# A Direction-based Geographic Routing Scheme for Intermittently Connected Mobile Networks

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## Abstract

*In a intermittently connected mobile network, a complete routing path from a source to a destination cannot be guaranteed most of the time. Therefore, traditional routing methods for ad hoc networks are not applicable in these situations. Current approaches for such networks are primarily based on redundant transmissions and single copy direct routing. However, they incur either high overhead due to excessive transmissions, or long delays due to incorrect path choices during forwarding. In this paper, we propose a DIrection-based Geographic routing scheme (DIG) for the intermittently connected mobile network. Relying on geographic location information, the packets are routed in an approximately ideal path to the destination, which significantly reduces the resources required in flooding-based algorithms and leads to decreased delays compared to direct routing. Theoretical analysis and simulations show that compared to epidemic routing and direct routing, DIG provides low transmission delays with very low overhead.*

## 1 Introduction

The rapid development of wireless communication techniques and electronic techniques enables almost every mobile device to be equipped with wireless communication capabilities, which makes the concept of ubiquitous computing very promising in the near future. One research area that has received increasing attention currently is mobile ad hoc networks (MANETs). Mobile ad hoc networks are collections of wireless mobile nodes which promise a convenient infrastructure-free communication. In the absence of any central control infrastructure, the hosts in MANETs communicate with each other in a multi-hop fashion [23, 12], in which a continuous connection between a source node and a destination node should be guaranteed. One special group of MANETs is Delay Tolerate Networks (DTNs) in which source nodes and destination nodes are intermittently connected. increasing attention in recent years. Examples of DTNs include wildlife monitoring sensor networks [14], interplanetary communication networks [4], vehicular ad hoc networks (VANETs) [32], terrestrial wireless networks, and ocean sensor networks [22, 20]. Such intermittent connectivity is a result of mobility [32], power management [14], wireless transmission range, sparsity [11], or malicious attacks [1]. Therefore, conventional internet routing protocols (e.g. RIP, OSPF) as well as ad-hoc network routing schemes, such as DSR [12], and AODV [23], that try to discover minimum cost of continuously connected paths before data is sent out are not applicable here.

Currently, almost all routing schemes proposed for DTNs are topology-based routing. That is, the data transmissions rely on nodes' addresses. One group of topology routing is flooding-based routing [14, 18, 28]. Despite their increased robustness and low transmission delay, flooding-based routing schemes (e.g. epidemic routing schemes) consume much energy, bandwidth, and memory space that are crucial to wireless network applications (e.g. wireless sensor networks). However, flooding-based routing can provide the shortest transmission delay for the data transmission, since all possible routing paths are tried. Another group is single copy-based routing, such as two-hop direct routing [27]. In two-hop direct routing, a source node transmits each segment of the source packet stream to each relay node. The packets are allowed to be buffered for a long time until the relay nodes meet the destination node. Although such a scheme brings about much lower overhead for packet transmission, it suffers from severe transmission delays if a node chooses a wrong path for the delivery.

Geographic routing is another routing category for MANETs which relies on geographic position information of mobile nodes instead of using network addresses. Since each node in geographic routing only maintains the location information about its current neighbor nodes, it is more scalable than the topology-based routing. This position information can be generated by Global Position System (GPS) or numerable virtual coordination methods [16, 8]. However, one requirement of geographic routing is that the source node should be aware of the location of the destination node. Fortunately, in the majority of applications of DTNs such as wildlife monitoring sensor networks [14], interplanetary communication networks [4] and etc, the position of the destination nodes (sinks) are determined and can be known by all the nodes in the system. It can be realized by periodically broadcasting the location information of the destination via satellites. The packets are routed to these location-determined sinks for data collection, data processing, or further transmission to clients via internet. Although geographic routing methods generate much less transmission overhead and have high transmission scalability for decentralize routing, current geographic routing methods proposed for the wireless ad hoc networks [15, 3] using a greedy transmission strategy are not applicable to DTNs. In MANETs, the packets can be greedily transmitted to the destination via the continuously connected link based on geographic locations of intermediate neighbor nodes. However, because of the huge delay between each transmission in DTNs, a node currently close to the destination node cannot be guaranteed to be close to the destination later or can forward the packet to a closer node in the near future. That is, no node can expect when and what node it will meet in the near future. Therefore, the traditional greedy routing methods for MANETs which only emphasize on current locations of the neighbor nodes are not applicable in DTNs.

In this paper, we present the design, implementation and evaluation of DIrection based Geographic routing schemes specific for intermittently connected mobile networks (DIG). When choosing a next-hop relay node, in addition to the distance between a next hop node and the destination node, the moving direction of each mobile node should also be considered. We assume that the destination nodes' locations are static or known by all the nodes in DTNs. Such assumption is realistic since most of the current applications [14, 4, 32] have location-determined data sinks. RFC4838 [5] defines an end-to-end message-oriented overlay called "bundle layer" that exists at a layer above the transport layer and below the application layer of a network. Packets are transmitted by the bundle layer into one or more protocol data units called "bundles", which are forwarded by mobile nodes. Our approach includes such a layer for packets transmission. We anticipate that most DTN nodes in the system will use some form of persistent storage for this– disk, flash memory, etc., but in this paper we assume the packets are stored in the node buffer to simplify the analysis.

In DIG, the data transmission is based on two factors: the location of a node and the possible communication time with a destination node. For a scenario in which mobile nodes have short transmission range, the moving direction can be directly used to reflect the possible communication time with a destination node. When the distance between the packets' current location and the destination's location is longer than a threshold distance, the bundles (blocks of several packets) are greedily forwarded to nodes whose moving directions are toward the destination and whose current locations is closer to the destination. Otherwise, the nodes whose moving directions are closest to the destination node are chosen as the next hops. Such mechanism helps to forward the packets to a node that has more communication time with a destination node. A longer communication time indicates more packets can be transmitted to a destination in one interaction. The term "buffer" refers to the queue where a mobile node stores received packets. A buffer management strategy is also implemented in DIG to reduce average packet transmission delay. We also build a module to theoretically analyze the performance of DIG. Theoretical and simulation results show that:

(1) With a large buffer queue, DIG achieves comparable delay to the epidemic routing scheme, but with much lower communication overhead.

(2) With a small buffer queue, DIG yields significantly shorter delay, lower overhead and higher throughput than epidemic routing scheme.

(3) Compared to single copy direct routing, DIG has much lower delay with comparatively high throughput.

In the next section, we discuss existing related work. Section 3 presents DIG routing algorithm. In Section 4, we analyze the performance of DIG theoretically. Simulation results are presented in Section 5. Finally, Section 6 concludes the paper.

## 2 Related Work

Although numerous routing protocols for wireless ad hoc networks have been proposed [23, 6, 12], traditional routing protocols are not appropriate for DTNs that are sparse and intermittently connected. These protocols do not work well even if the network is only "slightly" disconnected [27]. Consequently, several routing methods for DTNs are proposed in the recent years.

An initial method to deal with connectivity disruptions in DTNs is to reinforce connectivity on demand by sending out a number of specialized nodes (e.g. robots, satellites) which are assigned to fill the "communication gap" when a disconnection occurs [34, 17]. However, such a method needs global monitoring in the network. Therefore, it is not applicable to self-organized DTNs.

One categories of proposed methods is predicted routing [13, 4], that is, the routing path is determined before transmission. In [14], nodes record the history of past encounters in order to make fewer but more informed decisions. Those routing paths are predicted either by statistics of a mobility module or by a historical moving path record. However, these schemes reduce the transmission overhead of flood-based routing at a significant penalty to delivery delay. In [9], Dubois-Ferriere *et al* proposes an idea based on encounter ages to improve the route discovery process of regular ad hoc networks. Instead of searching for the destination, the source node searches for any intermediate node that has higher encountering frequency with the destination node. In [18], the author pointed out that consulting the age of the last node encountered when making forwarding decision results in superior performance than flooding.

The third category of methods for DTNs is opportunistic routing. The simplest approach is direct routing that lets the source or a moving relay node carry messages all the way to the destination [25]. Although these schemes can increase the capacity of the system [19], the delay could be very long. A faster way to perform opportunistic routing in DTNs is flooding-based epidemic routing [29]. The basic idea of this algorithm is to forward messages between two nodes when they contact with each other until the messages arrives at the destination. This scheme can guarantee a short delay by locating a shortest routing path at the cost of high network resource consumption. There are a number of improved approaches proposed to reduce the overhead of the epidemic routing [33, 18, 31, 26, 30]. In [33], a message is "gossiped" to other nodes instead of flooding. That is, a message is forwarded to partial neighbors. In [26], nodes remove redundant copies of certain messages when those messages have been transmitted. Network codings [30, 31] have been used to improve the performance of the flood routing. Although all these schemes can improve the performance of epidemic routing to a certain extent, they still inherit the shortcomings of flooding and can not significantly reduce transmission delays.

## 3 Direction-Based Geographic Routing Scheme

Based on the previous exposition, we identify a number of desirable design goals for a routing protocol in DTNs and propose a novel direction-based geographic routing for DTNs.

(1) In order to reduce transmission overload and resource consumption, rather than relying on flooding, DIG uses a single-copy routing scheme to avoid traffic congestion in the system.

(2) In order to reduce transmission delay, unlike existing topology-based single copy schemes [24, 25], DIG practically uses the location information of each node to assist packet forwarding and forward the packets towards to the destinations in a comparatively optimistic way.

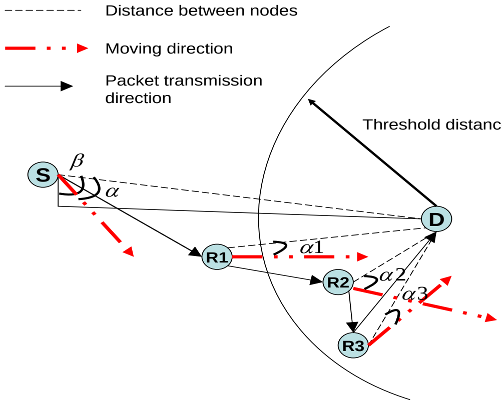


**Figure 1. Transmission processes**

(3) In order to achieve high scalability, DIG is only required to maintain a routing table containing the information of its current neighbor nodes, rather than the information of all nodes in the system.

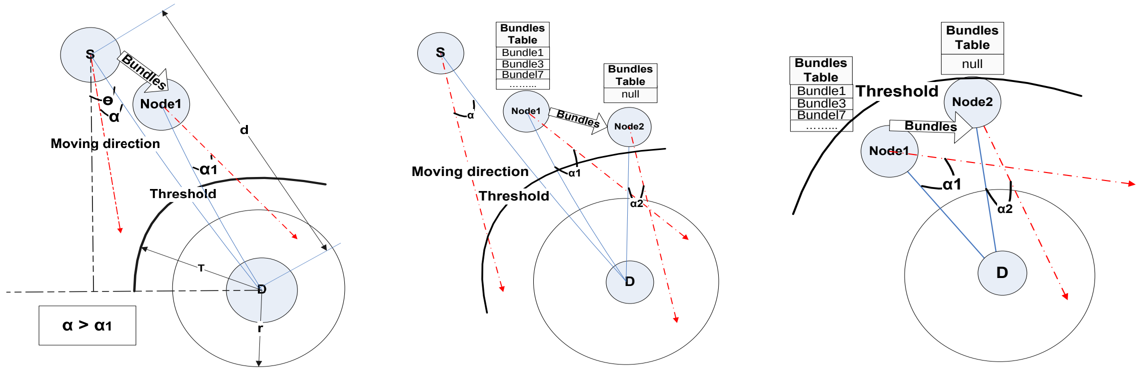
(4) In order to increase delivery throughput and reduce average transmission delay, DIG uses a packet handoff management scheme to manage the buffer.

### 3.1 Mobility models

In this paper, Uniform Mobility Model (UMM) [2] is adopted as our theoretical analysis scenario. In this model, each of the $m$ mobile nodes moves at speed $v$ inside a unit of circular disk. At time $t = 0$, the position of these nodes are distributed uniformly at random inside the disk. Moreover, the directions of motion of the $m$ nodes at time $t = 0$ are identical and independently distributed (i.i.d.) in $[0, 2\pi)$. At subsequent times, a node behaves as follows: it picks a direction uniformly at random from $[0, 2\pi)$ and moves in that direction for a certain distance at speed $v$. We assumed that the destination nodes are static or their locations are known to all the nodes in the system. There are numerous real environment scenarios such as interplanetary networks, terrestrial networks, wireless senor networks, and etc. that satisfy such an assumption.

### 3.2 Algorithm

In DIG, two nodes exchange their current locations, moving directions and packets when they meet. Figure 1 shows an example of packets (bundles) routing from a source node to a destination node in DIG. Basically, when packets are far from the destination node (i.e. beyond a threshold distance denoted by $T$), they will be forwarded to the mobile nodes whose positions and moving directions are



(a) Initial step (b) Beyond the threshold (c) Within the threshold

**Figure 2. Packet routing in DIG**

**Algorithm 1** Pseudo-code for DIG packet routing algorithm executed by node $n_j$.

```
while $n_j$'s packet.count()>0 do
  sort the packet in the order of the priority and time_stamp
  for packet $i = 1$ to packet.count() do
    if a communication link exists between $n_j$ and the destination node of packet $i$ then
      forward the packet $i$ to the destination node
    else
      if a neighbor node is within the transmission range of $n_j$ && not busy then
        exchange the position and moving direction information and analyze the location information of packet $i$'s destination and the location information of the neighbor node
        if $n_j$ is the source node of packet $i$ then
          if the neighbor node is closer to the destination of the packet $i$ than $n_j$ then
            forward packet $i$ to the neighbor node
          end if
        else
          if the location of $n_j$ is beyond $T$ to the packet $i$'s destination then
            if the location of neighbor node is closer to the destination && the neighbor node's moving direction is between $[\theta - \xi, \theta + \xi]$ then
              forward the packet $i$ to the neighbor node
            end if
          else
            // $n_j$ is within $T$ to the packet $i$'s destination
            if the moving direction of the neighbor node$<$ the moving direction of $n_j$ then
              forward the packet $i$ to the neighbor node.
            end if
          end if
        end if
      end if
    end if
  end for
end while
```

closest to the destination. As the packets are moving close to the destination node, they are forwarded to a mobile node whose moving direction is closest to the destination node, even if the distance of that node to the destination is longer. Because of the limited communication time between nodes, the closer moving direction to the destination can guarantee a longer communication time with the destination node.

**Direct Angle-Based Routing** Since each node knows the location information of the destination node, its current location and its current moving direction, the distance and the relative angle between the current node and the destination node can be calculated. Based on these two parameters, a direct angle-based routing algorithm can be proposed. This algorithm consists of the following phases. (1) As shown in Figure 2(a), considering the line joining a mobile node and a destination node (SD), let $\theta$ be the slope of the line $SD$ and $d$ be the distance between them. When a source node wants to send packets to a destination node, it forwards each part of the packet stream to its neighbor nodes when they meet. The positions of these next-hop nodes should be closer to the destination node than the source node, but there is no specific requirement on their moving direction in this phase. Since no node can predict which node it will meet in the future, having more nodes holding parts of the source packet stream can increase the probability that the packet stream can be forwarded to some promising relay nodes to the destination.

(2) After the bundles are forwarded to the relay nodes, the algorithm goes to the second phase. We defined a distance threshold $T$ to the destination node. As shown in Figure 2(b), if $d > T$, the relay node 1 seeks to find another relay node 2 whose position is closer to the destination node and its moving direction $\alpha 2$ is between $[\theta 1 - \xi, \theta 1 + \xi]$, where

$$\xi = \tau^k \arcsin(r/d) \leq \pi/2.$$

$\tau > 1$ is a weight value increasing with time, $k \in (0, 1)$ is a constant value which controls the changing speed of the angle, and $\theta 1$ is the slope of the line connecting node 1 and destination node. That is, the angle $\xi$ increases with time if a node cannot find a qualified next hop node for packet forwarding. In this way, the node can have more choices for next hop selection. However, the largest value of $\xi$ is $\frac{\pi}{2}$, which means the next hop node must move towards to the destination node, no matter how close the moving direction is. On the other hand, every time a relay node successfully finds another node for packet transmission, $\tau$ is reset to 1. That is, $\xi$ is reset to $\arcsin(r/d)$. We call this phase the "macro-control" phase, because packets are forwarded greedily with loose direction constrain to the destination node. Therefore, the packets can be transmitted comparatively faster to the destination node in this phase compared to the forwarding with strict direct constrain.

(3) As shown in Figure 2(c), when $d < T$, the mobile node will only forward packets to another node whose moving direction ($\alpha 2$) to the destination node is smaller than itself ($\alpha 1$), even if the position of the next hop node is farther to the destination node. If there are no better nodes nearby, that node will continually carry those packets by itself until it reaches the destination node. However, if a mobile node is communicating with the destination node at that time, no bundles will be forwarded to the next hop node even if the next hop node has closer direction to the destination node. We call this phase the "micro-control". Micro-control is used to guarantee more communication time between the mobile node and the destination node. In DTNs, the communication time between two nodes is limited, and the frequency of a node meeting a destination node is not very high. Therefore, after a node passes the destination node, it may take a long time to find and forward the remaining packets back to the destination node. It is intuitive that a node whose transmission direction is closer to the destination node has more communication time for the packet transmission. Since we should make full use of the communication time with the destination node, the node that is currently communicating with the destination node will not forward the packets to other nodes even though its current moving direction not as close as its neighbor nodes.

In general, DIG initially spreads the packets to several neighbor nodes for opportunistic routing in order to increase the probability that some of the packets are carried or will be carried by some promising nodes to the destination. Promising node refers to the node that has high chance to have long communication time with the destination node. In the macro-control phase, the packets destined to the same destination node are gathered to a number of mobile nodes that are close and moving toward to the destination node. Later in the micro-control phase, the packets are merged to certain nodes with closest direction to the destination for packet transmission.

However, one issue is raised in these transmission phases. The problem is that a smaller $\alpha$ can not always guarantee a closer moving direction or possible longer communication time between a wireless node and a destination node. Figure 3 shows that although $\alpha 0 < \alpha 3$, the communication time between $node3$ and the destination node is much longer than the communicatin time between $node1$ and the destination node. According to geometry properties, the long distance between two nodes affect the angle's relation to the destination node. Therefore, when the transmission range $r$ of mobile nodes is so large that $node1$ and $node3$ can communicate in a long distance, the mobile nodes will use the inaccurate angle relationship for the packet routing. However, if the transmission range of a mobile node is small, that is, two nodes can only communicate with each other when they are close, the prediction of the communication time between a mobile node and a destination node can be totally based on moving direction $\alpha$. If the $\alpha$ of a newly encountered node is smaller, the packets can be forwarded to this node for further forwarding. Therefore, because of the limitations of the direct angle-based routing, a more accurate transmission time prediction method should be used when the transmission range of mobile nodes is very large.

**Predicted Communication Time-Based Routing** The purpose of using angle calculation method is to predict the possible communication time with the destination node. However, given a node's current location, destination's location, and moving direction, the possible communication time of this node with the destination node can be directly calculated. Therefore, rather than using angle-based routing, the communication time can be directly calculated and used for the packets routing prediction. In Figure 3, we use $v$ to denote the moving speed of a wireless node, and use $L$ to denote the length from point $A$ to point $B$, represented by $AB = L$. Then, $L/v$ is the transmission time of a mobile node with a destination node. Similarly, we define the following representation: $AO = BO = R, OD = D, \angle OAB = M, \angle OAB = \alpha 2, \angle AOD = \alpha 1$. As Figure 3 shows, $\alpha = \alpha 2 + \alpha 1$. Therefore

$$\sin(\alpha) = \frac{d}{r} \cdot \sin(\alpha 2) = \frac{\sqrt{r^2 - (\frac{L}{2})^2}}{r}$$

$$\Rightarrow L = 2\sqrt{r^2 - d^2 \sin^2(\alpha 2)}$$

$$\Rightarrow T_{comm} = \frac{2\sqrt{r^2 - d^2 \sin^2(\alpha 2)}}{v},$$

where $T_{comm}$ denotes the predicted communication time of a node with a destination node. Therefore, in algorithm 1, instead of forwarding the packets to the next hop node with

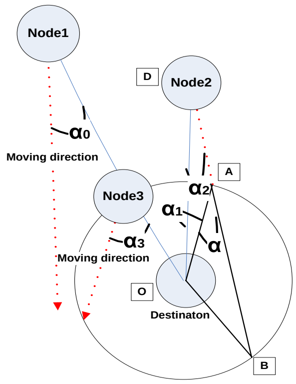


**Figure 3. Calculation of the communication time.**

smaller angle, the packets should be forwarded to a node with larger calculated $T_{com}$.

### 3.3 Packet Handoff Management

To ensure a short average transmission delay, a packet should be delivered to the destination node as soon as possible. However, a rely node may have several packets with various destinations at a time and the handover time between two nodes is limited. The transmission link between two nodes breaks if one node moves out the transmission range of another node. Therefore, the number of packets that can be transmitted during each communication is limited. DIG implements a packet handoff scheme to decide which packets have higher priority to be transmitted during the communication time in order to guarantee a short average transmission delay.

In addition to the traditional field such as the IDs for source node and destination node, DIG includes two new fields into each bundle's head : *priority* and $time\_stamp$. *Priority* is used to indicate the delivery urgency of packets indicated by the applications. $Time\_stamp$ is used to record the elapsed time since the packet's creation. In a node's buffer, the packets are arranged in decreasing order of *priority*. Within each level of priority, the packets are sorted in decreasing order of $time\_stamp$. When two nodes meet each other, the packets are delivered based on the ordered sequence in the buffer. Employing $time\_stamp$ guarantees that the longer the packets stay in a buffer, the higher priority it has to be delivered. It avoids long delays in the communication in which a packet stays in a buffer for an extended period of time.

## 4 Theoretical Analysis

### 4.1 Transmission throughput

Handoff nodes or encounters denote the encountered nodes that the packets can be delivered to. The following is the discussion of the number of encounters that a certain mobile node $M_1$ has in a time period $t$. As in [2], a node $M_i$ can be a *handoff node* of $M_1$ if

(1) $M_i$ moves in the direction $\alpha$ where $\alpha \in [\theta - \xi, \theta + \xi]$.

(2) $M_i$ encounters $M_1$ at sometime during the time period $[t_0, t_0 + t]$.

**Theorem 4.1** *Let $M$ be some mobile node seeking for handoff nodes and $Y_i$ be a Berboulli random variables, where $Y_i = 1$ if $M_i$ is a* handoff node. *For any $\theta \in [0, 2\pi)$, the number of encounters satisfies:*

$$\sum_{i=0}^{i=(m-1)} E[Y_i] > 2mt^2|v|^2 \cdot o(\sigma),$$

*which indicates that the number of encounters of a mobile node during a time period $t$ depends on the density and moving speeds of mobile nodes, where $m$ is the number of nodes the source node meets during the $t$ and $v$ denotes the moving speed of a node.*

**Proof** The number of encounters during a time period $t$ equals to the average number of encounters when $\alpha \in [\theta - \xi, \theta + \xi]$ in the $t$. That is,

$$E[Y_i] = \int_{\alpha=\theta-\xi}^{\alpha=\theta+\xi} E[Y_i|d_i = \alpha] Pr[d_i = \alpha].$$

The relative speed of $M_i$ to $M$ is $|2|v|sin\frac{\alpha}{2}|$. Thus, given that $d_i = \alpha, Y_i = 1$ iff $M_i$ lies in a region of area

$$\pi L^2 = \pi \cdot t^2 |2 \cdot |v| \cdot sin\frac{\alpha}{2}|^2$$

$$E[Y_i] = \frac{1}{2\pi} \int_{\alpha=\theta-\xi}^{\alpha=\theta+\xi} \pi L^2 = \pi t^2 |2 \cdot |v| \cdot sin\frac{\alpha}{2}|^2 \cdot d\alpha.$$

Suppose $\theta = 0$, we can get

$$E[Y_i] = \frac{1}{2\pi} \cdot \pi t^2 \cdot 4|v|^2 \cdot 2 \int_0^{\xi} sin\frac{\alpha}{2}^2 d\alpha$$

$$= 2t^2|v|^2(\xi - sin\xi).$$

Suppose $\xi - sin\xi > o(\sigma)$, we can get

$$\sum_{i=0}^{i=(m-1)} E[Y_i] > 2mt^2|v|^2 \cdot o(\sigma).$$

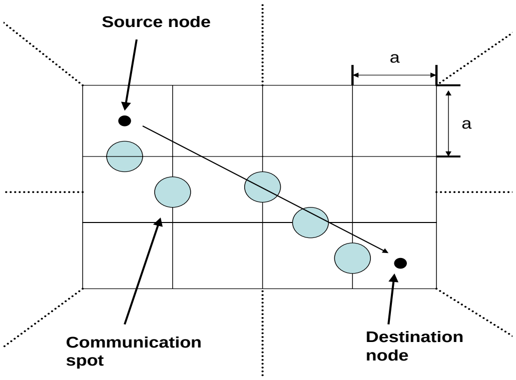


**Figure 4. Communication spots of DIG.**

Based on Theorem 4.1, the throughput of a node can be determined based on nodes density and mobility.

**Theorem 4.2** *Let* $\lambda_{mm}$ *denotes the bandwidth allocated for data transmission, then the amount of data that a mobile node can handoff to other nodes during the time period* $[t_0, t_0 + t]$ *is at least* $\lambda_{mm} r_0 m t^2 |v| \sigma$*. where* $r_0$ *denotes the moving distance of mobile nodes in a time period t.*

**Proof** Considering the motion of a mobile node $M_2$ relative to a mobile node $M_1$, $M_2$ moves at speed at most $2|v|$ if they move in opposite directions. Moreover, if $M_2$ covers a distance of at least $r_0$ during their encounter, the time duration of the transmission is $\frac{r_0}{2|v|}$. Hence, the expected amount of data delivered during an encounter is at least $\frac{\lambda_{mm} r_0}{2|v|}$. Followed by the Theorem 4.1, the amount of data that a mobile node can handoff to other nodes in $[t_0, t_0 + t]$ is at least $\lambda_{mm} r_0 m t^2 |v| \sigma$.

## 4.2 Transmission bound of DIG

In the uniform mobility model, mobile nodes are initially uniformly distributed, moving at a constant speed $v$, and the moving directions are i.i.d in the range $[0, 2\pi]$. Suppose in a big square the side length of each square cell is $a$. Among the total number of mobile nodes $n$, a fraction of them, $n_S$, are randomly chosen as senders, while the remaining nodes $n_R$ act like possible receiving nodes [10]. For a finite $a$ and a finite $n$, connectivity is guaranteed if $\frac{1}{a} > \frac{2log(n)}{n}$ [7]. $\bar{L}$ denotes the mean distance between the source node and destination node. Given that each cell hop has an average size of $1/a$, the average number of hops traversed by a bundle to the destination is $\frac{O(\bar{L})}{1/a}$.

To ensure that all required traffic can be carried to the destination node, the throughput of the packets transmission is less than channel capacity. That is,

$$\frac{O(\bar{L}) n_S \cdot Th(n)}{1/a} \leq n_S \lambda_{mm}. \Rightarrow Th(n) \leq \frac{\varepsilon \lambda_{mm}}{a}.$$

where $Th(n)$ denotes the throughput of the network with $n$ mobile nodes. Therefore, $Th(n) = \frac{1}{a} O(1)$.

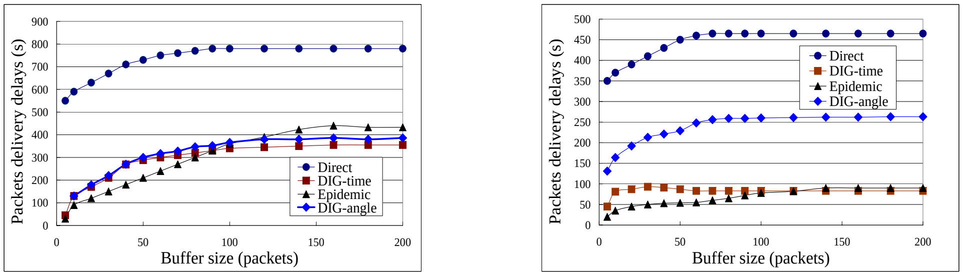
The average delay of DIG is the sum of the inter-cell packets transmission delay from the source cell to the destination cell and destination locating delay in order to find the destination node in the cell. The former is the product of the transmission hops and the delay in each hop. The size of the DTN is fixed in our analyze model, thus, the speed of the nodes is scaled down as $v = O(1/\sqrt{n}))$ [7]. Then,

$$O[(\frac{\bar{L}}{1/a} \frac{1}{v}) \frac{1}{a}] = O(\sqrt{n}).$$

If the destination node is a static node, the transmission delay is $O(\sqrt{n})$, that is, the destination node searching time is a constant time. If the destination node is a mobile node, the transmission delay is $O(\sqrt{n} + n/a)$, that is, the delay of destination locating is bound by $O(n/a)$ [10]. Since $O(n/a) >> O(\sqrt{n})$, the total delay is $O(n/a) + O(\sqrt{n}) \approx O(n/a)$, which is almost the same as direct routing but longer than epidemic routing. From the analysis above we can find that the DIG with single copy will lead to a longer delay in the scenario that the destination node is a randomly mobile node. However, in the scenario that the destination node is static, the delay performance of DIG is the best.

# 5 Performance Evaluation

This section demonstrates the distinguishing properties of DIG through simulations built on OMNeT++ [21]. We used epidemic routing scheme [29] to represent flooding-based schemes (Epidemic in the figures), and used direct routing scheme [10] to represent sing copy-based routing scheme (Direct in the figures). DIG-time represents communication time-based routing and DIG-angle represents angle-based routing. The simulation is based on the Uniform Mobility Model. This model consists of a $1500m \times 1300m$ space area where 50 nodes are i.i.d. placed. Three of the 50 nodes are randomly chosen to be static nodes serving as destination nodes. The location of the destination node is known to all the nodes in the system. The mobile nodes move at the speed of $0 - 20m/s$. A subset of 47 nodes generate one message per second for 2000 seconds to one of the three destination nodes, and the simulation is then run for another 2000 seconds to allow messages to be delivered. The distance threshold $T$ in the DIG is set to be $2r$, where $r$ denotes the transmission range of mobile nodes, if the transmission range of the mobile nodes changes, the $T$ will be changed. The TTL in the Epidemic was set to be 5 hops. The simulations in our previous tests indicated that these values were the “sweet spot” for the parameters. The transmission range $r$ is the distance that the signal of a mobile node can reach. We conducted experiments in two cases: $r = 50m$ and $r = 100m$ in order to see the impact



(a) Range = 50m (b) Range = 100m

**Figure 5. Packet delivery delay.**

of the transmission range on the routing performance. In the simulation, dropped packets will not be re-transmitted again. Three simulation metrics were used in the simulation:

(1) *Message delivery delay*. It is the average latency for a message to be delivered. This metric represents the efficiency of a routing scheme in fast routing.

(2) *Number of successfully delivered messages.* It is the number of packets that can be delivered to the destination. This metric represents the robustness and delivery capacity of a routing scheme.

(3) *Number of transmissions.* A transmission occurs when a node forwards a message to another node in the routing. This metric reflects the transmission overhead and the resource consumption of a routing scheme.

## 5.1 Message delivery delay

Figure 5 plots the message delivery delay versus buffer size. The figure shows that Direct generates much longer delays than others. It is because in Direct, the packets transmission delay is based on the meeting probability of the packets relay node and the destination nodes. Since only a singe copy of the packet is used in the system, the low probability of the meeting chance of packets relay nodes and destination nodes leads to a high transmission delay in Direct. In contrast, flooding-based Epidemic takes full advantage of all possible routing paths to the destination resulting in a low transmission delay. Such delay should be the lower bound of delay performance in DTNs, if the buffer size of the mobile nodes in the DTN are large enough to store a considerable amount of packet replications. Although DIG also uses single copy routing, instead of waiting for the relay node to meet destination node by chance, the packets in DIG are routed in a determined way based on the location information of nodes. DIG reduces the transmission delay of Direct significantly.

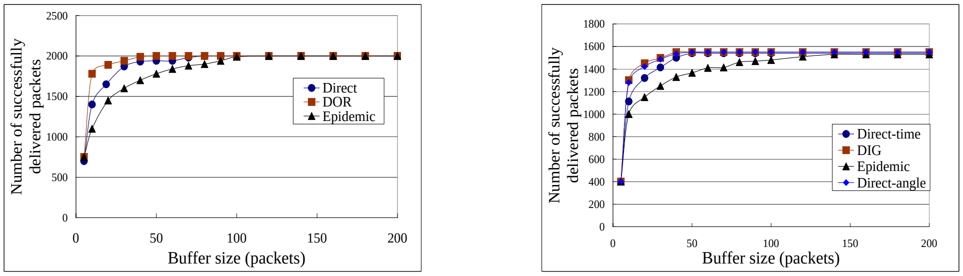
It is intriguing to see that the transmission delay increases as the queue size increases. It is because the low transmission delay is resulted from the fact that less packets are transmitted to the destination. Since no retransmission function is implemented in the simulation, the packets dropping caused by the channel congestion in the DTN with small buffer size leads to a short transmission time between the source node and destination node. While as the buffer size increase, the previous dropped packets, in the situation that the buffer size is small, are able to reside in the queues until they are delivered to their destinations. It increases the transmission time.

Furthermore, the figures show that the delay of DIG is not as sensitive to the buffer size as Epidemic. Since the DIG is single copy transmission which does not depend on the buffer storage as flooding in Epidemic, the performance of DIG will remain almost the same.

Comparing Figures 5(a) and (b), we can find that as the transmission range increases, the transmission delays of all routing schemes decrease. Intuitively, the larger transmission range makes it easier to find other neighbor nodes, which may be either the destination nodes or promising relay nodes, thus leading to a shorter delay. Moreover, the speed of the electromagnetic wave moves much faster than the moving node, thus the message delivery delay with a larger transmission range is shorter. However, for the DIG-angle, when the transmission range of the angle is small, the transmission delay of DIG-angle is almost same as DIG-time. However, in the scenario that the mobile nodes have long transmission range, the delay of DIG-angle is much longer than DIG-time. It is resulted from the inaccurate transmission direction prediction of the next hop. Some promising relay nodes which are close to the destination node and are moving closely to the destination node may be missed by DIG-angle.

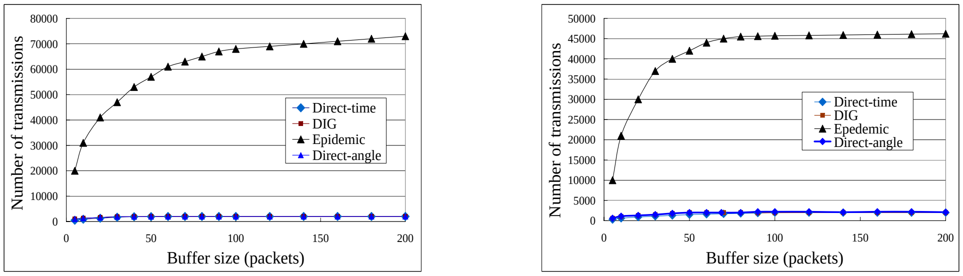
## 5.2 Message delivery capacity

Figure 6 depicts the number of successfully delivered messages versus the buffer size. It shows that as the queue size increases, so does the number of the successfully delivered messages due to the same reason observed in Figure 5.



(a) Range = 50m (b) Range = 100m

**Figure 6. Number of delivered packets.**



(a) Range = 50m (b) Range = 100m

**Figure 7. Number of transmissions.**

Larger queue size means more messages can be buffered and less message droppings, resulting in more successfully delivered messages.

Figure 6 also shows that the DIG and Direct are less sensitive to the queue size than Epidemic. A buffer congestion occurs when the buffer size is not big enough for all the packets, and some packets should be dropped off. DIG and Direct do not have buffer congestion problem due to their single copy routing, whereas Epidemic with flooding suffers from buffer congestion severely especially when the buffer size is small. Furthermore, we can see that DIG leads to more delivered messages than Direct with a smaller queue size. This is because the transmission delay of DIG is much less than Direct, it is more likely that DIG has more free buffer at all the time. Therefore, as the queue size is small, DIG will have less possibility to experience data congestion than Direct.

Moreover, Figure 6 indicates that when the buffer is large enough for all the packets, the delivery ability of all the routing schemes are almost the same. It is because there is no buffer congestion during the transmissions. DIG performs the best among the schemes with regards to the message delivery ability. Since both DIG-time and DIG-angle are single copy-based routing, they are not seriously affected by the buffer size. Therefore, the message delivery capacity of both routing methods are almost the same even with different transmission ranges.

Comparing Figures 6 (a) and (b), we can observe that as the transmission range increases, the number of successfully delivered messages also increases. The result is consistent with Theorem 4.1, which shows that with the increase of the transmission range, the communication time between two mobile nodes will increase, which subsequently increases the possibility of a mobile node meeting the destination node or promising forwarding nodes, and hence increases the number of successfully delivered messages.

## 5.3 Transmission Overhead

Figure 7 shows the number of transmissions versus the buffer size. The figure shows that DIG and Direct incurs much less transmissions, hence much lower communication overhead than Epidemic. It is because Epidemic is based on flooding in which a node sends all possible messages to nodes it encounters. In contrast, DIG and Direct only forward one copy of the packets in the network. That is also why Epidemic generates packet congestions in a high loaded network.

In conclusion, the experiment results show DIG has the merits of both epidemic routing which has an optimal delay and direct routing which has a low overhead in the transmission. It achieves an optimized tradeoff between Epidemic and Direct.

## 6 Conclusions

In this work, we investigated the problem of efficient routing in intermittently connected mobile networks. Current approaches in such networks are primarily based on redundant transmissions or single copy routing. However, they incur either high overhead due to excessive transmissions or long delay due to incorrect choices during forwarding. We proposed a Direction-based Geographic routing scheme (DIG), which overcomes the shortcoming of epidemic routing, and reduces the transmission delay of single copy routing scheme. Employing location information that facilitates nodes to be aware of each others' positions and moving directions, DIG outperforms epidemic routing and directing routing with respect to successful transmission, transmission delay and overhead.

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