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Geographic-Based Spray-and-Relay (GSaR): An Efficient Routing Scheme for DTNs

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Abstract—In this article, we design and evaluate the proposed
Geographic-based Spray-and-Relay (GSaR) routing scheme in
Delay/Disruption Tolerant Networks (DTNs). To the best of our
knowledge, GSaR is the first spray based geographic routing
scheme using the historical geographic information for making
routing decision. Here, the term spray means only a limited
number of message copies are allowed for replication in the
network.

By estimating a movement range of destination via the his-
torical geographic information, GSaR expedites message being
sprayed towards this range, meanwhile prevents that away from
and postpones that out of this range. As such, the combination
of them intends to fast and efficiently spray the limited number
of message copies towards this range, and effectively spray them
within range, in order to reduce the delivery delay and increase
the delivery ratio. Furthermore, GSaR exploits Delegation For-
warding (DF) to enhance the reliability of routing decision and
handle the local maximum problem, considered as the challenges
for applying geographic routing scheme in sparse networks. We
evaluate GSaR under three city scenarios abstracted from real
world, with other routing schemes for comparison. Results show
that GSaR is reliable for delivering messages before expiration
deadline and efficient for achieving low routing overhead ratio.
Further observation indicates that GSaR is also efficient in terms
of a low and fair energy consumption over the nodes in the
network.

Index Terms—DTNs, Geographic Routing, Spraying Messages,
Efficiency.

I. INTRODUCTION

THE research in Mobile Ad hoc NETworks (MANETs)
often assumes the contemporaneous end-to-end connec-
tivity, which inevitably poses challenges for relaying messages
in the challenged wireless networks, suffering from frequent
disruption, sparse network density and limited capability of de-
vices. With this in mind, Delay/Disruption Tolerant Networks
(DTNs) [1] receive great interest from research community

and are envisioned for many terrestrial applications. Apart
from InterPlanetary Networks (IPNs) [2], other examples of
DTNs include sparse Vehicular Ad hoc NETworks (VANETs)
[3], ocean sensor networks [4] and Pocket Switched Networks
(PSNs) [5].

Here, the intermittent connectivity in these networks can be
a result of mobility, energy, wireless range, sparse network
density. For example, if the encounter opportunity is unavail-
able, the node may store messages in its buffer and carry
them until a new connectivity for relaying these messages
is available, known as Store-Carry-Forward (SCF) routing
behavior. This inherent uncertainty about network topology
makes routing in DTNs to be a challenging problem.

Geographic routing, in general, requires that each node
knows its own location as well as the location of destination.
Different from topology based routing, geographic routing
exploits the geographic information instead of topological
connectivity information to relay messages, in order to grad-
ually approach and eventually reach the intended destination.
Although numerous previous works have been proposed in
designing powerful routing scheme using historical topology
information, geographic routing in DTNs has not received
much attention, as reviewed in [1].

In spite that geographic routing does not rely on the varied
network topology information to relay messages, the following
three challenges should be addressed if applying this scheme
in DTNs:

• Regarding geographic routing in MANETs, messages can
be greedily relayed towards destination via the continuously
connected path in a short time. However in DTNs, the node
which is currently closer to the destination may not be so
in the future. This is because that the node moving away
from destination may not encounter other nodes in a short
time, when considering the nodal mobility and sparse network
density.

• In MANETs, the local maximum problem problem[1] [6]
implies that the message can not be relayed with a positive
geometric progress towards destination. Here, for candidate
node[2] selection in DTNs, the utility metric is defined according

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[1]This problem implies that if a better relay node is unavailable, the message
carrier will keep on carrying its message. In light of this, the message delivery
is delayed or even degraded if a better relay node is never met. Using distance
metric as an example, any node closer to destination is qualified with a better
delivery potential. However, a message can not be relayed if any encountered
node which is farther away from destination.

[2]For the purpose of generalization, the candidate node is the relay node of
next hop, selected based a criterion which makes positive effort for message
delivery.

to the historical information to qualify the encountered node. However, conventional approaches designed for MANETs rely on the high network density, which is infeasible in DTNs due to sparse network density. In this case, the message delivery will be delayed because of the insufficient number of available encountered nodes for handling this problem.

• Considering the mobility of destination, this challenge limits the feasibility of using centralized location service system to distribute the realtime geographic information in sparse networks. This happens due to the fact that there is a long delay to request/reply the realtime location information in DTNs, thus the obtained information may be outdated and inaccurate for routing decision.

In literature, replicating message copies is effective to increase the delivery ratio in sparse networks, for which these replicated message copies increase the diffusion speed and the possibility that one of them would be delivered. In general, there are two ways to reduce replication redundancy: On one hand, previous works [7]–[11] replicate messages to any better qualified candidate node. On the other hand, the spray[3] based routing schemes [12]–[14] reduce the replication redundancy by limiting the number of message copies in the network. Compared with those in former branch, the schemes in latter branch inherently assume the nodal mobility is more sufficient for message delivery.

In this article, the proposed Geographic-based Spray-and-Relay (GSaR) is characterized into the latter branch, by delivering messages given the limited number of replications. Here, the message replication is controlled by a copy ticket cached in each message, where the initial value of this copy ticket is predefined based on scenario and distritbuted to the selected candidate node.

1) Given the historical location, moving speed as well as encounter time recorded in the past, the movement range of destination is estimated by referring to [15]. Here, based on the nature of spray based routing scheme, our intention is threefold:

   • Expedite message copies being sprayed towards this range, in order to reduce delivery delay.
   • Prevent message copies being sprayed away from this range, in order to reduce routing overhead.
   • Postpone message copies being sprayed out of this range, in order to increase delivery probability.

   As a back-up scheme, if the above historical geographic information of destination is unavailable, messages are sprayed considering the relative moving direction between pairwise nodes as well as their moving speed.

2) The local maximum problem has not been adequately addressed by other researchers in literature, particularly considering the limited number of message copies. Since this problem will delay message delivery, we propose to continually spray message copies, considering that the candidate node is unable to achieve delivery before message expiration deadline.

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[3]Assuming L is predefined value, each message can only be replicated for $(L-1)$ times. In general, the value of L is quite small compared with the total number of nodes in the network.

3) The Delegation Forwarding (DF) [16] is investigated for overcoming the limitation of routing decision, meanwhile enhancing the scheme for handling the local maximum problem. Here, the motivation for using DF overcomes the limitation if pairwise encountered nodes are with inconsistent status, such as the case that one of them is out of the movement range estimated for destination while another one is within this range. Furthermore, using DF intends to select the candidate node with the historically best delivery potential rather than that with a currently better delivery potential. This is important particularly when the number of message replications is limited, as GSaR only allows a limited number of nodes to carry messages.

4) Apart from the design of routing framework, messages are under prioritized transmission and deletion, by taking into account the limited bandwidth and buffer space. Since a message may expire before its candidate node encounters the destination, GSaR allocates the bandwidth and buffer space for the message that could be delivered within the expiration deadline, considering the mobility of candidate node as well as the awareness of destination's historical geographic information.

For performance evaluation, GSaR is compared with other routing schemes [7] [8] [12] [13] [17] under three city scenarios, namely Helsinki, Tokyo and San Francisco. Furthermore, we examine the energy consumption of GSaR accounted for transmission, to show its fairness. Simulation results show GSaR outperforms the compared routing schemes, in terms of a lower overhead ratio while maintaining the high delivery ratio. It also consumes a low and fair energy consumption over the nodes in the network.

The reminder of this article is as follows. The related work is presented in section II. Following the assumption and overview presented in III, the design of GSaR is detailed in section IV and evaluated in section V respectively. Finally, the conclusion is given in section VI.

II. RELATED WORK

A. Replication Based Routing Schemes

The schemes in this branch do not limit the number of copies of each message can be replicated in the network. The benchmark scheme, namely Epidemic [18], floods message copies to any node in the network. In spite that Epidemic achieves the highest delivery ratio, a huge network resource including bandwidth and buffer space are wasted for replication redundancy. Here, using the utility metric to qualify the nodal delivery potential for controlling replication has been studied by previous works.

1) Based on Historical Encounter Information: In Probabilistic ROuting Protocol using History of Encounters and Transitivity (PROPHET) [17], the utility metric is based on an encounter probability. The powerful Resource Allocation Protocol for Intentional DTN (RAPID) [19] treats the routing problem as a resource allocation aspect, where the utility metric is estimated as the remaining delivery delay. To reduce replication redundancy, Delegation Forwarding (DF) [16] is

proposed to optimize the candidate node selection, using the topology based utility metric.

2) Based on Geographic Information: As an alternative scheme to those using topology based historical encounter information, Distance Aware Epidemic Routing (DAER) [9] adopts current distance towards destination as the utility metric using realtime location information. Upon the design of DAER, Packet Oriented Routing (POR) [11] takes into account the distance factor for all the requested messages. Different from those considering stationary destination [10], [20], [21], it is highlighted that previous works rarely consider that the real-time location information of mobile destination might be unavailable due to sparse network density. With this in mind, Approach-and-Roam (AaR) [7] adopts historical geographic information including location, moving speed recorded in the past to estimate a movement range of destination, and replicates messages using a two-phases routing scheme. Converge-and-Diverge (CaD) [8] is further proposed to target the low routing overhead, while maintaining the delivery latency within an acceptable level.

B. Spray Based Routing Schemes

The schemes in this branch limit the replication redundancy by an initialized define copy ticket value L, where L implies that only $(L-1)$ copies of a message can be replicated in the network. Here, the binary version of Spray-and-Wait (SaW) [12], has been proven that it is effective to fast distribute $(L-1)$ message copies, by using a binary tree based distribution mechanism.

1) Based on Historical Encounter Information: Previous works [13] [22] further spray message copies to a better qualified candidate node based on utility metric. Borrowing from the utility metric adopted by [23], Spray-and-Focus (SaF) [12] adopts the Focus Phase instead of Wait Phase, decreasing the delivery delay via a utility forwarding approach. Here, the Focus Phase relies on forwarding message copies in a multi-hop way via the last encounter time. This is different from binary SaW in which the message with one remaining copy ticket is only relayed to its destination. Furthermore, REgioN-bAsed (RENA) [24] takes into account region concept, enabling message forwarding within region and message spraying between regions.

2) Based on Geographic Information: GeoSpray [14] borrows the geometric metric of GeOpps [25] for candidate node selection, requiring additional map topology information to find the Nearest Point (NP) via the navigation system. However, this scheme only considers the destination is stationary and highly relies on the selection of NP via map topology, particularly without handling the local maximum problem.

C. Key Contributions

Here, a summary of the related work is illustrated in Fig.1. To the best of our knowledge, GSaR is the first geographic scheme in the literature, by using historical geographic information of mobile destination, handling the local maximum under the design of spray based routing methodology. Different from our previous works [7] [8] which characterized as
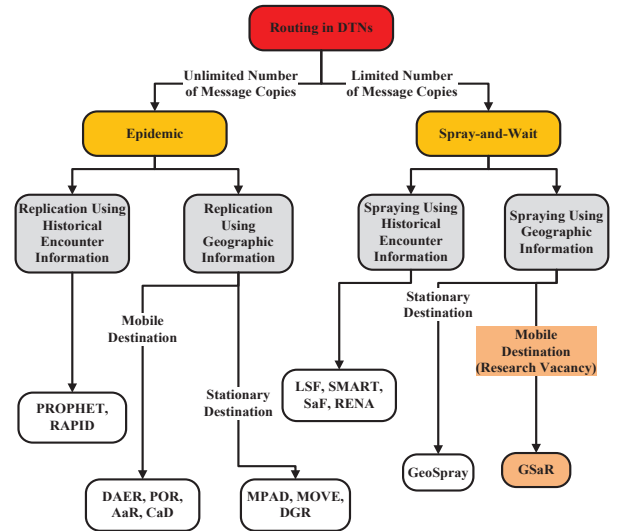

Fig. 1. An Overview of Related Work

utility replication based routing schemes, GSaR is advanced as follows:

- GSaR adopts the average historical moving speed to estimate the movement range of destination. Given the nature of spraying messages and distributing message copy tickets, GSaR further considers the movement status when the encountered node is moving away from the movement range estimated for destination.
- Upon this characteristic, the investigation of DF is considered in the design of GSaR, mainly for overcoming the limitation of routing decision, enhancing for handling the local maximum problem, and reducing routing overhead.
- GSaR is with the design to make routing decision if the historical geographic information of destination is unavailable. Therefore, it is entitled with an enhanced message management framework for transmission and deletion, based on the awareness of destination.

III. ASSUMPTION AND OVERVIEW

We assume that each node is equipped with the Global Positioning System (GPS), to obtain its own realtime geographic information including moving direction, current location and moving speed, where the factor of GPS error is not taken into account in this article. When pairwise node encounter, they will exchange, record and update the historical geographic information of each other. Here, a slotted based collision avoidance MAC protocol is applied, that only one connection for each message transmission is set up at each time slot.

Considering the sparse network density in DTNs, we rely solely on the basic ability of a node to communicate within its 1-hop neighbor node, thus the interference from a large transmission range is not taken into account. When pairwise node encounter, the routing decision is made based on whether the encountered node has better potential for message delivery. Otherwise, the message is carried until the destination is in proximity. The target of a routing scheme in DTNs is to achieve high delivery ratio with low routing overhead, while

the delivery delay is considered to be least important due to the delay tolerant nature of applications in DTNs.

The design of GSaR consists of the following functions:

Information Update: When pairwise nodes encounter, their current location, encounter time as well as the moving speed are exchanged by each other. These information are recorded in a local routing table, to estimate the movement range of each node. In addition to this, if both of these two nodes have the knowledge of a common node encountered in the past, the information in relation to that node is then updated towards the value recorded at a more recent time.

Spray Phase: Given the updated information, a movement range for destination is estimated, to support the following three cases for message spraying process. Here, each message records a copy ticket value C_M, where $(C_M \leq L)$ implies how many times it can be replicated in future. In this article, GSaR mainly adopts the binary spray process to fast distribute the $(L-1)$ message copies. This means the replicated message is entitled with $\frac{C_M}{2}$ copy tickets, while the original message maintains the rest $(C_M - \frac{C_M}{2})$ copy tickets.

- Based on selecting the candidate node moving towards this target range fast, to equally distribute message copy tickets enables more message copies to be sprayed within this target range, which reduces delivery delay.
- Besides, a long time duration for mobile node moving within this range contributes to message delivery, by either encountering destination directly or keeping on spraying the residual number of message copies.
- In contrast, when moving away from this range, the node which is close to this range measured within a time window is selected as the candidate node, with only $(C_M = 1)$ copy ticket distributed, to reduce the redundancy for spraying message copies.

In the worst case that the movement range estimated for destination can not be estimated due to infrequent encounter opportunity, as the information in relation to destination is unavailable, messages are sprayed considering the encounter angle as well as moving speed of pairwise nodes. Here, a larger encounter angle implies that two nodes are moving away from each other with a different relative direction, which contributes to an effective spraying process. Given that pairwise encountered nodes are moving in a consistent direction, spraying messages to the one with a faster moving speed expedites the spray process.

Relay Phase: When each message has been fully sprayed until $(C_M = 1)$, these message copies are then forwarded using single copy, following independent $(L-1)$ paths. Here, the selection of candidate node is based on the historical record, about the best potential to move towards the movement range estimated for destination, rather than selecting that with a better potential. The motivation behind this is to further reduce routing overhead, by filtering the node which does not significantly contribute to message delivery.

Message Management: Due to the intermittent connectivity in DTNs, messages may not be successfully transmitted. Besides, given the nature of SCF routing behavior, messages are stored in the nodal buffer space for a long time. Considering that the encounter duration between two nodes is limited, the

order for message transmission plays an important role on the routing performance. Considering the limited buffer space, it is essential to delete the least important message, to allocate the buffer space for an incoming message. Since GSaR only generates a limited number of copies of a message in the network, if one copy is successfully delivered, a method to delete other copies of this message timely is also essential to release buffer space for those undelivered messages.

IV. DETAILED DESIGN

With the introduction of above functions, we detail the design of GSaR in the following subsections via the important notations listed in TABLE I.

A. Information Update

We denote N_i as the node which carries the message M, while N_j is the encountered node without carrying this message. Here, N_d is as the destination node of M.

Based on the view of N_i, the required historical geographic information $\Psi(t_{i,d})$ for N_d contains the following records:

- $t_{i,d}$: Historical encounter time between N_i and N_d, recorded by N_i.
- $L(t_{i,d})$: Historical location (x_d, y_d) of N_d, recorded by N_i at $t_{i,d}$.
- S_d^{avg}: Historically average moving speed of N_d, as recorded by N_i. Note that S_d^{avg} is an average value of the cumulative moving speed of N_d at each encounter time.

As an example illustrated in TABLE II, $\Psi(t_{1,5})$ is denoted as the historical geographic information for N_5, consisting of the historical location $L(t_{1,5}) = (1000, 2000)$ and average moving speed $S_5^{avg} = 6 \ m/s$ recorded in the past, when N_1 encountered N_5 at $t_{1,5} = 1000s$. Given that N_1 encounters another node N_2, with $\Psi(t_{2,5})$ where $t_{2,5} = 2200s$, then the historical information about N_5, as recorded in $\Psi(t_{1,5})$, is updated according to that of in $\Psi(t_{2,5})$ because of $(t_{2,5} > t_{1,5})$. In another case that if N_2 did not meet N_5 in the past, then $\Psi(t_{2,5})$ is simply updated towards that of in $\Psi(t_{1,5})$. The example described herein can be referred between lines 5 and 13 in Algorithm 1.

Algorithm 1 Information Update

1: **for** each encounter between N_i and N_j **do**
2:     N_i records location, average moving speed and encounter time of N_j
3:     N_j records location, average moving speed and encounter time of N_i
4:     **for** each $((N_x \in K) \cap (N_i, N_j \neq N_x))$ met by N_i in the past **do**
5:         **if** N_j contains $\Psi(t_{j,x})$ **then**
6:             **if** $(t_{i,x} > t_{j,x})$ **then**
7:                 N_j replaces $\Psi(t_{j,x})$ with $\Psi(t_{i,x})$
8:             **else**
9:                 N_i replaces $\Psi(t_{i,x})$ with $\Psi(t_{j,x})$
10:             **end if**
11:         **else**
12:             N_j records $\Psi(t_{j,x})$ by using $\Psi(t_{i,x})$
13:         **end if**
14:     **end for**
15: **end for**

TABLE I
LIST OF NOTATIONS

N_i	Message carrier	$D_{i,d}$	Distance from the location of N_i to $L(d)_{i,j}$, similarly for $D_{j,d}$
N_j	Encountered node	θ_i	Moving direction of N_i, similarly for θ_j
N_d	Message destination	$\omega_{i,j}$	Encounter angle between N_i and N_j
M	Message carried by N_i	$\phi_{i,d}$	Relative angle between θ_i and $D_{i,d}$, similarly for $\phi_{j,d}$
T_M^{ini}	Initialized message lifetime	$T_{i,d}^{to}$	Time duration for N_i moving towards the movement range estimated for N_d, similarly for $T_{j,d}^{to}$
T_M^{ela}	Elapsed time since message generation	$D_{i,d}^{aw}$	Distance for N_i moving away from movement range estimated for N_d, similarly for $D_{j,d}^{aw}$
$t_{i,d}$	Historical encounter time between N_i and N_d recorded by N_i, similarly for $t_{j,d}$	$T_{i,d}^{in}$	Time duration for N_i moving within the movement range estimated for N_d, similarly for $T_{j,d}^{in}$
$L(t_{i,d})$	Historical location (x_d, y_d) of N_d recorded by N_i at $t_{i,d}$, similarly for $L(t_{j,d})$	V_M^{to}	Threshold value for recording $T_{j,d}^{to}$
$\Psi(t_{i,d})$	Historical geographic information of N_d recorded by N_i at $t_{i,d}$, similarly for $\Psi(t_{j,d})$	V_M^{aw}	Threshold value for recording $D_{j,d}^{aw}$
$t(d)_{i,j}$	Recent historical encounter time between N_d obtained from $t_{i,d}$ and $t_{j,d}$	V_M^{in}	Threshold value for recording $T_{j,d}^{in}$
$L(d)_{i,j}$	Recent historical location of N_d obtained from $\Psi(t_{i,d})$ and $\Psi(t_{j,d})$	W	Time window for calculating $D_{i,d}^{aw}$ and $D_{j,d}^{aw}$
K	Total number of nodes in the network	C_M	Copy ticket for M
t_{cur}	Current time in the network	L	Initialized value for C_M
S_d^{avg}	Recorded historically average moving speed of N_d	P_M	Message priority
R_d	Radius of the movement range estimated for N_d	$Bin_{(high)}$	High priority buffer space
S_i	Moving speed of N_i, similarly for S_j	$Bin_{(low)}$	Low priority buffer space

TABLE II
HISTORICAL GEOGRAPHIC INFORMATION $\Psi(t_{1,5})$ FOR N_5, BASED ON THE VIEW OF N_1

Routing Table of N_1			
ID of the Historically Encountered Node	Historical Location	Historically Average Moving Speed	Historical Encounter Time
N_5	$L(t_{1,5}) = (1000, 2000)$	$S_5^{avg} = 6\ m/s$	$t_{1,5} = 1000s$

(a) The $((D_{j,d} \geq R_d) \cap (\phi_{j,d} < \frac{\pi}{2}))$ Case   (b) The $((D_{j,d} \geq R_d) \cap (\phi_{j,d} \geq \frac{\pi}{2}))$ Case   (c) The $(D_{j,d} < R_d)$ Case
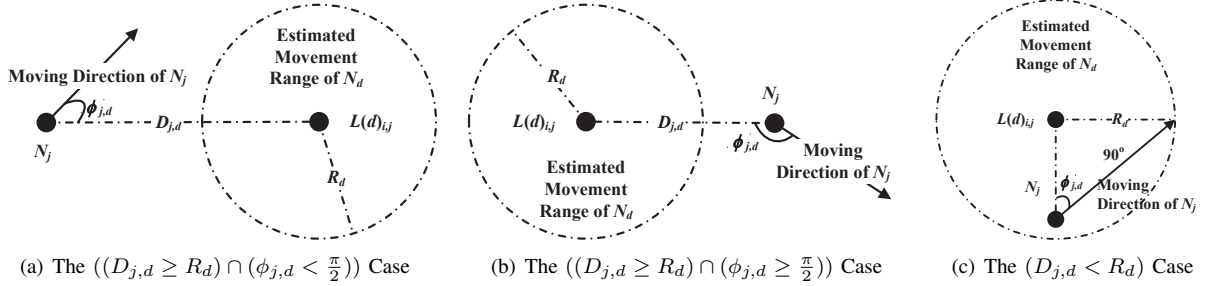
Fig. 2. Three Cases for Selecting Candidate Node

B. Candidate Node Selecting

We denote $L(d)_{i,j}$ as the recent historical location of N_d obtained from $\Psi(t_{i,d})$ and $\Psi(t_{j,d})$, following the above example about information update. Depending on the current time in the network t_{cur}, the estimated movement range for N_d is assumed as a circle, where its radius R_d is calculated as:

$$R_d = S_d^{avg} \times [t_{cur} - t(d)_{i,j}] \tag{1}$$

Here, $t(d)_{i,j} = \max[t_{i,d}, t_{j,d}]$ is denoted as a more recent time value between $t_{i,d}$ and $t_{j,d}$. Based on the distance $D_{j,d}$ measured from N_j to $L(d)_{i,j}$, and the moving direction of N_j as denoted by $\phi_{j,d}$, the following cases are considered for selecting the candidate node.

1) The $((D_{j,d} \geq R_d) \cap (\phi_{j,d} < \frac{\pi}{2}))$ Case: As illustrated in Fig.2(a), this case happens when N_j is moving towards the movement range estimated for N_d. We qualify N_j via its time duration $T_{j,d}^{to}$ to move towards the movement range estimated

for N_d, where:

$$T_{j,d}^{to} = \frac{D_{j,d} - R_d}{\cos \phi_{j,d} \times S_j} \tag{2}$$

Given $(T_{i,d}^{to} > T_{j,d}^{to})$, N_j is selected as a better relay node due to a faster proximity to this range, for reducing the delivery delay.

However, to calculate $T_{i,d}^{to}$ requires conditions $((D_{i,d} > R_d) \cap (\phi_{i,d} < \frac{\pi}{2}))$. Yet $T_{i,d}^{to}$ is invalid either if $(D_{i,d} < R_d)$ or $(\phi_{i,d} \geq \frac{\pi}{2})$, because the negative value of $T_{i,d}^{to}$ is unable for comparison. Note that in special case where $(T_{i,d}^{to} = 0)$, the routing decision for message M is omitted. Therefore, by using DF to overcome this limitation, a threshold value V_M^{to} is cached for message M, and we convert conditions:

$$((T_{i,d}^{to} > T_{j,d}^{to}) \cap (D_{i,d} > R_d) \cap (\phi_{i,d} < \frac{\pi}{2})) \tag{3}$$

into:

$$(V_M^{to} > T_{j,d}^{to}) \tag{4}$$

Here, V_M^{to} is denoted as an updated value of $T_{j,d}^{to}$. Thereby,

when conditions $((D_{j,d} \geq R_d) \cap (\phi_{j,d} < \frac{\pi}{2}) \cap (V_M^{to} > T_{j,d}^{to}))$ are satisfied, the value of $T_{j,d}^{to}$ is recorded into V_M^{to}. In GSaR, each node will locally check its individual motion status for every 1s, to calculate its individual moving speed and direction. During communication, this status information will be exchanged between two encountered nodes, such that they can obtain the speed, direction of each other.

Different from original application of DF, V_M^{to} is initialized with an infinitely large value, which considers the situation that $(D_{i,d} < R_d)$ or $(\phi_{i,d} \geq \frac{\pi}{2})$ when M is generated by N_i. Furthermore, initializing $(V_M^{to} = +\infty)$ avoids the failure of routing decision, particularly if $(D_{i,d} = R_d)$ happens at message generation. In light of this, the stated motivation focuses on comparing this time based utility metric, between the currently encountered node and previously encountered node, instead of comparing that between the message carrier and currently encountered node. Meanwhile, if N_j already has a copy of M, it is essential to update V_M^{to}, towards a smaller value between these two messages carried by both N_i and N_j.

Although using the time duration measured along progress distance to destination may also select the node whose $\phi_{j,d}$ is close to $\frac{\pi}{2}$, using DF will make the routing decision to be an optimality. This is because that apart from the gradually decreased[4] $(D_{j,d} - R_d)$, the gradual update for V_M^{to} implies either the smallest $\phi_{j,d}$ or largest S_j. As such the quality of the selected candidate node will be gradually optimized and converged. In contrast, when using $((T_{i,d}^{to} > T_{j,d}^{to}) \cap (D_{i,d} > R_d) \cap (\phi_{i,d} < \frac{\pi}{2}))$ for comparison, N_j might be selected to carry M, given that $\phi_{j,d}$ is close to $\frac{\pi}{2}$ while S_j is large. Consequently, although M has been relayed for several hops, it may not be sprayed close to the movement range estimated for N_d.

2) The $((D_{j,d} \geq R_d) \cap (\phi_{j,d} \geq \frac{\pi}{2}))$ Case: As illustrated in Fig.2(b), this case happens when N_j is currently moving away from the movement range estimated for N_d. We qualify N_j based on its projected distance $D_{j,d}^{aw}$ as calculated in equation (5), which is estimated from N_j' to the edge of the movement range estimated for N_d:

$$D_{j,d}^{aw} = D_{j,d} - W \times \cos \phi_{j,d} \times S_j - R_d \qquad (5)$$

Here, N_j' is denoted as the expected location estimated within a time window W. Upon this, the condition $(D_{i,d}^{aw} > D_{j,d}^{aw})$ implies N_j is closer to the movement range estimated for N_d.

However, we further note that calculating $D_{i,d}^{aw}$ requires $((D_{i,d} > R_d) \cap (\phi_{i,d} \geq \frac{\pi}{2}))$, which limits the routing decision either if $(D_{i,d} < R_d)$ or $(\phi_{i,d} < \frac{\pi}{2})$. This is because that the intention in this case considers both N_i and N_j are moving away from the movement range related to N_d, and only let the one with a closer proximity to this range to keep on carrying messages. Similar to the previous investigation on DF, another threshold value V_M^{aw} is cached in message, then conditions:

$$((D_{i,d}^{aw} > D_{j,d}^{aw}) \cap (D_{i,d} > R_d) \cap (\phi_{i,d} \geq \frac{\pi}{2})) \qquad (6)$$

are converted into:

$$(V_M^{aw} > D_{j,d}^{aw}) \qquad (7)$$

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[4]Considering that the information for N_d has not been updated via Algorithm 1, $D_{j,d}$ is always decreased given $(\phi_{j,d} < \frac{\pi}{2})$. Meanwhile, R_d is increased due to rare encounter.

By referring to the initialization of V_M^{to}, V_M^{aw} is also set with an infinitely large value and gradually updated towards a smaller value.

Thanks to updating V_M^{aw}, the candidate node will be gradually selected as the one, either with the $\phi_{j,d}$ close to $\frac{\pi}{2}$ or with the smallest S_j. Thus the value of $(W \times \cos \phi_{j,d} \times S_j)$ is quite small, considering the sparse network density and highly dynamic movement. In particular, even assuming $(\phi_{j,d} = \frac{\pi}{2})$, the candidate node which is closer to the movement range estimated for N_d will be selected in future, given that V_M^{aw} has been updated to $(D_{j,d} - 0 - R_d)$.

3) The $(D_{j,d} < R_d)$ Case: Considering that N_j has been within the movement range estimated for N_d, as illustrated in Fig.2(c), we define the time duration $T_{j,d}^{in}$ for N_j to move within this range, where:

$$T_{j,d}^{in} = \frac{\sqrt{(R_d)^2 - (D_{j,d} \times \sin \phi_{j,d})^2} + D_{j,d} \times \cos \phi_{j,d}}{S_j} \qquad (8)$$

The detail of calculating $T_{j,d}^{in}$ can be referred to [7]. Here, N_j is selected as the candidate node given $(T_{j,d}^{in} > T_{i,d}^{in})$, as a longer time duration moving within the movement range estimated for N_d implies a higher possibility to encounter N_d directly.

We note that calculating $T_{i,d}^{in}$ also requires that N_i is within the target range, as given by $(D_{i,d} < R_d)$. Following the previous discussion on using DF, here, conditions:

$$((T_{i,d}^{in} < T_{j,d}^{in}) \cap (D_{i,d} < R_d)) \qquad (9)$$

are converted into:

$$(V_M^{in} < T_{j,d}^{in}) \qquad (10)$$

Note that V_M^{in} is the corresponding threshold value defined in this case, to record the value of $T_{j,d}^{in}$. Different from the initialization of V_M^{to} and V_M^{aw}, V_M^{in} is set to be 0 and gradually updated towards a larger value. Therefore, by obtaining the largest value of V_M^{in} recorded in the past, message copies are ideally carried by at most $(L-1)$ candidate nodes within this range.

C. Spray Phase

Following the overview of GSaR presented in section III, the specific routing scheme is detailed from this subsection.

1) When $L(d)_{i,j}$ is Unavailable: If the historical geographic information is unavailable, messages are only sprayed based on the local movement status of pairwise encountered nodes. Here, the encounter angle $\omega_{i,j}$ is calculated as:

$$\omega_{i,j} = \begin{cases} |\theta_i - \theta_j| & \text{if } (|\theta_i - \theta_j| \leq \pi) \\ 2\pi - |\theta_i - \theta_j| & \text{else} \end{cases} \qquad (11)$$

Considering $(\omega_{i,j} > \frac{\pi}{2})$ shown in Fig.3, we propose to spray messages with $\frac{C_M}{2}$ copy tickets to N_j. This is because that if pairwise nodes are moving in a consistent direction, spraying messages does not significantly contribute to delivery. In contrast, if they are moving in different directions, spraying messages thus contributes to effective delivery, as the node holding the sprayed message copies may reach its destination on the move. This operation is presented between lines 11 and 13 in Algorithm 2.
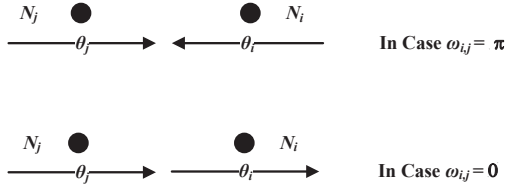
Fig. 3. Encounter Given Different $\omega_{i,j}$

As a special case where the encounter angle is ($\omega_{i,j}$ = 0), N_j is selected to spray messages if its moving speed S_j is faster than S_i. Following the presentation between lines 14 and 16 in Algorithm 2, this is because that a faster node would contribute to fast delivery, particularly considering that messages are rarely sprayed even with short lifetime.

2) When $L(d)_{i,j}$ is Available: In this case, the routing decision utilizes the threshold values V_M^{to}, V_M^{aw} and V_M^{in} defined in message header, as shown in Fig.4. Then the following operations are made, based on the selected candidate node as discussed in subsection B.

Fig. 4. Message Structure of GSaR

- Referring to Fig.2(a) that $((D_{j,d} \geq R_d) \cap (\phi_{j,d} < \frac{\pi}{2}) \cap (V_M^{to} > T_{j,d}^{to}))$, N_i distributes $\frac{C_M}{2}$ copy tickets for the message replicated to N_j. Following lines 19 and 22 in Algorithm 2, the motivation behind this is to fast spray message copies towards the movement range estimated for N_d, as the delivery ratio is increased by enabling more message copies to exist within this range.
- If considering the local maximum problem that $((D_{j,d} \geq R_d) \cap (\phi_{j,d} < \frac{\pi}{2}) \cap (V_M^{to} \leq T_{j,d}^{to}))$, M can not be sprayed until a node holding $(V_M^{to} > T_{j,d}^{to})$ is encountered. In the worst case, this problem would delay or even degrade message delivery, particularly if the message is close to its expiration deadline. With this in mind, we have inequality (12):

$$(T_M^{ela} + T_{i,d}^{to} \leq T_M^{ini}) \qquad (12)$$

Here, T_M^{ela} is the elapsed time starting from message generation, and T_M^{ini} is the initialized lifetime of message. Considering that $(T_M^{ini} - T_M^{ela})$ is calculated as the remaining message lifetime, conditions $((T_{i,d}^{to} > T_M^{ini} - T_M^{ela}) \cap (D_{i,d} > R_d) \cap (\phi_{i,d} < \frac{\pi}{2}))$ imply that M would expire before $T_{i,d}^{to}$. To this end, M is sprayed to N_j with $\frac{C_M}{2}$ copy tickets for handling this local maximum problem, aiming that N_j would encounter other nodes with a smaller value than $T_{i,d}^{to}$ at upcoming encounter opportunity.
Recall that calculating $T_{i,d}^{to}$ is inherently with limitation, either if $(D_{i,d} < R_d)$ or $(\phi_{i,d} \geq \frac{\pi}{2})$, we then convert the inequality:

$$((T_{i,d}^{to} > T_M^{ini} - T_M^{ela}) \cap (D_{i,d} > R_d) \cap (\phi_{i,d} < \frac{\pi}{2})) \qquad (13)$$

into:

$$(V_M^{to} > T_M^{ini} - T_M^{ela}) \qquad (14)$$

By removing conditions $((D_{i,d} > R_d) \cap (\phi_{i,d} < \frac{\pi}{2}))$, the inequality (14) implies that even V_M^{to}, as the smallest value of $T_{j,d}^{to}$ recorded in the network, is still longer than the remaining message lifetime $(T_M^{ini} - T_M^{ela})$. As highlighted between lines 23 and 25 in Algorithm 2, V_M^{to} is not updated in this case because of $(V_M^{to} \leq T_{j,d}^{to})$.

Algorithm 2 Spray Phase

1: set $(C_M = L)$
2: set $(V_M^{to} = +\infty)$
3: set $(V_M^{aw} = +\infty)$
4: set $(V_M^{in} = 0)$
5: **for** each encounter between N_i and N_j **do**
6:     **for** each M carried by N_i **do**
7:         **if** $(C_M > 1)$ **then**
8:             **if** N_j already has a copy of M **then**
9:                 update V_M^{to}, V_M^{aw} and V_M^{in}, for M and its copy carried by both N_i and N_j
10:             **else if** $L(d)_{i,j}$ is unavailable **then**
11:                 **if** $(\omega_{i,j} > \frac{\pi}{2})$ **then**
12:                     replicate M to N_j with $\frac{C_M}{2}$ copy tickets
13:                     keep $(C_M - \frac{C_M}{2})$ copy tickets for M in N_i
14:                 **else if** $((\omega_{i,j} = 0) \cap (S_i < S_j))$ **then**
15:                     replicate M to N_j with $\frac{C_M}{2}$ copy tickets
16:                     keep $(C_M - \frac{C_M}{2})$ copy tickets for M in N_i
17:                 **end if**
18:             **else if** $L(d)_{i,j}$ is available **then**
19:                 **if** $((D_{j,d} \geq R_d) \cap (\phi_{j,d} < \frac{\pi}{2}) \cap (V_M^{to} > T_{j,d}^{to}))$ **then**
20:                     update V_M^{to} towards $T_{j,d}^{to}$
21:                     replicate M to N_j with $\frac{C_M}{2}$ copy tickets
22:                     keep $(C_M - \frac{C_M}{2})$ copy tickets for M in N_i
23:                 **else if** $((D_{j,d} \geq R_d) \cap (\phi_{j,d} < \frac{\pi}{2}) \cap (V_M^{to} > T_M^{ini} - T_M^{ela}))$ **then**
24:                     replicate M to N_j with $\frac{C_M}{2}$ copy tickets
25:                     keep $(C_M - \frac{C_M}{2})$ copy tickets for M in N_i
26:                 **else if** $((D_{j,d} \geq R_d) \cap (\phi_{j,d} \geq \frac{\pi}{2}) \cap (V_M^{aw} > D_{j,d}^{aw}))$ **then**
27:                     update V_M^{aw} towards $D_{j,d}^{aw}$
28:                     replicate M to N_j with $(C_M = 1)$ copy ticket
29:                     keep $(C_M - 1)$ copy tickets for M in N_i
30:                 **else if** $((D_{j,d} < R_d) \cap (V_M^{in} < T_{j,d}^{in}))$ **then**
31:                     update V_M^{in} towards $T_{j,d}^{in}$
32:                     replicate M to N_j with $\frac{C_M}{2}$ copy tickets
33:                     keep $(C_M - \frac{C_M}{2})$ copy tickets for M in N_i
34:                 **else if** $((D_{j,d} < R_d) \cap (V_M^{in} > T_M^{ini} - T_M^{ela}))$ **then**
35:                     replicate M to N_j with $\frac{C_M}{2}$ copy tickets
36:                     keep $(C_M - \frac{C_M}{2})$ copy tickets for M in N_i
37:              **end if**
38:             **end if**
39:         **end if**
40:     **end for**
41: **end for**

- When N_j is moving away from the movement range estimated for N_d, as given by $((D_{j,d} \geq R_d) \cap (\phi_{j,d} \geq \frac{\pi}{2}))$, the message is sprayed to N_j satisfying $(V_M^{aw} > D_{j,d}^{aw})$, with $(C_M = 1)$ copy ticket distributed. Referring to Fig.2(b), this is because it is beneficial to spray more message copies towards the movement range in relation to N_d for reducing the delivery delay, rather than spraying them away from this range. Meanwhile, spraying the message with $(C_M = 1)$ distributed copy ticket also increases the diffusion speed, where it will be performed by Relay Phase introduced later on. This operation is presented between lines 26 and 29 in Algorithm 2.
- Considering that $(D_{j,d} < R_d)$ shown in Fig.2(c), mes-

sages are sprayed to the candidate nodes which are with long time duration moving within the movement range estimated for destination, this increases the possibility to directly encounter destination. In light of this, as presented between lines 30 and 33, N_i replicates a message copy to N_j, with $\frac{C_M}{2}$ copy tickets distributed given the condition $(V_M^{in} < T_{j,d}^{in})$.

- Besides, conditions $((D_{j,d} < R_d) \cap (V_M^{in} > T_M^{ini} - T_M^{ela}))$ are used to continually spraying message copies, if the local maximum problem $((D_{j,d} < R_d) \cap (V_M^{in} \geq T_{j,d}^{in}))$ happens. As highlighted between lines 34 and 36 in Algorithm 2, V_M^{in} is not updated in this case because of $(V_M^{in} \geq T_{j,d}^{in})$.

3) Property of Spray Phase: Here, we denote GSaR (WH) as the version without handling the local maximum problem in Spray Phase. By referring to [26] that given a consistent message delivery ratio, Direct Delivery (DD) [27] achieves the upper bound delivery delay for any routing scheme in DTNs, in which the message is only relayed and delivered when the destination is in proximity.

In the worst case that if candidate nodes are unavailable, GSaR (WH) behaves as DD since messages are never relayed. By using $((D_{j,d} \geq R_d) \cap (\phi_{j,d} < \frac{\pi}{2}) \cap (V_M^{to} > T_M^{ini} - T_M^{ela}))$, or $((D_{j,d} < R_d) \cap (V_M^{in} > T_M^{ini} - T_M^{ela}))$ to spray messages if better candidates node are unavailable, GSaR is less likely to behave as DD. Consequently, GSaR achieves a lower delivery delay than GSaR (WH), by spraying $(L - 1)$ message copies faster. Furthermore, since each of $(L - 1)$ candidate nodes of a message is selected along a routing path independently in the Relay Phase, a longer delay in the Spray Phase adversely affects the delay of the message in the Relay Phase, and sequentially deteriorates delivery ratio within the given expiration deadline.

D. Relay Phase

The Algorithm 3 illustrates the detail of Relay Phase. Given $((D_{j,d} \geq R_d) \cap (\phi_{j,d} < \frac{\pi}{2}) \cap (V_M^{to} > T_{j,d}^{to}))$ as shown in Fig.2(a), the message with $(C_M = 1)$ copy ticket is forwarded to N_j using single copy only, towards the movement range estimated for N_d. Since this given message can not be sprayed anymore, the Relay Phase further reduces the delay that message copies could move towards the movement range estimated for N_d, instead of awaiting the node which carries this message to reach the target range given its intrinsic mobility.

Considering $(\phi_{j,d} \geq \frac{\pi}{2})$, forwarding the message with $(C_M = 1)$ copy ticket results in redundancy, because such operation does not contribute to relaying this given message towards the movement range in relation to N_d. Besides, forwarding the message with $(C_M = 1)$ copy ticket within this range is also prevented. This is because that the message has already been within its target range, and particularly, some of its copies may be carried by the candidate node moving within this range. Thus the message delivery is achieved by relying on the mobility of $(L - 1)$ candidate nodes.

Here, the routing decision will be converged, by comparing V_M^{to} with $T_{j,d}^{to}$, where V_M^{to} is the historical value updated

between at most $(L - 1)$ message copies in an ideal case[5]. Since the message transmission is unidirectional, the message with $(C_M = 1)$ copy ticket is always forwarded to the node with a lower value than V_M^{to}. Note that this operation is also similar to the design of achieving loop free in traditional network, by setting a maximum value, such as hop count to prevent further message relay. Along with this, this given message is relayed to the node holds the smallest value of $T_{j,d}^{to}$ recorded in the past, rather than being relayed to a node only holds a smaller value than $T_{i,d}^{to}$. As such, the number of transmissions for this copy is further reduced, in contrast to the local greedy nature that only comparing with the current $T_{i,d}^{to}$.

Algorithm 3 Relay Phase

1: **for** each encounter between N_i and N_j **do**
2:     **for** each M carried by N_i **do**
3:         **if** N_j already has a copy of M **then**
4:             update V_M^{to}, V_M^{aw} and V_M^{in}, for M and its copy carried by both N_i and N_j
5:         **else if** $(C_M = 1)$ **then**
6:             **if** $((D_{j,d} \geq R_d) \cap (\phi_{j,d} < \frac{\pi}{2}) \cap (V_M^{to} > T_{j,d}^{to}))$ **then**
7:                 update V_M^{to} towards $T_{j,d}^{to}$
8:                 forward M to N_j, without carrying M in N_i
9:             **end if**
10:         **end if**
11:     **end for**
12: **end for**

E. Message Management

1) Defining Message Priority: The priority P_M to manage messages is defined as follows:

If both N_i and N_j do not obtain any information about destination N_d, P_M is calculated as:

$$P_M = 1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela})}{T_M^{ini}}\right)^{C_M} \quad (15)$$

Based on the current copy ticket value C_M and remaining message lifetime $(T_M^{ini} - T_M^{ela})$, this equation considers the possibility of a message to be delivered within its maximum expiration deadline T_M^{ini}. Therefore, both a larger value of $(T_M^{ini} - T_M^{ela})$ and C_M imply a higher delivery possibility. Given that $\left(1 - \frac{(T_M^{ini} - T_M^{ela})}{T_M^{ini}}\right)^{C_M}$ is the probability that a message entitling with C_M copy tickets is not delivered within deadline, thus the equation (15) presents the probability that at least one copy[6] of this message could be successfully delivered.

In another case if the historical geographic information of N_d is available, we classify P_M depending on whether N_j is currently within the estimated movement range for N_d:

- If $(D_{j,d} \geq R_d)$, the probability that M reaches the movement range of N_d before $(T_M^{ini} - T_M^{ela})$, is calculated as $\frac{(T_M^{ini} - T_M^{ela}) - V_M^{to}}{(T_M^{ini} - T_M^{ela})}$. Here, since V_M^{to} will not be updated

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[5] Although this message copy is not forwarded either given $((D_{j,d} \geq R_d) \cap (\phi_{j,d} \geq \frac{\pi}{2}))$, or $(D_{j,d} < R_d)$, V_M^{aw} and V_M^{in} are still updated. This is because that other copies of this message may still be performed by Spray Phase.

[6] It is referred as the one with $(C_M = 1)$ copy ticket only.

towards a smaller value in case that $((\phi_{j,d} \geq \frac{\pi}{2}) \cap (D_{j,d} \geq R_d))$ during routing process, a negative value of $(T_M^{ini} - T_M^{ela}) - V_M^{to}$ implies that M will expire before being sprayed towards the target range.

Next, by considering the copy ticket C_M, the message with a larger value of C_M implies it has not been sprayed extensively. Since a larger number of message copies will increase the message delivery probability, the message with a larger value of C_M is more important. Then, we have:

$$P_M = 1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela}) - V_M^{to}}{(T_M^{ini} - T_M^{ela})}\right)^{C_M} \quad (16)$$

- Similarly, when considering $(D_{j,d} < R_d)$, a negative value of $(T_M^{ini} - T_M^{ela}) - V_M^{in}$ implies that M will expire, before the maximum time duration moving within the movement range estimated for N_d. In this case, we have:

$$P_M = 1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela}) - V_M^{in}}{(T_M^{ini} - T_M^{ela})}\right)^{C_M} \quad (17)$$

In light of this, the message priority is defined by equation (18), where the P_M is calculated in an ideal case[7]. Meanwhile, the definition of P_M implies to transmit those messages processed by Spray Phase with a higher priority, due to a larger value of C_M.

$$P_M = \begin{cases} 1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela})}{T_M^{ini}}\right)^{C_M} & \text{if } L(d)_{i,j} \text{ is unavailable} \\ 1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela}) - V_M^{to}}{(T_M^{ini} - T_M^{ela})}\right)^{C_M} & \text{else if } (D_{j,d} \geq R_d) \\ 1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela}) - V_M^{in}}{(T_M^{ini} - T_M^{ela})}\right)^{C_M} & \text{else if } (D_{j,d} < R_d) \end{cases} \quad (18)$$

2) Message Transmission: It is observed that the message with the largest value of $1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela}) - V_M^{in}}{(T_M^{ini} - T_M^{ela})}\right)^{C_M}$ is considered with the highest priority for transmission. However, if we consider the case to transmit the message with the negative value of $1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela}) - V_M^{in}}{(T_M^{ini} - T_M^{ela})}\right)^{C_M}$, prior to those with the positive value of $1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela}) - V_M^{to}}{(T_M^{ini} - T_M^{ela})}\right)^{C_M}$, the former message may get expired before being delivered to its destination, although it is within the movement range estimated for destination.
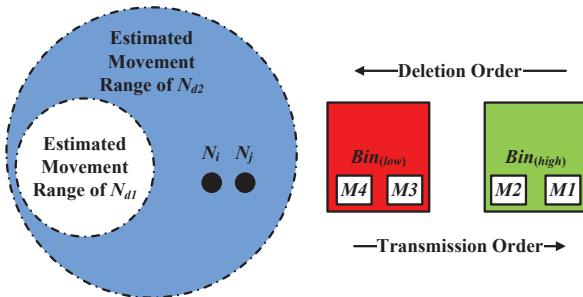

Fig. 5. Example of Message Management

Considering those sprayed without the knowledge of N_d, the messages replicated in relation to the movement range estimated for N_d are considered to be more important. This is because that it is desirable to transmit the messages with a higher priority if knowing where their destinations are. As an example shown in Fig.5 where N_i and N_j are unaware of the destination N_{d3} for $M3$, and N_{d4} for $M4$. Assuming that $P_{M1} = 1 - \left(1 - \frac{(T_{M1}^{ini} - T_{M1}^{ela}) - V_{M1}^{to}}{(T_{M1}^{ini} - T_{M1}^{ela})}\right)^{C_{M1}} = 3$, $P_{M2} = 1 - \left(1 - \frac{(T_{M2}^{ini} - T_{M2}^{ela}) - V_{M2}^{in}}{(T_{M2}^{ini} - T_{M2}^{ela})}\right)^{C_{M2}} = 1$, $P_{M3} = 1 - \left(1 - \frac{(T_{M3}^{ini} - T_{M3}^{ela})}{T_{M3}^{ini}}\right)^{C_{M3}} = 4$ and $P_{M4} = 1 - \left(1 - \frac{(T_{M4}^{ini} - T_{M4}^{ela})}{T_{M4}^{ini}}\right)^{C_{M4}} = 2$ respectively, then $M1$ is considered with the highest priority for transmission, although N_j is out of the movement range estimated for N_{d1}.

Algorithm 4 Message Management

1: **for** each encounter between N_i and N_j **do**
2:    both of them update the ID of the delivered messages
3:    both of them delete the copies of the delivered messages from their buffer space
4:    **for** each message M replicated to N_i **do**
5:       **if** both N_i and N_j have knowledge about N_d **then**
6:          P_M is calculated based on the cases, where $(D_{j,d} \geq R_d)$ or $(D_{j,d} < R_d)$
7:          transmit M according to the descending order of P_M
8:       **else if** neither N_i nor N_j has encountered N_d in the past **then**
9:          P_M is calculated based on the case where $L(d)_{i,j}$ is unavailable
10:          transmit M according to the descending order of P_M
11:       **end if**
12:    **end for**
13:    **if** N_j does not have sufficient buffer space to receive M **then**
14:       **if** neither N_i nor N_j has knowledge about N_d **then**
15:          N_j removes its carried messages with the lowest value of P_M from $Bin_{(low)}$
16:       **else**
17:          N_j removes its carried messages with the lowest value of P_M from $Bin_{(high)}$
18:       **end if**
19:    **end if**
20: **end for**

---

3) Buffer Management: Because of the intermittent connections between nodes in DTNs, each node uses a buffer to store the messages needed to transmit. Here, messages are classified into two bins $Bin_{(high)}$ and $Bin_{(low)}$ respectively, considering the awareness of destination based on the view of its current carrier. For example, if neither N_i nor N_j, did not meet N_d in the past, then the M destined to N_d is put in $Bin_{(low)}$.

Since each node may not have sufficient space to store all the received messages, messages classified into $Bin_{(low)}$ are deleted prior to those classified into $Bin_{(high)}$, following the same rule discussed for message transmission. Referring to Fig.5, an example for message deletion is also shown. This is implemented to keep the message where its destination is known, as compared to the case when keeping the message if without the knowledge about its destination. Regarding the messages classified into the same bin, they are also prioritized according to the definition of P_M. For example, the message with a negative value of $1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela}) - V_M^{in}}{(T_M^{ini} - T_M^{ela})}\right)^{C_M}$ is deleted prior to those with a

positive value of $1 - \left(1 - \frac{(T_M^{ini} - T_M^{ela}) - V_M^{to}}{(T_M^{ini} - T_M^{ela})}\right)^{C_M}$, although the former has already been within the movement range estimated for destination.

If a message copy is successfully delivered, it is essential to delete other copies of this message in the network, in order to free the buffer space for other undelivered messages. In this case, each node maintains a list to record the IDs of delivered messages in the network, then exchanges and updates the information in this list. Note that a node carrying the copy of the delivered message may not receive this knowledge in time, but the node will finally receive it with high probability because of the flooding nature of the acknowledgement information. In the worst case that a node without this knowledge will constantly carry the delivered message copy until the destination node is in proximity, the destination will delete the copy since it has been already received.

F. Discussion on Storage for Information Update

Firstly, the threshold values V_M^{to}, V_M^{aw} and V_M^{in} are the flags recorded in each data message. The size of each flag is very small compared with the size of data itself. Secondly, we do envision infinite buffer space for main evaluation, considering the nature of DTNs that nodes always store messages until a new encounter is available for message relay, known as Store-Carry-Forward. Therefore, the size of routing table can be ignored compared with data messages stored in each node. Concerning the storage overhead of maintaining the updated routing information, it is $O(K^2)$ where the number of nodes in network in denoted as K, similar to other works using history information for making routing decision. For real implementation, the structure of routing table should be a "Map <Key, Value>" structure, where "Key" is the nodal ID, and "Value" is a tuple containing historical based location, average moving speed as well as encounter time.

V. PERFORMANCE EVALUATION

The performance is evaluated using the Opportunistic Network Environment (ONE) [28] version 1.4.1, a well known java based simulator particularly contributes to the research on DTN routing. The main evaluation is based on the Helsinki city scenario shown in Fig.6(a).

Considering the map route has an effect on the performance of geographic routing assuming the continuous moving direction for prediction, we select other two city scenarios from real world shown in Fig.6(b) and Fig.6(c) respectively via OpenStreetMap, and convert them into the WKT format interpreted by ONE. Mobile node chooses the shortest path to a randomly selected place via the Dijkstra shortest path scheme, based on their current location and moving speed. Under city scenarios, 100 mobile nodes are configured with the uniformly varied [1~10] m/s moving speed along a generated path. We aim to examine how the variation of the nodal moving speed affects the performance of routing scheme. In other words, the nodal moving speed is different depending on the path that a node is moving.

For the purpose of generalization that GSaR ideally assumes a constant moving speed without movement restriction,

we also select a 1000×1000 m^2 Random WayPoint (RWP) scenario, where 100 mobile nodes with [5~5] m/s constant moving speed are configured. Note that mobile nodes move randomly and freely without restrictions in RWP, as compared to the city scenario where the nodal movement is restricted by the map route. In RWP, each node moves along a zigzag line from one waypoint to the next waypoint, where the waypoints are uniformly distributed over the given area. The initial distribution of mobile nodes under all scenarios varies based on the corresponding simulation seed.

The communication technique[8] is configured as 2Mbit/s bandwidth and 10m transmission range, referred to [7], [8] considering the communication between those short range devices, e.g., people with mobile phone in vehicles. Note that the network is sparse and highly dynamic, since the number of connectivities is small as compared to network area, considering the given speed configuration and transmission range. Messages are propagated via opportunistic behavior, as bridged by the lightweight mobile nodes via the Bluetooth. In our simulations, the message size is set to large value, envisioned for large file transmission in DTNs. Messages are set with 90 minutes lifetime, 30s generation interval and 500 KBytes size, generated before 27000s with additional $90 \times 60 = 5400$s to consume the unexpired messages.

Given the above default configurations, GSaR is compared with AaR [7], CaD [8], SaF [12], LSF [13] and PROPHET [17], where the time window W in GSaR is set with 5s. The default value L for all the spray based schemes is configured as 10, referring to [12] that choosing L equals to about 10% of the total number of nodes in the network. The performance is evaluated in terms of varied message lifetime, generation interval, varied maximum moving speed and value of L, given infinite buffer space. The effect of limited buffer space is also shown for further comparison. To provide average results, this 32400s = 9 hours' simulation is run independently with different seeds and shown with 95% confidence interval.

We further import an energy model for all the evaluated routing schemes to show their energy consumption. Here, the initial energy of the battery for mobile nodes is fixed as 3600000 units, and energy consumed for transmission is fixed as 100 units per 0.1s. Note that the energy might be wasted due to the unsuccessful transmission, where only a proportion of message size has been transmitted if the connectivity is disrupted. Then the product of the time duration for transmitting this proportion and the energy consumed is also taken into account. The main purpose we evaluate the energy consumption is to show the fairness of routing schemes. Note that we do not account for the energy consumption for nodal discovery and receiving, as their values are the same for all evaluated routing schemes. Here, only the energy consumption in relation to number of times a node relays messages is shown as result. A good fairness means the resource, such as energy used by each node to relay messages is equal.

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[8]In DTNs, knowledge of nodes in proximity is essential before initiating any kind of data transfer. For realistic application, a short range WiFi is alternative to Bluetooth within a large area, compared with the size of scenarios we use in simulation. The interval and duration of discovery can be adjusted based on the current node's location and the location of nodes it has encountered.

(a) Helsinki City, 4500m×3400m   (b) Tokyo City, 2500m×2500m   (c) San Francisco City, 2500m×2500m
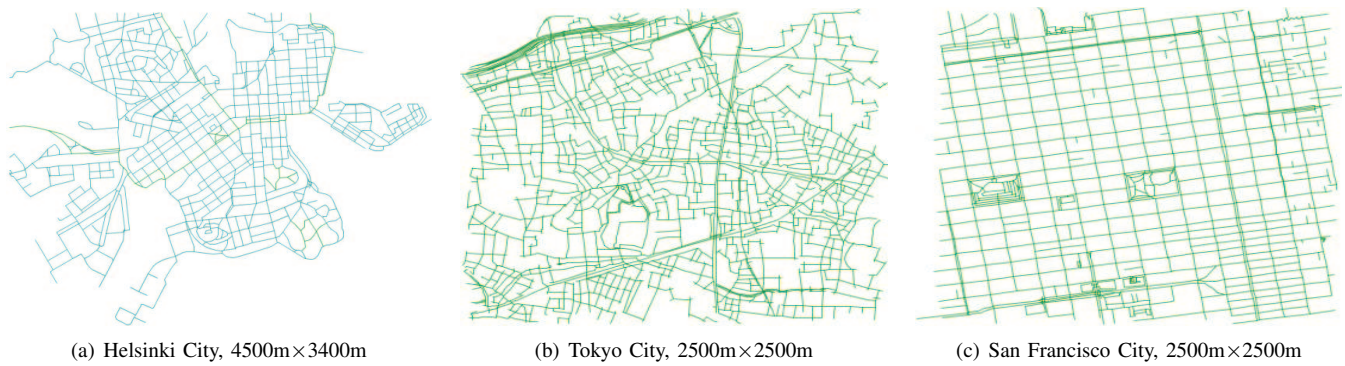
Fig. 6. Snapshots of the Helsinki City, Tokyo City and San Francisco City Scenarios

The evaluation metrics are explained as follows:

- **Delivery Ratio**: It is the ratio between the number of messages delivered and the total number of messages generated.
- **Average Delivery Latency**: It is the average delay for the messages to be delivered from the source node to destination.
- **Overhead Ratio**: It is the ratio between the number of relayed messages (excluding the delivered messages) and the number of delivered messages.

A. Influence of Message Lifetime

We observe GSaR outperforms other schemes in Fig.7(a) especially given short message lifetime. Here, GSaR overcomes the local maximum problem happens in each case, which further increases the possibility that messages can be delivered within the expiration deadline. In particular, CaD begins to outperform SaF given the increased message lifetime. This is because that although the redundant message replications in CaD are reduced by using DF, messages with short lifetime might not be delivered if using a less number of message copies. Since mobile nodes are with high speed, SaF also performs well in this case given the nature of spray based routing scheme, that is relying on the highly mobile node to deliver messages only via the limited number of copies. Here, the reason LSF performs worst given the short message lifetime is that only replicating a limited number of message copies is insufficient for delivery.

Meanwhile, GSaR keeps the lowest average delivery latency in Fig.7(b). Here, the slope of this performance implies the capability of routing decision, where PROPHET estimating the encounter probability based on the frequency, performs worst due to without considering the recent encounter time as adopted by LSF. The contribution from handling the local maximum problem also reduces the delivery latency by promoting message spraying, particularly if the message is close to its expiration deadline.

In Fig.7(c), GSaR and CaD benefit from a significantly decreased overhead ratio given the increased message lifetime, as compared to SaF and PROPHET. Since the number of message replications is unlimited in CaD, more message copies are replicated even if they may expire soon. In light of this, CaD is with the dramatically decreased overhead

ratio following an increased message lifetime. Although SaF achieves a close delivery ratio compared to GSaR and CaD, its overhead ratio is higher than these two geographic routing schemes, due to forwarding messages based on the unstable topology based encounter history.
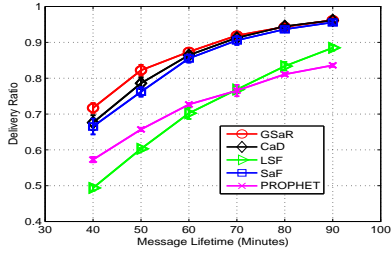
B. Influence of Message Generation Interval

In Fig.8(a), all the schemes benefit from the alleviated bandwidth contention, by achieving the increased delivery ratio. This is different from CaD without limiting the number of message copies, where the bandwidth contention becomes dramatically in case of 10 seconds generation interval.

GSaR also maintains the lowest average delivery latency in Fig.8(b). Compared with geographic routing scheme CaD, PROPHET does not achieve a significantly decreased average delivery latency, due to using the utility metric in relation to encounter frequency to make routing decision and message transmission. It is highlighted that the spray based routing schemes, like GSaR, SaF and LSF, obtain a dramatically decreased average delivery latency. This is because that replicating a small number of message copies does not result in too much bandwidth contention. The observation in Fig.8(b) implies that it is more effective to consider the nodal mobility and message lifetime for making routing decision and transmission, in addition to limiting the number of message replications for efficient delivery.

Although both GSaR and CaD handle the local maximum problem, they achieve a smoother slope regarding overhead ratio in Fig.8(c), due to the nature of DF to reduce the replication redundancy. Meanwhile, since LSF limits the number of message replications to be $(L-1)$ only, it is with the lowest overhead ratio.

### C. Influence of Maximum Moving Speed

In one case, if increasing the maximum moving speed with a moderate level, the message delivery ratio is accordingly increased because the high nodal mobility yields more encounter opportunities. In another case, a further aggressively high moving speed inevitably reduces the encounter duration, as such all the schemes suffer from a decreased delivery ratio. With this in mind, in Fig.9(a), all the schemes firstly obtain the increased delivery ratio if the maximum moving speed
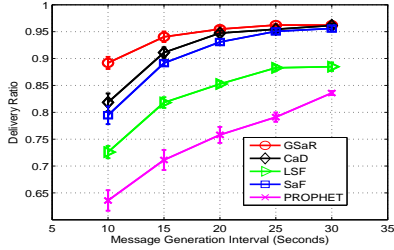
(a) Delivery Ratio
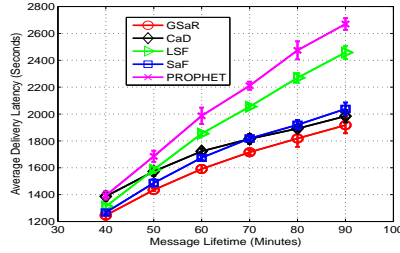
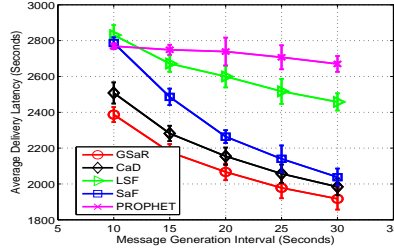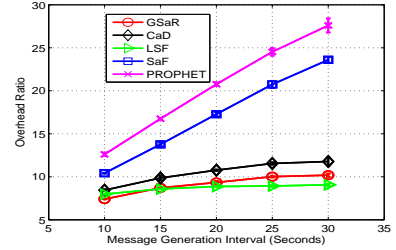(b) Average Delivery Latency
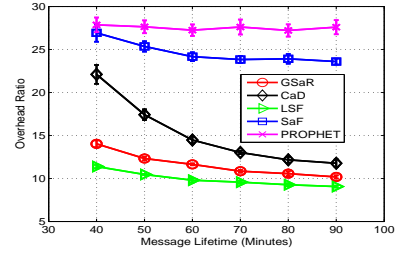
(c) Overhead Ratio

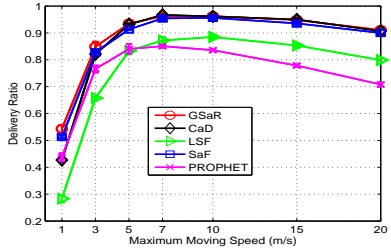Fig. 7. Influence of Message Lifetime

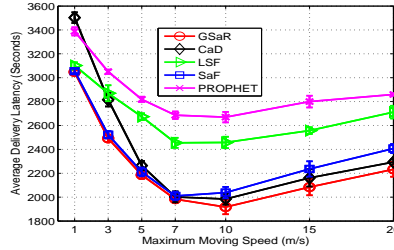(a) Delivery Ratio

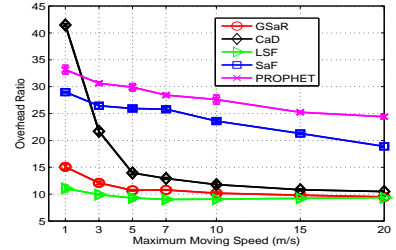(b) Average Delivery Latency

(c) Overhead Ratio

Fig. 8. Influence of Message Generation Interval

(a) Delivery Ratio

(b) Average Delivery Latency

(c) Overhead Ratio

Fig. 9. Influence of Maximum Moving Speed

is varied up to 7 m/s, while their performance is degraded if the maximum moving speed is faster. Without forwarding message with ($C_M = 1$) copy ticket, LSF performs worst if mobile nodes are not highly mobile, as indicated when the maximum moving speed is slower than 5 m/s.

Due to a moderately high mobility that helps to diffuse message copies, the average delivery latency is decreased for all the routing schemes. However, a further increased average delivery latency happens herein, because the encounter duration between pairwise nodes is insufficient to successfully transmit all the replicated messages. In light of this, all the schemes in Fig.9(b) suffer from a fluctuation regarding this performance metric, where GSaR keeps the lowest level.

GSaR also achieves the lowest overhead ratio in Fig.9(c), where the local maximum problem in Spray Phase is prevented, if mobile nodes are fast enough. This is because that, by using a smaller value of V_M^{to} and V_M^{in} to compare with ($T_M^{ini} - T_M^{ela}$), a less number of message copies are sprayed. In contrast, considering that CaD is without limiting the number of message replications, a slow moving speed yields more message copies to be replicated given local maximum

problem. Although CaD also reduces the message replication to the candidate node via DF, the slow nodal movement is unhelpful for message delivery. Therefore, CaD suffers from the highest overhead ratio given 1 m/s maximum moving speed, because it makes more message replications but most of them are not delivered.

D. Influence of Initial Copy Ticket Value

We observe LSF outperforms SaF at initial stage in Fig.10(a). This is because that when the number of message copies is very small, selecting the candidate node which met destination more recently, as performed by LSF, increases the message delivery potential. SaF performs worse than LSF given a small L, because the former sprays message without selecting candidate node. Here, GSaR outperforms LSF and SaF, by using historical geographic information to estimate the delivery potential of mobile node, rather than the historical topology based encounter information under high dynamic scenario. If continually increasing the value of L, SaF begins to outperform LSF. This is because a larger L contributes to a higher possibility that one of the sprayed ($L - 1$)

(a) Delivery Ratio

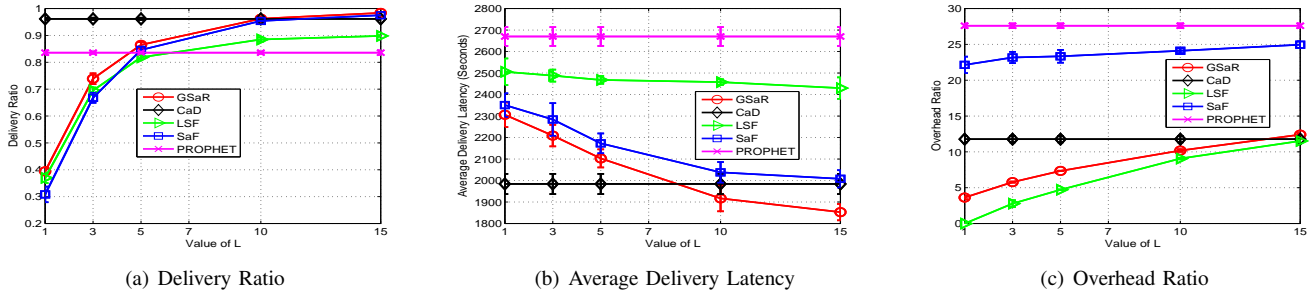(b) Average Delivery Latency

(c) Overhead Ratio

Fig. 10. Influence of Initial Copy Ticket Value

message copies can be delivered timely, particularly if with the assistance of forwarding scheme adopted by SaF.

In Fig.10(b), the average delivery latency is reduced by spraying more message copies. It is observed that GSaR and SaF benefit more from the increased L, due to further forwarding message with ($C_M = 1$) copy ticket, as compared to LSF which only relies on the direct encounter between destination to deliver this given message. The advantage of using geographic routing scheme is also indicated herein, as GSaR can achieve the lowest average delivery latency given the small L. Furthermore, LSF suffers from a smooth decreased average delivery latency, due to without using the nodal mobility to relay the message with ($C_M = 1$) copy ticket.

In Fig.10(c), all the spray based schemes suffer from the increased overhead ratio for delivering more messages. In GSaR, as the number of message being relayed is higher than ($L-1$), the overhead ratio of GSaR is slightly higher than LSF. Note that since SaF does not consider the stable convergence under high dynamic scenario, the message with ($C_M = 1$) copy ticket is forwarded with redundancy. As such SaF suffers from a higher overhead ratio than LSF and GSaR.

E. Influence of Buffer Space

In Fig.11(a), we observe GSaR achieves the highest delivery ratio particularly given a small buffer space. One reason is that GSaR only sprays a limited number of message copies into the network, thus the buffer occupation for message copies is less than that consumed by CaD and PROPHET. By comparing with SaF and LSF, another reason is that GSaR deletes the message with the least delivery potential if buffer overflows. Note that in GSaR, the delivery potential is estimated considering the number of copies, historical nodal movement as well as message lifetime. Different from the observation given infinite buffer space in Fig.7(a), SaF performs worse than LSF given the small buffer space herein. As indicated previously, the buffer space of some mobile nodes might be exhausted in SaF, due to always forwarding message with ($C_M = 1$) copy ticket to the nodes with unstable utility metric. This short-term behavior results in aggressive message deletion.

In Fig.11(b), since a larger buffer space increases the possibility that messages would survive in the network, all the schemes are with an increased average delivery latency. Although SaF achieves a lightly lower average delivery latency

than GSaR when the buffer space is smaller than 6MB, the former is with a lower delivery ratio Fig.11(a).

By using DF, GSaR and CaD benefit from a lower overhead ratio in Fig.11(c), with a smooth decreased slope. This is because that a large number of message copies results in aggressive contention of buffer space, while the deleted messages copies still require the future replication and transmission. In light of this, PROPHET and SaF perform worse than other schemes, due to either without limiting the number of message copies or without using DF to control redundancy. Since the number of message replications is limited up to ($L-1$) in LSF, it is with the lowest overhead ratio.

F. Comparison Between GSaR and AaR

TABLE III
COMPARISON BETWEEN GSaR AND AaR

	Delivery Ratio		Average Delivery Latency		Overhead Ratio	
	GSaR	AaR	GSaR	AaR	GSaR	AaR
Default Configuration	0.962 (±0.006)	0.990 (±0.001)	1917s (±60)	1902s (±17)	10.19 (±0.19)	20.48 (±0.36)
10s Generation Interval	0.892 (±0.011)	0.865 (±0.011)	2387s (±42)	2426s (±73)	7.40 (±0.02)	8.81 (±0.05)
2MB Buffer Space	0.636 (±0.014)	0.634 (±0.006)	1676s (±39)	1588s (±30)	12.47 (±0.24)	31.95 (±0.27)
1m/s Maximum Moving Speed	0.543 (±0.014)	0.515 (±0.015)	3048s (±14)	3321s (±42)	15.08 (±0.44)	36.02 (±0.25)
20m/s Maximum Moving Speed	0.911 (±0.008)	0.953 (±0.002)	2233s (±62)	2370s (±23)	9.50 (±0.13)	15.83 (±0.06)

From the results in TABLE III, we observe that GSaR as a spray based routing scheme, achieves a close delivery ratio and average delivery latency as the utility replication based scheme AaR. This is because GSaR replicates each message to a small number of candidate nodes, as compared to AaR makes message replication to each better candidate node selected greedily. Therefore, the latter yields more message copies, which degrades the performance given limited bandwidth and buffer space. Similar to CaD, AaR is also without the design when the historical geographic information is unavailable, as such GSaR outperforms AaR given slow moving speed.

G. Influence of Handling the Local Maximum Problem

In TABLE IV, the comparison between GSaR and GSaR (WH) is provided. In GSaR, messages are delivered by using
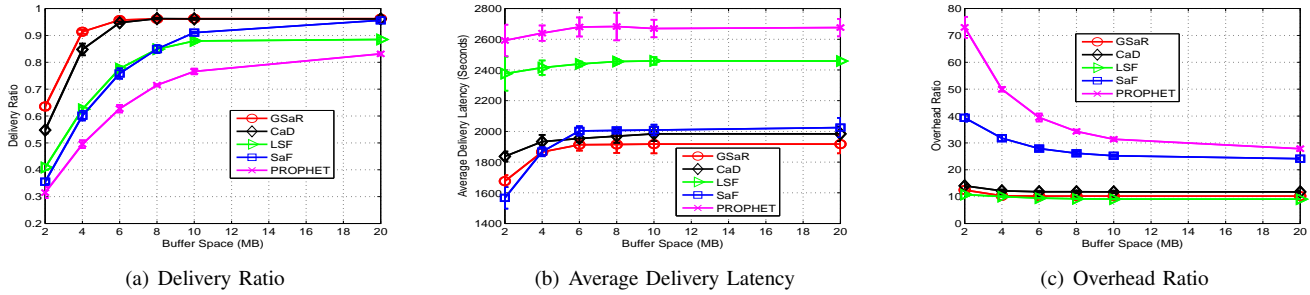
(a) Delivery Ratio

(b) Average Delivery Latency

(c) Overhead Ratio

Fig. 11. Influence of Buffer Space

TABLE IV
INFLUENCE OF HANDLING THE LOCAL MAXIMUM PROBLEM

Message Lifetime	Delivery Ratio		Average Delivery Latency		Overhead Ratio	
	GSaR	GSaR (WH)	GSaR	GSaR (WH)	GSaR	GSaR (WH)
40 Minutes	0.717 (±0.014)	0.651 (±0.002)	1246s (±31)	1224s (±35)	14.04 (±0.40)	12.60 (±0.17)
90 Minutes	0.962 (±0.006)	0.945 (±0.010)	1917s (±60)	1929s (±57)	10.19 (±0.19)	9.67 (±0.11)

more independent paths, thanks to handling the local maximum problem. Thus it outperforms GSaR (WH) by delivering messages faster before the expiration deadline, based on the discussed property of Spray Phase.

H. Discussion Regarding Fairness And Energy Consumption

The fairness is a measurement of the energy distribution over the different mobile nodes. In case of 10m transmission range, as shown in Fig.12(a), AaR consumes much energy than GSaR and CaD, due to the local greedy nature that selecting any candidate node with a better delivery potential than current message carrier. Furthermore, GSaR guarantees the lowest overall energy consumption and a relatively fair distribution over mobile nodes, particularly comparing with AaR. In Fig.12(b), when increasing the transmission range to 50m, AaR suffers from a large variation regarding energy distribution. In both cases, LSF maintains the highest residual energy due to replicating a message up to L times only, in spite of a lower delivery ratio particularly given 10m transmission range.

I. Performance Under Other Scenarios

Given the results under other scenarios, GSaR achieves a high delivery ratio as close to that achieved by AaR, CaD and SaF in Fig.13(a), Fig.14(a) and Fig.15(a) respectively, similar to previous results under the Helsinki city scenario. Note that since these three scenarios are with a smaller area, LSF achieves a higher delivery ratio given that nodal mobility is able to travel the entire area of these scenarios faster. Meanwhile, GSaR achieves the lowest overhead ratio in Fig.13(c), Fig.14(c) and Fig.15(c), although its average delivery latency is higher than AaR in Fig.13(b), Fig.14(b) and Fig.15(b). Note that by limiting the number of message replications, GSaR achieves a lower overhead ratio than CaD.
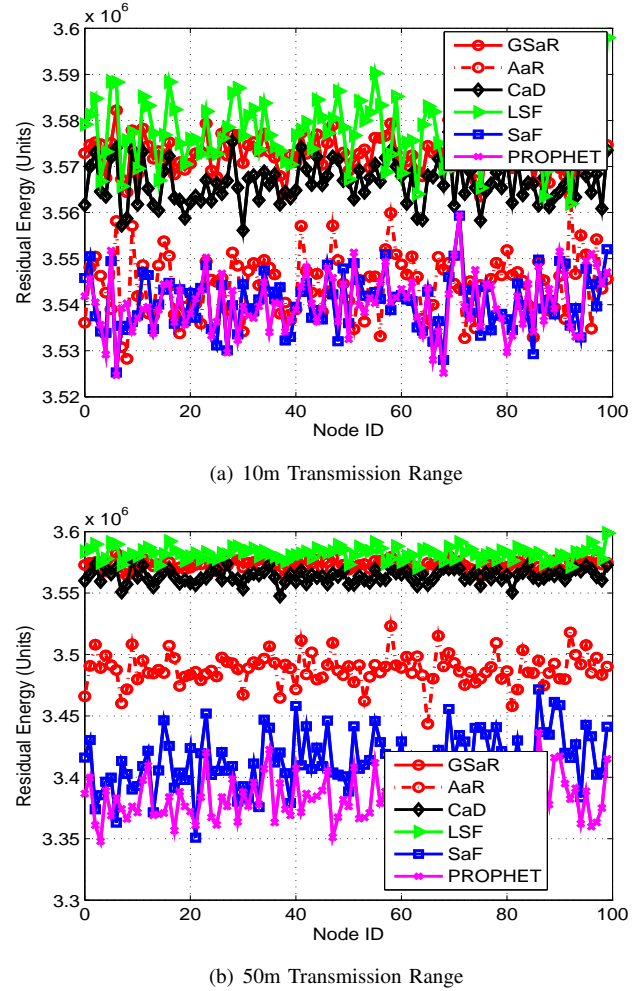

(a) 10m Transmission Range

(b) 50m Transmission Range

Fig. 12. Energy Distribution

VI. CONCLUSION

This article investigated the research on geographic routing in DTNs. The proposed GSaR is based on the spray based routing nature, by only creating a limited number of message copies in the network for efficient delivery. Considering that the realtime location of mobile destination is unavailable due to sparse network density, GSaR estimates a movement range of destination via its historical location, average moving speed recorded in the past. Mainly, the Spray and Relay Phases are performed to expedite message copies being sprayed towards
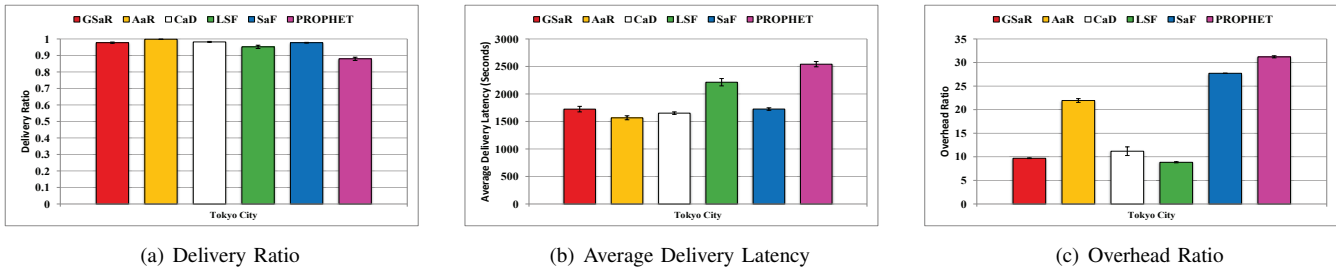
| (a) Delivery Ratio | (b) Average Delivery Latency | (c) Overhead Ratio |

Fig. 13.   Performance Under the Tokyo City Scenario With Default Configuration

| (a) Delivery Ratio | (b) Average Delivery Latency | (c) Overhead Ratio |
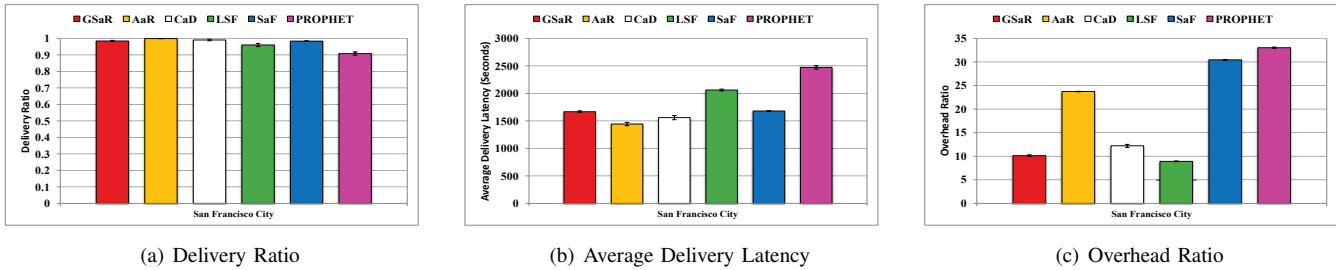
Fig. 14.   Performance Under the San Francisco City Scenario With Default Configuration

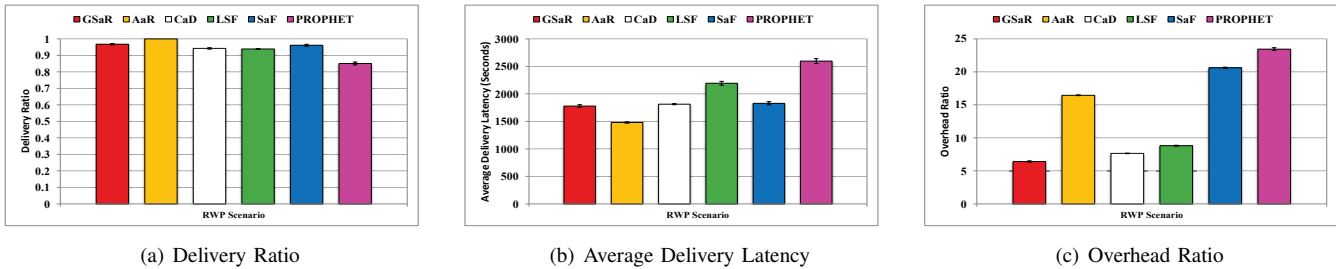| (a) Delivery Ratio | (b) Average Delivery Latency | (c) Overhead Ratio |

Fig. 15.   Performance Under the RWP Scenario With Default Configuration

this range, postpone them being sprayed out of this range as well as to prevent them being sprayed away from this range. Furthermore, the combination of them is based on the investigation of DF to overcome the limitation of routing decision as well as handling the local maximum problem. GSaR is evaluated with the design of message management to perform given the limited bandwidth and buffer space. Compared with existing routing schemes, one advantage of GSaR is the efficiency in terms of a low overhead ratio given high delivery ratio. Another advantage is a fair distribution of the lowest energy consumption over the mobile nodes in the network.

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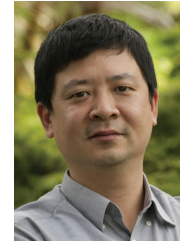
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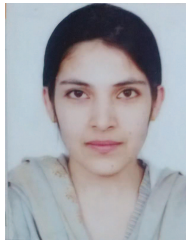

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