 2 has smaller hop number. Based on our analysis, shortest route might not be the best one, PCSR takes more consideration on power control and stability.

4. SIMULATION RESULTS

Simulation was done using NS 2-2.34 to compare the performance of PCSR with that of PEER and AODV protocol. For MAC layer protocol, IEEE 802.11 is employed. The network layer of PCSR shares information of the physical layer and MAC layer.

4.1 Simulation Environment and Parameters

Our simulated network consists of 50 wireless nodes randomly deployed in a rectangular area of 1500m×900m. The maximum allowed packets number is 64 for each node. The propagation-path-loss is configured as two-ray-ground model. Random way-point is used as node mobility model. There exist at most 20 constant bit rate (CBR) data connections between randomly selected source and destination pairs. The other parameters are shown in Table. 3. In our simulation, all results are achieved by averaging 10 times experimental results.

Table 3. Simulation parameters.

Parameter	value
Simulation time	500s
Maximum speed	0~16m/s
CBR data rate	2 packets/s
Packet size	512bytes
Bandwidth	2Mbps
Radio frequency	2.4GHz
Pause time	0s
Initial energy	1000J
$P_{T\text{-}max}$	0.2818W
$P_{R\text{-}th}$	$10^{-12.4}$W

By varying the maximum moving speed, the performances of the protocols are discussed. For ease of exposition, in what follows, we will use speed to denote the maximum speed. In addition, five runs are carried out to get an average result for each simulation configuration.

4.2 Metrics

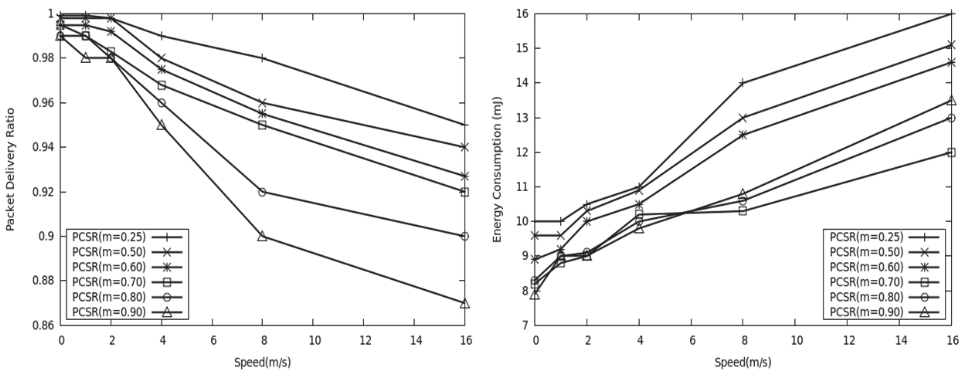
In this paper, network performance is evaluated with respect to network connectivity and power control. In detail, network connectivity is measured by packet delivery ratio (PDR) and average packet delay (APD). Power control is reflected by energy consumption and network lifetime. Hence, in order to evaluate the performance of the proposed scheme, four metrics are employed.

Specifically, packet delivery ratio is defined as the number of data packets received successfully divided by that of the packets expected to be delivered. Average packet delay is the sum of time taken by successful transmissions from sources to destinations divided by the total number of data packets successfully delivered. Energy consumption is defined as the ratio between the total energy consumption in network and the number of data packets received by destinations. Network lifetime is introduced as the point-in-time at which 10% number of nodes die due to battery depletion.

It should be noted that node speed has a non-negligible impact on the performance of the entire network. At the same time, the scalability on mobility is an important indicator to investigate the property of routing protocol. Therefore, our simulation experiment is conducted based on varying node speed.

4.3 Simulation Results

Through careful analysis and simulation, we observe that parameter *m* has significant influence on performance of PCSR. When the value of *m* is 0.25, 0.5, 0.60, RREQs have limited coverage area and the established links are more stable, which is shown in Fig. 3 (a); however from Fig. 3 (b), we can see that when the value of *m* is 0.25, 0.5, 0.60, PCSR wastes much energy due to more hop counts. In contrast, when *m* take values of 0.8 and 0.9, PCSR wastes less energy in low-speed situations which is owing to less hop counts, but it doesn't guarantee connectivity and stability due to relatively longer links. Moreover in high-speed scenarios, even when *m* takes big value such as $m = 0.9$, PCSR still consumes much energy because the probability of data retransmissions caused by link breaking gets high. However, when $m = 0.7$, PCSR can make a good balance between energy saving and connectivity maintenance in our scenario. Thus, unless otherwise stated, we set $m = 0.7$ in following consideration and simulation.

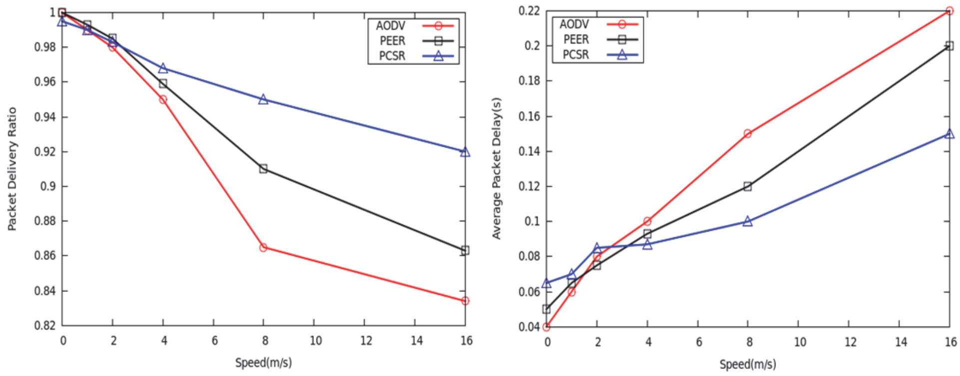


(a) (b)

Fig. 3. Impacts of different values of *m* on (a) packet delivery ratio; (b) energy consumption.

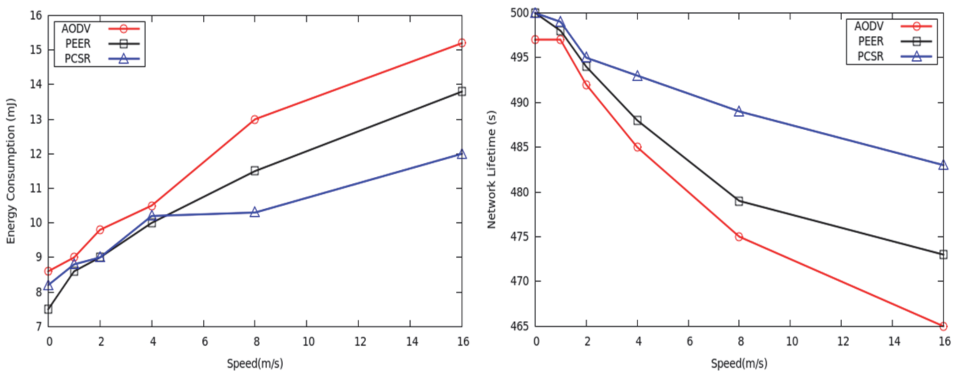
Fig. 4 shows the results of packet delivery ratio and average packet delay changing with varying node speed. As we can see in Fig. 4 (a), all three protocols are faced with PDR dropping and APD rising as nodes move faster. This is because dynamic topology leads to link breaking. It is obvious that PCSR outperforms PEER and AODV with the increasing of the mobility in terms of PDR. The reason is that in low-speed scenario, network topology is relatively stable and link breaking occurs infrequently, their performances are almost the same. However, as nodes move faster, topology changes frequently. In what situation, AODV cannot guarantee PDR due to interference and collision. Even though PEER notices such issue, mobility may invalidate the established paths because of its careless power control scheme. Whereas the data transmission power in PCSR is an appropriate value, which guarantees high delivery. Besides, in PCSR, RREQ's coverage range is small and link distance in the route is short, which ensures strong link stability.

Fig. 4 (b) shows that average packet delay of PCSR increases more slowly with increasing speed. However, this metric of PCSR is a little higher at low-speed (0m/s-2m/s) scenarios. That is because in PCSR, transmitted power of RREQ might be lower than the maximum transmitted power, which certainly results in larger hop counts. However, as nodes move faster (4m/s-16m/s), PCSR is less affected by mobility. From the analysis in Section 3, the next-hop neighbor in PCSR is closer to sender and thereby the link is more stable. Hence, PCSR has lower packet loss rate, resulting in lower packet delay.



(a) (b)

Fig. 4. Results of (a) packet delivery ratio; (b) average packet delay.



(a) (b)

Fig. 5. Results of (a) energy consumption; (b) network lifetime.

Fig. 5 (a) illustrates that PEER consumes remarkably less energy compared with AODV, which is owing to our transmission power control scheme. In addition, PCSR performs relatively better than PEER in high-speed scenario, even though their energy consumption is almost the same in low-speed situation. The reason for such phenomenon is that PEER did not pay attention to the influence of node mobility on network performance. If nodes move apart with high speed, the transmission power calculated by PEER may be not enough any longer, which leads to packets discarded by destination node. By contrast, PCSR makes a balance between energy conservation and connectivity as described in (5), which alleviates the rerouting with higher transmitted power. Besides, different from PEER, PCSR saves more energy since it maintains its LCT only utilizing RTS/CTS mechanism of MAC 802.11 without overhearing data packet.

In terms of network lifetime, PCSR has evident superiority in various mobility scenarios as shown in Fig. 5 (b). Such advantage benefits from our power control scheme. With speed increasing, link breaks frequently, nodes spend more energy to forward data packets all over the whole network and thereby the residual energy depletes quickly. As a result, PEER cannot keep enough lifetime due to nodes exhaustion. On the contrary, in PCSR, intending nodes possessing of higher energy level are activated to transmit packets as far as possible, which extends network lifetime apparently.

5. CONCLUSION

In this paper, a power controlled and stability-based routing (PCSR) protocol is put forward. In PCSR, a novel table LCT is constructed and maintained at each node based on energy, load, interference, and transmitted power. Utilizing the local state information in LCT, a power controlled routing protocol is designed for improving route stability. Employing our data transmission power control scheme, PCSR saves energy, especially in high-mobility scenarios. In addition, due to the accurate route cost metric and power control in RREQ broadcasting, PCSR can guarantee a stable route with reliable packet delivery and decreased delay.

For evaluating the performances, simulation experiment is conducted based on NS-2 simulator. It is indicated from the simulation results that PCSR outperforms AODV and another power control protocol PEER in terms of packet delivery ratio, average packet delay, energy consumption and network lifetime, which confirms our analysis.

In addition to improved routing protocols in MANET, there also have been a series of research achievements for wireless network communications recently [19-25] targeting at designing of the optimization algorithms [19, 20] in wireless sensor networks (WSN) and information security [21-25]. The motivation of network study is either to enhance the validity or to improve the reliability. In the future, we will work to combine routing algorithm with the data security and design more reliable solutions for wireless network transmission.

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