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Routing with Dynamic Cluster Awareness in DTNs

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***Abstract*—This paper proposes a cluster-based routing scheme for improving cost-effectiveness of message delivery in delay-tolerant networks. The proposed scheme is designed, as follows: (1) every node calculates the expected node density in network proximity; (2) every node perceives whether it stays in a cluster or not; (3) every node can ask for relay nodes to carry messages in a cluster; (4) a network system can control the quantity of message copies by measuring the message density of a cluster to help message distribution in a network. Performance under synthetical simulation shows that this scheme is able to obtain comparable effects in terms of delivery probability and message overhead ratio, particularly when the mobility models are in accord with human behaviour.**

Keywords*—Routing; cluster awareness; delay-tolerant networks; DTN.

I. INTRODUCTION

Delay tolerant networks (DTNs) aims to augment the effects of unscheduled delivery opportunities to increase the delivery ratio and shorten delivery time in distributed and unstructured networks. When end-to-end routing paths cannot persistently exist in highly dynamic environments, message delivery from a source to any destination depends on relay nodes that repeatedly forward message copies to encountered nodes during their movements. Prior routing designs in DTNs [1] often resorted to the message replication methodology [2][3] or specific utility functions of selecting relay nodes [4] to maximize the performance of message delivery in a network. Most efforts were based on sparse environment where nodes may contact few nodes, one by one sporadically. However, many real traces [5][6] found that people with mobile devices can aggregate at some hot spots, e.g., train stations and crossroads, and people in hot spots will *virtually* form clusters which they may re-visit frequently. Suppose that messages can be delivered to, stored in, or exchanged by nodes that stay in clusters. The probability of message delivery from a source to any destination could be increased potentially.

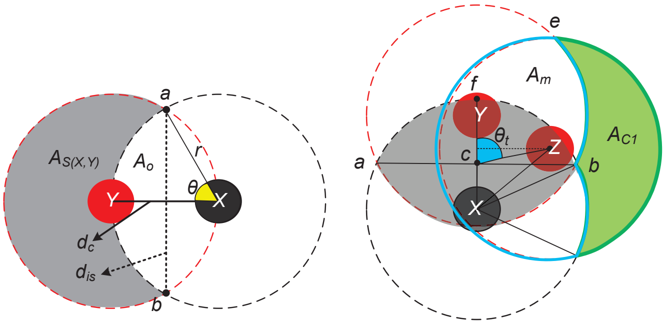
Regarding cluster-based routing in DTNs, recent studies [7][8][9][10] examined the situation of disjoint clusters in a network to increase the performance. In [7], when nodes are evenly distributed in a clustered DTN, this work employed ferries to carry messages between clusters, as well as gateway nodes in clusters that receive messages from ferries and deliver them to destinations in their clusters. In [8], mobile nodes with high contact probability can be grouped as clusters. Let each node be associated with only one cluster in a network. Its routing design was based on nodal contact probabilities that are given with an exponentially weighted moving average (EWMA) scheme. As a destination node exists in the same cluster, a node transmits the message only when it contacts the destination. In an inter-cluster case, the message will be sent to a gateway node that will find the cluster of the destination node. The work [10] assumed that a node is always associated to a certain hot spot in a network. It used a time-homogeneous semi-Markov process to design a hot-spot trajectory prediction method, which can derive the probability distribution of node arrival time at hot spots. Furthermore, [9] formulated the measure of local node density by the variance of inter-meeting times between consecutively encountered nodes in a network. Then, a density-aware routing scheme (DARS) was proposed to scatter messages to dense areas where destinations may be found. Comparatively, our study will release the above assumptions and consider realistic situations where nodes will form clusters not only in hot spots but transitions between two hot spots, e.g., crossroads. Without loss of generality, our study will not require message ferries that were commonly applied in previous cluster-based routing methods in DTN applications.

This paper designs a message routing scheme with dynamic cluster awareness, abbreviated as MDCA, in DTNs. The MDCA consists of two mutual phases. Firstly, MDCA measures the expected node density to group contacting nodes as a cluster. Without using global positioning systems on mobile nodes, MDCA estimates the expected communication area of contacted nodes, involving direct and indirect connections, to calculate the node density in network proximity. Secondly, MDCA measures the message density of a cluster and instructs nodes to replicate or forward messages to other nodes in the same cluster. A low-density message will be replicated to a node with high opportunity of moving to another cluster. As a node has the last copy of a message in a cluster and is going to leave the cluster, it will forward the last copy to another node in the cluster. Performance results under simulations show that MDCA can obtain higher delivery probability and lower message overhead than several typical schemes, including Epidemic [3], PRoPHET [4], and Spray and Wait (SnW) [2], under the mobility model with human behaviour patterns.

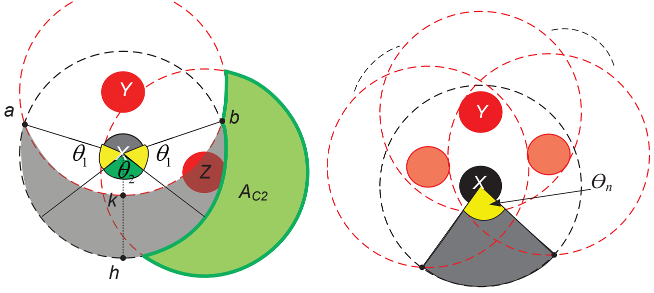
The rest of the paper is organized as follows: Section II describes the estimation of the expected communication area. Section III describes the MDCA scheme. Section IV presents the simulation and results. Section V presents the conclusion.

II. COMMUNICATION AREA ESTIMATION

This section formulates the estimation of communication area among contact nodes. The formulation has two parts: a basic case that a node contacts with a single one-hop node, and a complex case that a node contacts with multiple one-hop nodes, as specified in Sections II.A and II.B.



(a) Basic case with a one-hop node (b) In-contact case



(c) Non-contact case (d) θ_n in a non-contact case

Fig. 1. Illustrations of communication area among nodes: (a) single case, (b) in-contact case, (c) non-contact case, and (d) θ_n in a non-contact case.

A. Basic Case: Single One-Hop Node

Let each node have a common communication radius r. $R(i)$ denotes a communication area of a node i and is equal to πr^2. Fig. 1(a) depicts a basic case that node X directly contacts with node Y. When X encounters Y, their communication areas, denoted as A_E, can be expressed symmetrically as

$$A_E = R(X) + A_{S(X,Y)} = R(Y) + A_{S(X,Y)}, \qquad (1)$$

where $A_{S(X,Y)}$ depends on the size of an intersection area between $R(X)$ and $R(Y)$, denoted as A_o.

Let d_c denote the distance between X and Y, θ be the inner angle $\angle aXY$, and d_{is} be the distance between two points a and b. $A_{S(X,Y)}$ can be given as

$$A_{S(X,Y)} = R(Y) - A_o = R(Y) - \left(\frac{2\theta}{\pi}R(Y) - \frac{d_{is}d_c}{2}\right). \qquad (2)$$

Because the probability that Y appears at any position inside $R(X)$ is uniform, d_c is a random variable s. Then, the cumulative distribution function (CDF) and probability density function (PDF) with respect to S are given by

$$F_S(x) = \frac{\pi x^2}{\pi r^2}, \quad 0 \le x \le r,$$

$$f_S(x) = \frac{dF_S(x)}{dx} = \frac{2x}{r^2}, \quad 0 \le x \le r.$$

The expected value of S can be given by

$$E(S) = \int_0^r x f_s(x)dx = \frac{2r}{3}. \qquad (3)$$

In Fig. 1(a), the expected values of θ, angle $\angle aXb = 2\theta$ and d_{is} can be resolved using trigonometric functions. Then, the expected value of $A_{S(X,Y)}$ in (2) can be obtained, and denoted as $E(A_S)$ for brevity in the rest of this section.

B. Complex Case: Multiple One-Hop Nodes

When more than two nodes are considered, the complex situation involves two cases: as shown in Figs. 1(b) and 1(c)(d), the *in-contact case* that all one-hop nodes are in contact with each other, and the *non-contact case* that not all one-hop nodes directly contact with each other.

1) In-Contact Case: Fig. 1 (b) shows the in-contact case with three nodes X, Y and Z. Let A_{C1} indicate an additional communication area of $R(Z)-(R(Y)\cup R(X))$ after Z contacts with both X and Y. The gray area comprises four zones divided by the line $\overline{ab}$ and the extending line $\overline{cf}$. The result of calculating the expected value of A_{C1}, denoted as $E(A_{C1})$, is the same regardless of which one area that Z moves in.

The range scope of A_{C1} is variable with respect to Z's position on the arc $\widehat{bf}$ and distance apart from the centric point c. To obtain $E(A_{C1})$, the calculation process has two steps.

1) The first step defines a PDF with respect to Z's position on $\widehat{bf}$ and computes the size of a sector fcZ corresponding to $\angle YcZ$.
2) The second step determines $E(A_{C1})$ with respect to a couple of variables, i.e., distance from c to Z and the expected position on $\widehat{bf}$ given by the first step.

Step 1: Let A^t_{C1} mean the size of A_{C1} as Z moves around $\widehat{bf}$. As Fig. 1(b) shows, the upper and the lower bounds of A^t_{C1} denoted as A^{Max}_{C1} and A^{Low}_{C1} will occur when Z locates at the points b and f, respectively. Let A_m mean the overlapped area of $R(Z)\cap(R(Y)\cup R(X))$. The range of A^t_{C1} is given as:

$$A^{Max}_{C1} = R(Z) - A_m, \qquad (4)$$

$$A^{Low}_{C1} = A_{S(X,Z)} - E(A_{S(X,Y)}). \qquad (5)$$

Next, the distance from c to $\widehat{bf}$ will vary in the range between $r(1-\cos(\theta_{S(X,Y)}/2))$ and $r\sin(\theta_{S(X,Y)}/2)$, denoted as d_s and d_l. Since $\angle YcZ$ is a random variable θ_t, the PDF of θ_t is given below with an expected value of θ_t, denoted as $E(\theta_t)$.

$$f_{\theta_t}(\theta) = \frac{\int_{\theta-\Delta\theta}^{\theta} d_s + i\cdot\frac{d_l-d_s}{\pi/2}\,di}{\int_0^{\frac{\pi}{2}} d_s + i\cdot\frac{d_l-d_s}{\pi/2}\,di}, \quad 0 < \theta_t \le \frac{\pi}{2}.$$

With (4), (5) and $E(\theta_t)$, we get the expected area of A^t_{C1} as

$$E(A^t_{C1}) = A^{Low}_{C1} + \frac{E(\theta_t)}{\pi/2}(A^{Max}_{C1} - A^{Low}_{C1}). \qquad (6)$$

Step 2: The area of A_{C1} will shrink as Z moves close to c, and reach its minimum at c, denoted as A^{Min}_{C1}.

$$A^{Min}_{C1} = A_{S(X,Z)} + A_{o(X,Y)} - A_{o(Y,Z)}. \qquad (7)$$

Let $d_{E(\theta_t)}$ indicate the distance from $\widehat{bf}$ to c. The expected distance between Z and c, denoted as $d_{c,Z}$, is given as

$$d_{c,Z} = d_{E(\theta_t)}\frac{E(S)}{r} = \left(d_s + (d_l - d_s)\frac{E(\theta_t)}{\pi/2}\right)\frac{E(S)}{r}. \qquad (8)$$

Because the calculation of circle area is related to the square of radius, $E(A_{C1})$ can thus be obtained as

$$E(A_{C1}) = A^{Min}_{C1} + \left(\frac{d_{c,Z}}{d_{E(\theta_t)}}\right)^2(E(A^t_{C1}) - A^{Min}_{C1}). \qquad (9)$$

2) Non-Contact Case: When Z moves into the gray zone as shown in Fig. 1(c), the non-contact case happens because the connection between Y and Z is indirect. To resolve the additional communication area A_{C2}, it is prerequisite to know the variation of a non-contact angle, denoted as θ_n, corresponding to the arc $\widehat{ahb}$. Depending on the location of Z in the gray zone, the sector of θ_n is divided into two sub-sectors as indicated by θ_1 and θ_2. There exists intersection between $R(Y)$ and A_{C2} as Z moves in the sector of θ_1, but no intersection as Z moves to the sector of θ_2. Note that the angle of θ_1 reaches the maximum when the distance between Z and b is r. In addition, calculating A_{C2} in the sector of θ_2 is reduced to a basic single-hop case of $A_{S(X,Z)}$. Hence, the calculation process has two steps to obtain $E(A_{C2})$.

1) The first step obtains the expected distance between X and Z, and accordingly resovles the range of θ_1.
2) The second step obtains the expected angle of $\angle bXh$ and resolves the value of $E(A_{C2})$ with respect to θ_n.

Step 1: Let d_k and d_h denote the lengths of arc $\widehat{kb}$ and $\widehat{hb}$, as shown in Fig. 1 (c). Assume that the distance of $\overline{hk}$ is a random variable D_{C2}. Given that Z moves on the range of h to k, a PDF of D_{C2} can be given below with the expected value of D_{C2}, denoted as $E(D_{C2})$.

$$f_{D_{C2}}(d) = \frac{\int_{d-\Delta d}^{d} d_k + i \cdot \frac{d_h - d_k}{d_{c(X,Y)}}\, di}{\int_{0}^{d_{c(X,Y)}} d_k + i \cdot \frac{d_h - d_k}{d_{c(X,Y)}}\, di}, \quad 0 < d \le d_{c(X,Y)},$$

where $d_{c(X,Z)}$ means the expected distance between X and Z, and it is equal to $r - (E(S) - E(D_{C2}))$. Meanwhile, when both $\overline{bx}$ and $\overline{bZ}$ are equal to r, θ_1 can reach its maximum that can be given by $\theta_1 = \cos^{-1}\frac{d_{c(X,Z)}}{2r}$.

Step 2: Assume $\angle bXh$ in Fig. 1(c) is a random variable θ_u. The PDF of θ_u can be given below with an expected value of θ_u, denoted as $E(\theta_u)$.

$$f_{\theta_u}(\theta) = \frac{\int_{\theta-\Delta\theta}^{\theta} d_c(X,Y)\frac{i}{\theta_n/2}\, di}{\int_{\theta_1-0}^{\theta} d_c(X,Y)\frac{i}{\theta_n/2}\, di}, \quad 0 < \theta \le \theta_1.$$

Note that the range of A_{C2} is between the area size with Z at point b and the area size as the distance from Z to b is equal to r. With $E(\theta_u)$, $E(A_{C2})$ can be derived by (10) in accord with the ratio of quadratic dependence.

$$E(A_{C2}) = A_{C1}^{Max} + (A_{S(X,Z)} - A_{C1}^{Max})(\frac{E(\theta_u)}{\theta_1})^2. \tag{10}$$

Finally, we get the result of $E(A_{C2})$ below with respect to θ_n.

$$U(\theta_n) = \begin{cases} E(A_{C2}) \cdot \frac{2\theta_1}{\theta_n} + A_{S(X,Z)} \cdot (1 - \frac{2\theta_1}{\theta_n}), & \theta_n \ge 2\theta_1 \\ A_{S(X,Z)} \cdot \left(\frac{\theta_n}{2\theta_1}\right)^2, & otherwise. \end{cases} \tag{11}$$

Accordingly, the above results can be extended to the cases of multi-hop nodes. For example, if Y contacts with X and Z, but Z does not contact with node X. The distance between X and Z is a 2-hop distance. At the view of X, thus, the process of obtaining A_E is to visit Y first and Z next. When Y is visited, the event of X contacting with Y belongs to a single case. Then, when Z is visited, the event of Y contacting with X and Z belongs to the in-contact case.

III. ROUTING WITH DYNAMIC CLUSTERING

This section describes the MDCA scheme which can construct clusters, compute message density in a cluster, and select relay nodes in a cluster for message delivery in DTNs.

A. Cluster Construction

With the result of communication area estimation A_E, MDCA is able to learn the node density in a local area, denoted as $D_{Local} = n_L/A_E$, where n_L is the number of directed and indirected nodes in A_E. Then, the value of D_{Local} can be updated as the connections among these nodes is varied. Let $D_{Global} = \sum_1^m D_{Local}/m$ mean the average of D_{Local} among m clusters in a system. All nodes compare the different between D_{Global} and D_{Local}. If D_{Local} is larger than D_{Global}, a new cluster will emerge in a local area.

B. Message Density

When nodes enter into a cluster, they attempt to find the destinations of any carried message. If no destinations can be found in a cluster, nodes will decide whether to replicate carried messages or not depending on the density of every carried message in this cluster. The density of a message is determined by how many nodes in a cluster have seen or carried this message. Specifically, let M_i^s and M_i^c denote a set of messages that have been seen and a set of messages that are being carried by node i, respectively. A message is tagged as low density according to the following three cases where two subscripts, *new* and *old*, mean a new member and an original member in the current cluster.

- $M_{i\in new}^c - M_{i\in old}^c \neq \{\emptyset\}$: Some messages did not appear previously in this cluster.
- $M_{\in new}^s - (M_{i\in new}^c \cup M_{i\in old}^c) \neq \{\emptyset\}$: A new member has seen some messages that other members in this cluster do not carry yet. If such a message will come in again, it will be copied in this cluster.
- $M_{i\in old}^c - M_{i\in new}^s \neq \{\emptyset\}$: A new member has not seen some messages that old members in this cluster do carry. This implies that those message have not been distributed to the other cluster whence a new member just went through.

Thus, messages of low density will be replicated to relay nodes by referring to a probability P, expressed as

$$P(j) = 1 - \frac{n_j^s}{n(S_t)} \tag{12}$$

where n_j^s is the number of members that have seen a message j in a cluster, and $n(S_t)$ is the total of members in S_t that means a set of members in a cluster at time t. In addition, the priority of replicating these messages of low density in a cluster is determined by descending order of $P(j)$.

C. Relay Selection

MDCA uses the measure of link quality Q [11] to decide a number of relay nodes in a cluster. The link quality is originally used to measure the closeness between two nodes. Our design modifies it to measure the closeness between a node and clusters, and so a large value of Q indicates the higher frequency of contacting with nodes in other clusters. When every node in a cluster is assigned its value of Q, some nodes with a larger Q value than the average of Q are selected as relay-node candidates. The messages will be firstly replicated to the relay node with the largest Q value. After the buffer of the first relay node is full, the secondary candidate will be take to receive the remaining low-density messages, and so on.

D. Leaving on Nodes in/out a Cluster

MDCA attempts to keep at least one copy of that message in a cluster. Otherwise, a cluster could be dismissed, after all of the last message copies are carried out of the cluster. Let N_i denote the number of directly contacting nodes for any node i in a cluster. As a result of self-sensing the variance of N_i, a node is conscious of its moving toward the boundary of a cluster and leaving away the cluster soon. If a leaving node owns the last message copy in a cluster, it ought to forward it to another relay-node candidate that stays in the current cluster.

IV. PERFORMANCE RESULTS

This section describes the simulation model with special mobility patterns, and examines relative performance among MDCA, Epidemic, PRoPHET and SnW.

A. Simulation Model

We implemented the MDCA on the ONE simulator [12] and ran the simulation in 48 hours. During simulation, all nodes have the same settings as transmission speed of 250 KBs, transmission range of 10 m, and buffer size of 1 MB. The size of a message is 10 KB with its time-to-live (TTL) period of 12 hours. To make relative performance, SnW's replica quota per message is 8, and PRoPHET's parameters, i.e., P_{init}, β and γ, are set as 0.75, 0.25 and 0.98.

The performance is examined in terms of sensitivities to delivery probability and overhead ration under various node populations in a network.

- Delivery probability is the number of delivered messages divided by the total of created messages.
- Overhead ratio is the number of relayed times divided by the total of created messages.

B. Mobility Patterns

We employed two mobility models: random waypoint (RWP) model [13] and time-variant community mobility model (TVCM) [14]. In RWP, a message's TTL, total simulation duration, and the interval of generating a message are 12 hours, 48 hours and 360 seconds. In TVCM, they are 8 hours, 24 hours and 150 seconds. Also, the motion speed of a node is assigned randomly between 0.5 and 1.5 m/s in RWP.

The simulation context of TVCM is based on our NCU campus to imitate the movement behaviour of students from the department of communication engineering in NCU. As Fig. 2 shows, the map size is 701,601 m^2, including many hot spots like a sports field, a department building, a student canteen, several dormitories. Participating students with different movement patterns are allocated to separate dormitories and divided into four groups. During simulation, groups A and B have the same number of male students, groups C and D the same number female students, and the ratio of male to female students is 4 to 1. That is, the relative ratio of students in groups A, B, C and D is 4:4:1:1.

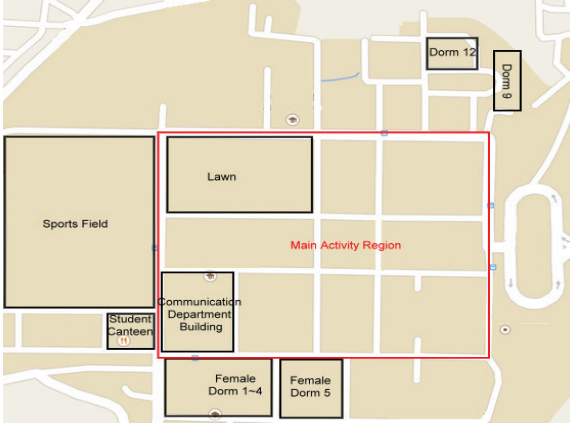


Fig. 2. Illustration of NCU campus.

Table I lists the probability settings to different patterns of four groups, where the main activity region is delimitated by the red line in Fig. 2. The simulation scenario regards students' lifestyle in campus. All students daily perform three different patterns: (1) during 8:00 am to 4:00 pm, students have classes at the department building; (2) during 4:00 pm to 12:00 am, students go sporting or back to dormitories; (3) during 12:00 am to 8:00 am, students stay in dormitories.

C. Results

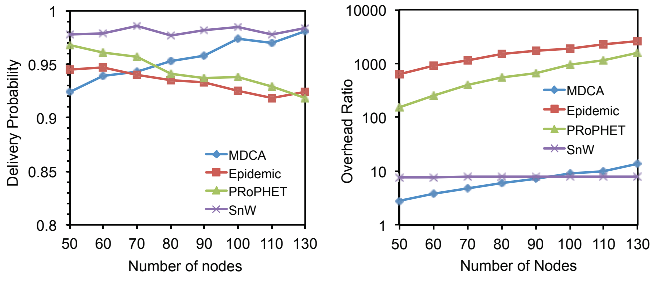
The performance results in the case of RWP are shown in Fig. 3. When the number of nodes grows in a network system, the delivery probability of MDCA rises up and approaches to the best performance by SnW. This result can be explained for that the characteristic or effect of clustering is not fully highlighted when the movement behaviour of nodes is random subject to the RWP model. By contrast, the performance of MDCA becomes remarkable under the TVCM model. As Fig. shown in 4, the delivery probability of MDCA is superior to Epidemic, PRoPHET and SnW. This is because the aggregation phenomenon of nodes in the case of TVCM is emphasized and becomes more clear than that in the case of RWP.

On the other hand, the overhead ratio of MDCA in both cases of RWP and TVCM are much lower than Epidemic and PRoPHET, and slightly higher than SnW. As compared with Epidemic and PRoPHET, MDCA is able to decide if the message should be replicated or not according to the density of a message in a cluster, so that the transmission overhead can be moderated. SnW will stop replicating message copies when the replica quota of a message is used up, and can thus result in the lowest transmission overhead. Notwithstanding, the difference of overhead ratio between SnW and MDCA may be not so critical, somehow, in comparison with unsatisfactory overhead ratio caused by Epidemic or PRoPHET under the logarithmic scale in Figs. 3(b) and 4(b).

TABLE I. A CASE STUDY OF TVCM – THE CONTEXT OF 50 STUDENTS IN NCU.

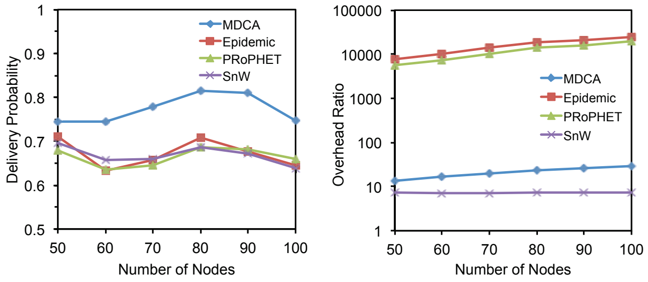
Group A						Group B					
B-1		B-2		B-3		B-1		B-2		B-3	
Hot spot	Prob.	Hot spot	Prob.	Hot spot	Prob.	Hot spot	Prob.	Hot spot	Prob.	Hot spot	Prob.
Dept. building	0.5	Dorm 12	0.7	Dorm 12	0.99	Dept. building	0.7	Dept. building	0.3	Dorm 9	0.99
Student canteen	0.2	Sport field	0.1	Main region	0.01	Student canteen	0.1	Dorm 9	0.3	Main region	0.01
Dorm 12	0.2	Lawn	0.1	-	-	Sport filed	0.1	Sport filed	0.3	-	-
Main region	0.1	Main region	0.1	-	-	Main region	0.1	Main region	0.1	-	-

Group C						Group D					
B-1		B-2		B-3		B-1		B-2		B-3	
Hot spot	Prob.	Hot spot	Prob.	Hot spot	Prob.	Hot spot	Prob.	Hot spot	Prob.	Hot spot	Prob.
Dept. building	0.6	Dept. building	0.2	Dept. building	0.99	Dept. building	0.5	Dorm 5	0.6	Dorm 5	0.99
Student canteen	0.2	Dorm 1-4	0.5	Dorm 1-4	0.01	Student canteen	0.2	Dept. building	0.1	Main region	0.01
Sport field	0.1	Sport field	0.2	-	-	Main region	0.1	Lawn	0.1	-	-
Main region	0.1	Main region	0.1	-	-	Main region	0.2	Main region	0.2	-	-



(a) Delivery probability (b) Overhead ratio

Fig. 3. RWP



(a) Delivery probability (b) Overhead ratio

Fig. 4. TVCM

V. CONCLUSION

This paper presents a novel cluster-based message forwarding scheme, called as MDCA, in DTNs. This scheme exploits the features of node aggregation induced by possible relationship between nodes to organize clusters in dynamic network environments. With dynamic cluster awareness, MDCA can distribute messages to adjacent clusters, thus improving the delivery probability. In addition, with the sense of message density, MDCA can control the number of message copies, so the transmission overhead is well moderated in DTNs. Furthermore, MDCA can achieve remarkable performance in response to the increase of node population, especially when the mobility model is consistent with human behaviour.

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