Wu J, Yang SH. Small world model-based polylogarithmic routing using mobile nodes. JOURNAL OF COMPUTER SCIENCE AND TECHNOLOGY 23(3): 327–342 May 2008

Small World Model-Based Polylogarithmic Routing Using Mobile Nodes

Jie Wu[1] (吴　杰) and Shu-Hui Yang[2] (杨书慧)

[1] *Department of Computer Science and Engineering, Florida Atlantic University, Boca Raton, FL 33431, U.S.A.*

[2] *Department of Computer Science, Rensselear Polytechnic Institute, Troy, NY 12180, U.S.A.*

E-mail: jie@cse.fau.edu; yangs6@cs.rpi.edu

Revised February 20, 2008.

Abstract The use of mobile nodes to improve network system performance has drawn considerable attention recently. The movement-assisted model considers mobility as a desirable feature, where routing is based on the store-carry-forward paradigm with random or controlled movement of resource rich mobile nodes. The application of such a model has been used in several emerging networks, including mobile ad hoc networks (MANETs), wireless sensor networks (WSNs), and delay tolerant networks (DTNs). It is well known that mobility increases the capacity of MANETs by reducing the number of relays for routing, prolonging the lifespan of WSNs by using mobile nodes in place of bottleneck static sensors, and ensuring network connectivity in DTNs using mobile nodes to connect different parts of a disconnected network. Trajectory planning and the coordination of mobile nodes are two important design issues aiming to optimize or balance several measures, including delay, average number of relays, and moving distance. In this paper, we propose a new controlled mobility model with an expected polylogarithmic number of relays to achieve a good balance among several contradictory goals, including delay, the number of relays, and moving distance. The model is based on the small-world model where each static node has "short" link connections to its nearest neighbors and "long" link connections to other nodes following a certain probability distribution. Short links are regular wireless connections whereas long links are implemented using mobile nodes. Various issues are considered, including trade-offs between delay and average number of relays, selection of the number of mobile nodes, and selection of the number of long links. The effectiveness of the proposed model is evaluated analytically as well as through simulation.

Keywords delay tolerant network (DTN), mobile ad hoc network (MANET), routing, simulation, small-world model, wireless sensor network (WSN)

1 Introduction

In several emerging networks including mobile ad hoc networks (MANETs), wireless sensor networks (WSNs), and the more recent delay tolerant networks (also called disruption tolerant networks) (DTNs)[1], one main issue centers around *whether mobility should be treated as a villain* (*undesirable*) *or a friend* (*desirable*)[2].

The traditional connection-based model (such as TCP/IP) used in MANETs and WSNs is built on the premise that the underlying network is connected and views node mobility as undesirable. However, mobility is treated as a side issue through a simple *recovery scheme*. For example, a route disruption caused by node movement is restored by either route rediscovery or a local fix in a typical reactive approach, assuming either that node movement is infrequent or that a node moves relatively slowly with respect to its transmission range. More recently, mobility has been identified as a serious threat to the traditional model[3]. The threat is mainly caused by the asynchronous sampling of Hello messages and various protocol delays that result in an *inconsistent global state*.

The more recent *movement-assisted* model tries to exploit node mobility for the routing process. The movement-assisted model typically follows a store-carry-forward paradigm, where a mobile node first stores the routing message, carries it while moving randomly or on a controlled path, and then forwards it to either an intermediate node or the destination. This model is motivated by the following potential application areas. 1) In MANETs, the network capacity increases with resource-rich (in terms of processing, memory, and energy) mobile nodes to reduce the average number of relays in a routing process[4]. 2) In WSNs,

---

Regular Paper

The work was supported in part by NSF of USA under Grant Nos. CCR 0329741, CNS 0422762, CNS 0434533, CNS 0531410, and CNS 0626240.

the network lifetime is prolonged with mobile nodes in place of (bottleneck) static sensor nodes[5,6] to support relay and/or simple processing. 3) In DTNs, the network connectivity can be ensured using mobile nodes to connect various parts of a disconnected network[7].

Movement-assisted models can be classified based on random (uncontrolled) movement (epidemic routing[8]) and controlled movement[7]. In controlled movement, various design issues exist, including the number of mobile nodes, trajectory planning, and node communication and synchronization. Although extensive work has been conducted on both models, relatively little work has been done on controlling the amount of relays in a routing process. In the traditional model, the average number of relays grows with the spatial diameter of the network (diameter-hop-count), that is, $O(\sqrt{n})$, where n is the number of nodes, assuming some sort of topology control has been applied to reduce the network density for energy saving and collision reduction. At the other end of the spectrum, most controlled, movement-assisted schemes use a constant number of relays. However, these schemes incur high latency issues in packet forwarding.

In our previous work[9], we propose a new model that avoids two extremes in terms of path length. The hierarchical structure of trajectory for mobile nodes[9] has the potential hot spot problem at rendezvous points (called eyes at different levels of hierarchy), where several carries meet and exchange messages.

Inspired by the small-world model of Watts and Strogatz[10], we consider a random, movement-assisted scheme to achieve a moderate constraint, which is an expected number of relays equal to $(\log m)^2$ in an $m\times m$ square area. The corresponding method is simply called *polylogarithmic store-carry-forward*. The main objective of using such a moderate constraint is to obtain better performance in other metrics, including latency, while maintaining moderate end-to-end throughput of each node, which is $O(\frac{1}{\log m})$, based on the analysis of the connection-based model by Gupta and Kumar[11]. Specifically, in a small-world model, each static node has "short" link connections to its nearest neighbors and "long" link connections to other nodes following a certain probability distribution. Each short link is a regular wireless connection whereas each long link is implemented using a mobile node with a moving trajectory that follows the long link. When long links follow a certain distribution, nodes can construct short paths effectively using local information. Here, a path consists of both short and long links. The trajectory of mobile nodes, however, is not limited to long links. It can be extended to include short links and to share multiple long links. More importantly, both packet route and the trajectory of mobile nodes are adjustable based on different network situations, including the sparse mode where the network of static nodes is disconnected.

Although the small-world model has been used in other fields, such as searching in the unstructured peer-to-peer networks, no systematic study has been done on its applications in MANETs, WSNs, or DTNs[12] using mobile nodes to emulate long links. In this paper, we will address some unique challenges in implementing the small-world model in emerging networks with mobile nodes, discuss some design issues related to parameter selections, and weigh several interesting trade-offs among delay, average number of relays, and moving distance. When modified appropriately, the proposed model can find applications in the following three related areas.

1) In a static MANET using connection-based routing, the throughput per source-to-destination pair decreases as $\frac{1}{\sqrt{n}}$ as the number of nodes per unit area n increases[11]. It is shown that mobility of the nodes increases the capacity of MANETs by reducing the number of relays, and hence, mutual interference of concurrent transmissions. The proposed random mobility-assisted model reduces the number of relays and finds short paths without resorting to global information.

2) In a WSN with mobile sinks, a packet to be reported to a sink can be viewed as a routing process to the sink (as the destination). Resource rich mobile nodes "re-enforce" the energy of static nodes by taking their role: forwarding or carrying the packet. Unlike a WSN with a static sink, where re-enforcement only needs to be done within the neighborhood of the sink (since static nodes in the neighborhood become heavily loaded)[5], our model is more general in the sense that the random trajectory of mobile nodes can re-enforce static nodes across the whole system.

3) In a DTN, networks are assumed to experience frequent, long-duration partitioning and may never have an end-to-end path during a given time frame. In our model, such a DTN can be represented as a network with missing short links to its nearest neighbors, i.e., some neighbors may not exist, which results in a partitioned network. Under this model, each mobile node can alternate the circulation process along the long link and act as a static sensor node by staying in its origin for a certain period to forward/receive a packet to/from one of its neighbors, when available, through a short link. As we will discuss later in trajectory sharing and planning of mobile nodes, in a more general case, one mobile node can emulate all long and short links in a given region.

In this paper, we focus mainly on some technical issues related to the proposed model as follows. 1) We propose a polylogarithmic store-carry-forward model based on the small-world model. 2) We present an indepth analysis on the use of mobile nodes to emulate long links (remote contacts) in the small-world model. 3) We devise both static and dynamic trajectory planning of mobile nodes for improving routing performance and reliability. 4) We extend the model to the sparse mode where the network of static nodes is disconnected. 5) We conduct extensive simulation on a custom simulator to validate the effectiveness of the proposed model.

The following assumptions are used in this paper. 1) Wireless nodes are either static or controlled mobile nodes. Mobile nodes are resource rich, such as a vehicle in a vehicle ad hoc network (VANET), compared with static nodes, and have no memory capacity limit. 2) Two static/dymanic nodes are neighbors if they are within the transmission range, which is set to one unit in this paper. 3) Each node (including the source) knows its location and the location of the destination. This can be achieved through GPS or non-GPS localization methods. In particular, when destination refers to a particular node (rather than a geographical location), some form of location management will be used, such as home region[13]. 4) Mobile nodes move with constant velocity. This model can also be easily extended to incorporate mobile nodes with variable velocities. 5) Data exchange between two nodes, static or dynamic within each other's transmission range, can be done instantly.

The reminder of the paper is organized as follows. Section 2 discusses the treatment of mobility in three related fields: MANETs, WSNs, and DTNs. A brief summary of the small-world model and its applications are also given in the section. Section 3 presents the proposed polylogarithmic store-carry-forward model together with some properties. Four main design issues are discussed in Section 4, together with solutions and applications. Simulation on the proposed model is given in Section 5. The paper concludes in Section 6.

2 Related Work

This section reviews existing work on mobility in three emerging networks and the small-world model. Focuses are on the differences between our model and the existing ones.

2.1 Mobility in MANENTs

With the dominating use of connection-based routing protocols (DSR, AODV, TORA, etc.), most mobility managements in MANETs adopt mobility-tolerant schemes. In a simple recovery scheme, a route disruption caused by node movement is made up by either route discovery or a local fix. Wu and Dai[3] pointed out the inconsistent global state problem, caused in part by node mobility. Several tolerant schemes have been put forward[3,14] as the first attempt to mask the effect of node movement and to construct a consistent global state.

In their seminal work, Grossglauser and Tse[4] show that mobility increases the capacity of MANETs based on the Gupta and Kumar model on network capability[11]. A series of efforts have been made based on the store-carry-forward paradigm, where a mobile node first stores the routing message, carries it for a while moving either randomly or controlled, and then forwards it to an intermediate node or the destination. Epidemic routing uses a random mobility model together with packet replication to speedup the delivery process. Garetto *et al.*[15] relaxed the "homogeneous mixing" assumption on the node mobility process, and analyzed the network capacity in the more realistic case in which nodes are heterogeneous and the motion of a node does not necessarily cover uniformly the entire space. In epidemic routing[8], nodes are all mobile and have infinite buffers. When a node has a packet to send, it propagates the packet to all nodes it meets. Eventually the packet is delivered to the destination in a bounded amount of time. In [16], a graph-based model was developed to capture the evolution of the connectivity properties of the disconnected system, bound of message delivery ratio in epidemic routing was analyzed using the model.

Our work here differs in that a combined random and controlled model is used. We provide a new delay and average number of relays (i.e., network capacity) trade-off based on the small-world model and achieve an expected polylogarithmic number of relays.

2.2 Mobility in WSNs

In WSNs, most models assume sensor nodes are static. More recent work considers a type of resource rich mobile sensor① for sensor coverage and lifetime extensions. The idea of using mobile sensors for sensor coverage is to re-deploy some mobile sensors to under-covered areas[5]. The idea of lifetime extension is to use resource rich mobile sensors to emulate the function of bottleneck or energy-depleting nodes, which can be a

---

①Mobile sensors here can be either a sensor with moving capability by itself or a sensor attached to another moving entity (such as a person or a vehicle).

relay node or a sink node.

When mobile nodes are used to emulate the function of relay nodes[5], bottleneck nodes (such as those around the sink) are "re-enforced" with additional energy through the use of mobile nodes for a certain period. Bottleneck nodes are around the sink when the sink is static. To reduce the burden of static nodes around the sink mobile nodes need only to circle around the sink. A routing process can also be modified to increase the probability of relaying through mobile nodes. When a mobile node is used to emulate a sink node, the sink can stay in multiple positions[17]. The objective of a routing process is then changed to reaching a nearby sink quickly. The energy saving can be substantial when sink mobility and routing are considered jointly[18]. Shah and Shakkottai[19] also studied the mobile fusion center (sink) issue in WSNs. They derived the aggregation data rate when the mobility pattern is known or unknown to the sensor nodes.

Our work is more general in the sense that any position in the network can potentially be a destination (the position of a dynamic sink in WSNs). In addition, our work focuses on reducing the average number of relays as the main means for energy saving for static sensor nodes.

2.3 Mobility in DTNs

Delay tolerant networks[1] (also called disruption tolerant networks[20]) are a class of emerging networks that experience frequent, long-duration partitions and may never have an end-to-end path in any given time period. Various forms of DTNs have been proposed, including interplanetary Internet[21], generic digital communication systems using the postal system[22], and PeopleNet, a wireless virtual social network[23]. Several models[24] have been proposed to abstract DTN in a graph model. However, DTN abstraction is more subtle than using extended graph models, as discussed in [25] on membership dynamics in collective communications and in [2] on connectivity in the traditional connection-based routing.

Routing in DTNs can also be classified as random movement and controlled movement. In [26], the epidemic routing method is extended. The new method uses wearable computers as a packet transport mechanism. Similar to epidemic routing, it also uses random pair-wise exchanges of data during movement of nodes, but with finite buffers. Therefore, a drop strategy is developed by exploiting node mobility statistics. The work in [27–29] also includes algorithms for data delivery in disconnected networks using node mobility. Message ferrying (MF)[7] is one of the most important methods for communication in DTNs using controlled node movement. In MF, some ferries, which are nodes that have completely predictable routes through the geographic areas, are employed for data delivery. Nodes route packets end-to-end using the ferries. Ferries move around according to the known routes. Multiple ferries could be deployed, which leads to several MF extensions with no ferry interaction, ferry relaying, or node relaying. In [30], Liu and Wu investigate scalable deterministic routing in DTNs. They proposed a simplified DTN model and a routing algorithm which routes on contact information compressed by three combined methods. Daly and Haahr[31] proposed the use of social network analysis techniques to forward data in a disconnected DTN, where individuals are often linked by a short chain of acquaintances.

In this paper, the predefined routes are not fixed, but are constructed based on a predefined distribution. Specifically, each node has four neighbors as in a regular 2-D grid. In addition, each node has one or more long link connections to remote nodes based on the distribution. The greedy geometric routing attains a polylogarithmic number of relays. In addition to exploiting the efficient use of mobile nodes along long links, we also systematically study the trade-off between long and short links, i.e., the trade-off between delay and number of relays. Although such trade-offs are captured in several graph models, with global information, our approach focuses on greedy methods based on local information.

2.4 Small-World Models

The small-world model[32] corresponds to a phenomenon in a social network where any two people have "six degrees of separation". More recently, it has been shown in [30] that this phenomenon is pervasive in many natural and artificial complex networks, and is captured by two measurements: small average path length and high clustering coefficient (defined as the average fraction of pairs of neighbors of a node that are also neighbors of each other).

Kleinberg[33] was the first to consider the small-world phenomenon from the algorithmic perspective, and proposed a model of a "navigable" small-world network that can find short paths between any two points in the network using local information only. Specifically, a 2-D grid model in an $m \times m$ space is considered, where each point has four local contacts (links) to its nearest neighbors and q long-range contacts (long links). The existence of a long link from u to v has a probability proportional to $d(u, v)^{-r}$, where $d(u, v)$ is the distance between them and r is a constant. It is shown that when $r = 2$, the expected delivery time is $O((\log m)^2)$ (called polylogarithmic in terms of m). The extension to a navigable hierarchical network is discussed in [34].

The small-world model has been successfully applied to support efficient searching in unstructured peer-to-peer networks. However, the extensions to wireless networks have been limited due to the lack of efficient means to support long links, although the potential advantage of using the small-world model was pointed out back in 2001[35]. The existing applications implement long links using wireline links[36] or at the application layer[37]. The former approach relies on wireline connections. In addition, the long link does not follow the small-world distribution. The latter case shifts the burden to the application layer. In our approach, we adopt a slightly different model for long link distributions. Long links are implemented by resource rich mobile nodes. We explore efficient uses of mobile nodes in implementing long links, including circular implementations of a sequence of long links, free-riders at intermediate nodes on the trajectory of a long link, the selection of the number of long links, trajectory planning of mobile nodes, and various performance trade-offs.

3 Polylogarithmic Store-Carry-Forward

This section presents the proposed polylogarithmic store-carry-forward model based on the small-world model together with its properties. Several design issues in the model are listed.

3.1 Basic Model

We assume a grid-based model[38] in an $m \times m$ space with the horizontal and vertical dimensions. Each 1×1 grid is associated with an address (i, j) where $i, j \in 0, 1, 2, \ldots, m$. All the deployed sensor nodes in a grid form a cluster and a clusterhead is selected to deal with the inter-grid communication. We simply view the cluster as a single node that has the address of its grid. We define the Manhattan distance between two nodes $u = (i, j)$ and $v = (i', j')$ to be the number of horizontal and vertical steps separating them:

$$d(u, v) = |i - i'| + |j - j'|.$$

Although the basic model can be easily converted to other models, the grid-based model is chosen for its simplicity.

Each node $u = (i, j)$ has four local links connecting four neighbors: $(i - 1, j)$, $(i, j - 1)$, $(i + 1, j)$, and $(i, j + 1)$, using a unit uniform wireless transmission range. In addition, u has q ($\geqslant 1$) long links. The probability of a long link to v such that $d(u, v) \leqslant 2m$ is $c[d(u, v)]^{-2}$ and the probability of a long link to v such that $d(u, v) > 2m$ is 0. Constant c should be selected so that

$$\sum_{v} c[d(u, v)]^{-2} = q.$$

To avoid boundary conditions, the $m \times m$ space is situated at the center of a $5m \times 5m$ space and nodes outside $m \times m$ can be used to relay, but not as sources or destinations. Although nodes not in the original $m \times m$ have *contacts* (through long links) outside the $5m \times 5m$ region, they will not be used to assist the routing process. Fig.1(a) shows a sample 6×6 network together with its 30×30 expanded network. Note that all contacts in the 6×6 network are within the 30×30 network. All contacts outside the extended network are not shown. Note that the proposed model is slightly different than the one in [33] in that we allow nodes in the $m \times m$ space to have long link contacts to the outside of the area. We can see that not all of the nodes in the central $m \times m$ and the extended $5m \times 5m$ regions have valid long links (and these links are not shown). This is because their long links are directed to the nodes in the expanded area which are far away from the central network. If we still use them as relays, the detour will be too large. However, if the relays do not generate too much additional moving distance, as will be discussed later in the long link jump condition, we can still use them. Fig.1(b) is a sample in a larger scaled network, where the center 30×30 area of a 150×150 network, is shown.

In the basic model, it is assumed that there are sufficient numbers of static and controlled mobile nodes so that there is at least one static node and one dynamic node in each grid point. At each grid point, one static node is used to act as a *place holder*. This node generates a new packet intended for a destination and it forwards or stores a by-pass packet. The mobile node circulates around the long link (u, v). This node picks up one or more packets at u and delivers them to v. We will discuss various solutions when the density condition fails. These solutions include extending the size of each grid point and the use of one mobile node to emulate functions of multiple static and dynamic nodes at several grid points.

The routing algorithm, inspired by the one in [33], follows a greedy approach where at each step, the current place holder u chooses a contact, through a short or long link, that is as close to the destination t as possible. The short link is through regular wireless communication while the long link is through a mobile node moving between $u = (i, j)$ and $v = (i', j')$. Typically, an X-Y routing in a 2-D mesh can be used, where the mobile node circulates along the circular trajectory $(i, j) \rightarrow (i', j) \rightarrow (i', j') \rightarrow (i, j') \rightarrow (i, j)$.

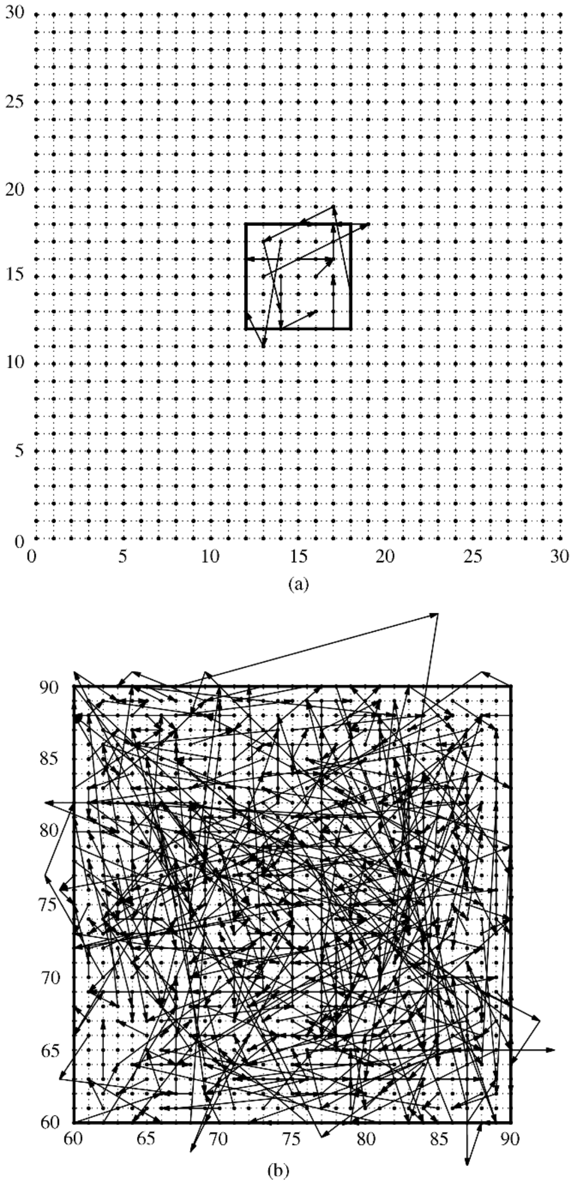


Fig.1. Sample small-world networks. (a) Center area 6 × 6 of a 30 × 30 network. (b) Center area 30 × 30 of a 150 × 150 network.

More specifically, the algorithm operates in phases. It is in phase i if the current node u satisfies $2^i < d(u, t) \leqslant 2^{i+1}$. At node u in phase i, a long link (u, v) is used if $d(v, t) \leqslant 2^i$. This condition is simply called the *long link jump condition* (Fig.2). Kleinberg[33] showed that in phase i, the expected time before the current place holder has a long link contact within Manhattan distance 2^i of t is bounded proportionally to $\log m$. Since there are $\lceil \log 2m \rceil$ phases, from phase 0 to phase $\lceil \log 2m \rceil - 1$, a bound on the number of links is proportional to $(\log m)^2$ (called polylogarithmic store-carry-forward) follows.

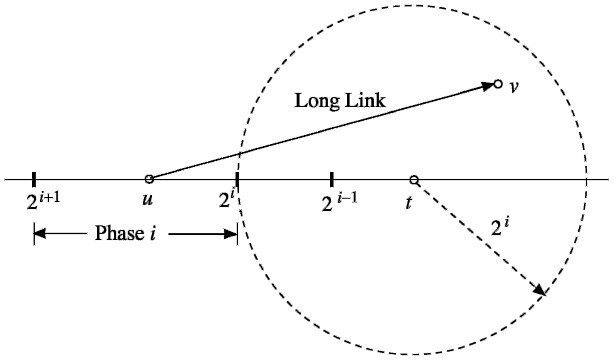


Fig.2. Greedy routing approach in phases and long link jump condition.

3.2 Basic Properties

We first show a slightly sharper bound on the probability of a long link that satisfies the long link jump condition for $q = 1$, assuming destination t is randomly distributed.

Theorem 1. *The probability of a long link* (u, v) *that satisfies the long link jump condition is at least* $\frac{1}{2^6}H(2m)^{-1}$, *where* $H(2m)$ *is the Harmonic series, which is defined as* $H(n) = \sum_{i=1}^{n} \frac{1}{i}$. *In addition,* $\ln(n + 1) \leqslant H(n) \leqslant \ln(n) + 1$. *So* $H(n)$ *is very close to* $\ln(n)$ *for a large* n.

Proof. Suppose node u has a packet intended for destination t. The probability that u chooses v is

$$d(u, v)^{-2} \Big/ \sum_{v \neq u} d(u, v)^{-2},$$

where $\sum_{v \neq u} d(u, v)^{-2} = \sum_{i=1}^{2m} (4i)(i^{-2}) = 4\sum_{i=1}^{2m} (i)^{-1} = 4H(2m)$. Hence, the probability that v is chosen is

$$[4H(2m)d(u, v)^2]^{-1}.$$

Assume S_i is the set of nodes within distance 2^i of t reachable from u. When phase $i = \lceil \log 2m \rceil - 1$,

$$|S_i| \geqslant 1 + \sum_{j=1}^{2^i} j > 2^{2i-1}.$$

Each element in S_i is within distance 2^{i+1} of u since the length of a long link is bounded by $2m$. Thus, the message enters S_i with a probability of at least

$$\frac{2^{2i-1}}{4H(2m)2^{2i+2}} = \frac{1}{2^6}H(2m)^{-1}.$$

When $i < \lceil \log 2m \rceil - 1$, $|S_i| = 1 + 4\sum_{j=1}^{2^i} j = 2(2^i)^2 + 2(2^i) + 1 > 2^{2i+1}$. Here, each element in S_i is within distance $2^{i+1} + 2^i < 2^{i+2}$. Thus the message enters S_i with a probability of at least

$$\frac{2^{2i+1}}{4H(2m)2^{2i+4}} = \frac{1}{2^5}H(2m)^{-1}.$$

Hence, the probability of a long link (u, v) that satisfies the long link jump condition is at least $\frac{1}{2^6}H(2m)^{-1}$. □

Note that when compared with the result in [33], since this result has the same asymptotic result, all other results in [33] stay. For example, the average number of short links at each phase is the reverse of the long link probability, i.e., $O(H(2m))$ which is $O(\ln m)$, and hence, $O(\log m)$. Since there are $\lceil \log 2m \rceil$ phases, the expected total moving distance through short links is $O((\log m)^2)$. The following result shows the worst case moving distance for both short and long links.

Theorem 2. *The total moving distance between source s and destination t through short links is bounded by $d(s, t)$ and the total moving distance through long links is bounded by $5d(s, t)$.*

Proof. Suppose s is in the k-th phase (with respect to t). There are $k + 1$ phases, $0, 1, 2, \ldots, k$. In phase k, the maximum number of short links is bounded by $d(s, t) - 2^k$. In phase i, with $0 \leqslant i < k$, the maximum number of short link moves is $2^{i+1} - 2^i$. If there is a long link jump at u in phase i, the new contact v is in phase $i - 1$ or less. Once phase 0 completes, the current node is either the destination (through a long link jump) or a node that is a neighbor of the destination, and hence, one more short link is needed. Therefore, the total moving distance through short links is bounded by

$$(d(s, t) - 2^k) + \Big(\sum_{i=0}^{k-1} 2^{i+1} - 2^i\Big) + 1 \leqslant d(s, t).$$

In phase k, the distance of the long link is bounded by $d(s, t) + 2^k$ based on the triangle inequity. In all other phases i, with $0 \leqslant i < k$, the distance of the long link jump is bounded by $2^{i+1} + 2^i$ based on the triangle inequity, since $d(u, t) \leqslant 2^{i+1}$ and $d(v, t) \leqslant 2^i$. Therefore, the total moving distance through long links is bounded by $(d(s, t) + 2^k) + \big(\sum_{i=0}^{k-1} 2^{i+1} + 2^i\big) < d(s, t) + 4(2^k) < 5d(s, t)$. □

3.3 Design Issues

In this paper, we will focus on several unique issues when mobile nodes are used to emulate long links in an emerging network with mobile nodes.

1) Support for free-riders at intermediate nodes of long links.
2) Efficient implementation of mobile nodes through trajectory sharing.
3) The effect of multiple long links per grid point.
4) Delay, average number of relays, and moving distance trade-offs.
5) Trajectory planning of mobile nodes in the sparse mode.

In a network with mobile nodes, any intermediate nodes on the trajectory of a long link (u, v) can attach their packets to the mobile node if v is closer to their intended destination. These intermediate nodes are *free-riders*. Trajectory sharing refers to sharing of multiple long links that form a cycle to reduce waiting delay. The effect of multiple long links includes the average path length in terms of delay, average number of relays, and moving distance. Delay, average number of relays, and moving distance trade-offs deal with trading between long links, which have a relatively long delay (and moving distance) but fewer number of relays, and short links, which have a greater number of relays but a short delay (moving distance).

4 Design Details

This section gives an in-depth discussion on the first four design issues listed in the previous section, together with solutions and possible applications in three emerging networks. In the subsequent discussion, grid point and node will be used interchangeably.

4.1 Free-Riders

In the small-world model, each long link (u, v) is directional, where u is called *home* and v the *destination*. The mobile node circles along (u, v) first to v and (v, u) back to u. Two methods of circulation can be used: 1) *home-based*, where the mobile node stays at node u unless there is a packet intended for v; 2) *movement-based*, where the mobile node keeps on circulating.

There are two types of free-riders (also called data hitchhikers) for a long link (u, v).

1) Node u has a packet for destination t and (u, w) for an intermediate node w meets the long link jump condition. Node w is called a *type I free-rider* for link (u, v) (see Fig.3(a)).

2) Intermediate node w on the trajectory has a packet for destination t and (w, v) meets the long link jump condition. Node w is called a *type II free-rider* for link (u, v) (see Fig.3(b)).

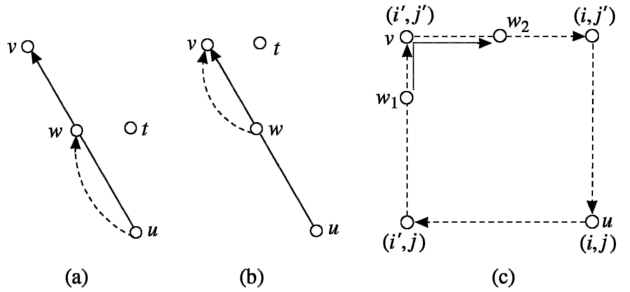


Fig.3. Free-riders. (a) Type I. (b) Type II. (c) General type with one turn between w_1 and w_2.

In the movement-based approach, we assume the mobile node will stay at each intermediate node for a short period of time Δ to pick any free-riders. The following results show the probability of free-riders given the probability p of a long link (u, v).

Theorem 3. *For a given packet at* u*, the probability for the existence of a type I free-rider* (*an intermediate node* w) *is* $O(1)p$.

Theorem 4. *The probability of a type II free-rider for each intermediate node on the trajectory to destination* v *is also* $O(1)p$.

The proofs of these two theorems are shown in the appendix. These results show that the probability of both type I and type II free-riders have the same order of magnitude compared with p.

A more general type of free-rider is from w_1 and w_2 when both of them are on the trajectory of a mobile node on the long link (u, v) (including the return path (v, u)) that satisfies the long link jump condition with respect to a destination t. In this case, we pose an additional constraint on the trajectory from w_1 to w_2 to meet the triangle inequity property as shown in Theorem 2. Another stricter constraint is to ensure a shortest path from w_1 to w_2, i.e., the trajectory on the cycle corresponds to the shortest path from w_1 to w_2. The shortest path condition can be ensured by allowing at most one turn (X dimension to Y dimension or X to Y) in the routing process as shown in Fig.3(c). Both Theorems 3 and 4 hold for the general type of free-rider. When the source node w_1 tries to find its long link (w_1, w_2) in the trajectory of (u, v) (including (v, u)), it should check every node from w_1 to a reachable node in the trajectory with at most one turn. There may be more than one node that satisfies the long link jump condition. In this case, the one that is closest to t is selected as w_2.

4.2 Long and Short Link Trade-Offs

Long and short link trade-offs deal with delay, average number of relays, and moving distance. These trade-offs are important in networks like MANETs and WSNs, since the average number of relays directly relates to network capacity in MANETs and energy consumption of static sensors. Although the expected number of short links is $H(2m)$ before using a long link at each phase, a long link is skipped for short links in the following situations. 1) *To avoid regular moving delay.* The speed of a moving node is significantly lower than that of a normal wireless transmission through a short link. 2) *To avoid waiting delay.* The moving node may not be available when a packet is ready to be forwarded at an intermediate node. 3) *To avoid excessive moving delay.* Excessive moving delay occurs when several long links in a cycle have to be used before reaching the next contact.

The local place holder needs to keep some information to facilitate the above trade-offs. The regular moving delay can be calculated by dividing the length of each long link by the moving speed of mobile nodes. A counter is needed for each link to keep track of the remaining time of the round trip of a mobile node along the long link. The trading point is the threshold above which short links are used to trade long links.

Excessive moving delay can be avoided or reduced without resorting to local links. For example, if the objective is to limit the number of long link relays, then a node u in phase i is allowed to use the long link contact v separated by k long links in a cycle if v is within 2^{i-k} of destination t. To avoid excessive moving distance, a *shortcut* can be used to reach v directly. However, $k - 1$ intermediate nodes are skipped and packets initiated from these nodes cannot be forwarded. This situation can be mended by using multiple mobile nodes with some following the regular trajectory and others following the shortcut if needed.

4.3 Multiple Long Links

When $q > 1$, multiple long links per grid point are available. We assume that long links are independent and follow the same distribution model. Multiple long links provide more choices. However, they do not give a linear speedup in terms of path length reduction. Suppose two long links' jump areas are S_i and S_j. Let $Pr(S_i \cup S_j)$ denote the probability that destination t is in either S_i or S_j, then $Pr(S_i \cup S_j) = Pr(S_i) + Pr(S_j) - Pr(S_i \cap S_j) < Pr(S_i) + Pr(S_j)$. When

k is small, the probability of area overlap is small, which corresponds to a close-to-linear speedup in path reduction. As k increases, the probability of area overlap increases, and linear speedup cannot be maintained although path reduction continues.

Multiple long links can increase the probability of cycle formation among them to reduce delay. However, the cycle formation process is more complex since each node has multiple outgoing links and probably multiple incoming links. A node may be involved in multiple cycles. These multiple cycles can themselves be combined to form large cycles. Based on the delay reduction theorem using cycles, the reduction rate is a constant (two) which is independent of the size of the cycle. Therefore, it is preferable that a short cycle is maintained for the purpose of reliability (multiple cycles to guard against broken cycles) and memory efficiency (shortened route information stored at each node of a cycle).

To find a short cycle, the Dijkstra's shortest path algorithm can be applied. The following approach can be used with local information only: to avoid generating large cycles, each node performs an *expanded ring search* for a cycle using TTL by sending out an "initiation message". The TTL is incremented linearly or exponentially at each round. A node u stops sending out "initiation message" if a cycle is found and u is the initiator. However, node u still participates in the forwarding process of "initiation message" packets. In addition, nodes other than the initiator in the cycle still send out "initiation message". The initiation process at a particular node stops when either a cycle is found or TTL exceeds a predefined threshold.

4.4 Reactive Long Link Initialization

In order to improve the ratio of the usage of long links, we developed the reactive long link initialization approach. We call the basic PSCF a proactive PSCF where the trajectory of each mobile node is determined before the execution of the system. Then, in the reactive PSCF, the long link of each place holder is calculated during the initialization phase, but its direction changes to the direction of the destination of the first generated packet in its corresponding place holder.

In the small-world model, for a fixed node u, the existence of a long link from u to any other fixed node v in the network has a probability proportional to $d(u,v)^{-r}$. Therefore, generally speaking, the probabilities of the long link for node u pointing to each direction are identical, i.e., the direction is randomized. In the reactive PSCF, although the direction of the long link changes, it is still randomized. This is because the destination of the first packet is generated randomly. Therefore, the network is still a small-world model.

In the reactive PSCF, since the direction of the long link is determined based on the direction of the destination of the first generated packet, the probability of the packet being delivered via the long link is increased. The performance of PSCF will increase, too. However, none of the subsequent generated packets take any advantage of the reactive long link initialization. In the long run, we can reset the direction of the long link according to the first packet in the waiting list when the mobile node returns each time. Thus, the overall performance can be improved, especially when the data rate is relatively low.

4.5 Trajectory Sharing

Using mobile nodes for long links causes delay, the expected delay for a long link (u,v) is $\frac{d(u,v)}{v(m)}$, where $v(m)$ is the moving velocity of the mobile node. We assume Δ time period at each intermediate node is included in the calculation of $\frac{(u,v)}{v(m)}$. Trajectory sharing deals with multiple long links forming a cycle with multiple mobile nodes circulating around it. Specifically, suppose $(u_1,u_2),(u_2,u_3),\ldots,(u_k,u_1)$ forms a cycle and $d(u_i,u_{i+1})=l_i$ and $d(u_k,u_1)=l_k$. We have k mobile nodes circulating around the cycle of length $\sum_{i=1}^{k} l_i$.

Theorem 5. *The expected average delay using trajectory sharing reduces the expected delay by half.*

Proof. Again, consider a k-node cycle. When each long link is used individually, the average delay for (u_i,u_{i+1}) is l_i. Therefore, the expected average delay for these k nodes is $\sum_{i=1}^{k}\frac{l_i}{k}$. In the k-node cycle, the average delay using one mobile node is $\sum_{i=1}^{k}\frac{l_i}{2}$. Using k nodes, the expected average delay is $\sum_{i=1}^{k}\frac{l_i}{2k}$. □

Note that the expected average delay is for all nodes in the cycle. Each individual node may have an increased expected delay. For example, suppose three nodes in a cycle have link lengths $l_1=1$, $l_2=5$, and $l_3=6$. The expected average delay is 2, which is larger than the individual delay of l_1.

Cycle structures also offer "look ahead" capability. Let us consider node u_1 in cycle (u_1,u_2), $(u_2,u_3),\ldots,(u_j,u_{j+1}),\ldots,(u_k,u_1)$. Instead of using u_2 as the only possible long link jump, u_1 can use any other node $u_2,\ldots,u_j,\ldots,u_k$ for its long link contact. The link selection criterion still stands; that is, if u_1 is in phase i with respect to destination t, the selected long link contact u_j should be within 2^i of t. An additional constraint can be placed on the trajectory from u_1 to u_j, to meet the triangle inequity property as shown in

Theorem 2, that is,

$$\sum_{i=1}^{j-1} l_i \leqslant d(u,t) + d(u_j,t),$$

or an even stricter condition can be imposed, say, all intermediate nodes $u_2, u_3, \ldots, u_{j-1}$ should be along the shortest path from u_1 to u_j.

To detect cycles when $q = 1$, each node initiates an "initiation" message and sends it to its long link neighbor unless an "initiation" is received. The initiation time is randomly selected at each node for a given period to reduce simultaneous initiations. When node u receives an "initiation" message, it performs one of the following actions. 1) If it has not sent out its initiation, u will forward the initiation to its neighbor (along the long link) after attaching its ID in the route field. 2) If it has sent out its initiation, the current message will be dropped. 3) If the current initiation contains the node ID of v, the complete route is copied at u, the message is changed to "found" with v as the initiator and is then forwarded to its neighbor. When node u receives a "found" message, a copy of the complete route is made unless u is the initiator of the "found" message. In the latter case, the message is dropped.

A variation of the protocol is possible to speedup the process where each node can selectively forward an "initiation" message even when the node itself has sent out one or more "initiation" messages. This approach is useful when the current node has just sent out its "initiation" or has forwarded an "initiation" message with a short route, but the current "initiation" has a long route. However, this variation incurs message overhead.

4.6 Sparse Mode

The proposed model and the corresponding PSCF can be extended to the sparse mode, where some place holders may not have mobile nodes to associate with them. We can set the density of mobile nodes, r, to control the sparse degree. This also means that each place holder has the probability r to have a mobile node that belongs to it. The distribution of mobile nodes is random.

In the sparse mode, the trajectory of mobile nodes is important in networks such as DTNs and VENETs to connect parts in a disconnected network (consisting of static nodes). Mobile node shortages can be remedied through sharing, such as using fewer mobile nodes in a cycle and one mobile node to route around multiple long links from the same node.

In the sparse mode, each place holder still generates packets according to the data rate. If no mobile node is available, the packets stay at the place holder until there are some bypassing mobile nodes. The bypassing mobile nodes can serve as long links for the current place holder if the long link jump condition is met. Or, they can serve as short links to carry the packets to the four neighbors of the current place holder. Therefore, the degree of connectivity of the original partitioned network can be increased using node mobility.

5 Simulation

In this section, we present the results of our simulation of the proposed polylogarithmic store-carry-forward routing algorithm with various tunable parameters.

5.1 Simulation Environment and Settings

All approaches are tested on a custom simulator. We set up the simulation in a $5m \times 5m$ square area. Each 1×1 grid (viewed as a single point/node) is associated with the address (i,j), where $i,j \in 0,1,\ldots,m$. As mentioned in Section 3, only nodes in the center $m \times m$ area work as the source/destination. Nodes outside that area may be used as relays. In this simulation, each grid, which is viewed as a single node, represents a group of nodes in a grid. Since we assume that the group of nodes in each grid can communicate directly to transfer message, we can omit the detailed intra-grid message transferring. Thus we only need to concentrate on the inter-grid message ferrying. This approximation can also help perform a larger scaled simulation. We compare our algorithm, PSCF, with two extremes: 1) X-Y routing (XY) without using mobile nodes, and 2) one-hop approach where the mobile node goes directly to the destination (Direct). Since free-riders are permitted in PSCF, for fair comparison, we also simulate the direct routing with free riders version (Direct-S), where mobile node picks up messages whose destinations are within its trajectory. Thus, even with the free-rider policy, mobile nodes do not change their trajectory, and the numbers of relays of all messages do not change, and the delay of their original messages are not affected.

The following parameters are considered in the simulation. 1) The network size m. We use two values, 50 and 100, to check the scalability of the algorithm. 2) The number of long links q. We set q to 1 in the basic simulation, then we increase it to examine the performance of PSCF with multiple long links. 3) Different data rate, which is represented by data generating probability p of each static node in each round. 4) With and without free-riders. We check the effect of the support of free-riders at intermediate nodes of long links on the overall performance. 5) Different trade points, which is represented by a fixed timer whose value is tunable. 6) With and without reactive long link direction initialization. In the reactive manner, in PSCF, the direction of the long link is initialized based on the destination of the first generated message. 7) With and without trajectory sharing. 8) The density of mobile nodes d. We assume that the velocity of mobile nodes is 1, one time unit, which is also the time unit of the timers. The transmission by short links, including setup time and wireless transmission delay, is assumed to be one time unit or one in thousand time units when the package is quite small. In the sparse mode, the probability that a grid has a mobile node is d.

The performance metrics are:

1) *Relative Moving Distance*, which is represented by the ratio between actual moving distance of data and the physical distance of source and destination.

2) *The Number of Relays.* This measures the number of hops to transmit message from source to destination.

3) *Delay.* This is the total time consumption from message source to destination, including waiting and moving time.

4) *The Delivery Ratio.* In sparse mode, some generated messages may fail to be delivery due to the lack of mobile nodes.

5.2 Simulation Results

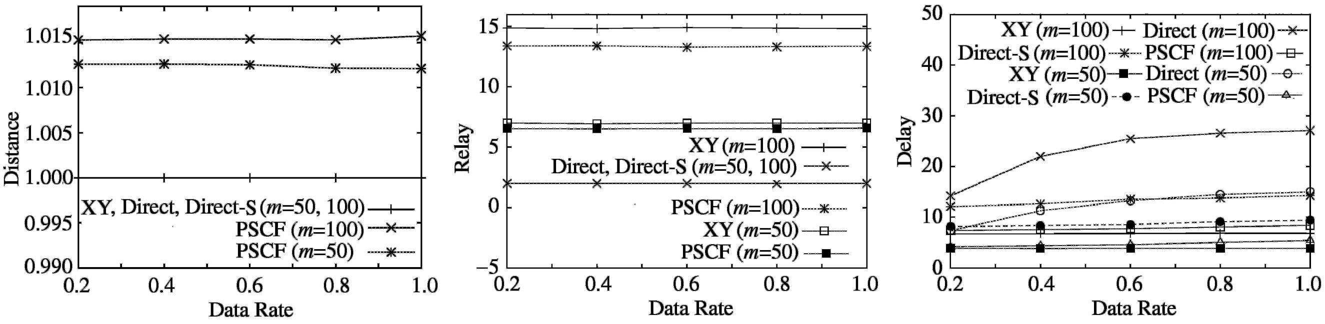
Fig.4 is the comparison of the four algorithms, XY, Direct, Direct-S, and the proposed PSCF with the basic settings (no free-rider, single long link, no reactive mode). In Fig.4(a), PSCF has a greater moving distance than the other three, which all deliver data along the shortest path. However, the detour PSCF makes is moderate. The relative moving distance is around 1.015 with $m = 100$. In Fig.4(b) Direct and Direct-S have the smallest fixed number of relays, which is 2. PSCF has a smaller value than XY. Fig.4(c) shows that Direct has the greatest delay and Direct-S reduces the delay via free-riders, while those of PSCF and XY are quite small. PSCF has a longer delay than XY because of the waiting done when a long link is chosen. Among all these figures, only the delay of PSCF and Direct/Direct-S vary with the data rate.

Fig.5 is the comparison of PSCF with and without free-riders at the intermediate nodes of long links. Since the support for free-riders provides more available long links, it makes the performance (advantage or disadvantage) of PSCF over XY and Direct more significant. In Fig.5(a), we can see that with free-riders, PSCF has a larger moving distance. Fig.5(b) shows that the free-rider policy provides less relays. Fig.5(c) shows that with free-riders, PSCF has a larger delay.

Fig.6 is the result of the test on trade point in PSCF. We set a fixed timer for each long link. Even if the long link jump condition holds, data is passed on by a short link if the timer expires and the mobile node still does not show up. The longer the allowed waiting time, the larger the moving distance as shown in Fig.6(a). Fig.6(b) shows that a longer waiting time makes a fewer number of relays, which makes the long link effectiveness more significant. And Fig.6(c) shows that longer waiting time also makes PSCF have a larger delay.

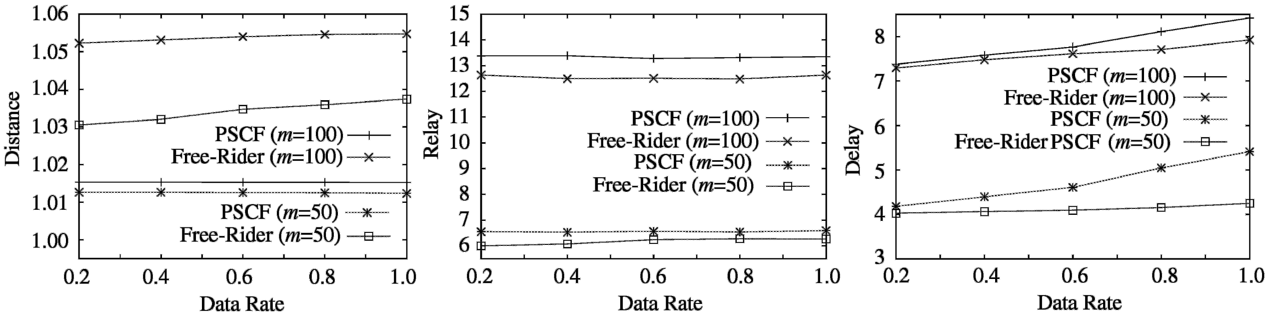
Fig.7 shows the performance of PSCF and Direct with multiple long links for each node. PSCF has larger moving distance with more long links as in Fig.7(a). Fig.7(b) shows that Direct has fixed number of relays, while PSCF has smaller one when the number of long links is small. Fig.7(c) shows that the delay of Direct decreases with more available mobile nodes, while that of PSCF increases.

Fig.8 is the comparison of PSCF with or without the reactive long link direction initialization. There are three curves in these figures. One is the basic PSCF,



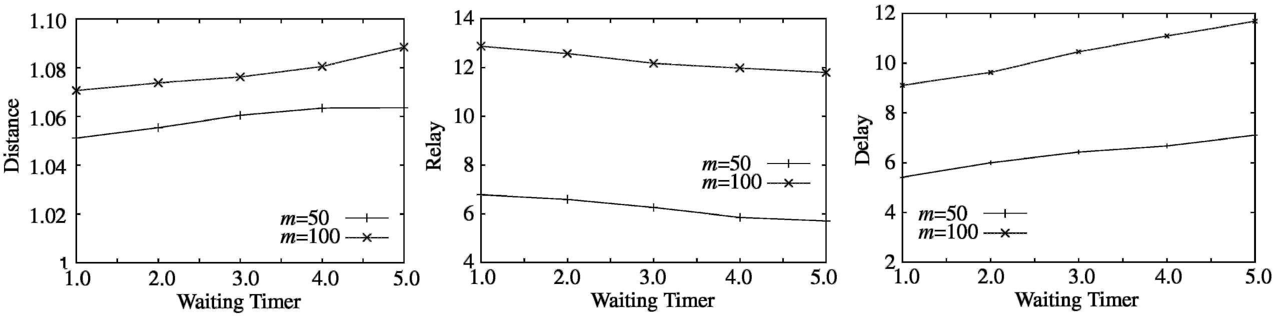
(a) (b) (c)

Fig.4. Comparison of PSCF, XY, Direct/Direct-S. (a) Distance. (b) Relay. (c) Delay.



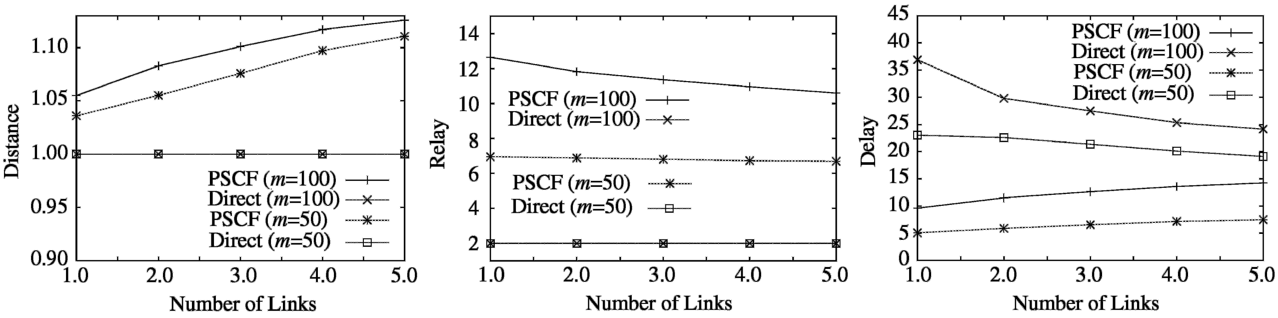
(a) (b) (c)

Fig.5. PSCF with/without free-riders. (a) Distance. (b) Relay. (c) Delay.



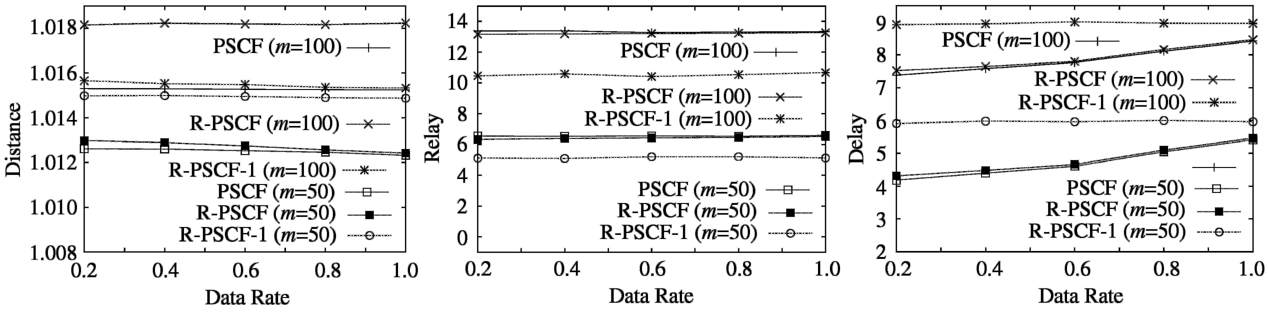
(a) (b) (c)

Fig.6. PSCF with different timers. (a) Distance. (b) Relay. (c) Delay.



(a) (b) (c)

Fig.7. PSCF with multiple long links. (a) Distance. (b) Relay. (c) Delay.



(a) (b) (c)

Fig.8. PSCF with/without reactive long link. (a) Distance. (b) Relay. (c) Delay.

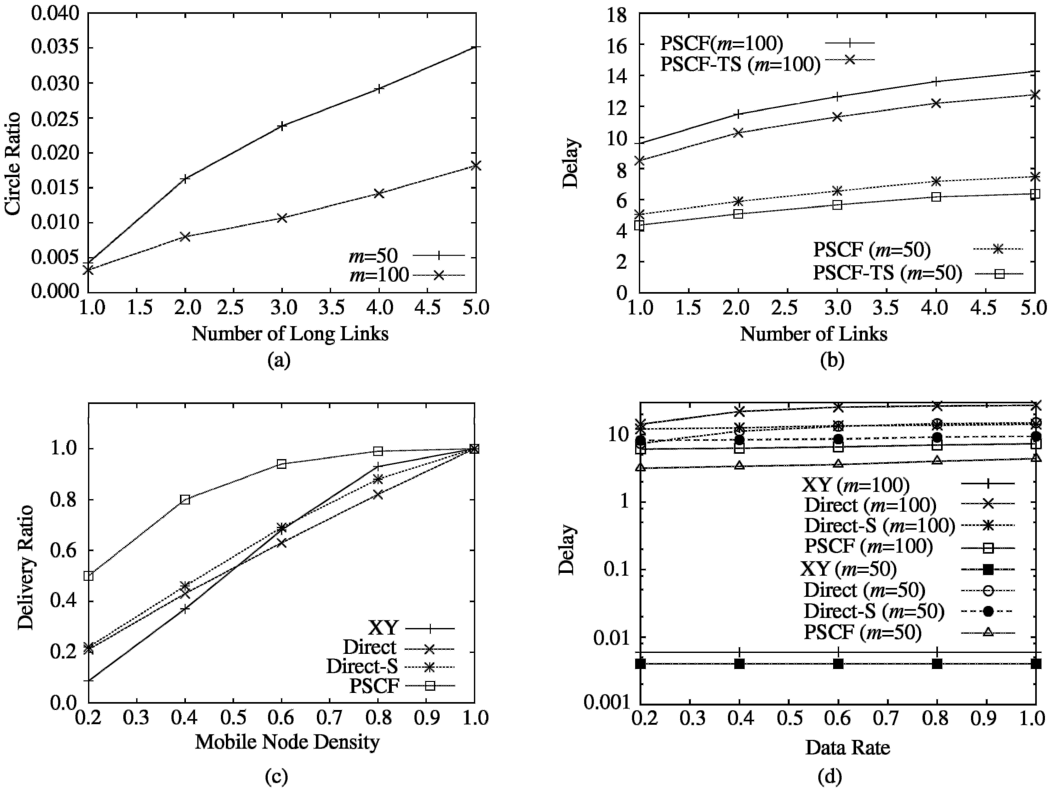


Fig.9. (a) Percentage of circle involved long links. (b) Delay of PSCF with and without trajectory sharing. (c) Delivery ratio in sparse mode. (d) Delay comparison when wireless transmission is of one in a thousand time unit.

the second is the PSCF with reactive long link initialization (R-PSCF), and the third is the performance of the first generated message in each grid in R-PSCF (R-PSCF-1). In Fig.8(a), the moving distance of R-PSCF is larger than that of PSCF; in Fig.8(b), the relay of R-PSCF is smaller than that of PSCF; and in Fig.8(c), the delay of R-PSCF is larger than that of PSCF. However, since R-PSCF changes only the first message's delivery route, the average performance is seldom affected especially when the simulation lasts a relatively long time. Therefore, the difference between R-PSCF and PSCF is slight. R-PSCF-1 is the average performance of the first generated message of each grid. We can see that the performance of R-PSCF-1 is more significant than that of R-PSCF.

Fig.9(a) is the analysis of long links involving circles in the network, that is, the ratio of long links that form circles. We can see that when the number of long links increases, the ratio increases with it. When the network is smaller, more links are involved in circles. Fig.9(b) is the delay comparison of PSCF with and without trajectory sharing. With trajectory sharing, the delay decreases slightly. Note that trajectory sharing does not affect moving distance or the number of relays.

Fig.9(c) shows the comparison of the delivery ratios in the sparse mode. In XY, the sparse mode means that some fixed place holders may missing and their neighbors cannot transmit packets to them. Therefore, the network may get disconnected. In Direct/Direct-S, the sparse mode refers to when mobile nodes are missing in the place holders as in the PSCF method. The delivery ratio of Direct is approximately the density of mobile nodes. This is due to the fact that the generated message can only be delivered if there is a mobile node in the grid. The delivery ratio of Direct-S is slightly higher than that of Direct, since with the help of sharing, some grids without mobile node can also send out the generated message via by-passing mobile nodes. When the density of the mobile nodes is small, XY has a smaller delivery ratio than that of Direct due to the high degree of disconnectivity. When the density d exceeds 0.5, the delivery ratio of XY increases quickly and outperforms that of Direct. PSCF has the largest delivery ratio.

Fig.9(d) shows the delay comparison of PSCF, XY, Direct, and Direct-S when the time consumption of one hop wireless transmission is of one in a thousand time units. We can see that in this case, the delay of XY is very small compared with the other methods. The delay of PSCF is smaller than that in Fig.4(c) since it also contains some short link transmission in the entire trajectory. Although the delay of PSCF is significantly higher than that of XY, it reduces the number of relays, and more important, increases the delivery ratio in sparse network, as in Fig.9(c).

The simulation results can be summarized as follows.

1) The proposed algorithm generates a smaller number of relays than XY while still maintaining a moderate moving distance and delay which makes PSCF more suitable for wireless ad hoc or sensor networks.

2) When we analyze the properties of PSCF, we can see that a larger network makes the performance of PSCF more significant, and also the support for free-riders, multiple long links, longer waiting time for the long links, and reactive long link initialization.

3) Trajectory sharing can slightly improve the performance of PSCF in terms of delay, while not affecting moving distance or relay.

4) In the sparse mode, PSCF has the largest message delivery ratio compared to XY and Direct, especially when the network is relatively sparse.

6 Conclusions

In this paper, we propose a new controlled mobility model with an expected polylogarithmic average number of relays to achieve a good balance among several contradictory goals. The model is based on the small-world model where each node has "short" link connections to its nearest neighbors and "long" link connections to other nodes following a certain probability distribution. Several dynamic trajectory planning and sharing methods for mobile nodes are proposed to enhance the efficiency. In our future work, we will include more analytical study, including network throughput analysis. More in-depth simulation and parameter trade-offs will also be studied.

References

[1] Fall K. A delay-tolerant network architecture for challenged Internets. In *Proc. ACM SIGCOMM*, Karlsruhe, Germany, Aug. 2003, pp.27–34.

[2] Wu J. Mobility in ad hoc wireless networks: A villain or a friend? In *Proc. Third International Workshop on Mobile Distributed Computing*, in Conjunction with *IEEE ICDCS*, Columbus Ohio, June 2005, p.547.

[3] Wu J, Dai F. Mobility-sensitive topology control in mobile ad hoc networks. In *Proc. IEEE IPDPS*, Santa Fe New Mexico, April 2004, pp.522–535.

[4] Grossglauser M, Tse D. Mobility increases the capacity of ad-hoc wireless networks. In *Proc. IEEE INFOCOM*, Anchorage Alaska, April 2001, pp.1360–1369.

[5] Wang W, Srinivasan V, Chua K C. Using mobile relays to prolong the lifetime of wireless sensor networks. In *Proc. ACM MobiCom*, Cologne, Germany, Aug. 2005, pp.270–283.

[6] Hull B, Bychkovskiy V, Chen K, Goraczko M, Shih E, Zhang Y, Balakrishnan H, Madden S. CarTel: A distributed mobile sensor computing system. In *Proc. the SenSys*, Boulder Colorado, Oct.–Nov. 2006, pp.125–138.

[7] Zhao W, Ammar M, Zegura E. Controlling the mobility of multiple data transport ferries in a delaytolerant network. In *Proc. IEEE INFOCOM*, Miami Florida, Mar. 2005, pp.1407–1418.

[8] Vahdat A, Becker D. Epidemic routing for partially-connected ad hoc networks. Technical Report, Duke University, 2002.

[9] Wu J, Yang S, Dai F. Logarithmic store-carry-forward routing in mobile ad hoc networks. *IEEE Transactions on Parallel and Distributed Systems*, 2007, 18(6): 735–748.

[10] Watts D, Strogatz S. Collective dynamics of small-world networks. *Nature*, 1998, 393: 440–442.

[11] Gupta P, Kumar P R. The capacity of wireless networks. *IEEE Transactions on Information Theory,* 2000, 46(2): 388–404.

[12] Das S, Nandan A, Pau G, Sanadidi M Y, Gerla M. Evaluating mobility pattern space routing for DTNs. In *Proc. the 1st ACM VANET*, in Conjunction with *ACM MobiCom*, Philadelphia Pennsylvania, Oct. 2004.

[13] Wong V W S, Leung V C M. Location management for next-generation personal communicaition networks. *IEEE Networks*, 2000, 14(5): 18–24.

[14] Wu J, Dai F. Mobility management and its applications in efficient broadcasting in mobile ad hoc networks. In *Proc. IEEE INFOCOM*, Hong Kong, China, Mar. 2004, p.350.

[15] Garetto M, Giaccone P, Leonardi E. On the capacity of ad hoc wireless networks under general node mobility. In *Proc. IEEE INFOCOM*, Anchorage Alaska, May 2007, pp.357–365.

[16] Pellegrini F, Miorandi D, Carreras I, Chlamtac I. A graph-based model for disconnected ad hoc networks. In *Proc. IEEE INFOCOM*, Anchorage Alaska, May 2007, pp.373–381.

[17] Wang Z M, Basagni S, Melachrinoudis E, Petrioli C. Exploiting sink mobility for maximizing sensor networks lifetime. In *Proc. the 38th Hawaii International Conference on System Sciences* (*HICSS*), Big Island Hawaii, Jan. 2005, p.287.1.

[18] Luo J, Hubaux J P. Joint mobility and routing for lifetime elongation in wireless sensor networks. In *Proc. IEEE INFOCOM*, Miami Florida, Mar. 2005, 3(3): 1735–1746.

[19] Shah D, Shakkottai S. Oblivious routing with mobile fusion centers over a sensor network. In *Proc. IEEE INFOCOM*, Anchorage Alaska, May 2007, pp.1541–1549.

[20] BAA04-13: Disruption tolerant networking (DTN). Technical POC: Preston Marshall, DARPA/ATO, 2004.

[21] Burleigh S, Hooke A, Torgerson L, Fall K, Cerf V, Durst B, Scott K, Weiss H. Delay-tolerant networking — An approach to interplanetary Internet. *IEEE Communications Magazine*, 2003, 41(6): 128–136.

[22] Wang R Y, Sobti S, Garg N, Ziskind E, Lai J, Krishnamurthy A. Turning the postal system into a generic digital communication mechanism. In *Proc. ACM SIGCOMM*, Portland, Oregan, Aug.–Sept. 2004, pp.159–166.

[23] Motani M, Srinivasan V, Nuggehalli P S. Peoplenet: Engineering a wireless virtual social network. In *Proc. ACM MobiCom*, 2005, pp.243–257.

[24] Jain S, Fall K, Patra R. Routing in a delay tolerant network. In *Proc. ACM SIGCOMM*, Cologne, Germany, Aug. 2004, pp.145–158.

[25] Zhao W, Ammar M, Zegura E. Multicasting in delay tolerant networks: Semantic models and routing algorithms. In

Proc. ACM SIGCOMM Workshop on Delay Tolerant Networks, Cologne, Germany, Aug. 2005, pp.268–275.

[26] Davis J, Fagg A, Levine B. Wearable computers as packet transport mechanisms in highly-partitioned ad-hoc networks. In *Proc. the International Symposium on Wearable Computing*, ETH Zurich, Oct. 2001.

[27] Chen Z, Kung H, Vlah D. Ad hoc relay wireless networks over moving vehicles on highways. In *Proc. ACM MobiHoc*, Long Beach California, Oct. 2001, pp.247–250.

[28] Juang P, Oki H, Wang Y, Martonosi M, Peh L, Rubenstein D. Energy-efficient computing for wildlife tracking: Design tradeoffs and early experiences with zebranet. In *Proc. ASPLOS*, San Jose, California. Oct. 2002, pp.96–107.

[29] Small T, Haas Z. The shared wireless infostation model — A new ad hoc networking paradigm (or where there is a whale, there is a way). In *Proc. ACM MobiHoc*, Annapolis, US, 2003, pp.233–244.

[30] Liu C, Wu J. Scalable routing in delay tolerant networks. In *Proc. ACM MobiHoc*, Montreal, Canada, Sept. 2007.

[31] Daly E, Haahr M. Social network analysis for routing in disconnected delay-tolerant MANETs. In *Proc. ACM MobiHoc*, Montreal, Canada, Sept. 2007, pp.32–40.

[32] Milgram S. The small world problem. *Psychology Today*, 1967, 1(1): 61–67.

[33] Kleinberg J. The Small-world phenomenon: An algorithmic perspective. In *Proc. the 32nd ACM Symposium on Theory of Computing*, Portland Oregon, May 2000, pp.163–170.

[34] Kleinberg J. Small-world phenomena and the dynamics of information. In *Proc. Advances in Neural Information Processing Systems* (*NIPS*), Vancouver, Canada, Dec. 2001.

[35] Blazevic L, Buttyan L, Capkun S, Giordano S, Hubaux J, Le Boudec J. Self-organization in mobile ad-hoc networks: The approach of terminodes. *IEEE Communications Magazine*, 2001, 39(6): 166–174.

[36] Chitradurga R, Helmy A. Analysis of wired short cuts in wireless sensor networks. In *Proc. IEEE International Conference on Pervasive Services*, Beirut, Lebanon, July 2004, pp.167–176.

[37] Dimtar T *et al.* Small world application layer for ad hoc networks. In *Proc. Telekomunikacioni Forum Telfor*, Belgrade, 2003.

[38] Xu Y, Heidemann J, Estrin D. Geography informed energy conservation for ad hoc routing. In *Proc. ACM MobiCom*, Long Beach California, Oct. 2001, pp.70–84.

Jie Wu is a distinguished professor at the Department of Computer Science and Engineering, Florida Atlantic University and a program director at National Science Foundation. He has published over 400 papers in various journals and conference proceedings. His research interests are in the areas of wireless networks and mobile computing, routing protocols, fault-tolerant computing, and interconnection networks. Dr. Wu was on the editorial board of IEEE Transactions on Parallel and Distributed Systems and was a co-guest-editor of IEEE Computer and Journal of Parallel and Distributed Computing. He served as the program co-chair for MASS 2004, executive program vice-chair for ICDCS 2008, and program vice-chair for ICPP 2000. He was also general chair for MASS 2006 and general chair for IPDPS 2008. He is the author of the text "Distributed System Design" published by the CRC press. He was also the recipient of the 1996∼1997, 2001∼2002, and 2006∼2007 Researcher of the Year Award at Florida Atlantic University. Dr. Wu has served as an IEEE Computer Society Distinguished Visitor and is the Chairman of IEEE Technical Committee on Distributed Processing (TCDP).

Shu-Hui Yang is currently a post-doctoral research associate in the Department of Computer Science at Rensselaer Polytechnic Institute. She received her Ph.D. degree in computer science in 2007 from Florida Atlantic University. She received her B.S. and M.S. degrees in 2000 and 2003, respectively, from Jiangsu University, and Nanjing University, China. Her current research focuses on the design of localized routing algorithms in wireless ad hoc and sensor networks and distributed systems. She is a member of IEEE.

Appendix

To simplify the discussion, S_i, the jump area for nodes in phase i is simply represented as a diamond (shape) with radix 2^i. Based on the proof of Theorem 1, the size of S_i is bounded by $\frac{1}{2}r^2 < |S_i| \leqslant 2r^2+2r+1$, where $r=2^i$.

Proof of Theorem 3. We first consider the long link (u,v) as a straight line. The diamond for u to an intermediate node w is centered at w with two opposite corners also on the line (see Fig.10). Therefore, the proof can be focused on calculating the overall non-overlapped area size of a sequence of diamonds for all intermediate nodes. That is, we need to show that the area size is $O(1)r^2$.

The line can be partitioned into sections with the j-th section covering $(2^j, 2^{j+1}]$ (starting from u). Each intermediate node in the j-th section has a diamond S_j. The overall area covered in the j-th section is $2^j(2(2^j)-1)+(2^j-1)^2$, where $2^j(2(2^j)-1)$ corresponds to the rectangle area (portion) of S_j in the j-th section and $(2^j-1)^2$ corresponds to two triangle areas of the same size covered by the portion of S_{j+1} in the j-th section (see Fig.10). Likewise, there are two triangle areas covered by S_j residing in the $(j-1)$-th section. Therefore, the overall area size from section 0 to $i-1$ is $S=\sum_{j=0}^{i-1}2^j(2(2^j)-1)+(2^j-1)^2$. Clearly $S<\sum_{j=0}^{i-1}2(2^j)^2+(2^j)^2=3r^2(\frac{1}{4}+\cdots+\frac{1}{4}^{i-1})<r^2$ and $S>\sum_{j=0}^{i-1}(2^j)^2>\frac{1}{4}r^2$.

For the additional area covered in the i-th region, it is bounded by $(r-1)^2<r^2$ (when v is at the posi-

tion 2^{i+1}). In addition, the actual routing that follows the X-Y routing will generate an "L" shaped line instead of a straight line. However, the over- and under-calculation at the turn point is bounded by $\frac{1}{2}r^2$. Therefore, the overall area is $O(1)p$. $\square$

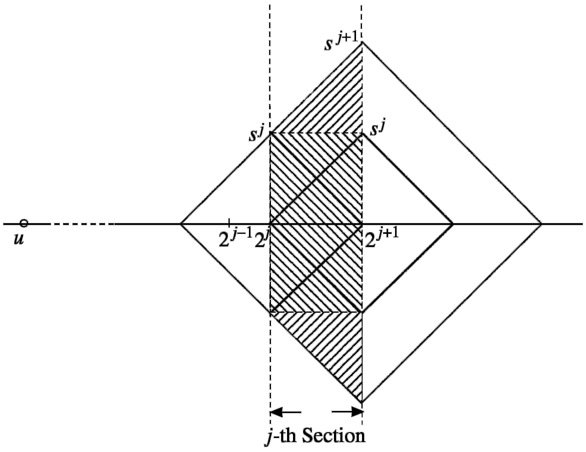


Fig.10. Overall area covered in the j-th section.

Proof of Theorem 4. The probability p depends on the link probability (i.e., $d(u,v)^{-2}$) and size of S_i. In addition, assume u is in the i-th section (starting from v), we have

$$c\frac{|S_i|}{(2^i)^2} > p > c\frac{|S_i|}{(2^{i+1})^2}$$

for an appropriate constant c. Also, $\frac{1}{2}(2^i)^2 < |S_i| \leqslant 3(2^i)^2$, we have,

$$3c = \frac{3(2^i)^2}{(2^i)^2}c > p > \frac{\frac{1}{2}(2^i)^2}{(2^{i+1})^2}c > \frac{1}{8}c.$$

For an intermediate node w at the j-th section, its probability p' satisfies

$$c\frac{|S_j|}{(2^j)^2} > p' > c\frac{|S_j|}{(2^{j+1})^2}$$

for the same constant c. Similarly, we have $3c > p' > \frac{1}{8}c$. In terms of p, we have

$$24p > 3c > p' > \frac{1}{8}c > \frac{1}{24}p.$$

$\square$