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Adaptive and distance-driven power control scheme in mobile ad hoc networks

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Abstract: In order to save the energy and reduce the latency of the end-to-end transmission in mobile ad hoc networks, an adaptive and distance-driven power control (ADPC) scheme is proposed by means of distance research in random geometrics. Through mathematical proof, the optimal number of relay nodes and the optimal location of each node for data transmission can be obtained when a distance is given. In the ADPC, first, the source node computes the optimal number and the sites of the relay nodes between the source and the destination nodes. Then it searches feasible relay nodes around the optimal virtual relay-sites and selects one link with the minimal total transmission energy consumption for data transmission. Simulation results show that the ADPC can reduce both the energy dissipation and the end-to-end latency of the transmission.

Key words: power control; mobile ad hoc networks; energy efficient route; optimal virtual relay-site

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Recently, mobile ad hoc networks (MANETs) have become the emerging wireless networks. The diverse mobile applications in MANETs are conducted with disaster relief efforts[1], battlefields[2], and ad hoc conferences[3], which may excessively consume the limited onboard energy supply of mobile nodes. Due to the lack of a stable energy supply, power is often a precious resource in MANETs. An effective power control scheme can coordinate each node to achieve the minimal total transmission power consumption and the optimal route between a source-destination pair, and it can also improve network capacity[4]. Therefore, trying to prolong the expected operation lifetime of the MANETs has received significant attention.

Traditional power control schemes have been proposed to reduce the interference[5-6] and energy consumption[7-8] in MANETs. Many efforts have been made to explore an adaptive power control scheme, mainly including the centralized[9-10] and distributed methods[11-14]. The centralized power control schemes usually require a central controller, which has the full information of all the rest of the nodes and allocates the power for them. However, the collection and computation of the global network information may cost additional energy from each node. On the other hand, the latency in information updating on the nodes will degrade the performance of power control.

Many existing research efforts focus on the distributed methods. In Ref. [12], a distributed power control algorithm, DTRNG, was presented based on the relative neighborhood graph (RNG) to make each sensor determine its transmission power independently. The DTRNG first finds the minimal transmission power for the communication with each neighbor node. Then the DTRNG algorithm removes the largest edge of each triangle of the RNG to reduce the transmission power and keep the network connected. Furthermore, the DTRNG is developed to be the DTCYC algorithm, which removes the largest edge of each circle rather than each triangle. Obviously, the DTCYC is more efficient in saving energy and extending the lifetime of the network.

Power is a potential bottleneck when only interference is considered for power control in MANETs. An autonomic and distributed joint routing scheme was designed for a dynamic environment in Ref. [13], which can dynamically serve routing and power control for each node to receive the maximal number of packets before the node dies. In this scheme, the joint routing and power control problem in wireless multi-hop networks is formulated as a Markov decision process. According to the state transition probability, a distributed method, which can find the optimal policy, is presented for only a restricted braid topology. A distributed transmit power control algorithm which makes all links have the same rate was proposed in Ref. [14]. In this distributed algorithm, each node gets the knowledge of the average link rates around itself and allocates its transmission power to achieve the average rate. This iterative operation will continue until all the links reach the same rate. Then the end-to-end throughput will be optimal with the decrease in the power consumption of the nodes in multi-hop transmission. An early

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work, the GEAR[15], which is one of the popular routing protocols based on the geographic location, outperforms other greedy algorithms addressing the energy consumption.

The transmission range, which is related to the distance between two communication nodes, is usually the most valuable metric in energy-efficient power control. Considering the randomly distributed nodes in MANETs, many research efforts have attempted to address the distance issue by identifying the distribution of the distance between nodes in wireless networks[16-17]. In Ref. [18], a distance effective routing algorithm was proposed and it made each node maintain location information through flooding and broadcasting by other nodes at the optimal frequency. Ref. [19] evaluated the impact of variable transmission ranges on the network capacity, network connectivity, and energy cost. Motivated by Ref. [19], more efforts have been made to explore the power control method for variable transmission ranges. A more precise model of energy consumption vs. communication distance in wireless networks was achieved by using probabilistic distance distributions[20]. An optimal power control scheme for mobile ad hoc networks, which optimizes the hop count according to the distance between the source and the destination nodes for improving the network capacity is presented in Ref. [21].

Considering that the total length of the path segments is usually much larger than the Euclidean distance between the source-destination pair in the multi-hop routing methods, which results in more total power consumption of the involved mobile nodes, we introduce the best data-relay sites for the transmission. The simulation results demonstrate that the ADPC scheme achieves an optimal performance in terms of total energy consumption and packet end-to-end latency.

1 System Model

1.1 Optimal number of relay nodes

In this study, the nodes in MANETs are supposed to be randomly distributed. Two terms are used to research how to establish a link between the source-destination pair through power control.

Definition 1 (baseline) The virtual line segment from the source to the destination is defined as the baseline.

Intuitively, the length of a path is shorter if the path is closer to the baseline.

Definition 2 (OVS) The ideal positions of the relay nodes on the baseline are defined as the optimal virtual relay-site (OVS). As nodes may be absent on these positions.

Let $E = E_{tx} + E_{rx}$ be the amount of energy dissipation on each node, which is composed of two parts: the receiving cost $E_{rx} = Q(i)E_{elec}$ and the transmission cost $E_{tx} = Q(i) \cdot (E_{elec} + \varepsilon d^{\lambda})$. Here, d is the distance between the source and the destination; λ represents the path-loss exponent ($\lambda \geqslant 2$); and $Q(i)$ represents the amount of data transmitted/received by a node. Considering that there is no relationship between E_{rx} and the communication distance, we exploit the relationship between E_{tx} and the distance to find the optimal transmission distance/power for each node. According to Ref. [22], E_{tx} can be computed as

$$E_{tx} = \begin{cases} Q(i)(E_{elec} + \varepsilon_{Friis} d^2) & d \leqslant d_0 \\ Q(i)(E_{elec} + \varepsilon_{two\text{-}ray} d^4) & d \geqslant d_0 \end{cases} \tag{1}$$

Let the energy consumed per bit in the transceiver electronics be E_{elec} = 50 nJ/bit, the coefficients ε_{Friis} = 10 pJ/(bit · m^2), $\varepsilon_{two\text{-}ray}$ = 0.001 3 pJ/(bit · m^4) and the threshold distance d_0 = 75 m. From Eq. (1), the energy dissipation of a node sharply increases when $d \geqslant d_0$. Therefore, it is sensible to deploy relay nodes for energy saving when the distance of each source-destination pair is larger than d_0.

Aiming at finding out the optimal number of relay nodes, we first study the total energy cost per bit with different numbers of relay nodes, which are uniformly distributed on the baseline. Fig. 1 shows the relationship between the total dissipated energy and the transmission distance, which is less than 150 m. 0 relay represents that there are no relay nodes. 1, 2 and 3 relays are the 1, 2 and 3 relay node cases, respectively. From this figure, the direct communication will cost more energy than 1 relay case, which occurs when the communication distance is around 90 m. Furthermore, we explore the distribution of the optimal relay node number under different transmission distances to minimize the total transmission energy consumption. Fig. 2 shows the optimal relay nodes number when the communication distance varies from 0 to 500 m. It should be noticed that each relay node is uniformly distributed. For the minimal total energy cost, there should be five relay nodes in transmission between the source and the destination when the source-destination distance varies from about 430 to 500 m. Similarly, 4, 3, 2 and 1 relay nodes are optimal for the ranges [345 m, 430 m], [260 m, 345 m], [175 m, 260 m] and

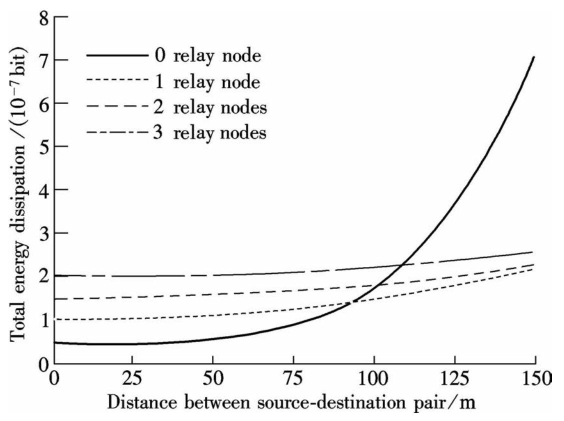

Fig. 1 Total energy dissipation vs. relay nodes number

[90 m, 175 m]. And the direct transmission is the most efficient method when the distance between the source-destination nodes is less than 90 m.

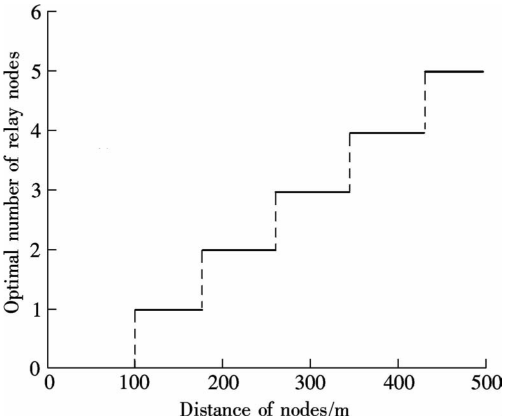

Fig. 2 Optimal number of relay nodes vs. distance

1.2 Optimal sites of relay nodes

From Eq. (1), when the communication distance is close to d_0, the difference of the energy consumption in the two equations is not significant. So we do not strictly distinguish the results of the two equations when the distance is close to d_0.

In the multi-hop transmission scenario with 1 relay node, the relay node is assumed to be distributed on the baseline between the source-destination pair. Let the Euclidean distance between the source and the relay be d_1, and the Euclidean distance between the relay and the destination be d_2. Therefore, the Euclidean distance between the source and the destination is $d = d_1 + d_2$, as shown in Fig. 3.

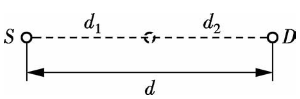

Fig. 3 Transmission with one relay node

Theorem 1 (best site for 1 relay) If one relay node is optimal in the transmission, the minimal energy dissipation can be achieved when the relay node is on the middle point of the baseline.

Proof For convenience, we assume that $d_1 \geqslant d_2$, and three distance cases should be considered. Let E_1^{total}, E_2^{total} and E_3^{total} be the energy dissipation of the transmission in each case, respectively.

1) If $d_1 = d_2 = \frac{d}{2}$, which is less than d_0 or close to d_0, $E_1^{\text{total}} = 2E_{\text{elec}} + \varepsilon_{\text{Friis}} \frac{d^2}{2}$.

2) If $d_0 > d_1 > d_2$, $E_2^{\text{total}} = 2E_{\text{elec}} + \varepsilon_{\text{Friis}}(d_1^2 + d_2^2)$.

3) If $d_1 > d_0 > d_2$, $E_3^{\text{total}} = 2E_{\text{elec}} + \varepsilon_{\text{two-ray}} d_1^4 + \varepsilon_{\text{Friis}} d_2^2$.

With $d_2 = d - d_1$, ΔE_{21} can be expressed as $\Delta E_{21} = E_2^{\text{total}} - E_1^{\text{total}} = \varepsilon_{\text{Friis}}\left(2d_1^2 - 2dd_1 + \frac{d^2}{2}\right)$. Due to $d_1 > \frac{d}{2}$, $\frac{\partial \Delta E_{21}}{\partial d_1} = \varepsilon_{\text{Friis}}(4d_1 - 2d) > 0$, which means that ΔE_{21} is monotonely increasing and $\Delta E_{21} > 0$. So the energy cost of $d_0 > d_1 > d_2$ is greater than that of $d_1 = d_2 = \frac{d}{2}$, namely $E_2^{\text{total}} > E_1^{\text{total}}$. This conclusion can also be derived from the Cauchy-Schwarz inequality.

By Eq. (1), ΔE_{31} can be computed as $\Delta E_{31} = E_3^{\text{total}} - E_1^{\text{total}} = \varepsilon_{\text{Friis}}\left(d_2^2 - \frac{d^2}{2}\right) + \varepsilon_{\text{two-ray}} d_1^4$. With $E_2^{\text{total}} > E_1^{\text{total}}$, we have $d_1^2 + d_2^2 > \frac{d^2}{2}$. Then $\Delta E_{31} > \varepsilon_{\text{two-ray}} d_1^4 - \varepsilon_{\text{Friis}} d_1^2$. Considering the value of $\varepsilon_{\text{Friis}}$ and $\varepsilon_{\text{two-ray}}$, we have $\varepsilon_{\text{two-ray}} d_1^4 > \varepsilon_{\text{Friis}} d_1^2$, namely $E_3^{\text{total}} > E_1^{\text{total}}$.

The proof of $d_1 \leqslant d_2$ can be conducted in the similar way.

Therefore, the minimal total energy dissipation can be achieved when the relay node is uniformly distributed on the baseline.

In the following, the scenario where more than one relay nodes are needed in the transmission is studied. If n relay nodes are needed, we can take Fig. 4 as an example.

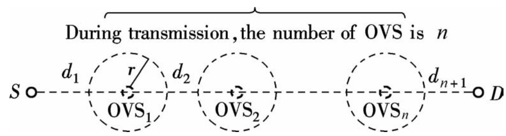

Fig. 4 Transmission with n relay nodes

Theorem 2 (positions of multiple OVSs) If two or more relay nodes are needed, the multi-hop transmission achieves the minimal total energy dissipation when the relay sites are uniformly distributed on the baseline, where any two adjacent relay nodes have the same distance with others.

Proof Assume that the number of the relay nodes is n, and three abstract distance cases are considered. Let E_1^{total}, E_2^{total} and E_3^{total} represent the total energy dissipation of the transmission in each case respectively.

1) If all relay nodes are uniformly distributed, $E_1^{\text{total}} = \frac{d}{n+1} E_{\text{tx}} = \frac{d}{n+1} E_{\text{elec}} + \varepsilon_{\text{Friis}} \left(\frac{d}{n+1}\right)^3$.

2) If all relay nodes are not evenly distributed and the distance between any two adjacent relay nodes is not larger than d_0 or is close to d_0, $E_2^{\text{total}} = \frac{d}{n+1} E_{\text{elec}} + \varepsilon_{\text{Friis}}(d_1^2 + d_2^2 + \cdots + d_n^2 + d_{n+1}^2)$, where $d = d_1 + d_2 + \cdots + d_n + d_{n+1}$.

3) If all relay nodes are not evenly distributed, but the distance between any two adjacent relay nodes shows two states, namely less than d_0 and larger than d_0, $E_3^{\text{total}} = \frac{d}{n+1} E_{\text{elec}} + \varepsilon_{\text{Friis}}(d_1^2 + d_2^2 + \cdots + d_{i-1}^2 + d_i^2) + \varepsilon_{\text{two-ray}}(d_{i+1}^4 + \cdots + d_n^4 + d_{n+1}^4)$, where $d_1, d_2, \cdots, d_i \leqslant d_0$, while $d_{i+1}, \cdots, d_n, d_{n+1} > d_0$, and $d = d_1 + d_2 + \cdots + d_i + d_{i+1} + \cdots + d_n + d_{n+1}$.

$E_2^{\text{total}} - E_1^{\text{total}} = \varepsilon_{\text{Friis}} \left(d_1^2 + d_2^2 + \cdots + d_n^2 + d_{n+1}^2 - \left(\frac{d}{n+1}\right)^3 \right)$. As $d_1 + d_2 + \cdots d_n + d_{n+1} = d$, we can obtain $(n+1)(d_1^2 + d_2^2 + \cdots + d_n^2 + d_{n+1}^2) = (1+1+\cdots+1+1)(d_1^2 + d_2^2 + \cdots + d_n^2 + d_{n+1}^2) \geqslant (d_1 + d_2 + \cdots + d_n + d_{n+1})^2 = \left(\frac{d}{n+1}\right)^2$. So $(d_1^2 + d_2^2 + \cdots + d_n^2 + d_{n+1}^2) \geqslant \left(\frac{d}{n+1}\right)^3$, and the two values are equal only when $d_1 = d_2 = \cdots = d_n = d_{n+1} = \frac{d}{n+1}$. Therefore, $E_2^{\text{total}} > E_1^{\text{total}}$.

Considering each distance larger than d_0, we can always find a corresponding distance that is less than d_0. So the number of the segments longer than d_0 is bigger than that of the segments that are shorter than d_0. From the proof of Theorem 1, we know that the sum energy dissipation of the two distances is greater than the consumption with two equal values of the total distance. In addition, for the left distances that are less than d_0, with the just proved result $E_2^{\text{total}} > E_1^{\text{total}}$, we can come to the conclusion that the sum energy dissipation of these distances is larger than the consumption with the equal values of the total distance. To sum up, $E_3^{\text{total}} > E_1^{\text{total}}$.

Therefore, when the relay nodes are more than one, the transmission energy dissipation reaches the minimum value when the relay nodes are distributed on each equal diversion point.

2 ADPC Scheme

We assume that each node knows its location information, e. g. , via GPS or other localization techniques, and it can broadcast their location information on demand. Before data transmission, the source node will initiate a site calculation process to establish a link between the source and the destination nodes for the optimal total energy dissipation.

Aiming at reducing the total energy consumption, the ADPC scheme adopts the following three steps. First, it initiates a calculation process for the optimal relay nodes number and computes the OVSs on the baseline; then it searches the nearest nodes around OVSs as the optimal relay nodes and uses the active skipping strategy to further shorten the tour; finally it determines the proper locations around the optimal sites to conduct data transmission.

The calculation of the optimal number of relay nodes is shown in Algorithm 1.

Algorithm 1 Find out the optimal number of relay nodes

```
Require: relayNum, d;
Ensure: relayNum;
relayNum←0, d←Dist(src,dest);
if d≤d_0 then
   consumedEnergy←E_elec + ε_Friis d^2;
else
   consumedEnergy←E_elec + ε_two-ray d^4;
end if
for j←1; j≤(d/d_min + 1); j++ do
   if d/(j+1)≤d_0 then
      temp←E_elec + ε_Friis (d/(j+1))^2
   else
      consumedEnergy←E_elec + ε_two-ray (d/(j+1))^4
   end if
   if temp < consumedEnergy then
      consumedEnergy←temp
      relayNum++;
   end if
end for
return relayNum;
```

In this algorithm, relayNum is the number of relay nodes; d is the distance between the source-destination pair, which is obtained from the function Dist(srcNode, destNode); src and dest represent the source node and the destination node, respectively; and $d_{\min}$ is the low limitation of the distance between any two OVSs. The value of $d_{\min}$ is set to be the half of the possible maximum direct transmission distance, namely $d_{\min} = \frac{90}{2}$ m $= 45$ m. After the number of relay nodes n is acquired, the positions of each optimal relay node can be calculated based on the previous OVS conclusion. The time complexity of this algorithm is $O\left(\frac{d}{d_0}\right)$. If there are no nodes at the OVSs, we will search for feasible nodes around the OVSs. The search range is a circle with the OVS as the center and r as the radius, as shown in Fig. 4.

From the distribution in Fig. 2, the maximum distance using direct transmission is around 90 m, so the maximum distance of relay nodes cannot be greater than this value, namely $\frac{d}{n+1} + 2r \leqslant 90$. In addition, the search scopes of the adjacent two relay nodes are not supposed to overlap each other, preventing finding the same feasible relay node. So the search range should also satisfy the condition that $2r < \frac{d}{n+1}$. Therefore, the radius of the search range can be determined by

$$r = \max\left\{\frac{d}{n+1} + 2r \leqslant 90, 2r < \frac{d}{n+1}\right\} \tag{2}$$

where d is the distance of the source-destination pair. The source node searches feasible relay nodes within each search scope. Only when there exist feasible relay nodes in all the search scopes, does the source node transverse each combination of the nodes from each feasible set. It will choose the link with minimum energy consumption for data transmission. The process of selecting the optimal link from feasible nodes is shown in Algorithm 2.

Algorithm 2 Process of selecting the optimal link

```
Require: src, dest;
Ensure: relay[ ];
  relay[0]←src;
  if relayNum = =0 then
    return relay;
else
    for j←1; j < relayNum; j + + do
      optRelay[j].x←[src.x + (dest.x-src.x)]/(j+1);
      optRelay[j].y←[src.y + (dest.y-src.y)]/(j+1);
      searchRange←min{d0 - d/(j+1), d/(2(j+1))};
        relay[j] ← search(optRelay[j], searchRange);
    end for
  end if
  return relay;
```

In this algorithm, relay[ ] is used for storing possible location information of the relay nodes; optRelay[ ] stores the optimal location of relay nodes obtained from calculation; search(optRelay[j], searchRange) means finding the nearest node around the OVS of optRelay[ ] within the search range with a radius of searchRange. The time complexity of this algorithm is O(relayNum).

If there is any search scope with no feasible relay nodes, the source node will abandon this optimal number of relay nodes. In addition it recalculates the sub-optimal number of the relay node, using the above similar algorithm.

As the nodes are randomly distributed in the network, we can obtain the probability of finding relay nodes and establishing a link by calculation. Our method will work well if the probability is close to 1; otherwise, the effect is not so ideal. In this case, we will add the number of ideal relay nodes, and search feasible relay nodes in the same way as the original case until a link is established.

3 Performance Evaluation

In order to evaluate the performance of the proposed ADPC scheme, we compare it with the benchmark, GEAR, mentioned before. The GEAR algorithm handles routing to a specific target region. Here we search a smaller target region to a destination node. When the packets are forwarded, the GEAR algorithm exploits a heuristic, geographical and energy-sensitive method to select neighbors and to serve the packets being relayed.

3.1 Simulation setup

We consider a square field with a size of 500×500 m^2, where 150 nodes are randomly deployed. Assume that the amount of data generated by each source node per round is 1 KB. Considering that the transmission range in the GEAR is a constant value, we conduct two sets of experiments with the transmission ranges of 70 and 100 m, respectively. In the ADPC, the transmission range of the node can be adjusted to achieve the minimum total transmission dissipation. In the experiments, we only consider the exhaust of transmitting data. 1×10^4 random sets of network topologies are generated for each case with one pair of source-destination nodes which are randomly assigned. The energy dissipation is calculated according to Eq. (1).

Primarily, we focus on looking for a method with minimum total transmission dissipation and a fast link for data transmission. So we develop two metrics that approximately capture the related performance of the established link.

3.2 Average energy dissipation

The consumed energy is determined after a link is selected. We are concerned with the average energy consumption of each number of relay nodes to find out whether the ADPC can achieve the minimum total transmission consumption.

In the GEAR, each node transmits with a fixed transmission range. Fig. 5 shows the average dissipated energy of all the nodes with a varying number of relay nodes. GEAR-70 and GEAR-100 represent the average energy dissipation of the GEAR algorithm, in which the node transmission ranges of nodes are 70 and 100 m, respectively, and the ADPC curve represents the average energy cost of our proposed power control scheme. Therefore, the average energy dissipation of the GEAR with the transmission ranges are 70 and 100 m increase proportionally to the number of relay nodes. As expected, the ADPC algorithm outperforms both the GEAR-70 and the GEAR-100 algorithms. Although the ADPC is in an ascending trend with the increase in the number of relay nodes, it achieves 30% less than the GEAR-100 in terms of the average energy dissipation of the relay nodes. Therefore, the ADPC is more suitable when the distance between the source-destination pair is far away.

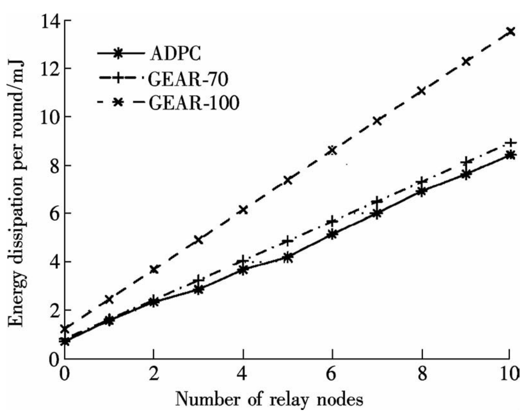

Fig. 5 Comparison for average energy dissipation

3.3 End-to-end transmission latency

The end-to-end latency of transmission is the average time that packets spend in traversing from the source to the destination. Intuitively, the value of the end-to-end latency reflects how efficient a transmission link is. Assume that the time of a one-hop transmission is 1 s. To study the stability of the algorithm, we conduct a series of experiments. Fig. 6 shows the distribution of the packet end-to-end latency with a varying number of experiments. Due to the fact that the average dissipated energy is higher when the transmission range of a node is 100 m in the GEAR, the transmission range of a node is set to be 70 m in the GEAR in this set of experiments. From Fig. 6, we can see that the ADPC always outperforms the GEAR. The ADPC is 5.4% to 7.1% less than GEAR in terms of end-to-end latency. The main reason is that the ADPC prefers to choose the optimal number of relay nodes, which means that the ADPC usually has fewer relay nodes and a smaller end-to-end latency. Furthermore, the end-to-end latency in the ADPC algorithm is more stable than that of the GEAR. Therefore, the ADPC is less sensitive to the number of the nodes than the GEAR in MANET.

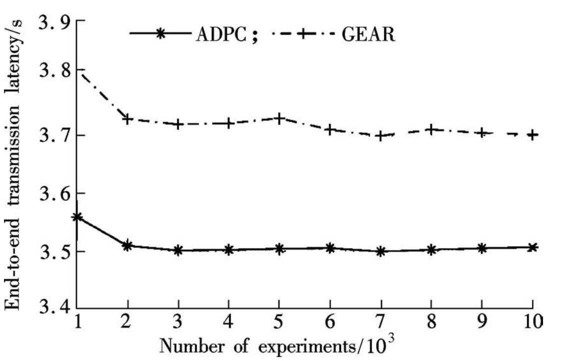

Fig. 6 Comparison for packet end-to-end latency

4 Conclusion

Aiming at finding minimal average energy dissipation and achieving fast transmission rate, we study the problem of relaying packets from the source to the destination. The proposed ADPC scheme exploits the theory of stochastic geometry and selects relay nodes around OVSs in a short time. This strategy attempts to reduce the average transmission energy dissipation. Each node knows its own position and most of the computing work is conducted by the source node. The simulation results show that the ADPC is more adaptive to a real network environment, achieves less average transmission energy consumption than the GEAR, and has smaller end-to-end transmission latency. We use the method of traversing each feasible relay node to find out an optimal link. In future, we plan to study search ranges, which will simplify the process of establishing a link.

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一种移动自组织网络中自适应的距离驱动功率控制方法

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摘要: 为减少 MANETs 中节点的能量消耗,并同时减少传输过程中端到端的时延,引入随机几何中距离研究的方法,构建出一种自适应的距离驱动功率控制方法(简称 ADPC). 经数学证明可知,任意给定一个距离,可以得出传输数据所需最优中继节点个数及最优中继节点位置. 在 ADPC 中,源节点首先根据与目的节点间的距离,计算通信所需的最优中继节点数量及最优中继节点位置;然后在最佳中继节点周围搜索可行的中继节点,并选择一条总能耗最小的链路,进行数据传输. 仿真结果表明,所提 ADPC 方法能够降低传输能耗、减少端到端的传输时延.

关键词: 功率控制;移动自组织网络;节能路由;虚拟最优中继

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