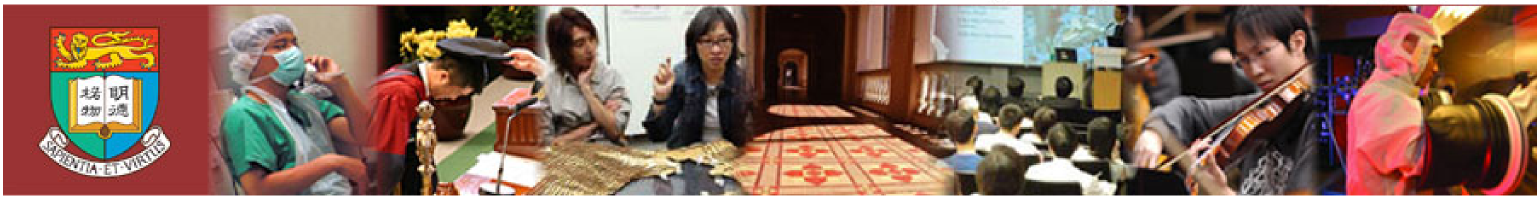

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Effect of Information on Routing Performance in Multi-hop Wireless Networks

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***Abstract*—A key issue impacting wireless network performance is network information. In wireless networks, a significant amount of bandwidth and power resource is consumed to disseminate and maintain routing information. Previous work has presented different methods to broadcast and store such routing information so as to reduce the overhead. However, the amount of information required for a routing algorithm to be effective is not studied theoretically. In this paper, we consider two kinds of routing information, i.e., location information and link state information, and study the quantitative relationship between the available routing information and network performance. It is assumed that each node in the network can only obtain information of its k-hop neighbors, and for each packet, a distance vector based algorithm is employed to minimize the number of hops for the packet to reach its destination with the limited information. We then present a methodology to derive the analytical result on the quantitative relationship between routing performance and the information available for each node. The analysis in this paper can be a valuable tool on designing routing algorithms in wireless networks.**

I. Introduction

Wireless networks have attracted much attention recently. Due to such wireless characteristics as wireless interference, scarce bandwidth resource, and dynamic network conditions, designing an efficient and reliable routing strategy is a challenging task. Many routing algorithms for wireless networks have been proposed [1]. They are mainly based on two different algorithms: link-state algorithm [2] and distance vector algorithm [3]. In link-state algorithms, each node sends the link-state costs of its neighbors to all other nodes in the network. Based on the link-state information of the whole network, the route can be established by applying a shortest-path algorithm. Examples include Global State Routing (GSR) [4], Source-Tree Adaptive Routing (STAR) [5], Hierarchical State Routing (HSR) [6], Optimized Link State Routing (OLSR) [7], Topology Broadcast Reverse Path Forwarding (TBRPF) [8], and so on. In distance vector routing, instead of disseminating the link-state cost information, each node in the network exchanges the distance vector information, i.e. information regarding node positions, distance, and so on, and a greedy forwarding algorithm is used to determine routes. Protocols based on distance vector algorithm include Destination-Sequenced Distance Vector (DSDV) [9], Distance Routing Effect Algorithm for Mobility (DREAM) [10], Ad hoc On-demand Distance Vector (AODV) [11], Location-Aided Routing (LAR) [12], and so on.

Most previous research related to routing has focused on developing routing protocols so that the routing information can be disseminated and maintained with less communication overhead. But how much information is required for effective routing? It is obvious that the routing performance depends not only on the routing algorithm, but also on the quantity of available network information. If every node gets more network information, such as information of the location, the channel state, and the traffic condition, the routing algorithms can be more efficient and more reliable. However, due to the limitations of wireless networks, collecting such information may consume valuable bandwidth resource. So, the objective of our research is to investigate the relationship between routing performance and available network information.

Some researchers have studied the overhead of maintaining routing information from the perspective of information theory [13]–[15]. However, they focus on the issue of the presence of information errors, i.e., they analyze the overhead required to ensure that the information error is within a given threshold. Our work will focus on the quantitative relationship between the routing performance and the available information. Since the link-state based protocols must maintain full topological knowledge at all nodes, this paper only focuses on the distance vector based algorithms. In this paper, we consider two kinds of routing information, namely, the location information and the link state information, and study the quantitative relationship between the available routing information and the achievable network performance. It is assumed that each node in the network can obtain information of its k-hop neighbors, and a greedy forwarding algorithm is employed to minimize the number of hops for a packet to reach its destination with the limited information. We then present a methodology to derive the analytical result on the quantitative relationship between routing performance and the available information.

The rest of the paper is organized as follows. Section II describes the network model. Section III analyzes the relationship between the available network information and the routing performance. The numerical results are presented in Section IV. Section V concludes the paper.

II. Model And Definitions

A. Network Model

We scale space and suppose that N nodes are uniformly located in a region of area 1 m^2. We assume that the nodes are

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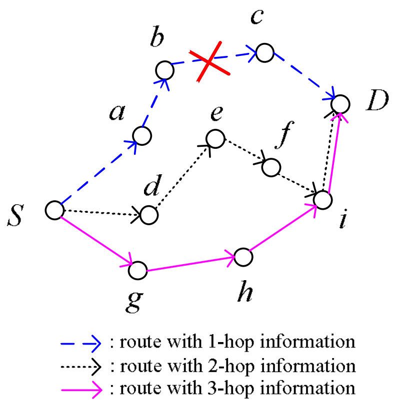


Fig. 1. Illustration of routing strategy

homogeneous, and all transmissions employ the same power and the same communication parameters. The communication range is R_C, i.e., each node can transmit with a maximum radius R_C. n_i denotes the i-th node, and d_{ij} denotes the distance between Node n_i and Node n_j. There is a directed link $l_{ij}(i \neq j)$ from n_i to n_j if $d_{ij} \leq R_C$. Nodes n_i and n_j are said to be each other's k-hop neighbor if there exists a route with no more than k links between n_i and n_j.

Due to wireless interference, traffic congestion, low battery power, and so on, the link may be disconnected although the sender and receiver are within the communication range. Let the random variable LS_{ij} denote the link state of l_{ij}, and

$$LS_{ij} = \begin{cases} 1 & \text{if } l_{ij} \text{ is available} \\ 0 & \text{otherwise} \end{cases}$$

Node n_j is said to be n_i's k-hop *achievable* neighbor, if n_j can be reached within k hops from n_i, i.e., there exists a route from n_i to n_j, which consists of no more than k links, and all the links are available. Note that the set of k-hop *achievable* neighbors is a subset of the set of k-hop neighbors.

In order to facilitate the analysis, we assume that the link states are independent and identically-distributed random variables which follow the Bernoulli distribution, i.e.,

$$\Pr\left(LS_{ij} = 1\right) = \rho,$$

and

$$\Pr\left(LS_{ij} = 0\right) = 1 - \rho.$$

Although this assumption may not hold in general, theoretical analysis in [15] and simulation studies in [16] show that the dependency between two neighboring links is weak and can be negligible.

B. Routing Strategy

Our analysis focuses on the distance vector based protocols, and the greedy forwarding algorithm introduced in [17] is used here as the routing strategy. We assume a quasi-static model with slowly moving nodes, i.e., when the packet is forwarded, the locations of the nodes remain unchanged until the packet arrives the destination. Suppose Node S sends a packet to Node D, and the distance between S and D is

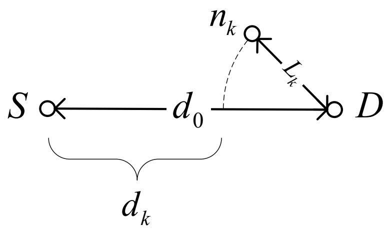


Fig. 2. Illustration of $k-$hop progress

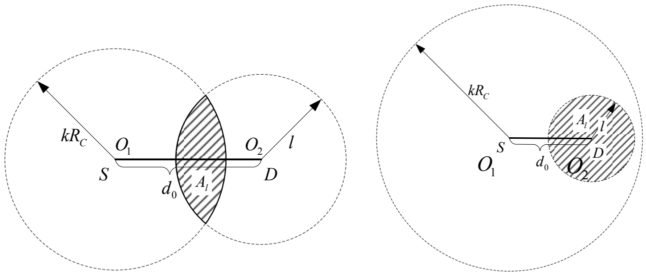
d_{SD}. If the packet is forwarded from S to a relay node, say n_i, through a route which consists of j hops, then the j-hop progress is defined as $d_j = d_{SD} - d_{iD}$, where d_{iD} is the distance between Node D and Node n_i, and the per-hop progress is defined as $d = (d_{SD} - d_{iD})/j$. The goal of the greedy forwarding algorithm is to minimize the number of hops required for a packet to travel from the source node to the destination node, which is equivalent to maximizing the per-hop progress d. In this protocol, each node is equipped with a GPS (Global Positioning System) receiver which provides the node's location information. It is assumed that each node knows its own position, and the position of its packet's destination, and each node $n_i, i = 1, \cdots, N$, knows LS_{ji}, where n_j is an immediate neighbor of n_i. Each packet is marked with the location information of its destination by the source node. If the information collection range is k hops, i.e., each node can obtain the location information and the link state information of the nodes within k hops, the forwarding node can make an optimal choice in choosing the relay nodes within k hops. If the forwarding node cannot find a k-hop achievable neighbor which is closer to the destination than it is, it will keep the packet and the progress will be zero.

It is obvious that with more information, larger per-hop progress can be achieved. As shown in Fig. 1, Node S sends a packet to Node D. There are three possible routes, namely, Route 1 ($S \rightarrow a \rightarrow b \rightarrow c \rightarrow D$), Route 2 ($S \rightarrow d \rightarrow e \rightarrow f \rightarrow i \rightarrow D$), and Route 3 ($S \rightarrow g \rightarrow h \rightarrow i \rightarrow D$). If each node gets only one-hop information, S will select a as its next hop because $d_{aD} < d_{dD} < d_{gD}$, and the packet has to go through Route 1. However, since the link l_{bc} is unavailable, this route will fail. If each node can get two-hop information, S will choose d as its next hop, because Node e, a two-hop neighbor of S via Node d, is the closest to D, and the packet has to go through Route 2, which takes five hops for the packet to transmit from S to D. If each node can get three-hop information, the chosen route will be Route 3, which consists of only four hops. So, a larger information collection range increases the probability of finding a better relay node and contributing larger progress.

III. Analysis

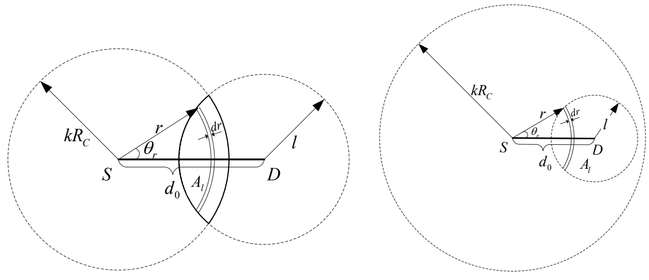
In this section, we will analyze how the routing performance, namely, the per-hop progress, increases with the information collection range.

As shown in Fig. 2, Node S wants to send a packet to Node D, and the distance between S and D is d_0. Node n_k,



(a) $kR_C \le d_0 + l$ (b) $kR_C > d_0 + l$

Fig. 3. Illustration of A_l



(a) $kR_C \le d_0 + l$ (b) $kR_C > d_0 + l$

Fig. 4. Illustration of $q(k,l)$

which is a k-hop achievable neighbor of S, is chosen as a relay node by the greedy forwarding algorithm. Suppose the distance between n_k and D is L_k, ($L_k \in [0, d_0]$). We only consider the situation when k is no larger than the minimum number of hops between S and D. Our objective is to find the relationship between the per-hop progress d and the information collection range k, where d is defined as

$$E(d) = E\left(\frac{d_0 - L_k}{k}\right) = \frac{d_0 - E(L_k)}{k}, \qquad (1)$$

and

$$E(L_k) = \int_0^{d_0} l\ f_{L_k}(l)\ dl = \int_0^{d_0} l\ \ dF_{L_k}(l) \qquad (2)$$

where $f_{L_k}(l)$ is the probability density function of L_k, and $F_{L_k}(l)$ is the probability distribution function of L_k, given by

$$F_{L_k}(l) = \Pr(L_k \le l) = 1 - \Pr(L_k > l).$$

First, let us find $\Pr(L_k > l)$. $L_k \le l$ implies that there is a k-hop achievable neighbor of the source node S within the range l of the destination node D. As shown in Fig. 3, O_1 is the circle with center S and radius kR_C. Since each node can only communicate with the nodes within a range of R_C, all the k-hop neighbors of the source node S are within the circle O_1. O_2 is the circle with center D and radius l. The distance between any node in O_2 and the destination node D is less than l. Therefore, $L_k \le l$ means that at least one node in the shaded area A_l, which is the intersection of O_1 and O_2, is a k-hop achievable neighbor of S, i.e. there exists at least one node satisfying the following two conditions:

1) the node is in A_l,
2) the node is a k-hop achievable neighbor of S.

For a given node n_i, the probability that it satisfies both conditions is denoted by $q_i(k,l)$. Then $1 - q_i(k,l)$ is the probability that n_i is not in A_l or it is not a k-hop achievable neighbor of S. Since the nodes are homogeneous and uniformly distributed, the probability is the same for all the nodes (except the source node and the destination node), namely,

$$q_1(k,l) = q_2(k,l) = \cdots = q(k,l)$$

$L_k > l$ implies that none of the nodes satisfy the two conditions. Since there are totally $N-2$ nodes except the source node and the destination node,

$$\Pr(L_k > l) = (1 - q(k,l))^{N-2}$$

So,

$$F_{L_k}(l) = 1 - (1 - q(k,l))^{N-2} \qquad (3)$$

We shall now determine $q(k,l)$. Suppose the coordinates of n_i and n_j are (x_i, y_i) and (x_j, y_j), respectively. We can use (d_{ij}, θ_{ij}) to describe the relationship between n_i and n_j, where d_{ij} represents the distance between n_i and n_j, and θ_{ij} is equal to $\arctan(y_j - y_i)/(x_j - x_i)$. Applying the uniformity property, the probability density function of (d_{ij}, θ_{ij}) is

$$f_{(d_{ij},\theta_{ij})}(r,\theta) = \frac{2\pi r}{s} \times \frac{1}{2\pi} = r \qquad (4)$$

where s is the size of the region, which is set to 1. For simplicity, we use $f(r,\theta)$ instead of $f_{(d_{ij},\theta_{ij})}(r,\theta)$.

Let h_{ij} denote the minimum number of hops required for a packet to be transmitted from n_i to n_j, and $\alpha_{k|r,\theta}$ denote the conditional probability that node n_j is a k-hop achievable neighbor of n_i given that the relative location of n_j with respect to n_i is (r,θ), i.e.

$$\alpha_{k|r,\theta} = \Pr\{h_{ij} \le k \,|d_{ij} = r, \theta_{ij} = \theta\}$$

Therefore, we have

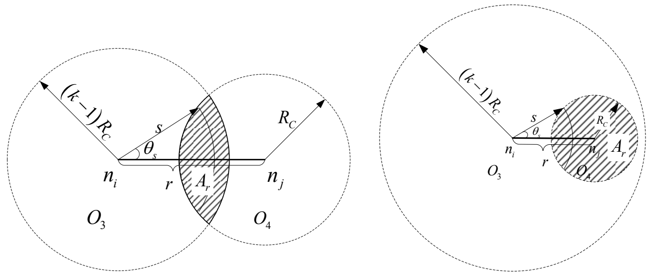
$$q(k,l) = \iint_{A_l} \alpha_{k|r,\theta} f(r,\theta)\, d\theta dr$$

From Equation (4), we can see that with respect to a given node, the distribution of any other nodes is symmetrical in terms of θ. In addition, the communication range is the same for each node, and the communication area of each node is a circle. So, the random variables h_{ij} and θ_{ij} are independent. Then $\alpha_{k|r,\theta}$ can be rewritten as $\alpha_{k|r}$, and $q(k,l)$ can be expressed as (Fig. 4),

1) when $kR_C \le d_0 + l$,

$$\begin{aligned} q(k,l) &= \int_{d_0-l}^{kR_C} \int_{-\theta_r}^{\theta_r} \alpha_{k|r}\, r d\theta dr \\ &= 2\int_{d_0-l}^{kR_C} \alpha_{k|r}\, r\theta_r d\theta dr \end{aligned} \qquad (5)$$

where $\theta_r = \arccos\frac{r^2+d_0^2-l^2}{2rd_0}$



(a) $(k-1)R_C \leq R_C + r$ (b) $(k-1)R_C > R_C + r$

Fig. 5. Illustration of A_r and $\alpha_{k|r}$

2) when $kR_C > d_0 + l$,

$$\begin{aligned} q(k,l) &= \int_{d_0-l}^{d_0+l} \int_{-\theta_r}^{\theta_r} \alpha_{k|r}\, r d\theta dr \\ &= 2\int_{d_0+l}^{kR_C} \alpha_{k|r}\, r\theta_r d\theta dr \end{aligned} \quad (6)$$

where $\theta_r = \arccos \frac{r^2+d_0^2-l^2}{2rd_0}$

Hence,

$$q(k,l) = 2\int_{d_0+l}^{R} \alpha_{k|r}\, r\theta_r d\theta dr \quad (7)$$

where $R = \min\{kR_C, d_0 + l\}$

Now we would like to calculate $\alpha_{k|r}$. Obviously, n_j is a one-hop achievable neighbor of n_i if and only if 1) $d_{ij} \leq R_C$, and 2) $LS_{ij} = 1$. So,

$$\alpha_{1|r} = \begin{cases} \rho & r \leq R_C \\ 0 & r > R_C \end{cases}$$

When $r > R_C$, as shown in Fig. 5, O_3 is the circle with center n_i and radius $(k-1)R_C$, and all the $(k-1)$-hop neighbors of n_i are within the circle O_3. O_4 is the circle with center n_j and radius R_C, and all the one-hop neighbors of n_j are within the circle O_4. Therefore, n_j is a k-hop $(k \geq 2)$ achievable neighbor of n_i if and only if there exists a node, say n_{k-1}, satisfying the following three conditions, 1) it is in the shaded area A_r, 2) it is a $(k-1)$-hop achievable neighbor of n_i, and 3) $LS_{\{k-1\}j} = 1$.

For Node n_i, let w_k represent the event that a given node, say n_j, is its k-hop achievable neighbor. So,

$$\begin{aligned} \alpha_{k|r} &= \Pr\{n_j \text{ is } w_k \,|d_{ij} = r\} \\ &= \Pr\{\text{at least one node satisfies the three conditions}\} \end{aligned} \quad (8)$$

Let $\beta(k,r)$ denote the probability that a node is in A_r and this node is w_{k-1}. Then $1 - \rho\beta(k,r)$ is the probability that a node does not satisfy all the conditions, and we have

$$\alpha_{k|r} = 1 - (1 - \rho\beta(k,r))^{N-2}$$

and $\beta(k,r)$ can be expressed as the function of $\alpha_{k-1|r}$ (using the same way as calculating $q(k,l)$),

$$\beta(k,r) = 2\int_{r-R_C}^{R_2} \alpha_{k-1|s}\, \theta_s s ds$$

where $\theta_s = \arccos \frac{s^2+r^2-R_C^2}{2sr}$, and $R_2 = \min\{(k-1)R_C, r + R_C\}$.

Hence, we can have the recurrence relations of $\alpha_{k|r}$

$$\alpha_{k|r} = 1 - \left(1 - \rho\int_{r-R_C}^{R_2} \alpha_{k-1|s}\, 2\theta_s s ds\right)^{N-2} \quad (9)$$

Since $\alpha_{1|r}$ and the relationship between $\alpha_{k|r}$ and $\alpha_{k-1|r}$ is known, $\alpha_{k|r}$ can be calculated.

So, substituting Equation (9) in Equation (7), we can obtain $q(k,l)$. Then combining Equation (1), Equation (2), and Equation (3), the per-hop progress can be derived,

$$E(d) = \frac{d_0 + \int_0^{d_0} l \ d\left(-2\int_{d_0-l}^{R} \alpha_k(r)\,\theta_r r dr\right)^{N-2}}{k}$$

IV. Numerical Results

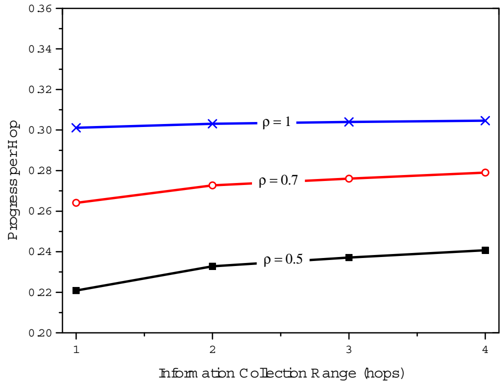
In this section, we give the quantitative relationship between the per-hop progress and the information collection range. Nodes are located in a 1×1 square area according to the uniform distribution. The number of nodes in the network is 36, 54, 63 and 126, respectively. The communication range is set to 0.2 and 0.4, respectively. The information collection range varies from one to four hops. The probability that a given link is available is set to 0.5, 0.7, and 1, respectively.

Fig. 6 shows how the per-hop progress varies with the information collection range for the four network densities. It is obvious that as the information collection range increases, the per-hop progress increases, as it should. The per-hop progress also increases with the density of the network. This is because there are more choices of relay nodes when the network density is higher. However, in all the scenarios, the improvement in per-hop progress saturates very quickly. Compared to one-hop information, two-hop information only gives an improvement of less than 5%. When the available information is increased beyond two hops, the per-hop progress is almost the same. From the results, we can conclude that the routing performance approximates the optimal value when only two-hop information is available.

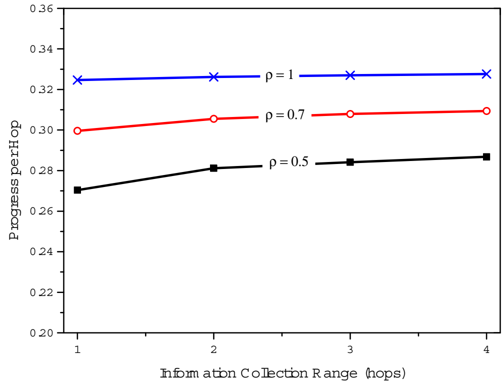
V. Conclusions

In this paper, we study the amount of information required for effective routing. To the best of our knowledge, this is the first such study. It is assumed that k-hop network information is available for each node in the network. We build a model based on the distance vector algorithm, and then present a method for computing the routing performance with the given k-hop network information.

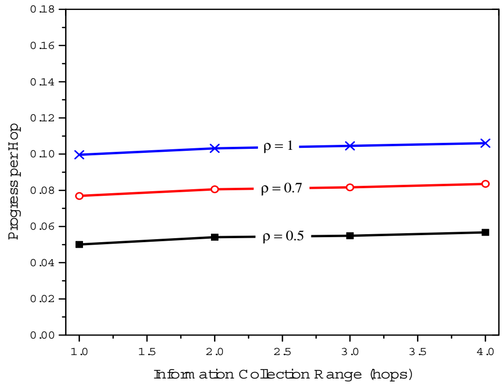
In this work, we only consider the routing information in terms of space (number of hops). However, in wireless networks, routing information varies with both time and space. As part of our future work, we intend to consider the effect of routing information in terms of time, i.e., we shall study how often routing information should be updated, and investigate the relationship between the updating rate and the routing performance.



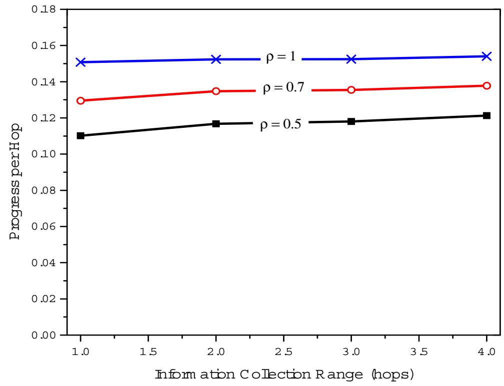
(a) $N = 36, R_C = 0.4$



(b) $N = 54, R_C = 0.4$



(c) $N = 63, R_C = 0.2$



(d) $N = 126, R_C = 0.2$

Fig. 6. Progress per hop

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