A Novel Mechanism for Flooding Based Route Discovery in Ad Hoc Networks

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***Abstract*—To avoid the problem of wireless broadcast storm, the Random Rebroadcast Delay (RRD) approach was introduced in the process of flooding-based route discovery in DSR and AODV protocols. We identify the "next-hop racing" phenomena due to the RRD approach and propose a Positional Attribute based Next-hop Determination Approach (PANDA) to address this problem. Based on positional attributes such as the relative distance, estimated link lifetime, transmission power consumption, an intermediate node will identify itself as good or bad candidate for the next-hop node and use different rebroadcast delay accordingly. Through simulations we evaluate the performance of PANDA using path optimality, end-to-end delay, and transmission power consumption. Simulation results show that PANDA can: (a) improve path optimality, and end-to-end delay, (b) help find data paths with only 15%~40% energy consumption compared to the RRD approach.**

***Index Terms*— Flooding based route discovery, mobile ad hoc networks, PANDA, positional attributes based routing, power aware routing.**

I. Introduction

A mobile ad hoc network (MANET) consists of a set of wireless devices that are capable of moving around freely and cooperate in relaying packets on behalf of one another. It does not require any fixed infrastructure or centralized administration. MANETs have many potential applications in a variety of fields, like military tactical communication, disaster rescue and recovery, and collaborative group meeting.

Many routing protocols have been proposed for use in MANETs [1]. Most of these proposals can be classified into two main categories: proactive protocols (e.g., DSDV [2]) and reactive (or on-demand) protocols (e.g., TORA [3], DSR [4] and AODV [5]). In general, proactive protocols rely on periodic exchange of routing information and each node maintains knowledge of the entire network topology, while reactive protocols depend on a query-based approach where a mobile node performs route discovery and route maintenance only when needed. Some of the on-demand protocols, like DSR and AODV, use flooding based query-reply mechanisms to search for a new route. In this paper, we restrict our discussion to on-demand protocols with route discovery based on flooding techniques.

Flooding based route discovery works as follows. When a node S has some data to send to node D but has no existing route to the destination, it will initiate a route discovery process by broadcasting a route-request packet. An intermediate node I, upon receiving the route-request packet for the first time, will rebroadcast the route-request again if it does not know a route to the destination node D. Finally, when the route-request packet reaches a node (which may be the destination node D itself) that has a route to node D, a route-reply packet is sent back to the sender node S. To prevent broadcast storm due to synchronization, it was proposed in [11] that a random delay can be introduced before rebroadcasting a message and responding to a broadcast message. In particular, the delay time is uniformly distributed between 0 and 10 milliseconds. We argue that although this Random Rebroadcast Delay (RRD) approach is adequate for solving the problem of broadcast storm, it is not the most suitable one in term of searching for a better route to the destination. A better route may be based on metrics like shortest hops, bandwidth, transmission power, and battery lifetime.

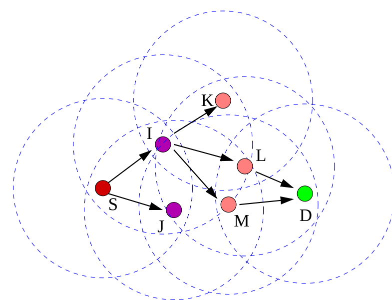

Fig. 1. "Next-hop racing": A scenario using uniformly distributed rebroadcast delay in the flooding based route discovery process

Let us consider a scenario shown in Figure 1. Two intermediate nodes, I and J, receive a route-request packet from node S almost at the same time. Assume that node I is moving much faster than node J such that node I will move out of node S's range sooner than node J does. So we can say node J is a better candidate as the next hop in term of link lifetime. Since the rebroadcast delay is uniformly distributed between 0 and 10 milliseconds, it is possible that node I will rebroadcast the route-request message earlier than node J. In order to reduce routing overhead, each node will only rebroadcast a route-request packet for the same source-destination pair once within a certain period. Thus nodes K, L and M will relay the packet sent from node I and ignore the one sent from node J. In other words, node I, which is a worse next-hop candidate in term of link lifetime, "wins" over node J which is instead a better choice. We term this behavior as "next-hop racing."

Our motivation for this paper is based on this observation. We propose to use positional attributes such as location and velocity information in determining the rebroadcast delay time, while aiming at finding a longer-lived route with a smaller number of hops to the destination. We term our approach as Positional Attribute based Next-hop Determination Approach (PANDA). We will show that the PANDA approach can also be applied to discover routes based on other constraints like minimal transmission power consumption. In some cases like sensor networks, end-to-end delay may not be as important as energy conservation. It is desirable to discover routes that incur less power consumption when transferring data from source to destination. Our proposed approach is shown to perform very well in these scenarios, saving transmission power up to 60%~85% compared to the RRD approach.

The rest of this paper is organized as follows. In Section II, we discuss the basics of PANDA approach. The detailed designs of PANDA algorithms are presented in Section III. In Section IV we discuss the simulation of PANDA, and show its performance improvement by comparing the results of PANDA and the RRD approach. Related works are discussed in Section V. The paper is concluded in Section VI.

II. PANDA BASICS

The basic idea of PANDA is to discriminate neighboring nodes as good or bad candidates for the next hop on the basis of positional attributes that are of interest. These attributes can be relative distance and link lifetime estimation, and transmission power consumption. As mentioned earlier, discrimination is done at the downstream node side. Good candidates will use shorter rebroadcast delay, while bad candidates use longer delay such that the good candidates usually go first. Since good candidates usually go before bad ones, a better route in terms of metrics such as hop count, delay, power consumption, or residual battery, can be found.

We assume that each mobile node is equipped with Global Positioning System (GPS) so that it is aware of its geographical location and velocity information. To let the downstream nodes learn the previous-hop node's location and velocity information, we assume that these information is carried with the route-request message in each hop. Upon receipt of a route-request packet, an intermediate node can compare its own location and velocity with that of the previous-hop node and then determine the rebroadcast delay according to the algorithm it uses, namely, PANDA-LO (Location Only), PANDA-LV (Location & Velocity), or PANDA-TP (Transmission Power).

PANDA algorithms are fully distributed in the sense that there is no intercommunications among the neighboring nodes except that they get the location and velocity information from the previous-hop node. Upon receiving a route-request message from the same previous-hop node, all the neighboring nodes run the same algorithm locally and independently to determine their own rebroadcast delays. Note that this decision is made with local knowledge, i.e., information of current intermediate node and previous hop node. PANDA algorithms are designed in such a manner that, while competing for being chosen as the next-hop node, neighboring nodes cooperate in a way such that good candidates usually go earlier than bad ones. Compared to the RRD approach, this feature naturally leads to the discovery of better end-to-end routes in terms of the desired QoS metrics.

III. PANDA DESIGNS

In this section we will discuss the detailed designs of different PANDA algorithms. We first present PANDA-LO (Location Only) algorithm and PANDA-LV (Location & Velocity) algorithm, both of which are employed to find a route with the smallest number of hops and lowest end-to-end delay. To show PANDA's capability in searching routes based on other constraints, we will also discuss PANDA-TP (Transmission Power) algorithm, which aims at searching a power-conserving route in sensor networks.

A. PANDA-LO

In this approach, when determining the rebroadcast delay, we only consider the distance between two nodes without estimating the link lifetime. The basic idea is that the farther away a neighboring node is from the upstream node, the shorter rebroadcast delay it will use. Thus, a route-request packet usually attempts to make a big jump in each hop of rebroadcasting. Intuitively, a shorter path in term of hop count will be found from source to destination using this approach.

Consider the example shown in Figure 2. When node A, B and C receive a route-request packet from node S, node A, which is farthest away from node S, will identify itself as the best next-hop candidate and use the shortest rebroadcast delay,

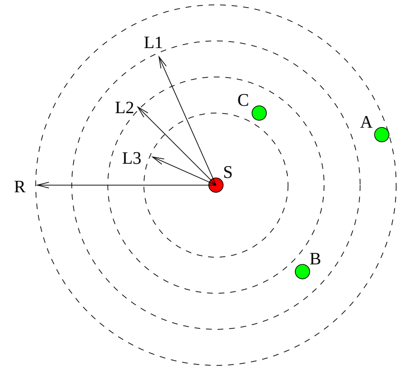

Fig. 2. An example of "PANDA-LO" approach

while node C, which is closest to node S, will identify itself as a bad candidate and will wait until node A and B are done (without being aware of their existence though).

The calculation of link distance is based on the location of the current intermediate node and that of the previous-hop node. Take node A for example. When node A receives the route-request from node S, node A will calculate its distance to the upstream node S as follows:

$$\parallel SA \parallel = \sqrt{(X_s - X_a)^2 + (Y_s - Y_a)^2}, \tag{1}$$

where (X_s, Y_s) and (X_a, Y_a) are S and A's locations, respectively. Having the distance information, node A can use PANDA-LO to determine its rebroadcast delay accordingly.

A possible implementation of "PANDA-LO" approach is shown in Algorithm 1. We choose appropriate threshold values for L_1, L_2, and L_3 such that $L_1 > L_2 > L_3$. This algorithm classifies neighboring nodes into four classes which will determine to use different rebroadcast delays. In Algorithm 1, t_1 is the base time of delay in milliseconds, and the function $uniform(0, t_1)$ will return a random value uniformly distributed between 0 and t_1. As our design goal, a node in a better class of next-hop candidates will use shorter rebroadcast delay. Note that the delay times of different classes do not overlap each other, which is intended to guarantee that good candidates go first. However, due to the randomness incurred by $uniform(0, t_1)$, candidates within a single class may go before each other randomly.

Algorithm 1 Determining Rebroadcast Delay in "PANDA-LO"

at node A
if $\parallel SA \parallel > L_1$
  delay = $t_1 + uniform(0, t_1)$ //this is Class 1
else if $\parallel SA \parallel > L_2$
  delay = $2 * t_1 + uniform(0, t_1)$ //this is Class 2
else if $\parallel SA \parallel > L_3$
  delay = $3 * t_1 + uniform(0, t_1)$ //this is Class 3
else
  delay = $4 * t_1 + uniform(0, t_1)$ //this is Class 4

We want to point out that PANDA-LO may lead to fragile paths because it does not consider the link lifetime in the process of route discovery.

B. PANDA-LV

To overcome the problem of fragile routes in PANDA-LO, PANDA-LV uses both location and velocity information to determine the rebroadcast delay. By estimating the link lifetime and choosing neighboring nodes with stable links as the next

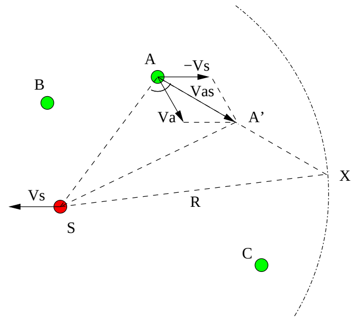

Fig. 3. An example of "PANDA-LV" calculation

hops in route discovery, we expect to find longer-lived as well as relatively shorter path from a source to a destination.

Consider the example shown in Figure 3. An upstream node S broadcasts (or rebroadcasts) a route-request packet, and its downstream nodes are A, B and C. How will the downstream node determine if it is a good candidate or not? Let's consider node A for example. First, node A will calculate its distance to the upstream node S by using equation (1). Node A will also estimate the lifetime of the link between nodes A and S based on the distance and relative velocity. Assume the wireless transmission range is R. In Figure 3, assume V_s and V_a are S and A's velocity respectively. Let $V_{a,s}$ be the relative velocity of node A to node S, θ be the angle $\angle SAA'$ (or $\angle SAX$) , and $\| AX \|$ be the distance that node A can move before it is out of the transmission range of node S(assuming S and A would not change their moving speeds and directions during this period). Based on the cosine theorem, the formulas we use to calculate the estimated link lifetime are as follows:

$$\| V_{a,s} \| = \| V_a - V_s \| = \| AA' \| \tag{2}$$

$$cos(\theta) = \frac{\| SA \|^2 + \| AA' \|^2 - \| SA' \|^2}{2 * \| SA \| * \| AA' \|} \tag{3}$$

$$\| AX \| = \sqrt{\| SX \|^2 - \| SA \|^2 + \| SA \|^2 * cos^2(\theta)} + \| SA \| * cos(\theta) \tag{4}$$

$$LIFETIME_{a,s} = \frac{\| AX \|}{\| V_{a,s} \|} \tag{5}$$

Note that $LIFETIME_{a,s}$ is the estimated lifetime of the link between node A and S. Intuitively, the longer the lifetime of each link along the path, the longer-lived the route is as a whole.

Algorithm 2 Determining Rebroadcast Delay in "PANDA-LV"

at node A
if $\| SA \| > L_1$ && $LIFETIME_{a,s} > T_1$
  delay = $t_1 + uniform(0,\ t_1)$ //this is Class 1
else if $\| SA \| > L_1$ && $LIFETIME_{a,s} > T_2$
  delay = $2 * t_1 + uniform(0,\ t_1)$ //this is Class 2
else if $\| SA \| > L_2$ && $LIFETIME_{a,s} > T_3$
  delay = $3 * t_1 + uniform(0,\ t_1)$ //this is Class 3
else
  delay = $4 * t_1 + uniform(0,\ t_1)$ //this is Class 4

Having the distance and link lifetime information, node A can run Algorithm 2 to determine its qualification and set its rebroadcast delay accordingly. In Algorithm 2, L_1 and L_2 are two threshold values for distance, and T_1, T_2, and T_3 are threshold values for the estimated link lifetime. We choose appropriate values for these thresholds, which satisfy $L_1 > L_2$ and $T_1 > T_2 > T_3$, such that Class 1 is better than Class 2, which is in turn better than Class 3, and so on. As in Algorithm 1, good candidates use shorter rebroadcast delay.

C. PANDA-TP

In some cases such as wireless sensor networks, power conservation is more important than reduction of end-to-end delay. These networks normally have high node density and very low mobility. To achieve the goal of power conservation, it would be desirable to break a big single hop into several small hops such that each small hop needs very small transmission power and the overall power consumption along the path is much smaller than a big single hop, as demonstrated in the following example.

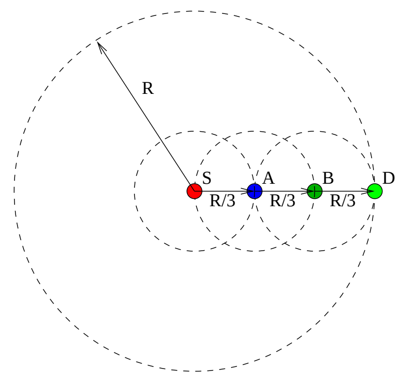

Fig. 4. Transmission power: single hop v.s. multihop

Let us consider the example shown in Figure 4. Node S can send data to node D directly in one single hop of distance R, or in three small hops of distance R/3 via intermediate nodes A and B. We assume each node requires the same minimal receiving power P_{RXmin} for correct packet reception. We also assume the propagation loss L is a simple function of distance R as follows [8]:

$$L = c * R^{\alpha}, \tag{6}$$

where c and α are constants. So, the required transmission power for a single hop over distance R and that for a small hop over distance R/3 are, respectively:

$$P_{TX(S\ to\ D\ directly)} = P_{RXmin} * L = P_{RXmin} * c * R^{\alpha} \tag{7}$$

$$P_{TX(S\ to\ A)} = P_{TX(A\ to\ B)} = P_{TX(B\ to\ D)} = P_{RXmin} * c * (R/3)^{\alpha} \tag{8}$$

We obtain the total transmission power along the path and the ratio of power consumption as:

$$P_{TX(S\ to\ D\ via\ A\ and\ B)} = 3 * P_{RXmin} * c * (R/3)^{\alpha} \tag{9}$$

$$Ratio = \frac{P_{TX(S\ to\ D\ via\ A\ and\ B)}}{P_{TX(S\ to\ D\ directly)}} = \frac{3 * P_{RXmin} * c * (R/3)^{\alpha}}{P_{RXmin*c*R^{\alpha}}} = \frac{1}{3^{(\alpha-1)}} \tag{10}$$

Note that the propagation constant α is often assigned a value between 2 and 4 in practice, which makes the power consumption ratio small. For a given distance, as the number of hops increases, the power consumption ratio decreases. Thus, in the route discovery phase, it is desirable to choose close neighboring nodes as next-hop candidates.

PANDA-TP algorithm is shown in Algorithm 3. Referring to Figure 2, L_1, L_2 and L_3 are distance threshold values that satisfy the relation: $L_3 < L_2 < L_1$. In the PANDA-TP algorithm, neighboring nodes are also classified into four classes. Each hop attempts to make a relatively small jump, and thus the total power consumption of the route is reduced.

Algorithm 3 Determining Rebroadcast Delay in "PANDA-TP"

at node A

if $\| SA \| < L_3$

  delay = $t_1 + uniform(0,\ t_1)$ //this is Class 1

else if $\| SA \| < L_2$

  delay = $2 * t_1 + uniform(0,\ t_1)$ //this is Class 2

else if $\| SA \| < L_1$

  delay = $3 * t_1 + uniform(0,\ t_1)$ //this is Class 3

else

  delay = $4 * t_1 + uniform(0,\ t_1)$ //this is Class 4

IV. SIMULATIONS AND RESULTS

In this section we evaluate the performance of PANDA approaches through simulations. We use the *ns-2* simulator [18] to simulate PANDA-LO and PANDA-LV algorithms. The Monarch Group's mobility extension [19] to the *ns-2* simulator provides detailed implementation of IEEE 802.11 radio and MAC specifications. In order to compare the results of the PANDA approaches and the RRD approach, we utilize the codebase of DSR in the *ns-2* simulator and integrate PANDA-LO and PANDA-LV algorithms into DSR. Although our discussion and simulation of PANDA-LO and PANDA-LV is based on DSR, these PANDA algorithms are applicable to other flooding based routing protocols for MANETs, such as AODV. We have integrated PANDA into AODV and the simulation results are quite similar to that of DSR. To avoid repetition, we show the results based on DSR scheme only. In any case, the proposed approach is independent of the underlying routing algorithm.

We also evaluate the capability of PANDA-TP scheme in term of finding power conserving end-to-end routes in wireless sensor networks. We focus on the power consumption of the routes discovered by PANDA-TP and by the RRD approach. We assume that sensor nodes can dynamically control their transmission power, which is not supported in the *ns-2* simulator. Considering our simulation goal and the ease of implementation, we wrote our own discrete event simulation program, instead of modifying the *ns-2* simulator, to compare the performance of PANDA-TP and the RRD approach.

A. PANDA-LO and PANDA-LV

The simulation area is 1500×300 square meters with 100 nodes uniformly deployed. A node's speed is uniformly distributed in the range of (0, 20) meters per second, and its wireless transmission range is 250 meters. The nodes move according to the Random Waypoint model [11]. There are 30 CBR connections, and the communication pattern is peer-to-peer communications, as is provided by the Monarch Group's mobility extension [19] to *ns-2*. Each simulation runs for 500 seconds. For different mobility degree, we use different *pause-time* of 0, 30, 60, 150, 300, and 500 seconds.

First, let us observe the path optimality ratio shown in Figure 5. Here the path optimality ratio is defined as actual path length over the shortest path length. So the lower the ratio, the better is the path. Both PANDA-LO and PANDA-LV achieve better path optimality than RRD. This is because PANDA algorithms attempt to make a longer jump in each hop of rebroadcast in the process of route discovery, which naturally leads to shorter end-to-end route in term of number of hops. We can also observe that the improvement in path optimality increases as the *pause-time* becomes larger. This phenomena can be explained in this way: with a stationary network topology, once a route is discovered between a pair of source and destination, the route will be used for quite a long time because no route breakage is likely to occur. Since RRD is likely to discover longer routes than PANDA, a more static network topology means that a larger number of packets will have to go through longer routes

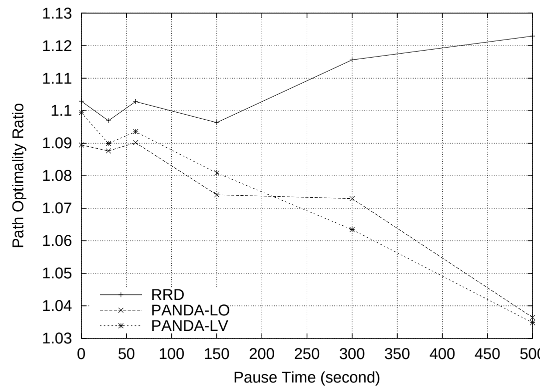

Fig. 5. Comparison of path optimality ratios

in RRD. This is the reason why PANDA will perform even better than RRD in a static ad hoc network.

Now, let us compare the end-to-end delays shown in Figure 6. PANDA-LV has lower end-to-end delay than RRD, while PANDA-LO does not show this improvement. This is due to the fact that PANDA-LO may lead to fragile routes without considering the link lifetime. On the contrary, PANDA-LV approach can discover routes that are shorter in term of hop count, and longer-lived in term of link lifetime. Since the path has smaller number of hops, the packets will face less queuing delay waiting for wireless channel, comparing to that in RRD. Since the path is longer-lived, fewer route breakages will occur and thus data packets will face less buffering delay waiting for new routes. So PANDA-LV can achieve better end-to-end delay than RRD.

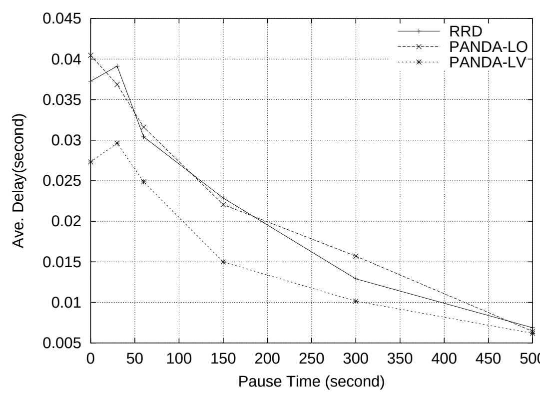

Fig. 6. Comparison of end-to-end delays

B. PANDA-TP

In this simulation we compare the performance of PANDA-TP and the RRD approach. We only consider a static network topology. The simulation area is 1500×300 square meters. For different node density, we use 20, 40, 60, 80, 100 nodes. For each node density, we run multiple simulations with different connection numbers and obtain average results. For both RRD and PANDA-TP approaches, we assume that the wireless nodes can dynamically control their transmission range. In the route discovery phase, however, the nodes will use a fixed transmission range of 250 meters for broadcasting route-request packets. Once the route is discovered, an *en route* node will dynamically change its transmission range based on the link distance to the next-hop node.

We define path energy ratio as the power consumption of the route discovered by PANDA-TP over that of the route found

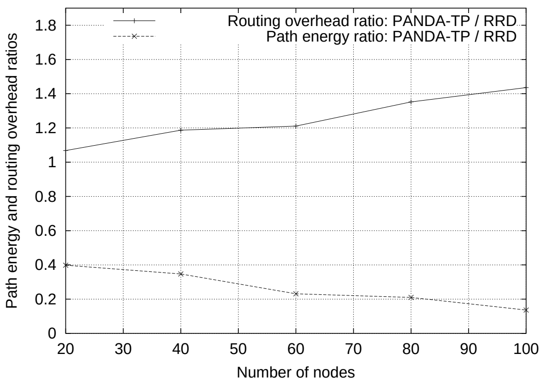

Fig. 7. Energy conserving route discovery

by the RRD approach. The routing overhead ratio is defined as the number of routing packets in PANDA-TP approach over the same parameter in the RRD approach. As shown in Figure 7, the path energy ratio is as low as only 15%~40%, which translates to a huge saving of energy in sensor networks. We observe that as the number of nodes increases, the path energy ratio decreases. This means PANDA-TP can save even more power under high node density. The cost we pay is in term of routing overhead, which is about 10%~45% more than the RRD approach. This extra overhead increases as the network density increases. We argue that this cost is worth because the route discovery process is infrequently executed in these static networks. Once the routes are found, they will be used to transfer data packets over a long period. So by greatly reducing the power consumption of data paths, we can prolong the overall system lifetime, even though we need to pay more in the route discovery phase.

V. Related Works

A variety of techniques have been developed to reduce the flooding overhead in on demand protocols. DSR aggressively utilizes route cache to reduce the routing overhead [4]. LAR [6], DREAM [7], and LAKER [9] all attempt to utilize geographical location information to reduce the flooding overhead. A gossiping-based approach [10] was proposed to reduce the flooding overhead in ad hoc routing protocols, where each node forwards a route-request packet with some probability.

Location-aided rebroadcast delay has been investigated in [12] and [13], in which distance-based and location-based schemes are proposed to address the problem of broadcast storm in a mobile ad hoc network. A comprehensive summary of various broadcast techniques in ad hoc networks can be found in [14]. Our proposal of PANDA is similar to [12], [13] in the sense that we also attempt to utilize location information to determine rebroadcast delay. But we use location information in a different manner. In our PANDA approaches, location information is used to determine if an intermediate is a good or bad candidate for the next-hop node. Additionally, we utilize velocity information to estimate the link lifetime, which can lead to the discovery of longer-lived end-to-end routes.

A number of power aware routing protocols have been proposed for wireless ad hoc networks. In PARO [15], an intermediate node will redirect the traffic of a direct communication between two other nodes via itself by inserting itself into the path whenever it determines that doing so will save overall transmission power consumption. Other protocols, such as [16], take residual battery capacity into consideration and attempt to avoid routes where many intermediate nodes are close to battery exhaustion. Similarly, the authors of [17] argued that usually routing traffic through the minimal power path may drain out the batteries of certain nodes along the path, which in turn may disable further information delivery even if there are many nodes with plenty of energy. PANDA-TP shares the same goal as PARO in finding routes with multiple shorter-distance hops. Unlike PARO, PANDA-TP utilizes location information to determine rebroadcast delay in the route discovery process, which is targeted to choose close neighboring nodes as the next hop and hence reduce the overall transmission power of the path.

VI. Conclusions

The random rebroadcast delay (RRD) approach used in both DSR and AODV may lead to the "next-hop racing" phenomena. In this paper we have proposed a Positional Attribute based Next-hop Determination Approach (PANDA) to address the problem of "next-hop racing". Through simulation studies, we evaluated the performance of PANDA algorithms. The PANDA approach can also be applied in searching routes in terms of other constraints such as transmission power or any quality of service measure. In summary, the PANDA approach can be considered as a generic framework for improving the performance, quality, and energy conservation of routing algorithms in ad hoc networks.

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