

Spraying the Replication Probability With Geographic Assistance for Delay Tolerant Networks

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Abstract—Receiving great interest from the research community, Delay Tolerant Networks (DTNs) are a type of Next Generation Networks (NGNs) proposed to bridge communication in challenged environments. In this paper, the message replication probability is proportionally sprayed for efficient routing mainly under sparse scenario. This methodology is different from the spray based algorithms using message copy ticket to control replication. Our heuristic algorithm aims to overcome the scalability of spray based algorithms since to determine the initial value of copy ticket requires the assumption that either the number of nodes known in advance or the underlying mobility model follows the Random WayPoint (RWP) characteristic.

Specifically, in combining with the assistance of geographic information to estimate the movement range of destination, our routing decision is based on the encounter angle between pairwise nodes, and dynamically switched between our designed two routing phases named as geographic replication and replication probability spray. Furthermore, messages are under transmission with the consideration of redundancy pruning. Simulation results show our heuristic algorithm outperforms other well known algorithms in terms of delivery ratio, transmission overhead, average latency as well as buffer occupancy time.

I. INTRODUCTION

A set of improved versions of Spray-and-Wait [1] have been proposed for efficient routing in Delay Tolerant Networks (DTNs) [2] during the last few years. The core concept is to define an initial copy ticket value for each generated message to limit the number of replications, and enable intermediate nodes carrying these message copy tickets to encounter destination for efficient routing.

However, the primary problem for these algorithms is how to determine the initial value of copy ticket if the underlying mobility does not follow the Random WayPoint (RWP), or the number of nodes is unknown in reality. In this paper, we adopt the mechanism to spray the message replication probability rather than copy ticket, to overcome the limitation of spray based algorithm since to determine the value of copy ticket is not taken into account by our proposed algorithm. This approach is more feasible in reality to achieve the similar low transmission overhead of spray based algorithms particularly under sparse scenario.

Considering moving direction, we further propose it is unnecessary to replicate message to the intermediate node moving away from destination. To replicate message towards its destination, message is processed with geographic consideration if the encounter angle between pairwise nodes is large

since they are moving with different direction. However, the opportunistic scenario of DTNs is assumed to be sparse or highly mobile, which is unrealistic to obtain the realtime location of destination because of the long delay for information request or rapid change of location. In light of this, we propose to estimate the movement range of destination and promote message replication based on the proximity to this range. In addition, pairwise nodes are moving with similar direction if their encounter angle is small, thus the message replication is probabilistic for redundancy reduction in this case, where this replication probability is proportionally distributed according to our proposed utility metric.

The contributions in this paper are as follows:

- By means of our defined utility metric, a methodology to spray the message replication probability rather than message copy ticket is proposed, thus the number of replications is unlimited.
- With the assistance of geographic information, a heuristic routing algorithm consisting of two routing phases is proposed. Based on the scheduling priority for these two routing phases, messages are under prioritized transmission to tolerate frequent disruption due to high mobility with the consideration of redundancy reduction.

- We simulate Epidemic [3], Adaptive Epidemic [4], POR [5] (POR is based on realtime location information) and EBR [6] (EBR is a powerful spray based algorithm) for performance comparison under the Helsinki city scenario.

We firstly argue to spray the message replication probability is a potential approach to achieve efficiency if the existing spray based algorithms are limited by their requirement. Besides, it is also difficult to obtain the realtime location in DTNs due to sparse network density and high mobility.

II. RELATED WORK

In this paper, we omit the routing algorithms with the assistance infrastructure such as message ferry/data mule and throwbox/gateway, since they either focus on route design or location deployment for infrastructure.

Without such assistance, the early stage algorithms are based on the utility metric to select candidate node, using single copy based forwarding [7].

Inherently, it is effective to replicate message regardless of candidate node selection for achieving maximum delivery ratio under even with redundancy [3]. Motivated by this limitation,

Spray-and-Wait [1] limits the number of replications by a copy ticket defined for each generated message.

Up to now, there have been some evolutions of Spray-and-Wait. In [8], message is sprayed to the encountered node qualified by utility metric. The work in [9] focuses on how to dynamically determine the value of copy ticket. Based on oracle information about network, copy ticket is proportionally sprayed in [6]. In order to achieve the target latency, to control the spray depth is proposed in [10].

Inherently, these spray algorithms focus on how to utilize the limited number of replications. Furthermore, the work in [11] has proved the optimal approach to proportionally spray the copy ticket relies on the initialized value of copy ticket. However, to determine this value is always a challenging problem in reality rather than RWP scenario, since the initialization is only based on the assumption of exponentially distributed inter meeting time. As well, it is also limited by the lack of knowledge about the number of nodes in the network, as mentioned in [1].

Another methodology for redundancy reduction is to replicate message based on utility metric. In [12], message is replicated using encounter probability with aging and transitivity consideration. Based on the distance towards destination, geographic algorithm [5] assumes the realtime location is shared by all of the nodes in the networks or the delay to obtain such information can be ignored.

III. OUR PROPOSED ALGORITHM

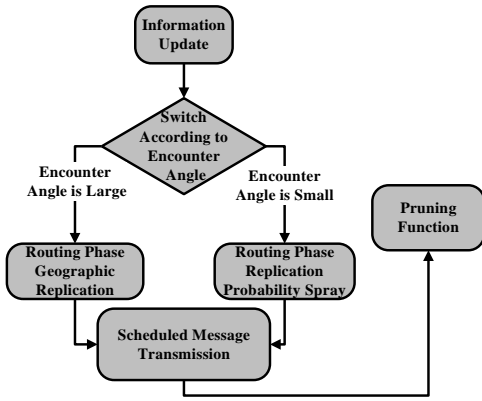


Fig. 1. Function Flowchart

The overall function flowchart is illustrated in Fig.1 and the detail of the design is introduced in the following subsections. Briefly, driven by the encounter angle between pairwise encountered node, the key insight of our heuristic algorithm is to probabilistically replicate message according to the proportionally distributed probability (we name as replication probability spray) if pairwise nodes encounter with a small angle. Otherwise, to replicate message towards its destination in case of large encounter angle is for sufficient replication given the limited message lifetime, named as geographic replication. The designed scheduled message transmission and the specific process after transfer further promote the performance with the consideration of load balancing and redundancy pruning.

A. Definition of Utility Metric

Considering mobility factor, we address three conventional metrics of pairwise encountered nodes N_i and N_j , which are history encounter count $C_{i,j}$, history encounter duration $D_{i,j}$ and history inter meeting time $I_{i,j}$, where $i, j \in S$ and S is the total number of nodes in the networks.

Particularly, the history inter meeting time consists of history encounter duration $D_{i,j}$ and disruption time until pairwise nodes encounter again. As illustrated in Fig.2, a high ratio of $\frac{D_{i,j}}{I_{i,j}}$ indicates a more efficient inter meeting time since more messages can be transmitted during this encounter duration. We propose an accumulative formula to smooth the factor of large variation within the number of encounters, where the utility $U_{i,j}$ is defined as:

$$U_{i,j} = \frac{\sum_{k=2}^{C_{i,j}} \left(\frac{D_{i,j}^{k-1}}{I_{i,j}^k} \right)}{(C_{i,j} - 1)} \quad (1)$$

where $D_{i,j}^{k-1}$ is the encounter duration before the k^{th} encounter and it is valid after the first encounter. With the time elapsing this property is useful since the node experiences a large number of encounters is more likely to successfully route the message to the final destination than those who have infrequent encounters.

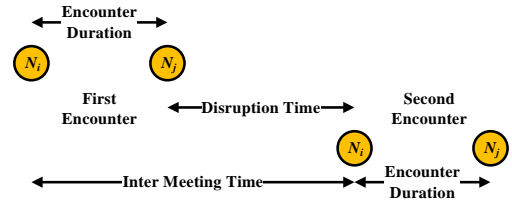


Fig. 2. Encounter History of Pairwise Nodes

Inherently, to estimate the delivery potential of encountered nodes based on local knowledge is unreasonable since the factor of other history encountered nodes is ignored. To overcome this limitation, pairwise nodes would calculate and update their $U_{i,j}$ for each other. Afterwards, they would add their local routing information to each other for the purpose of extending knowledge. To this end, they can obtain the knowledge from their neighbors' history encounter information.

Based on the above analysis, an improved utility $U'_{i,j}$ is proposed:

$$U'_{c,d} = \frac{\sum_{k=1}^n U_{c(k),d} + U_{c,d}}{\xi + 1} \quad (2)$$

where n is the number of history encountered nodes $c(n)$ of current carrier c , d is the corresponding destined node. In detail, ξ is initialized with zero and increased by one if $c(n)$ contains $U_{c(n),d}$ for d . Therefore, the local node would obtain an abstract average knowledge for d not only based on itself but also based on the history information from its neighbors. As an example in TABLE I, the $U'_{6,2}$ for N_2 based on the view of N_6 is calculated as:

$$U'_{6,2} = \frac{U_{1,2} + U_{5,2} + U_{6,2}}{2 + 1} = \frac{0.6 + 0.3 + 0}{2 + 1} = 0.3 \quad (3)$$

TABLE I
EXAMPLE OF ROUTING TABLE RECORDED BY N_6

current carrier N_6	$U_{6,1}$	0.4
	$U_{6,5}$	0.2
	$U_{6,2}$	0.0
history encountered N_1 of N_6	$U_{1,6}$	0.4
	$U_{1,2}$	0.6
	$U_{1,4}$	0.3
history encountered N_5 of N_6	$U_{5,2}$	0.3
	$U_{5,8}$	0.1
	$U_{5,6}$	0.2

B. Information Update

Algorithm 1 Information Update

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1: if connection is up then
2:   both  $N_i$  and  $N_j$  update the number of encounter  $C_{i,j}$ 
3:   both  $N_i$  and  $N_j$  update the inter meeting time  $I_{i,j}$ 
4:   for each  $M_i$  in  $N_i$  do
5:     for each  $M_j$  in  $N_j$  do
6:       if  $M_i$  equals to  $M_j$  then
7:          $N_j$  adds the ID of nodes in  $\aleph(M_i)$  to  $\aleph(M_j)$ 
8:          $N_i$  adds the ID of nodes in  $\aleph(M_j)$  to  $\aleph(M_i)$ 
9:       end if
10:    end for
11:  end for
12:  both  $N_i$  and  $N_j$  update  $\delta(t_{i,j})$  and  $\delta(t_{j,i})$ 
13:  if  $N_j$  contains  $\delta(t_{j,k})$  then
14:    for each  $\delta(t_{i,k})$  in  $N_i$  do
15:      for each  $\delta(t_{j,k})$  in  $N_j$  do
16:        if  $t_{i,k} > t_{j,k}$  then
17:           $N_j$  replaces  $\delta(t_{j,k})$  with  $\delta(t_{i,k})$ 
18:        else
19:           $N_i$  replaces  $\delta(t_{i,k})$  with  $\delta(t_{j,k})$ 
20:        end if
21:      end for
22:    end for
23:  else
24:     $N_j$  records  $\delta(t_{j,k})$  by  $\delta(t_{i,k})$ 
25:  end if
26: else if connection is down then
27:   both  $N_i$  and  $N_j$  update the encounter duration  $D_{i,j}$ 
28: end if

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TABLE II
INFORMATION FORMAT OF $\delta(t_{i,k})$

Node ID	History Location	History Speed	Encounter Time
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Borrowing the ID identified for each node, the carrier count $\aleph(M)$ is denoted as the number of nodes have carried message M . In addition, we assume each mobile node can only obtain its local realtime location by means of the Global Positioning System (GPS) without consideration of GPS error. Specifically, as illustrated in TABLE II, the definition of geographic information $\delta(t_{i,k})$ is about the history location $L(t_{i,k})$ of N_k together with its speed S_k obtained by N_i at their encounter time $t_{i,k}$. This information is updated to the value obtained at more recent time if both of pairwise

nodes encountered N_k . Otherwise one of them records other's information for backup. The current $\delta(t_{i,j})$ and $\delta(t_{j,i})$ of pairwise encountered nodes N_i and N_j are also exchanged for information update. A detail process regarding information update is illustrated in Algorithm 1.

In particular, the information update activated when encounter event happens is essential for all of the routing algorithms in DTNs, rather than the periodic update for traditional algorithms in Mobile Ad hoc NETWORKS (MANETs).

C. Routing Framework

With an appropriate time window ΔT for the location update, we adopt the mobility vector to indicate the trajectory. Specifically, ΔV_i is the variation of N_i 's mobility vector within previous ΔT , which consists of the specific variation of location ΔX_i and ΔY_i . Therefore, the encounter angle θ between N_i and N_j can be calculated by geometry.

In our routing framework, messages are processed respectively by replication probability spray and geographic replication phase according to the decision made from the encounter angle $\theta \in [0, \pi]$ between pairwise nodes:

$$\theta = \begin{cases} |\nu_i - \nu_j| & \text{if } |\nu_i - \nu_j| \leq \pi \\ 2\pi - |\nu_i - \nu_j| & \text{else} \end{cases} \quad (4)$$

Where ν_i and ν_j are the moving direction of N_i and N_j . Generally, if θ is large enough, it makes sense to adopt geographic replication since it only replicates message towards destination for sufficient delivery. Relatively, it is unnecessary to replicate message by geographic replication if θ is quite small since pairwise nodes are moving with similar direction. In light of this, we adopt the replication probability spray for efficiency. In particular, a large value of $\frac{\theta}{\pi}$ indicates a large encounter angle and vice versa.

1) *Geographic Replication*: Suppose the history location of destination N_d obtained at more recent time is $L(d)_{i,j}$ since $\delta(t_{i,d})$ and $\delta(t_{j,d})$ for N_d are consistent after update. Then the estimated movement range of N_d is defined as a virtual circle of which the radius is \aleph , under the assumption of constant moving speed S_d :

$$\aleph = (t_{cur} - t_d) * S_d \quad (5)$$

where t_{cur} is the current time in the network and t_d is the more recent time value between $t_{i,d}$ and $t_{j,d}$. The distance from the location of N_j to $L(d)_{i,j}$ is denoted as $dist_{j \rightarrow d}$ at t_{cur} .

The condition $dist_{j \rightarrow d} < \aleph$ indicates N_j is within the movement range estimated for N_d , thus message M carried by N_i is replicated for sufficient delivery. As N_j is out of such range given $dist_{j \rightarrow d} \geq \aleph$, M is replicated to N_j only if the angle ϕ between its current moving direction $\nu_j \in [0, 2\pi]$ and the line connection of $dist_{j \rightarrow d}$ is smaller than $\frac{\pi}{2}$. As an example illustrated in Fig.3, the current moving direction of N_j is parallel to the tangent of virtual circle estimated for N_d , thus it makes sense that N_j will not encounter N_d , since the encounter only happens if the current moving direction of N_j follows the secant of this circle.

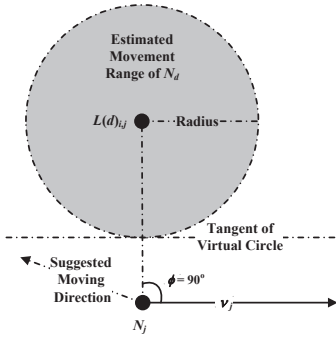


Fig. 3. An Example of Geographic Replication

2) *Replication Probability Spray*: The novelty of replication probability spray is to proportionally spray the replication probability of M according to our defined utility metric for its destination N_d . Generally, the initial replication probability for each generated message is set to 1. If pairwise nodes N_i and N_j encounter, the replication probability $RP(M_i)$ of M carried by N_i and the $RP(M_j)$ of the replicated M to N_j are calculated according to a weighted distribution approach:

$$RP(M_i) = U'_{i,d} * \left[\frac{RP(M_i)}{U'_{i,d} + U'_{j,d}} \right] \quad (6)$$

$$RP(M_j) = U'_{j,d} * \left[\frac{RP(M_i)}{U'_{i,d} + U'_{j,d}} \right] \quad (7)$$

This formula guarantees a large replication probability of M is sprayed to the candidate node with higher utility metric for N_d . In addition, if both N_i and N_j already carry M , the replication probability is firstly normalized as the maximum value between $RP(M_i)$ and $RP(M_j)$ to guarantee a sufficient probability for subsequent replication, these values are recalculated according to equation (6) and equation (7).

3) *Scheduled Message Transmission*: As there are two routing phases designed, to determine their scheduling priority is essential. In light of this, we design a dynamic scheduling mechanism with the scheduling priority SP defined as:

$$SP = \sum_{k=1}^m G_{(M,j)} \quad (8)$$

where m is the number of enqueued messages processed by each routing phase. We assume the determined candidate node N_j has a gravitation for message M carried by N_i . Thus the gravitation $G_{(M,j)}$ is defined as:

$$G_{(M,j)} = \frac{\Psi_M * \Psi_j^{free}}{(T_M^{ini} - T_M^{cur})^2} \quad (9)$$

where Ψ_M is the size of M and Ψ_j^{free} is the free buffer space of N_j . T_M^{ini} is the initial lifetime of M and T_M^{cur} is its current lifetime. In particular, this formula not only balances the traffic load by taking into account free buffer size, but also it more focuses on achieving less delivery latency since the message lifetime squarely affects its priority. If the distance regarding message lifetime is large, accordingly N_j as the next

Algorithm 2 Routing Framework

```

1: for each encounter between  $N_i$  and  $N_j$  do
2:   Information Update
3:   for each message  $M$  in  $N_i$  do
4:     initialize  $L(d)_{i,j}$  by  $\delta(i,d)$  and  $\delta(t_{j,d})$ 
5:     generate a random number  $Ran \in [0, 1]$ 
6:     if  $N_j$  already has  $M$  then
7:       define  $max = [RP(M_i), RP(M_j)]$ 
8:        $N_j$  recalculates  $U'_{j,d}[\frac{max}{U'_{i,d} + U'_{j,d}}]$  for  $RP(M_j)$ 
9:        $N_i$  recalculates  $U'_{i,d}[\frac{max}{U'_{i,d} + U'_{j,d}}]$  for  $RP(M_i)$ 
10:    else if  $\frac{\theta}{\pi} > Ran$  then
11:      if  $L(d)_{i,j}$  is available then
12:        if  $dist_{j \rightarrow d} < \mathfrak{R}$  then
13:           $N_i$  replicates  $M$  to  $N_j$ 
14:        else if  $dist_{j \rightarrow d} \geq \mathfrak{R}$  and  $\phi < \frac{\pi}{2}$  then
15:           $N_i$  replicate  $M$  to  $N_j$ 
16:        end if
17:      end if
18:    else if  $\frac{\theta}{\pi} \leq Ran$  then
19:      if  $RP(M_i) > Ran$  then
20:        calculate  $U'_{j,d}[\frac{RP(M_i)}{U'_{i,d} + U'_{j,d}}]$ 
21:        if  $U'_{j,d}[\frac{RP(M_i)}{U'_{i,d} + U'_{j,d}}] > 0$  then
22:           $N_j$  replicates  $M$  with  $U'_{j,d}[\frac{RP(M_i)}{U'_{i,d} + U'_{j,d}}]$ 
23:           $N_i$  recalculates  $U'_{i,d}[\frac{RP(M_i)}{U'_{i,d} + U'_{j,d}}]$  for  $RP(M_i)$ 
24:        end if
25:      end if
26:    end if
27:  end for
28: end for
29: if  $SP_G \geq SP_R$  then
30:    $N_i$  transmits  $M$  in  $Q_G$  from the one with lowest  $\aleph(M)$ 
31: else
32:    $N_i$  transmits  $M$  in  $Q_R$  from the one with lowest  $\aleph(M)$ 
33: end if
34: for each transferred  $M$  do
35:   if is transmitted by replication probability spray then
36:      $N_i$  deletes  $M$  with probability of  $(1 - RP(M_i))$ 
37:   end if
38: end for

```

hop might not receive M since M might be expired before message transfer, as such $G_{(M,j)}$ is small.

Therefore the SP_G for geographic approach and the SP_R for replication probability spray can be calculated respectively. Specifically, the queue Q_{geo} for geographic replication phase and the Q_{rps} for replication probability spray phase is scheduled based on a larger value of SP , where the calculation of SP is reset after each successful transfer of each message.

With respect to the messages transmitted using same routing phase, we utilize the previously defined carrier count $\aleph(M)$ for their priority, since this updated information in Algorithm 1 is used to estimate the number of nodes have carried M . Therefore, message with the least $\aleph(M)$ is regarded as the highest priority for transmission, since it is most fresh in the network.

4) *Pruning Function*: Since the messages are replicated according to different routing phases, they are processed respectively after successful transfer. Regarding message repli-

cated by geographic replication, the current carrier always keeps the original message since it moves with a different direction between encountered node, which guarantees the sufficient message diffusion. Relatively, message processed by replication probability spray is likely to be deleted if its $RP(M_i)$ is quite small after spray process, which implies a large replication probability has been sprayed to a better candidate node moving with the similar direction, thus it is unnecessary for the current carrier to keep message.

IV. PERFORMANCE EVALUATION

The results are evaluated by the Opportunistic Network Environment (ONE) [13]. The Helsinki city scenario area is 15.3 km^2 where 126 mobile nodes are classified as 80 pedestrians with [0.5-1.5]m/s, 40 cars with [2.7-13.9]m/s and 6 trams with [7-10]m/s. The buffer size is set to be large enough so that messages are not dropped due to buffer exhaustion. In particular, each node has an interest to visit some places rather than randomly select the next point based on route. The connectivity is 2Mb/s with 20 meters transmission range as the Bluetooth technique. An initial 3600s is used to collect the history information required for routing decision and messages are generated between 3600s and 18000s. The ΔT for local location update is 1s. Considering the delay tolerant characteristic of DTNs, the message lifetime is set with 2.5 hours.

A. Algorithms for Comparison

We compare our heuristic algorithm with Epidemic [3] and Adaptive Epidemic [4] for performance evaluation. As well, with the geographic assistance to enable the message diffusion towards destination, geographic algorithm POR [5] is compared. As mentioned, the heuristic is applied if either the underlying mobility model does not strictly follow RWP, or the number of nodes in the network is unknown in advance, these requirements are difficult for the application of spray based algorithms. In light of this, EBR [6] is selected for comparison where the initial value of copy ticket is set with 13 determined by 10% number of nodes in the network. This is a recommended value advised in [1] if the knowledge of network mobility model is unavailable. In particular, the realtime location is shared by all of the nodes in POR. The parameter configuration of Adaptive Epidemic and EBR are based their default values. We plot the average value for the results evaluation to smooth the random factor.

B. Evaluation Results

Given the large enough message lifetime, the overhead ratio² achieved by our algorithm is close to EBR in Fig.4(c), thanks to the proportionally distributed message replication probability assisted by the geographic replication. Inherently, the message replication count is without limitation in our algorithm, whereas to some extent, EBR is limited by the initial value of copy ticket. Therefore, our approach achieves

²The overhead ratio is given by the ratio between the number of successful relayed messages and the total number of messages delivered.

TABLE III
INITIAL SIMULATION CONFIGURATION

Simulation Time	21600 seconds (6 Hours)
Bandwidth	2Mb/s
Transmission Range	20m
Buffer Size	1500MB
Number of Nodes	126
Message Size	500kB ~ 2MB
Message Generation	Every 9s between 3600s and 18000s
Message Lifetime	2.5 Hours
Scenario Mobility	Helsinki City Model

lower latency in Fig.4(b) than EBR because of more replications. Assisted by the greedy geographic replication, the delivery ratio in Fig.4(a) is enhanced particularly given small message lifetime. Besides, to delete message with the smallest replication probability contributes to the lowest average buffer time in Fig.4(d)³.

Inherently, the alleviated bandwidth contention increases message delivery ratio in Fig.5(a) and overhead in Fig.5(c). Even EBR achieves a slightly less overhead than our proposed algorithm, the significant drawback of EBR is the high latency in Fig.5(b) as well as the buffer time in Fig.5(d). These negative aspect is due to the limited number of replications and the lack of the pruning function. In particular, the increased generation rate does not directly affect the buffer time for all of compared algorithms since the buffer space is set to be large enough.

The results in Fig.6(a) and Fig.6(c) keep an increment growth since more messages can be delivered because of the increased transmission range. EBR achieves the lowest overhead ratio given the large transmission range, since its number of replications is partially limited by the initial copy tickets. However, the overhead ratio achieved by our algorithm is close to EBR when the transmission range is around 20 meters, this implies our efficiency under sparse scenario. Apart from the overhead ratio, the proposed algorithm still performs well particularly if the transmission range is large enough since the history information is updated more frequently. This is beneficial to the movement range estimation for destination and message deletion. In light of this, the improvement in Fig.6(b) and Fig.6(d) become significant.

V. CONCLUSION

A heuristic routing algorithm for DTNs has been proposed in this paper, which sprays the message replication probability rather than copy ticket. The main motivation is to loose the scalability problem of spray based algorithm, that is to determine the initial value for copy ticket. Based on our defined utility metric for replication probability distribution, the heuristic algorithm dynamically switches between the designed geographic replication phase and the replication probability spray phase according to encounter angle between

³The average buffer time is defined as the average value of the time period for the carried messages in the buffer of each node.

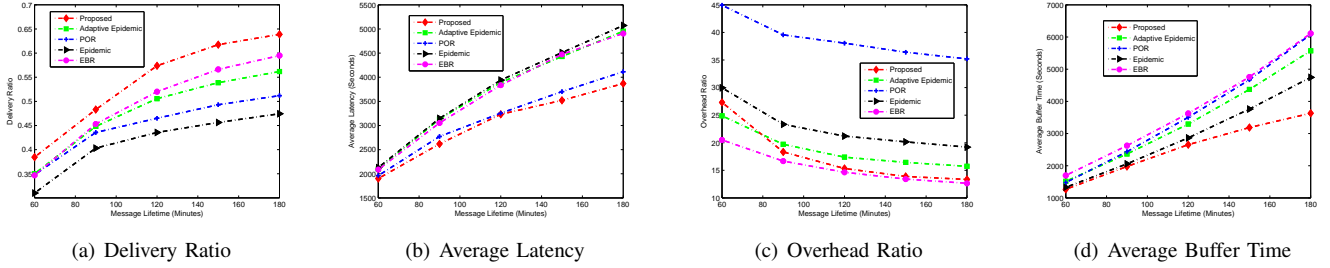


Fig. 4. Effect of Message Lifetime in Case of 20 Meters Transmission Range and 9s Message Generation Rate

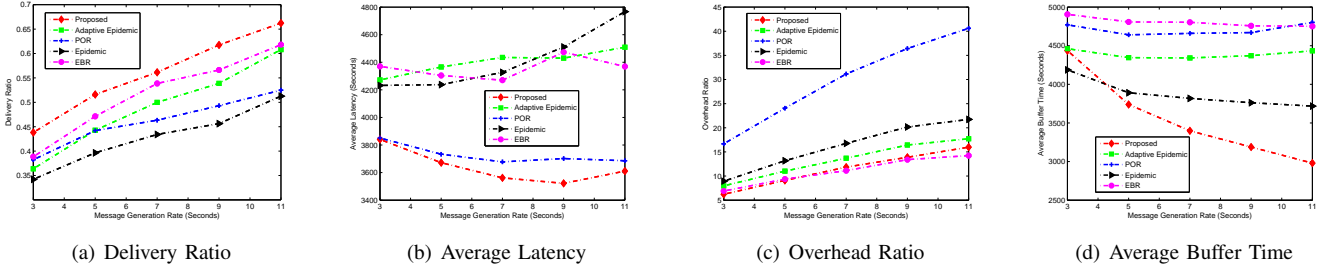


Fig. 5. Effect of Message Generation Rate in Case of 2.5 hours Message Lifetime and 20 Meters Transmission Range

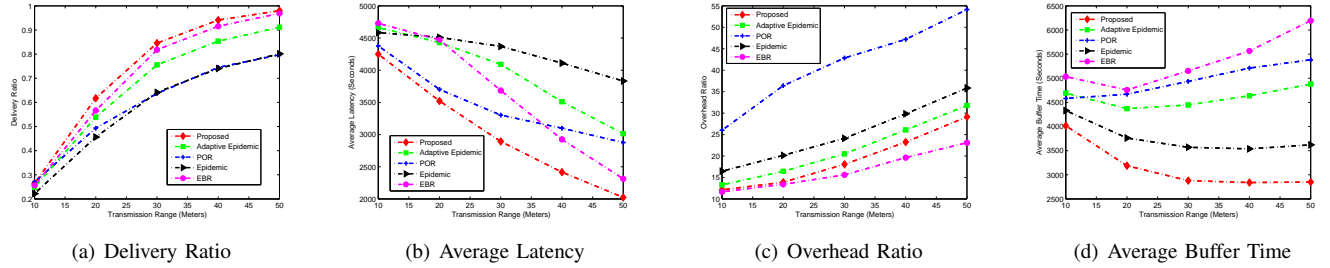


Fig. 6. Effect of Transmission Range in Case of 2.5 Hours Message Lifetime and 9s Message Generation Rate

pairwise nodes. In addition, our algorithm is with prioritized message transmission between each phase as well as the redundancy pruning for performance enhancement. Evaluated under the Helsinki city, the proposed algorithm outperforms the literature algorithms in terms of evaluation metrics as well as low buffer occupancy particularly with small transmission range and relatively sufficient message lifetime, thus is more feasible in sparse DTNs.

Since the idea of the proposed approach is unique and worthwhile investigating given a huge number of existing works, the future work will focus on the deduction of overhead upper bound as well as how to reduce the signalling overhead taking into account the GPS error.

VI. ACKNOWLEDGEMENT

The funding leading to this work is from the EU FP7 MONET project and EPSRC UK-CHINA Science Bridge UC4G project. The authors wish to acknowledge the support from Datang Wireless Mobile Innovation Center (DWMIC) China Academy of Telecommunication Technology (CATT).

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