A Trajectory-Driven Opportunistic Routing Protocol for VCPS

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***Abstract*—By exploring sensing, computing and communication capabilities on vehicles, Vehicular Cyber-Physical Systems (VCPS) are promising solutions to provide road safety and traffic efficiency in Intelligent Transportation Systems (ITS). Due to high mobility and sparse network density, VCPS could be severely affected by intermittent connectivity. In this paper, we propose a Trajectory-Driven Opportunistic Routing (TDOR) protocol, which is primarily applied for sparse networks, e.g., Delay/Disruption Tolerant Networks (DTNs). With geographic routing protocol designed in DTNs, existing works primarily consider the proximity to destination as a criterion for next-hop selections. Differently, by utilizing GPS information of on-board vehicle navigation system to help with data transmission, TDOR selects the relay node based on the proximity to trajectory. This aims to provide reliable and efficient message delivery, i.e., high delivery ratio and low transmission overhead. TDOR is more immune to disruptions, due to unfavorable mobility of intermediate nodes. Performance evaluation results show TDOR outperforms well known opportunistic geographic routing protocols, and achieves much lower routing overhead for comparable delivery ratio.**

***Index Terms*—VCPS, Sparse Networks, DTNs, Trajectory.**

I. INTRODUCTION

With continuously increasing attention on transiting information systems from the pure cyber space to a hybrid cyber-physical space, Vehicular Cyber-Physical Systems (VCPS) [1] aim to integrate computing/communication capabilities into Intelligent Transportation Systems (ITS). It supports various applications [2], including road safety improvement, on-road infotainment, and environment estimation, etc.

By applying Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communications [3], existing research works have shown great gains on achieving delay reduction as well as reliable data transfer in the physical world, through optimal routing protocols in Vehicular Ad hoc NETworks (VANETs). Furthermore, with opportunistic routing, the nodal mobility is able to improve the coverage of network. This inspires fruitful exchanges of speed/location information [4], [5], and delivers data to the "sink node" for postprocessing.

In VCPS, the major challenge for V2V communication comes from the intermittently disrupted connectivity, normally due to the short encounter duration between vehicles. As the research efforts from Delay/Disruption Tolerant Networking (DTN) routing [6], the communication in VCPS is conducted to a "Store-Carry-Forward (SCF)[1]" manner. Such SCF-enabled routing protocols have been intensively studied in literature, as a feasible way to tackle intermittently disrupted connectivities in VCPS [7]. As already identified in [6], majority of previous works aim to capture the topological information (e.g., the number of encounters, encounter duration, inter-meeting time, etc) [8]–[12] for message delivery. In sharp contrast, a few works [13]–[17] studied how to enable geo-centric approaches to bridge network communication.

GPS has been widely used in ITS. In [18], the use of road-map information for ground vehicles tracking is proposed to enhance vehicles' position prediction. In contrast to vehicle detection and tracking, [19] promotes autonomous car navigation using road profile. For communication purpose, geographic routing [20], as originally applied in dense networks, requires each node to know the location of its own (and also the location of destination). Upon this condition, a message is gradually delivered to its destination, referring to message delivery under a scenario with high network density. The message delivery is generally based on a certain criterion (e.g., the shortest distance) that is used to select appropriate relay node. Here, the geometric information including distance, direction as well as moving speed can contribute to various metrics [21], [22] for the selection of relay node.

As a closely related approach to geographic routing, Trajectory Based Forwarding (TBF) [23] was fundamentally an alternative to routing in a dense networks. Essentially, the forwarding path is initialized and formulated as a continuous function (a sequence of road topological links), this is different from geographic routing that treats as a discrete set of points (e.g., the coordinates of intermediate nodes). By concept, TBF relays a trajectory-embedded message to the node, in geographical proximity to the dedicated trajectory. This is different from geographic routing that concerns the proximity to destination (e.g., distance to the destination). Therefore, based on the trajectory fueled by TBF, a trajectory-driven routing nature is advanced by greedy decisions.

Different from geographic routing applied in dense networks [20]–[23], the sparse network density (which drives opportunistic communication) inevitably brings challenges to enable

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[1]When a vehicle carries a message while there is no contemporaneous end-to-end path to its destination or even a connectivity to any other vehicle, the message would be stored, and wait for the upcoming encounter opportunity with other vehicles to relay the message.

the traditional geographic routing in VCPS. Further to [6] that identifies the research vacancy of geographic routing in DTNs, a recent review [24] has identified several challenges arising from network sparseness, with solutions [13]–[17] under the umbrella of geographic routing. In spite of these, in this paper we investigate trajectory-driven routing, with concerns on the opportunistic communication in VCPS.

Inevitably, enabling TBF for VCPS needs to cater challenges from sparseness of network, as dynamically changed vehicles mobility may deteriorate reliable message delivery (suffering from lower delivery ratio) and increase communication cost (suffering from higher routing overhead). Certainly, there are insufficient vehicle encounters in sparse networks, for which the estimation of nodal delivery becomes important.

The aforementioned issues are generally translated as "which are selected as relays", primarily concerning nodal mobility. Our contributions are as follows:

1) TDOR enables source node to compute a mobility-immuned trajectory towards message destination to guide message delivery. The trajectory is initialized to a) relay the message towards trajectory if the message is isolated (not geographically close to the trajectory); b) relay the message towards destination by associating with the trajectory. Such a trajectory-driven policy can significantly reduce redundant routing overhead, which benefits from the logic that messages will not be re-played to nodes that are isolated from the trajectory. (e.g., nodes tend to move away or are currently too far away from the trajectory)
2) A multi-queueing system is designed, such that the message with the highest delivery potential is prioritized for transmission. This utilizes the knowledge extracted from trajectory and vehicles mobility to improve the utilization of transmission bandwidth, given opportunistic encounter with limited inter-vehicle communication duration.

II. Related Works

Various architectures for VCPS have been proposed in recent year. A CPS [2] application framework has been suggested for provisioning of a generic service to represent, manipulate, and share knowledge across DTNs, without persistent network connectivity. Since the underlying network of VCPS often suffers more from the intermittent connectivity due to vehicle mobility and sparse network density, the message delivery must be reliable against the connectivity disruptions.

In the literature, Direct Delivery (DD) [25] limits only the source node to deliver messages. Although this scheme performs only one times transmission, it is extremely slow as the delivery only happens when the destination is in proximity. Therefore, other proposed works relay messages via the qualified nodes based on utility metric [13], [26], without replicating any copy of a message. Even if they can achieve a faster delivery than DD, the performance on message delivery is dramatically degraded in sparse networks. Therefore, using redundant message copies has been widely investigated, with two main branches depending on whether or not to limit the number of copies in replicated message delivery.

A. *Unlimited Copy-Based Message Delivery*

Since Epidemic [27] floods message copies within networks, it only performs well when no contention exists for shared network resources like bandwidth and buffer space. In contrary, many previous works further utilize topological utility metrics [8]–[12] to qualify nodes for selected replication, compared to a few works which utilize geographic utility metrics [14], [15]. To enhance routing efficiency, Delegation Forwarding (DF) [28] enables a message to cache an updated threshold value (initially, it equals to the topological utility metric for destination), and relays a message copy towards a node (with a better utility metric than this cached threshold). As applied in Delegation Geographic Routing (DGR) [15], if without using DF, a node does not keep a threshold value and certainly the message carrier does not update this value after it encounters a better quality node. While if with DF, a node will raise this threshold value to the quality of a better candidate node, and further uses this threshold value for relay node selection. Thus, with the increase of its level, the replication chance of message carrier is expected to be decreased, which means the number of copies duplicated for a message will be reduced.

B. *Limited Copy-Based Message Delivery*

It is valid for previous works in this branch, that when a number of nodes in the network are sufficiently mobile, replicating a message with a limited number of copies is able to achieve an efficient message delivery. Authors in [29] propose Spray-and-Wait (SaW) algorithm, in which a copy ticket is defined for each message, to control the number of time a message can be replicated. Considering the heterogeneous nodal mobility, replicating the limited number of message copies [30] to better qualified nodes has been investigated. To expedite delivery via topological utility metric, Encounter Based Spraying Routing (EBSR) [12] further relays (but without generating additional copies) each copy. Based on geographic utility metric and underlying map topology, GeoSpray [16] calculates the Nearest Point (NP) to destination via underlying map topology to guide message relay. The Best Heterogeneity Geographic Relay (TBHGR) [17] further discusses the influence of heterogeneous nodal mobility.

C. *Research Motivation*

It should be noted that previous routing schemes [21], [22] been applied to dense VANETs (with concerns on vehicular density), however are not necessarily applicable to sparse networks. Our focus in this paper is on geographic routing designs particularly for sparse networks. As summarized in TABLE I, even though there have been some works addressing geographic routing in DTNs, by explicitly identifying the research vacancy and challenges from network sparseness, none of them is trajectory-driven. In other words, instead of making routing decision based on the proximity to destination, TDOR solves the problem by checking the proximity to trajectory, and further enables cost-efficient message delivery associated with the trajectory. This benefits to a significantly lower routing overhead, without degrading message delivery.

TABLE I
SUMMARY OF RELATED WORKS

Not Based on Geographic Information
DD [25], Epidemic [27], PROPHET [8], DTLSR [9], RAPID [10], CAMF [12], EBRR/EBSR [11], SaW [29], LSF [30]
Based on Geographic Information
—Not Trajectory Driven—
MOVE [13], AeroRP [26], GSaR [14], DGR [15], GeoSpray [16], TBHGR [17]
—Trajectory Driven—
TDOR

III. PRELIMINARY

A. System Component

We consider sparse VANETs consisting of a number of vehicles and fixed destinations. Each vehicle is equipped with Global Position System (GPS) and captures its own movement information, including current location, moving direction and speed. The locations of stationary destinations (data collection points) are available at nodes, via already recorded digital map topology.

A slotted based collision avoidance MAC protocol is applied for contention resolution, such that only one connection can be established between two encountered nodes at each time slot. Different from those works proposed for dense networks, we expect that in networks that are quite sparse, only a few vehicles would be close enough each time to compete for the transmission bandwidth simultaneously.

We consider a unicast application session, where a message is delivered from the source node to destination node, via the help of intermediate relays for delivery. Two vehicles can only communicate when they encounter, i.e., when they are within the communication range of each other. We define this as an "encounter opportunity" between them. Due to the sparse network density, the network connectivity is unavailable in a majority of time. The duration from the time when pairwise vehicles move in, until move out of transmission range of each other, is defined as "encounter duration". Although we envision for delay tolerant based data collection applications, messages are usually with a certain lifetime, namely Time-To-Live (TTL).

B. Overview of TDOR

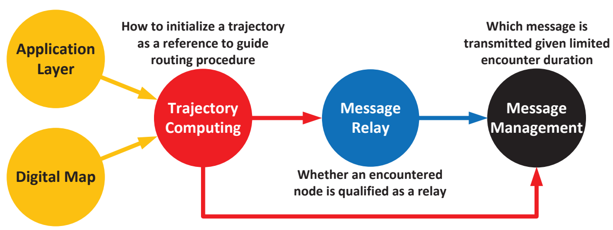

Fig. 1. TDOR System Operation

As illustrated in Fig. 1, the soul of TDOR is driven by the **Trajectory Computing Phase**. The operation in this phase further guides the **Message Relaying Phase** that happens with an "encounter opportunity". Next, based on the knowledge of computed trajectory and certain messages to relay, the **Message Management Phase** implements the transmission process within "encounter duration".

- **Trajectory Computing Phase:** This is only triggered once when the source node sends a message. The source node calculates a trajectory and embeds the computed trajectory information into the message. This means there is no need for each node to remember the trajectory of all its carried message, instead can learn from the message itself. The way to generate a trajectory will be explained in Section IV-A. Note that each node locally computes its desirable trajectory towards message destination, as operated in a distributed manner.
- **Message Relaying Phase:** It is executed by the node carrying the message (or a message copy), when it encounters other possible relays. The key is to decide whether or not an intermediate node would be better to help with relaying the message. Detailed selection criteria will be given in Section IV-B.
- **Message Management Phase:** Due to the short encounter duration between vehicles, not all messages can be successfully transmitted. Hence, it is practical to rank the messages in order to ensure the one with the highest delivery potential to get transmitted. The message ranking criterion is detailed in Section IV-C.

C. Basic Idea - An Example

The basic idea of TDOR is to select a set of relay nodes, which have higher potential to deliver message towards destination. For example, the mobility of nodes A, B, C, D and source node are shown in Fig. 2, where their encounters occur as follows:

1) The source node has a message for delivery, computes the shortest trajectory (embedded in that certain message) towards the destination.
2) Although the source node will encounter nodes A and B, only node B is selected as relay. This is because the mobility of node B makes forwarding progress (e.g., enabling the message to be in proximity to the destination) towards destination, while following the trajectory indicated by the source node. In contrast, as the mobility of node A will be farther away from the trajectory, it is not selected as a relay.
3) Given a potential encounter between nodes B and C (e.g., node B is much faster than node C), the message would be further relayed to node C, due to the trajectory proximity (although the latter will not make persistent contribution to message delivery).
4) Given an encounter between nodes C and D, the latter is selected as a relay, and eventually delivers the message towards the destination.

The message delivery process is always driven by the trajectory (computed by the source node), as well as instantaneous mobility of selected relay nodes which positively contribute to message delivery. This is different from nature of our previously proposed schemes such as [15], [17]. It is worthy noting that the vehicle encounters do not need to happen at

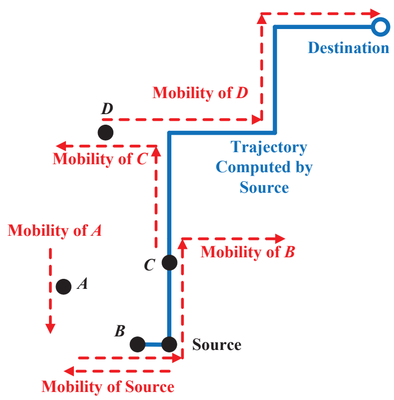

Fig. 2. An Example of Message Relay in TDOR

intersection, wherein under realistic city map a (straight/non-straight) path between two intersections could be formed by a set of coordinates, other than the example in Fig. 2.

In TDOR, the message follows a trajectory established at the source node, but each intermediate node (carrying the message or its copy) takes a greedy decision to infer the possible next hop. In a network where nodal coordinates are known, the message may be relayed to the node that is the geographically closest to the desired trajectory. Since the location of (stationary) destination is known in advance, the trajectory followed by the message normally consists of several sequent paths, and the routing process reduces to cartesian forwarding.

IV. Design of TDOR

TABLE II
List of Notations Defined in TDOR

$\mathcal{L}$	Trajectory computed by source node, with $\|\mathcal{L}\|$ sequent coordinates
l_i	A coordinate in $\mathcal{L}$, where $\forall i \leq \|\mathcal{L}\|$
M	Message, with TTL defined as TTL_M
u	Message carrier
v	Possible relay node, with coordinate l_v
d	Message destination
$D_{v,i}$	Distance between coordinates l_v and l_i
$\theta_{v,i,i+1}$	Relative angle between two lines formed by $D_{v,i}$ and $D_{i,i+1}$
ζ	Trajectory segment associated by a node
$\theta_{v,\zeta}$	Diversity to the associated trajectory segment ζ, in relation to node v
$\theta^m_{v,\zeta}$	Maximum diversity to associated trajectory segment ζ, in relation to node v
$\overrightarrow{\phi_{v,i}}$	Trajectory proximity to l_i of $\mathcal{L}$, where $i=1$ or $\|\mathcal{L}\|$
$\phi_{v,i}$	Angle between the moving direction of node v, and l_i
$\mathcal{P}_v$	Moving path of node v, with $\aleph_v$ as the next index that node v will traverse
$T^1_M, T^{\|\mathcal{L}\|}_M$	Threshold values as flags in M
$F_{v,\zeta}$	Forwarding progress of node v, in relation to its associated ζ
S_v	Moving speed of node v
$\mathcal{C}_M$	Flag to record number of message copies of M

A. Trajectory Computation Phase

The trajectory computation is triggered, when the source node starts to relay the message (i.e., the source node encounters the first node in network). This means that the trajectory of a message will not be computed since message generation.

The trajectory computation action translates a sequence of road links towards destination, into a set of coordinates (e.g., a set of continuous coordinates form the path towards destination in Fig. 2). In TDOR, we assume that this procedure requires the appropriate mechanism that allows vehicle to read the digital map, and to extract[2] the required information in order to compute the trajectory from the source node to destination. Once the computation procedure is finished, the trajectory is recorded into a dedicated flag in the message.

Definition 1 ***Trajectory:*** *It represents a set $\mathcal{L}$ which consists of $|\mathcal{L}|$ road link elements. Each element $l_i = (x_i, y_i), \forall i \leq |\mathcal{L}|$ is of a two dimensional coordinate.*

Description: The encoded trajectory consists of a sequence of road links, with pairwise starting point and ending point. Basically, the starting point is the current location of source node (only when it starts to relay a message) which generates the message, while the ending point is the location of message destination.

The set $\mathcal{L}$ is computed based on a pre-stored digital map about the network. Here, as already illustrated in Fig. 2, the shortest path policy is applied to form $\mathcal{L}$, regardless of the mobility of source node. ■

Definition 2 ***Trajectory Segment:*** *It consists of two sequent coordinates included in $\mathcal{L}$.*

Description: A trajectory segment consists of two sequent coordinates in $\mathcal{L}$, given by $l_i = (x_i, y_i)$ and $l_{i+1} = (x_{i+1}, y_{i+1})$, where $\forall i \leq (|\mathcal{L}| - 1)$. A trajectory $\mathcal{L}$ includes $(|\mathcal{L}| - 1)$ segments. ■

Definition 3 ***Trajectory Association:*** *Defined as $(v \odot \mathcal{L})$, it represents the fact that either a node v is moving along the trajectory $\mathcal{L}$, or geographically close to $\mathcal{L}$. If that does not happen, $(v \otimes \mathcal{L})$ is defined.*

Description: This is important to guide message delivery procedure, where node v strategically is not qualified as a better relay, given $(v \otimes \mathcal{L})$. This happens when node v has not traversed the starting point of trajectory $\mathcal{L}$, or has already traversed the ending point (the location of destination) of trajectory $\mathcal{L}$. In the worst case, node v would never approach $\mathcal{L}$, with its mobility in an opposite direction to $\mathcal{L}$. In detail, the trajectory association $(v \odot \mathcal{L})$ is determined via two steps:

Firstly, the coordinates of node v and a trajectory segment must form a triangle, as given by Equation (1). Note that $D_{v,i}$ is the distance between coordinates l_v and l_i, where l_v is the

[2]Trajectory coding and storing can limit the protocol scalability, because a longer trajectory is in line with a larger number of coordinates to be stored in the message header. Wherein vehicles in CPS are with sufficient computation capability to execute this task.

$$\begin{cases} D_{v,i} + D_{v,i+1} - D_{i,i+1} = 0 & \text{if node } v \text{ is moving along } \mathcal{L} \\ (D_{v,i} + D_{v,i+1} > D_{i,i+1}) & \\ \text{ and } (D_{v,i} + D_{i,i+1} > D_{v,i+1}) & \\ \text{ and } (D_{v,i+1} + D_{i,i+1} > D_{v,i}) & \text{else if node } v \text{ is in proximity to } \mathcal{L} \end{cases} \quad (1)$$

location of node v. Specifically, in Equation (1), the first sub-case implies that node v is currently moving along a trajectory segment which consists of two sequent coordinates l_i and l_{i+1}, where $\forall i \leq (|\mathcal{L}| - 1)$. The second sub-case implies that node v is geographically in proximity to the trajectory segment. In the latter case, a triangle must be formed, via three coordinates l_v, l_i and l_{i+1} respectively, and the summation of two edges of triangle must be longer than the third edge).

Secondly, we denote $\theta_{v,i,i+1}$ as the angle between two lines formed by $D_{v,i}$ and $D_{i,i+1}$, where $\theta_{v,i,i+1}$ can be given by cosine theorem:

$$\theta_{v,i,i+1} = \arccos\left(\frac{D_{v,i}^2 + D_{i,i+1}^2 - D_{v,i+1}^2}{2 \times D_{v,i} \times D_{i,i+1}}\right) \quad (2)$$

Note that, such calculation is the same as $\theta_{v,i+1,i}$. In addition to the condition at line 5 of Algorithm 1, the condition $\left(\theta_{v,i+1,i} < \frac{\pi}{2}\right)$ and $\left(\theta_{v,i,i+1} \leq \frac{\pi}{2}\right)$ must hold true to guarantee $(v \odot \mathcal{L})$. This implies node v should be with forwarding progress towards the destination. As an example in Fig. 3, $\left(\theta_{v,1,2} < \frac{\pi}{2}\right)$ and $\left(\theta_{v,2,1} < \frac{\pi}{2}\right)$ are given to determine the trajectory association of node v.

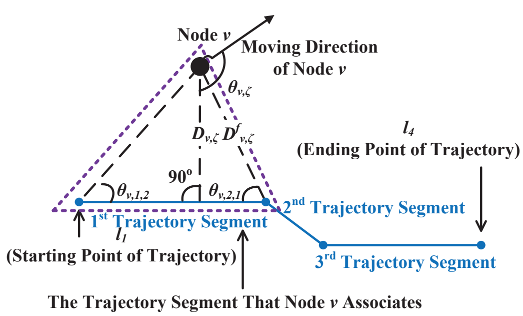

Fig. 3. An Example of Trajectory Association

Therefore, by knowing nodal association with the trajectory $\mathcal{L}$, e.g., $(v \odot \mathcal{L})$ or $(v \otimes \mathcal{L})$, the key of TDOR is to: 1) relay the message towards a node which is associated with $\mathcal{L}$. 2) let the selected node further relay the message towards the destination. The trajectory $\mathcal{L}$ provides a reference for a set of relay nodes that are involved in the **Message Relay Phase**. ■

Definition 4 ***Associated Trajectory Segment:*** *Given that a node is associated with $\mathcal{L}$, it can only be associated with a segment formed by two sequent coordinates of $\mathcal{L}$.*

Description: Algorithm 1 presents the logic to determine the associated trajectory segment. Firstly, the operations between lines 2 and 10 find all trajectory segments (formed by sequent locations l_i and l_{i+1} of $\mathcal{L}$, where $\forall i \leq (|\mathcal{L}| - 1)$, that node v associates), and includes them into a temporary set $\mathcal{H}$ with size $|\mathcal{H}|$.

Algorithm 1 Determine Trajectory Association and ζ

1: define a temporary set $\mathcal{H}$
2: **for** $(i = 1; i \leq (|\mathcal{L}| - 1); i++)$ **do**
3:   **if** $(D_{v,i} + D_{v,i+1} - D_{i,i+1} = 0)$ **then**
4:     include l_i, l_{i+1} into $\mathcal{H}$
5:   **else if** $(D_{v,i} + D_{v,i+1} > D_{i,i+1})$ and $(D_{v,i} + D_{i,i+1} > D_{v,i+1})$ and $(D_{v,i+1} + D_{i,i+1} > D_{v,i})$ **then**
6:     **if** $(\theta_{v,i,i+1} \leq \frac{\pi}{2})$ and $(\theta_{v,i+1,i} < \frac{\pi}{2})$ **then**
7:       include l_i, l_{i+1} into $\mathcal{H}$
8:     **end if**
9:   **end if**
10: **end for**
11: **if** $(|\mathcal{H}| = 0)$ **then**
12:   **return** $v \otimes \mathcal{L}$
13: **else if** $(|\mathcal{H}| > 2)$ **then**
14:   **for** $(j = 1; j \leq (|\mathcal{H}| - 1); j++)$ **do**
15:     $\theta_{j,v,j+1} = (\pi - \theta_{v,j,j+1} - \theta_{v,j+1,j})$
16:   **end for**
17:   $\zeta = \{l_j, l_{j+1}\} \leftarrow \underset{j \leq (|\mathcal{H}|-1)}{\arg\max} \ (\theta_{j,v,j+1})$
18:   **return** $v \odot \mathcal{L}$
19: **end if**

At line 11, $|\mathcal{H}| = 0$ means there is no trajectory association, as such $v \otimes \mathcal{L}$ is returned. Otherwise, as presented at line 13, if there are more than two coordinates included in $\mathcal{H}$, the angle $\theta_{j,v,j+1} = (\pi - \theta_{v,j,j+1} - \theta_{v,j+1,j})$ formed by l_v, and l_j and l_{j+1} implies the degree of forwarding progress of node v associated with $\mathcal{L}$. For example, as $\theta_{1,v,2} = (\pi - \theta_{v,1,2} - \theta_{v,2,1})$ is given in Fig. 3. At line 17, the trajectory segment through which the node v experiences the largest $\theta_{j,v,j+1}$, is determined as the trajectory segment ζ that node v associates. In this case, $v \odot \mathcal{L}$ is returned at line 18. ■

B. Message Relay Phase

From this section, we denote nodes u and v as the message carrier and encountered node (a possible relay node), while node d is the message destination. The purpose is to find the nodes which are associated with trajectory.

TDOR Logic: In each encounter between nodes u and v, they will compute their trajectory association related to $\mathcal{L}$. Note that the formulation of $\mathcal{L}$ is based on the trajectory computation, when node u starts to relay message M. In summary, the message delivery in TDOR is decoupled into the following three cases, and detailed in subsections below:

- The $((u \otimes \mathcal{L}) \& (v \otimes \mathcal{L}))$ case, no association: This happens when both nodes u and v are not associated with $\mathcal{L}$ (e.g., imagining both nodes u and v are located at left-hand side of trajectory in Fig. 3).
- The $((u \otimes \mathcal{L}) \& (v \odot \mathcal{L}))$ case, single association: This happens only when node v is associated with $\mathcal{L}$, whereas node u is not.
- The $((u \odot \mathcal{L}) \& (v \odot \mathcal{L}))$ case, double association: This happens when both nodes u and v are associated with $\mathcal{L}$.

Inherently, if using traditional geographic routing policies, a node that is geographically closer, or with a faster proximity to the destination is selected most likely. In TDOR, that node does not need to be a relay if it is not associated with $\mathcal{L}$. Such a trajectory-driven message delivery would benefit to low routing overhead (due to redundant relay) but does not contribute to successful delivery.

Differentiated Queuing System: Messages processed through one of above three cases are differentiated into a dedicated queue. This multi-queuing system classifies the message with certain delivery potential from others.

- The Low Priority Queue (LPQ): This involves the message to be transmitted to the relay node v which is not associated with $\mathcal{L}$, given by the $((u \otimes \mathcal{L})\&(v \otimes \mathcal{L}))$ case.
- The Medium Priority Queue (MPQ): This involves the message transmission to the relay node v which associates with $\mathcal{L}$ (but does not exactly moving along its associated trajectory segment). It includes $((u \otimes \mathcal{L})\&(v \odot \mathcal{L}))$ and $((u \odot \mathcal{L})\&(v \odot \mathcal{L}))$ cases.
- The High Priority Queue (HPQ): This includes message processed by $((u \odot \mathcal{L})\&(v \odot \mathcal{L}))$ case, only when the relay node v moves along $\mathcal{L}$.

1) The $((u \otimes \mathcal{L})\&(v \otimes \mathcal{L}))$ Case: As both nodes u and v are not associated with $\mathcal{L}$, the policy is to find whether node v has a better potential (depending on its mobility) to associate with $\mathcal{L}$, as defined by trajectory proximity. Messages involved for this case are included in LPQ, as they are isolated to $\mathcal{L}$.

Definition 5 ***Trajectory Proximity:*** *Given the mobility of node v, the trajectory proximity to l_i is defined as $\overrightarrow{\phi_{v,i}}$, where i = 1 or $|\mathcal{L}|$. The trajectory proximity happens when node v will approach either the starting point of $\mathcal{L}$ as l_1, or its ending point $l_{|\mathcal{L}|}$. Here, the calculation of $\overrightarrow{\phi_{v,i}}$ is given as:*

$$\overrightarrow{\phi_{v,i}} = \frac{\sum_{k=\aleph_v}^{|\mathcal{P}_v|-1} \phi_{k,i} + \phi_{v,i}}{|\mathcal{P}_v| - \aleph_v + 1} \tag{3}$$

Description: Here, $\mathcal{P}_v$ is a set (with size $|\mathcal{P}_v| > 1$) which includes a number of coordinates that node v will traverse. $\aleph_v$ is the index of the path segment that node v will traverse along $\mathcal{P}_v$ as such $\aleph_v < |\mathcal{P}_v|$. As an example in Fig. 4, $|\mathcal{P}_v| = 5$ and $\aleph_v = 2$, thus $\overrightarrow{\phi_{v,i}} = \frac{\sum_{k=2}^{5-1} \phi_{k,i} + \phi_{v,i}}{5-2+1} = \frac{\sum_{k=2}^{4} \phi_{k,i} + \phi_{v,i}}{4}$. The calculation of $\overrightarrow{\phi_{v,i}}$ starts from the location l_v of node v. Besides, $\phi_{k,i}$ is the angle between the k^{th} path that node v will traverse, and the coordinate l_i of $\mathcal{L}$. This computation reflects how diverse and possible that node v will approach towards l_i. In special case where $\aleph_v = |\mathcal{P}_v|$, $\overrightarrow{\phi_{v,i}} = \phi_{v,i}$. ■

We denote the coordinates of starting point and ending point of $\mathcal{L}$, as l_1 and $l_{|\mathcal{L}|}$, respectively. Since TDOR assumes opportunistic hop-by-hop, rather than contemporaneous end-to-end communication nature, the possibility that nodes u and v are close to both l_1 and $l_{|\mathcal{L}|}$ simultaneously will not happen. This makes sense as the $\mathcal{L}$ computed from source to destination is normally long, particularly via a large city map. Therefore, only the situation that nodes u and v are in proximity to either the starting point of $\mathcal{L}$ (as l_1), or the ending point of $\mathcal{L}$ (as $l_{|\mathcal{L}|}$, the message destination) will happen, with dedicated routing logics introduced as follows:

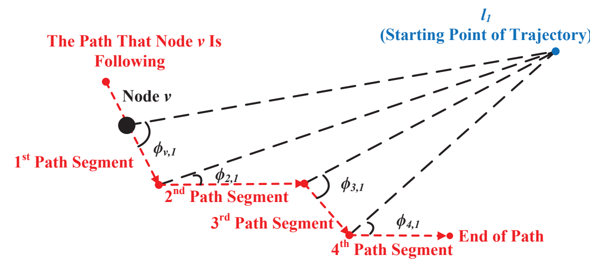

Fig. 4. An Example of Trajectory Proximity

Algorithm 2 Message Delivery in $((u \otimes \mathcal{L})\&(v \otimes \mathcal{L}))$ Case

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1: set T_M^1 and $T_M^{|\mathcal{L}|}$ with infinitely large value
2: **for** each encounter between nodes u and v **do**
3:   **for** each M carried by node u **do**
4:     **if** node v already has a copy of M **then**
5:       select a smaller value, from T_M^1 and $T_M^{|\mathcal{L}|}$ in M carried by pairwise nodes
6:       update T_M^1 and $T_M^{|\mathcal{L}|}$ towards that smaller value, for both M in pairwise nodes
7:     **else if** both nodes u and v are in proximity to l_1 **then**
8:       **if** $\left(T_M^1 > \overrightarrow{\phi_{v,1}}\right)$ and $\left(\overrightarrow{\phi_{v,1}} < \frac{\pi}{2}\right)$ **then**
9:         update T_M^1 towards $\overrightarrow{\phi_{v,1}}$
10:         replicate M to node v
11:       **end if**
12:     **else if** both nodes u and v are in proximity to $l_{|\mathcal{L}|}$ **then**
13:       **if** $\left(T_M^{|\mathcal{L}|} > \overrightarrow{\phi_{v,|\mathcal{L}|}}\right)$ and $\left(\overrightarrow{\phi_{v,|\mathcal{L}|}} < \frac{\pi}{2}\right)$ **then**
14:         update $T_M^{|\mathcal{L}|}$ towards $\overrightarrow{\phi_{v,|\mathcal{L}|}}$
15:         replicate M to node v
16:       **end if**
17:     **end if**
18:   **end for**
19: **end for**
20: include M into LPQ

- **When nodes u and v are in proximity to l_1:** Here, node v will be selected as the relay if $\left(\overrightarrow{\phi_{u,1}} > \overrightarrow{\phi_{v,1}}\right)$ and $\left(\overrightarrow{\phi_{u,1}} < \frac{\pi}{2}\right)$ and $\left(\overrightarrow{\phi_{v,1}} < \frac{\pi}{2}\right)$. This is because node v would move closer to l_1 than node u, depending on the trajectory proximity.
  In order to further reduce the routing overhead, we bring the DF [28] which was originally applied for topological routing schemes in DTNs. In order to implement such an optimization policy in TDOR, additional flag T_M^1 is recorded in message M. Once a message is generated, a flag T_M^1 of message is initialized as an infinitely large value. This is different from the idea of using original DF for topological routing scheme, where T_M^1 is just set as nodal utility (with a certain value rather than $+\infty$) calculated based on network topological information. Details about implementation DF for topological routing scheme and its analysis can be referred to [12].
  As presented between lines 8 and 10 in Algorithm 2, the optimized message delivery is given by:

$$\left(T_M^1 > \overrightarrow{\phi_{v,1}}\right) \text{ and } \left(\overrightarrow{\phi_{v,1}} < \frac{\pi}{2}\right) \tag{4}$$

Note that, upon successful message transmission, the value of T_M^1 will be updated towards $\overrightarrow{\phi_{v,1}}$. This is mainly recorded as the $\overrightarrow{\phi_{v,1}}$ of historical relay node, and to be further compared with that of a future encountered node. In this context, the condition (4) focuses on comparing the trajectory proximity between the future encountered node and historical relay node, instead of comparing that between the future encountered node and current message carrier.

If node v already has a message copy, the value of T_M^1 in its carried message might be different from that in node u. To make a converged decision, a smaller value between $\overrightarrow{\phi_{v,1}}$ and $\overrightarrow{\phi_{u,1}}$ is obtained, and updated for both of them. This operation is referred to lines 5 and 6 in Algorithm 2.

- **When nodes u and v are in proximity to $l_{|\mathcal{L}|}$:** Here, node v will be selected as the relay if $\left(\overrightarrow{\phi_{u,|\mathcal{L}|}} > \overrightarrow{\phi_{v,|\mathcal{L}|}}\right)$ and $\left(\overrightarrow{\phi_{u,|\mathcal{L}|}} < \frac{\pi}{2}\right)$ and $\left(\overrightarrow{\phi_{v,|\mathcal{L}|}} < \frac{\pi}{2}\right)$. Similarly, another flag $T_M^{|\mathcal{L}|}$ is defined to trigger the optimized routing decision herein. Then, as presented between lines 13 and 15 in Algorithm 2, we have $\left(T_M^{|\mathcal{L}|} > \overrightarrow{\phi_{v,|\mathcal{L}|}}\right)$ and $\left(\overrightarrow{\phi_{v,|\mathcal{L}|}} < \frac{\pi}{2}\right)$ to qualify node v, where the updating of $T_M^{|\mathcal{L}|}$ follows the same rule for updating T_M^1.

Above two conditions are utilized to develop a complete message delivery decision, presented in Algorithm 2.

2) The $((u \otimes \mathcal{L})\&(v \odot \mathcal{L}))$ Case: The quality of node v is checked through its trajectory segment diversity.

Definition 6 ***Trajectory Diversity:*** *Given that node v is associated with a trajectory segment of ζ, its mobility is bounded by the maximum trajectory diversity $\theta_{v,\zeta}^m$.*

Description: In the $((u \otimes \mathcal{L})\&(v \odot \mathcal{L}))$ case, although node u does not associate with $\mathcal{L}$ while node v does, directly relaying the message to node v would still bring routing redundancy. This is due to that the mobility of node v will be diverse from the associated trajectory segment ζ, shown in Fig. 3.

We define the maximum diversity of the associated trajectory segment, as an angle $\theta_{v,\zeta}^m$ between the moving direction of node v and its associated trajectory segment ζ. For this purpose, we first need to obtain the distance that node v is vertical to ζ, denoted as $D_{v,\zeta}$ in Fig. 3.

Based on Heron's formula, the area of triangle (with purple color and dot based triangle in Fig. 3) Δ formed by sides D_{v,ζ_0}, D_{v,ζ_1} and D_{ζ_0,ζ_1} is given by Equation (5), where we denote ζ_0 and ζ_1 as two sequent coordinates which form ζ.

$$\Delta = \sqrt{\mathcal{A} \times (\mathcal{A} - D_{v,\zeta_0}) \times (\mathcal{A} - D_{v,\zeta_1}) \times (\mathcal{A} - D_{\zeta_0,\zeta_1})} \tag{5}$$

where:

$$\mathcal{A} = \frac{D_{v,\zeta_0} + D_{v,\zeta_1} + D_{\zeta_0,\zeta_1}}{2} \tag{6}$$

Besides, Δ can also be given by:

$$\Delta = \frac{D_{v,\zeta} \times D_{\zeta_0,\zeta_1}}{2} \tag{7}$$

By substituting Equation (5) into Equation (7), we obtain:

$$D_{v,\zeta} = \frac{2 \times \sqrt{\mathcal{A} \times (\mathcal{A} - D_{v,\zeta_0}) \times (\mathcal{A} - D_{v,\zeta_1}) \times (\mathcal{A} - D_{\zeta_0,\zeta_1})}}{D_{\zeta_0,\zeta_1}} \tag{8}$$

Finally, we obtain Equation (9) by substituting Equation (6) into Equation (8):

$$\theta_{v,\zeta}^m = \min\left[\arccos\left(\frac{D_{v,\zeta}}{D_{v,\zeta}^f}\right), \left(\frac{\pi}{2} - \arccos\left(\frac{D_{v,\zeta}}{D_{v,\zeta}^f}\right)\right)\right] \tag{9}$$

Where $D_{v,\zeta}^f$ is equivalent to D_{v,ζ_1} as shown in Fig. 3 (in this example, $\theta_{v,\zeta} > \theta_{v,\zeta}^m$ occurs). ■

The maximum trajectory diversity based message delivery depends on two conditions:

- As $\left(\theta_{v,\zeta} < \theta_{v,\zeta}^m\right)$ and $(D_{v,\zeta} \neq 0)$ presented between lines 3 and 5 in Algorithm 3, a message copy is replicated from nodes u to v, if the angle (referring to $\theta_{v,\zeta}$) between the moving direction of node v and the forwarding progress of ζ is smaller than $\theta_{v,\zeta}^m$. Messages involved for this case are included in MPQ, as node v is not moving along $\mathcal{L}$.
- Alternatively, the condition $(D_{v,\zeta} = 0)$ and $(\theta_{v,\zeta} = 0)$ presented between lines 6 and 8, implies that node v is moving along ζ meanwhile progressing towards the destination. As such, a message copy is replayed from nodes u to v. Messages involved for this case are included in HPQ.

Algorithm 3 Message Delivery in $((u \otimes \mathcal{L})\&(v \odot \mathcal{L}))$ Case

```
1:  for each encounter between nodes u and v do
2:      for each M carried by node u do
3:          if (θ_{v,ζ} ≤ θ^m_{v,ζ}) and (D_{v,ζ} ≠ 0) then
4:              replicate M to node v
5:              include M into MPQ
6:          else if (D_{v,ζ} = 0) and (θ_{v,ζ} = 0) then
7:              replicate M to node v
8:              include M into HPQ
9:          end if
10:     end for
11: end for
```

3) The $((u \odot \mathcal{L})\&(v \odot \mathcal{L}))$ Case: The major message delivery decision executed in this case considers that both nodes u and v are associated with $\mathcal{L}$, which is decoupled as follows:

When nodes u and v associate with different ζ: The condition $(F_{u,\zeta} \Rightarrow F_{v,\zeta})$ at line 3 in Algorithm 4 holds true, if the trajectory segment that node v associates, is with a more forwarding progress than node u towards the destination. The forwarding progress can be determined, by checking the ending point of ζ. Note that as ζ belongs to $\mathcal{L}$, then the ending point in ζ with a higher value of index i where $i \leq \mathcal{L}$, indicates a faster forwarding progress. As such, node u relays a copy of message M to node v, following the same rule in Algorithm 3.

When nodes u and v associate with the same ζ: In Algorithm 4, the condition $(F_{u,\zeta} \Leftrightarrow F_{v,\zeta})$ at line 5 holds true, if nodes u and v have equivalent forwarding progress:

Algorithm 4 Message Delivery in $((u \odot \mathcal{L})\&(v \odot \mathcal{L}))$ Case

1: **for** each encounter between nodes u and v **do**
2: **for** each M carried by node u **do**
3: **if** $\left(F_{u,\zeta} \Rightarrow F_{v,\zeta}\right)$ **then**
4: replicate M to node v, following Algorithm 3
5: **else if** $\left(F_{u,\zeta} \Leftrightarrow F_{v,\zeta}\right)$ **then**
6: **if** $\left(D_{u,\zeta}=0\right)$ and $\left(D_{v,\zeta}=0\right)$ **then**
7: **if** $(S_u < S_v)$ and $\left(\theta_{u,\zeta}=0\right)$ and $\left(\theta_{v,\zeta}=0\right)$ **then**
8: replicate M to node v
9: delete M in node u
10: **else if** $\left(\theta_{u,\zeta}=\pi\right)$ and $\left(\theta_{v,\zeta}=0\right)$ **then**
11: replicate M to node v
12: **end if**
13: include M into HPQ
14: **else if** $\left(D_{u,\zeta}=0\right)$ and $\left(D_{v,\zeta}\neq 0\right)$ and $\left(\theta_{u,\zeta}=\pi\right)$ and $\left(\theta_{v,\zeta} < \theta^m_{v,\zeta}\right)$ **then**
15: replicate M to node v
16: include M into MPQ
17: **else if** $\left(D_{u,\zeta}\neq 0\right)$ and $\left(D_{v,\zeta}=0\right)$ and $\left(\theta_{v,\zeta}=0\right)$ **then**
18: replicate M to node v
19: include M into HPQ
20: **else if** $\left(D_{u,\zeta}\neq 0\right)$ and $\left(D_{v,\zeta}\neq 0\right)$ and $\left(\theta_{v,\zeta} < \theta^m_{v,\zeta}\right)$ **then**
21: replicate M to node v
22: include M into MPQ
23: **end if**
24: **end if**
25: **end for**
26: **end for**

Particularly, when both of them move along the trajectory segment, given by the condition $(D_{u,\zeta}=0)$ and $(D_{v,\zeta}=0)$ at line 6 of Algorithm 4, the node with a faster speed is thereby selected as relay. The message involved for this case is included in HPQ, as its delivery is exactly following the trajectory towards the destination. Specifically:

- Presented between lines 7 and 9, given the condition $(S_v > S_u)$, node u relays M to node v, without enabling node u to keep its carried message. As both of them are moving towards the destination (along the certain trajectory segment ζ), only letting a faster node to keep M is able for fast delivery. Note that this happens when both of them are moving towards the destination, with the condition $(\theta_{u,\zeta}=0)$ and $(\theta_{v,\zeta}=0)$ given.
- Between lines 10 and 11, given $(\theta_{u,\zeta}=\pi)$ and $(\theta_{v,\zeta}=0)$, message M is relayed to node v. This is because that node u will move way from the destination, whereas node v will not. Here, node u still keeps its message, in order to disseminate the message copy to other nodes (associated with ζ) in future.

Besides, when either nodes u or v moves along the ζ, the following policies are applied:

- In case of the condition shown at line 14, a copy of message is relayed to node v, only if $\left(\theta_{v,\zeta} < \theta^m_{v,\zeta}\right)$ and $(\theta_{u,\zeta}=\pi)$. This is because as node u moves away from destination, it is beneficial to relay a message copy to node v (which is with forwarding progress towards the destination). Messages involved for this case are included in MPQ.
- If only node v is moving along its associated trajectory segment, a copy of M is relayed to v given $(\theta_{v,\zeta}=0)$ at line 17. Messages involved for this case are included in HPQ.
- If both nodes u and v are not moving along the associated trajectory segment, a copy of M is relayed to node v, given the condition $\left(\theta_{v,\zeta} < \theta^m_{v,\zeta}\right)$ at line 20. Messages involved for this case are included in MPQ.

4) Communication Cost of TDOR: The communication cost in a wireless network is often proportional to the number of transmissions. The more the transmissions, the higher the consumption transmission bandwidth at an encounter. Here, the communication cost of $((u \otimes \mathcal{L})\&(v \otimes \mathcal{L}))$ case is scaled by $O(\sqrt{K})$, where K is the number of mobile nodes in network. This is because the optimized solution is applied to fast converge the solution, as referring to [12]. In [15], we have already studied the utilization of that for a general geographic routing scheme DGR (which is not trajectory driven as featured in TABLE I). Besides, as $((u \otimes \mathcal{L})\&(v \odot \mathcal{L}))$ and $((u \odot \mathcal{L})\&(v \odot \mathcal{L}))$ cases concern only a number of nodes (by searching from $\sqrt{K}$ nodes found in $((u \otimes \mathcal{L})\&(v \otimes \mathcal{L}))$ case) associated with trajectory, the cost of TDOR is given by $C_{TDOR} < O(\sqrt{K})$.

C. Message Management Phase

In message management phase, firstly messages are prioritized in sequence. Next, by following three cases of association (no association, single association and double association), the queued messages are transmitted.

1) Message Prioritization: Messages are prioritized also referring to the above three cases of association:

LPQ: As nodes involved in this case are not associated with trajectory $\mathcal{L}$, the priority P^l_M given in Equation (10), is mainly driven by the trajectory proximity as previously given in Equation (3):

$$P^l_M = \begin{cases} \frac{TTL_M}{T^1_M} & \text{if node } v \text{ is in proximity to } l_1 \\ \frac{TTL_M}{T^{|\mathcal{L}|}_M} & \text{if node } v \text{ is in proximity to } l_{|\mathcal{L}|} \end{cases} \quad (10)$$

Equation (10) implies how possible node v would be in proximity to $\mathcal{L}$, given by the smallest value of $\overrightarrow{\phi_{v,1}}$ or $\overrightarrow{\phi_{v,|\mathcal{L}|}}$ learnt from network, as recorded in T^1_M or $T^{|\mathcal{L}|}_M$ respectively. Note that, it is easy to transfer the geometric value recorded in T^1_M or $T^{|\mathcal{L}|}_M$, to an angle degree of $90 = \frac{\pi}{2} \approx 1.57$ in radians. In general, a closer proximity meanwhile with longer remaining message lifetime TTL_M, reflects that the message M is with much chance to be relayed to a node associated with $\mathcal{L}$.

MPQ: Here, the message is prioritized according to $\theta_{v,\zeta}$ and TTL_M. Equation (11) implies that the message with the longest TTL should be transmitted with the highest priority, as the selected relay node v (with small $\theta_{v,\zeta}$) has already been associated with $\mathcal{L}$.

$$P^m_M = \frac{TTL_M}{\theta_{v,\zeta}} \quad (11)$$

HPQ: In this case, the relay node v is currently moving along with a road segment of the trajectory $\mathcal{L}$. Then message delivery probability is given by $1-(1-X)^{\mathcal{C}_M}$. Here, X is the probability to deliver a message copy towards destination, given that there have been $\mathcal{C}_M$ copies[3] of a message M exist. Then the priority in this case P_M^h is given by Equation (12):

$$P_M^h = 1 - \left(1 - \frac{TTL_M - \frac{D_{v,\aleph_v} + \sum_{i=\aleph_v}^{|\mathcal{L}|-1} D_{i,i+1}}{S_v}}{TTL_M}\right)^{\mathcal{C}_M} \quad (12)$$

Equation (12) reflects the potential of node v to deliver M before TTL_M, given its mobility towards the destination. In the worst case, P_M^h turns to 0 if $\frac{TTL_M - \frac{D_{v,\aleph_v} + \sum_{i=\aleph_v}^{|\mathcal{L}|-1} D_{i,i+1}}{S_v}}{TTL_M} \leq 0$. Driven by the target to reduce delivery delay, this implies that the message (with long TTL_M) to be relayed to the node which fast traverses $D_{v,\aleph_v} + \sum_{i=\aleph_v}^{|\mathcal{L}|-1} D_{i,i+1}$, is transmitted with the highest priority. Here, $D_{v,\aleph_v}$ is known as the remaining distance that node v needs to traverse along ζ.

2) Message Transmission: Considering how possible messages can be delivered via dedicated cases presented above, messages included in LPQ, MPQ and HPQ are transmitted based on the following rules. The idea is to transmit the message with highest potential for delivery, with the highest priority, compared to those in different queues or even in the same queue.

- Messages included in HPQ are transmitted prior to those included in MPQ and LPQ, while those in LPQ are with the lowest transmission priority. Facilitated from a faster mobility, the motivation behind is to faster deliver message, that carried by the nodes which are moving along the $\mathcal{L}$.
- Those messages included in the same queue, are transmitted following the descending order of dedicated priority defined in each case.

If a message copy is delivered successfully, it is essential to delete other copies of this message in the network, in order to free the bandwidth for transmitting 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[4] 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.

V. Performance Evaluation

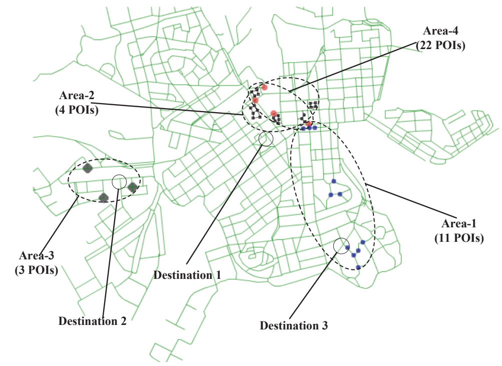


Fig. 5. Evaluation Scenario

The evaluations are based on Opportunistic Network Environment (ONE) [31]. The scenario is based on the abstracted downtown map of Helsinki city (Fig. 5) with an area of 4500×3400 m^2. Compared to applying historical position information, the application of city map is compulsory to evaluate geographic routing because nodal speed, direction as well as distance are captured by TDOR in real-time. The moving speeds of mobile nodes are randomly chosen from [30∼50] km/h. Following the configuration of DGR [15], and TBHGR [17] for opportunistic routing in sparse networks, the communication technique is set with 30m transmission range and 4 Mbit/s bandwidth, considering as the low power WiFi technology.

TABLE III
Movement Interest of Each Group

Group ID	Area	Number of POIs	Movement Interest
Group-1	Area-1	11	$[0 \sim 80\%]$
Group-2	Area-2	4	$[0 \sim 80\%]$
Group-3	Area-3	3	$[0 \sim 80\%]$
Group-4	Area-4	22	$[0 \sim 80\%]$

Envisioning for a heterogeneous network, we also assign four types of Points-Of-Interests (POIs), by default 3 destinations are deployed shown in Fig. 5, 30 mobile nodes of each group are allocated to each type of POI defined in TABLE III. For example, 80% movement interest reflects that a group of mobile nodes are with 80% probability moving around the POIs, while with 20% probability roaming in the entire network. As such, mobile nodes will encounter more likely and frequently, due to a high interest with a type of POI.

The following three DTN routing protocols are evaluated:

- **Epidemic** [27]: It floods message copies to any node in network, with a communication cost scaled by $O(K)$.
- **DGR** [15]: A geographic routing scheme based on the stationary destination, meanwhile handles the challenges from sparse network density. Its communication cost is scaled between $[O(\sqrt{K}), O(K))$.
- **TBHGR** [17]: A geographic routing scheme taking nodal heterogeneity into account, e.g., visiting preference to a

[3]Here, since all the nodes in the networks are differentiated by their IDs, a heuristic method to estimate the number of nodes which have carried the message is developed. An additional flag in each message is used to keep a list of these IDs, and its initialization is performed by recording the ID of node that generates the message. Therefore, the initial value of $\mathcal{C}_M$ equals to 1, meaning just 1 message copy exists since message generation. Upon a successful transmission from nodes u to v, the message including its replicated copy in both nodes u and v, will record the ID of node v. Moreover, the nodal IDs will be exchanged when pairwise encountered nodes both carrying the message or its copy. Note that this information exchange is operated together with the exchange of routing information, when nodes u and v encounter.

[4]Compared with data message, the ACK message is with quite small size that only contains nodal ID (e.g., string format). Therefore, the bandwidth and buffer space consumed by ACK can be ignored. In fact, the real implementation of ACK is operated as a table list in each node, to record the ID of the delivered messages, rather than recording a whole message copy in this list. Here, the way to exchange ACK can be aligned with the exchange of nodal speed, direction as involved in routing decision, thus no need to create additional signalling operation.

place, such that messages generated within one domain are efficiently delivered to the destination located in another domain. It also assumes stationary destination. Different from DGR, TBHGR limits the number of copies a message can be replicated up to L, where its communication cost is scaled by $O(L)$.

Major results are with 10 run and 95% confidence interval, while 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, where 1 means all generated messages are delivered.
- **Average Delivery Latency**: It is the average delay for a message to be delivered from the source node to its destination.
- **Overhead Ratio**: It is the ratio between the number of relayed messages (excluding the delivered messages) and the number of delivered messages.

Messages are randomly generated at all mobile nodes for every 30s, with 60 minutes TTL and 1MB size. The nodal buffer space is set to be 1GB. The number of times that a message can be replicated in TBHGR is configured as 12. This follows [29] that choosing L equals to around 10% number of mobile nodes in a network. To measure the full activity of a network, the message generation ends before 18000s with an additional 3600s allowed to consume the unexpired messages.

A. Influence of Movement Interest

By default, we set 0% movement interest for evaluation in other subsections, only vary it in this subsection with other settings fixed. In Fig. 6(a), all schemes benefit from a high movement interest, meaning the mobility of mobile nodes tends to converge around those POIs. This is because nodes are highly possible to move around dedicated POIs of areas, rather than just roaming across an entire network. As such, messages are likely delivered since 3 destinations are deployed close to those POIs. We also observe that TBHGR achieves the worst performance, given 0% movement interest. This is because it limits the number of copies a message can be replicated, whereas most of them are not delivered due to infrequent encounters or not converged mobility. In comparison to DGR, the advantage of trajectory driven routing nature in TDOR is reflected through a higher delivery ratio.

In Fig. 6(b), all schemes experience a decreased average delivery latency, primarily due to that mobile nodes would move towards destinations with high possibility. In case of 80% movement interest, TDOR suffers from a higher delivery latency than TBHGR and DGR, due to delivering more messages shown in Fig. 6(a) from the 0% movement interest case. Note that as these three schemes rely on relay node selection, their delivery latency decrease follow the same trend. Besides, we observe Epidemic benefits from increased movement interest, by achieving the lowest delivery latency. This is because with flooding nature for message delivery, the possibility that one of message copies to be delivered, will be higher than those schemes with selection of relay node, e.g., TDOR. As such, one of message copies will be delivered faster, due to flooding nature.

The observation in Fig. 6(c) shows Epidemic suffers from the highest overhead ratio (around 120 as the upper bound, which equals to the total number of nodes in network), due to its flooding nature. Also, the overhead ratio of DGR and TBHGR is increased, following the increased movement interest. In contrast, TDOR achieves the lowest overhead ratio while keeping a stable trend, from which the efficiency of trajectory driven routing policy is demonstrated.

B. Influence of Network Density

In this case, the value of L in TBHGR also increases with network density. Fig. 7(a) shows TDOR achieves a higher delivery ratio than DGR and TBHGR. Compared to DGR which does not limit the number of copies a message can be replicated, TBHGR with this limitation thereby is with the worse performance.

In Fig. 7(b), Epidemic benefits most from the increased network density, with its average delivery latency decreased with a dramatic trend. As all message replications are limited with a predefined constant, TBHGR experiences the least decrease regarding average delivery latency. Here, since the latency only counts for delivered messages, we consider T-DOR outperforms DGR because of a higher delivery ratio.

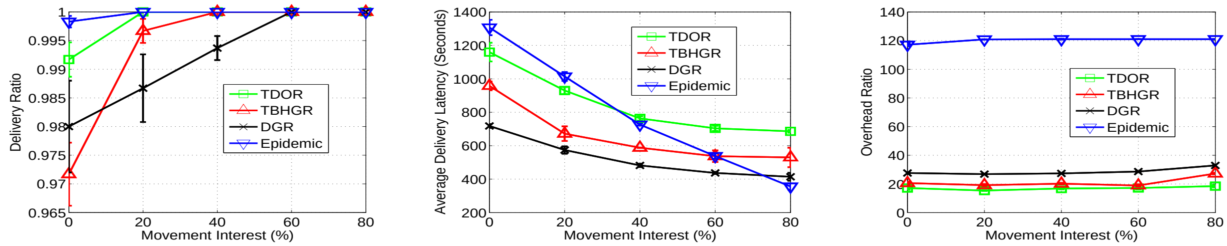
The observation in Fig. 7(c) shows Epidemic suffers from the highest overhead ratio, as it naively floods messages to any encountered node. In comparison, TDOR, DGR and TBHGR achieve a considerable lower overhead ratio, thanks to mobility-based relay node selection. Here, the close performance between TDOR and TBHGR implies that, the trajectory driven routing policy could reduce massive redundant message replications. This happens even if TDOR does not initially limit the number of L copies a message can be replicated (as performed by TBHGR).

C. Influence of Message Generation Interval

In Fig. 8(a), TDOR, DGR and TBHGR benefit from the alleviated bandwidth contention (from 10s to 30s per message generation), by achieving the increased delivery ratio. This is different from Epidemic in which the bandwidth contention becomes dramatically in case of 10 seconds generation interval. Such observation implies replicating massive message copies does not positively contribute to delivery, particularly given limited communication capacity between mobile nodes.

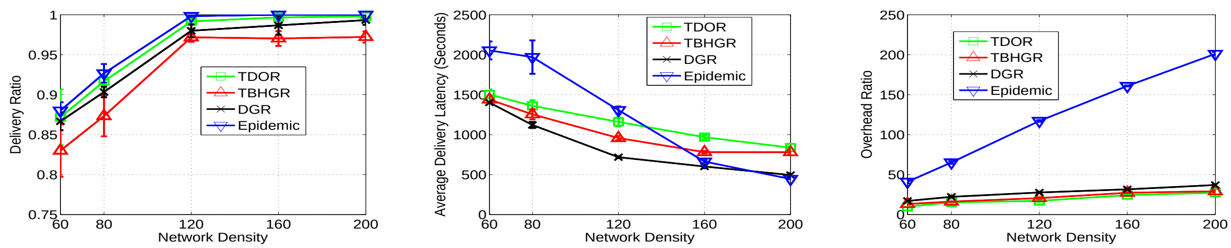
In Fig. 8(b), as TDOR already efficiently replicates messages driven by the trajectory computation at source, it does not benefit from alleviated bandwidth contention, thus is without dramatically reduced average delivery latency. In comparison, Epidemic and DGR experience considerable benefit. This is because those infrequently generated messages will not bring contention, as such the average delivery latency decreases.

TDOR achieves the lowest overhead ratio in Fig. 8(c). Note that, Epidemic and DGR are with increased overhead ratio due to delivering more messages. This is different from the efficiency of TDOR (thanks to trajectory-driven delivery) and TBHGR (thanks to limiting L message copies).



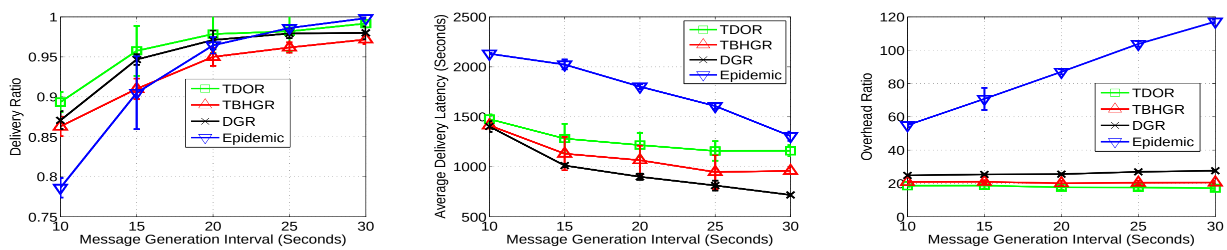
(a) Delivery Ratio (b) Average Delivery Latency (c) Overhead Ratio

Fig. 6. Influence of Movement Interest



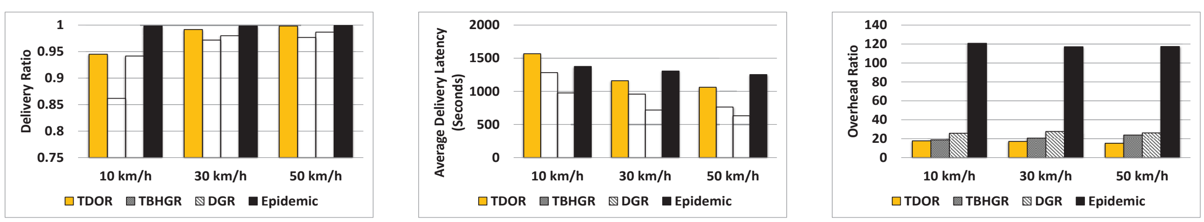
(a) Delivery Ratio (b) Average Delivery Latency (c) Overhead Ratio

Fig. 7. Influence of Network Density



(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 Moving Speed

D. *Influence of Moving Speed*

In Fig. 9(a), all the schemes benefit from a faster moving speed (by varying the low bound value of speed, from 10 km/h to 50 km/h), with increased delivery ratio. This is because a faster moving speed brings frequent encounters, as such the possibility that a message copy is relayed to a better qualified node or delivered increases. In particular, we observe TDOR and DGR achieve similar performance given 10 km/h speed. This implies the accuracy of trajectory-driven nature in sparse networks, rather than the geographical replication nature in DGR. If increasing the moving speed to 50 km/h, TDOR begins to outperform DGR. This implies that DGR does not capture the fast mobility accurately than TDOR, certainly the trajectory computation is immune to the mobility of source and intermediate nodes. Besides, Epidemic always achieves the highest delivery ratio, as it floods message copies to each node in the network.

Due to the same reason driving increased delivery ratio, all schemes experience decreased average delivery latency in Fig. 9(b). With flooding nature for message delivery, the possibility that one of message copies to be delivered, will be higher than those schemes with section of relay node, e.g., TDOR. This means one of message copies will be delivered faster, due to flooding. Therefore, Epidemic ideally (without considering bandwidth contention) achieves the lowest latency, highest delivery ratio but with highest overhead ratio. Here, due to fast nodal moving speed, some messages may not be successfully transmitted, thus the delivery latency is increased.

In Fig. 9(c), TDOR achieves a decreased overhead ratio. This is mainly because that the node which is geographically closer (with faster speed) to the trajectory will be selected as relay, different from TBHGR and DGR which select relay nodes that are just in proximity to destination. As such, the latter two schemes experience an increased overhead, even in case of a faster nodal speed.

E. Influence of Distribution of Destinations

Since previous results are shown given pre-deployed destinations, we further implement a location distribution function depending on the nodal movement interest. Here, a certain number of coordinates of destinations are selected from the 40 POIs as already illustrated in Fig. 5. For example, the case with "7 Destinations" indicates the locations of 7 destinations are randomly selected from 40 POIs.

In Fig. 10(a), Fig. 10(b) and Fig. 10(c), we observe that the performance of delivering messages to a single destination, significantly differs from the case with multiple destinations. Even though an increased number of destinations will trigger much different trajectories towards destinations, TDOR still captures the nodal mobility associated to trajectory, by achieving a higher delivery ratio than DGR and TBHGR but with a lower overhead ratio. This demonstrates the efficiency of TDOR and its tolerance for the distribution of destinations.

VI. Conclusion

In this paper, we propose a trajectory-driven routing protocol for VCPS. As the trajectory towards destination is computed by the source node when needed, such a source based routing nature is immune to the mobility of intermediate nodes. By considering the mobility proximity to the certain trajectory, TDOR is decoupled into a routing policy with three cases to relay messages with differentiated transmission orders. Evaluation results under the Helsinki city scenario show the advantages of TDOR over well known opportunistic geographic routing protocols, in terms of much lower routing overhead with comparable delivery ratio.

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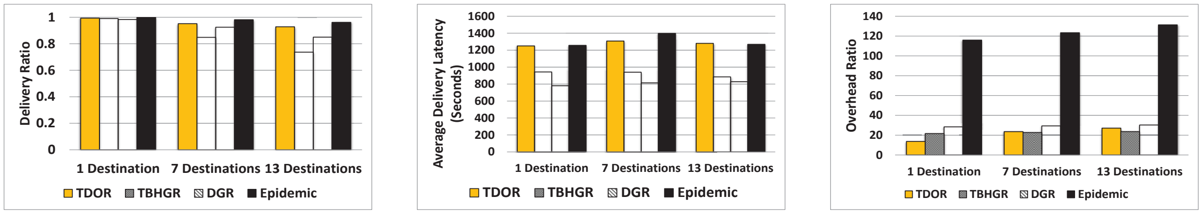

(a) Delivery Ratio (b) Average Delivery Latency (c) Overhead Ratio

Fig. 10. Influence of Destinations Distribution

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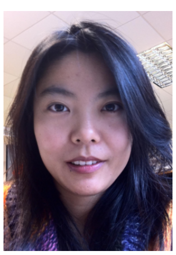

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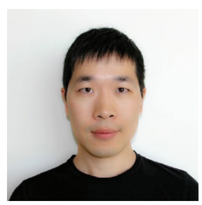

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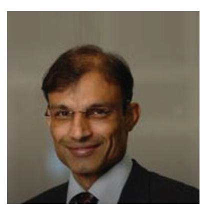

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