A Delay and Cost Balancing Protocol for Message Routing in Mobile Delay Tolerant Networks

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Abstract

The increasing pervasiveness of mobile devices with networking capabilities has led to the emergence of Mobile Delay Tolerant Networks (MDTNs). The characteristics of MDTNs, which include frequent and long-term partitions, make message routing a major challenge in these networks. Most of the existing routing protocols either allocate an unlimited number of message copies or use a fixed number of message copies to route a message towards its destination. While the first approach unnecessarily floods the network, the rigidity of the second approach makes it inefficient from the viewpoint of message replication. Hence, the question that we address in this paper is: "how to dynamically allocate message copies in order to strike a balance between the delay and cost of message delivery?". We present a novel adaptive multi-step routing protocol for MDTNs. In each routing step, our protocol reasons on the remaining time-to-live of the message in order to allocate the minimum number of copies necessary to achieve a given delivery probability. Experiment results demonstrate that our protocol has a higher delivery ratio and a lower delivery cost compared to the state-of-the-art Spray-and-Wait and Bubble protocols.

Keywords: mobile, delay tolerant, routing, epidemic, spray-and-wait

1. Introduction

Mobile Delay Tolerant Networks (MDTNs) are composed of a set of mobile devices, such as cell phones or sensor units, which can communicate with each other via short range wireless protocols (e.g. Bluetooth). A number of networking scenarios have been categorized as MDTNs, such as Vehicular Ad-hoc NETworks (VANETs) [21] and Pocket Switched Networks (PSNs) [13]. The

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characteristics of MDTNs include frequent and long-term network partitions which makes message routing one of the major challenges in these networks. In order to deal with the intermittent connectivity between nodes (i.e., mobile devices), message routing in MDTNs is often performed in a "store-carry-and-forward" manner [7], in which a node may store and carry a message for some time before forwarding it to another node [35].

In the literature, a number of routing protocols have been proposed for MDTNs. Nevertheless, most of them are inflexible from the viewpoint of message replication. For instance, flooding-based routing protocols [36], which refers to those protocols that always rely on an unlimited number of message copies to route a message, generate a very large number of redundant message copies. This approach can put undue stress on the limited resources of mobile devices []. On the other hand, quota-based routing protocols [29, 31] allocate a fixed number of message copies for routing a message. The rigidity of this latter approach makes it inefficient, as a fixed number of message copies cannot suit all routing situations.

To the best of our knowledge, the adaptability of the number of message copies been addressed only by Bulut et al. in [3]. Routing in [3] is divided into multiple periods. In each period, the source node of a message sprays a certain number of message copies into the network. The source node dynamically chooses the allocation of message copies at the beginning of each period, until the message is delivered to the destination node or the Time-To-Live (TTL) expires. The protocol presented by Bulut et al. assumes that all nodes move under the same mobility pattern in a given network space. However, the reality is different. Recent studies [2, 18, 12] on the spatial characteristics of human mobility from real world traces demonstrate that humans in real-life tend to roam in smaller sub-regions rather than the whole network space. In addition, the allocation of message copies in [3] relies on the assumption that the source node is aware of the successful delivery of a message at any given instant. However, such an assumption rarely holds in reality, due to the frequent and long-term network partitions faced by MDTNs.

In this paper, we present a novel routing protocol in MDTNs, called the Community-based Adaptive Spray (CAS) routing protocol. The goal of this protocol is to allocate the minimum number of message copies for a message while still achieving a high delivery ratio. Our protocol exploits the community structure of human networks. A community is defined as a set of nodes which frequently co-exist and encounter (see Section 3.1). It has been demonstrated in the literature that nodes in a MDTN often form such structures [15].

Our protocol is composed of two major parts. First, a sub-protocol responsible for gathering mobility information about nodes upon encountering each other. This sub-protocol aims at learning/synchronizing the topologies of communities in the network. Second, a sub-protocol responsible for the routing process. Routing is organized around the notion of gateways between communities. Specifically, a gateway towards a community C is the node in a given community that has the highest probability to encounter any node in C. To route a message towards a given destination node, the source of a message uses the community topology to pre-compute the multi-hop path that traverses the minimal number of communities through their gateway nodes and that has the highest delivery probability. Furthermore, once the routing process is engaged, our routing protocol allocates a given number of message copies at each hop depending on the remaining TTL of the message. The urgency of delivering a message rises as the TTL of the message approaches expiration. The CAS protocol raises the number of message copies in the network in proportion to the remaining TTL in order to increase the probability of message delivery before time runs out. This strategy keeps the number of message copies in the network low while achieving a high delivery ratio.

The contributions of this paper are twofold:

- We propose a novel routing protocol that dynamically allocates message copies according to the remaining TTL of each message.
- The analysis of our protocol shows that it is the generalization of many existing protocols including Direct [34], Epidemic [36], Spray-and-wait [31], and some community based routing protocols [5]. By generalization, we mean that our protocol can dynamically decide to behave like one of these algorithms in order to better suit the current situation.

This paper is a considerably extended version of our previous work [26]. The major additions to the current paper include the following. First, we demonstrate that our routing protocol can represent a class of routing protocols. Second, we develop an analytical model to compute the cover time of the topology of communities. At the same time, we validate the accuracy of our analytical model by comparing its theatrical results with the simulation results obtained using a standard simulator. Third, we present new experiments to evaluate the performance of our protocol.

The remainder of the paper is organized as follows. Section 2 discusses related work on routing in MDTNs. In Section 3, we introduce the system model and the information maintained by each node. In Section 4, we describe our proposal in detail. In Section 5, we develop and evaluate an analytical model of our routing protocol, which is utilized to estimate the cover time of the topology of communities. The simulations and results are presented in Section 6. Finally, we conclude the paper and discuss open issues in Section 7.

2. Related work

In the literature, a variety of routing protocols have been proposed for MDTNs. The protocols can be classified into two broad categories based on the number of message copies utilized in the routing process [34, 33, 6]: single-copy and multi-copy.

In single-copy routing protocols, such as Direct Delivery [34] and First Contact [17], a single copy for each message exists in the network at any instant. Therefore, these routing protocols achieve the minimum transmission overhead in terms of the number of message copies employed during the routing process. However, due to the frequent and long-term network partitions that characterize MDTNs, these protocols often suffer from low delivery ratio and long delivery latency [10].

In order to guarantee a higher delivery ratio and a lower delivery latency, multi-copy protocols distribute multiple copies of each message in the network. Based on whether the number of message copies of a message is limited or not, multi-copy routing protocols can be further divided into flooding-based [36] and quota-based protocols [29, 31].

Epidemic [36] is a well known flooding-based protocol. It achieves the optimal routing performance in terms of delivery ratio and delivery latency at the cost of huge resource consumption, which makes it unpractical for resource constrained devices. In addition, the massively redundant messages can cause network congestion, which in turn can severely degrade the routing performance [1, 30].

Quota-based routing protocols [29, 31] achieve more reasonable delivery cost by restricting the number of message copies that they allocate for each message. Specifically, at any point in time, a fixed number of copies of each message exists in the whole network. However, the one-size-fits-all approach for allocating message copies is insufficient. It is obvious that a message with a shorter remaining TTL would need more copies than a message with a longer TTL to ensure successful delivery. The existing protocols do not take this factor into account. Additionally, these protocols assume that all nodes have the same capability of visiting every region covered by the network. However, reality is different. Recent studies [2, 18, 12] on the spatial characteristics of human mobility from real world traces demonstrate that humans usually roam in some relatively small sub-regions rather than the whole network space.

Aside from the aforementioned spatial characteristics of human mobility, human movement is also shown to be driven by social relationships [2, 28]. Hence, the nodes which frequently coexist in a common location are considered to consist of a community. The utilization of community structure has been proved to improve routing performance [15]. Therefore, the community structure has been widely utilized in the design of routing protocols. Such routing protocols are known as community-based routing protocols, which can belong to the class of either single-copy or multi-copy protocols.

Hui and Crowcroft in [14] proposed a community-based routing protocol for MDTNs, called LABEL. In LABEL, it is assumed that each node possesses a label indicating its community. The label of nodes (i.e., the community structure) is then utilized to guide the forwarding of messages. Specifically, each message is forwarded to the nodes in the same community as the destination node.

Hui et al. in [15] presented a community-based routing protocol, named Bubble. Bubble combines centrality, which indicates the relative importance of a node in the network, and community structure to identify relay nodes. In Bubble, a message is forwarded from a node to the nodes that have a larger global centrality value (i.e, the total number of encountered nodes) than the current node until it reaches a node in the same community as the destination node. The message is then forwarded from a node to the nodes that have a larger local centrality value (i.e. the number of encountered community member nodes). Similar to [15], Li et al. in [22] proposed a community-based routing protocol, called IFR. The difference between IFR and Bubble is that IFR floods a message inside the community of the destination node.

Nevertheless, the centrality of nodes cannot accurately steer a message to the destination node [37]. To address this issue, Dang and Wu in [5] presented a routing protocol, named Clustering routing. Clustering routing utilizes gateway nodes to deliver the messages whose source node and destination node belong to different communities. Gateway nodes are the nodes which have the highest probability of encountering the nodes in other communities. However, messages in [5] are routed under Direct Delivery protocol, which is generally considered to be inefficient when the TTL of a message is limited [33].

Our work differs from the aforementioned works in two ways. First, the CAS routing protocol can dynamically allocate the minimum number of copies for each message while achieving a predefined delivery ratio, according to the TTL of a message. Second, our routing protocol is more generic than most routing protocols, which includes Direct, Epidemic, Spray-and-wait, and Clustering routing [5], as it can behave as one of these algorithms in specific routing situations.

3. System model

In this section, we first present the network model. We then introduce the information maintained by each node. Finally, we explain how the information maintained by nodes is updated.

3.1. A delay tolerant network model

Node. We define a node as a mobile device. We assume that each node is equipped with a radio interface (e.g., Bluetooth) for short-range communication, and that the transmission range of all nodes is the same. Two nodes are considered to meet, if they are in the transmission range of each other. We assume that a node can only communicate with one other node at the same time. Two meeting nodes can exchange messages with each other. We also assume that each node has a unique identifier.

Community. We define a community C as a set of nodes which frequently co-exist and meet. Recent studies [2, 28] have indeed shown that human mobility is actually driven by social relationships. Thus, the meeting frequency of nodes in the same community is considered to be much higher than that of nodes in different communities. We also assume that each community has a unique identifier. The set of nodes in a community C will be indicated hereafter by $C = \{u_1, u_2, \ldots, u_n\}$, where $n = |C|$. Moreover, we assume that a node can only belong to one community.

Inter-contact time between two nodes. The inter-contact time (also known as inter-meeting time) between two nodes is the time interval between two successive encounters between them.

Mobility Model. Mobility models are generally characterized by the inter-contact time between two nodes [3, 33]. Karagiannis et al. in [18] demonstrated that under a large class of mobility scenarios in real life, the inter-contact time follows a power-law in a finite range, and then exhibits an exponential decay. It is consistent with the suggestion made by Gonzalez et al. in [8] that a power law with an exponential decay is a very good approximation of human mobility patterns. Additionally, Chaintreau et al. in [4] pointed out that the exponential decay eliminates the issue of infinite message forwarding delay. Building on these previous studies, the inter-contact time of nodes is assumed to be exponentially distributed or have an exponential tail characterized by a contact rate (the inverse of the expected inter-contact time of any pair of nodes). This is a widely accepted assumption in MDTNs [3, 33, 25, 9].

Inter-contact time between a node and a community. The inter-contact time between a node u and a community C is the time interval between any two successive contacts between node u and any node member of the community C.

Gateway. A node w in a community C_i is defined as the gateway connecting to another community C_j if node w's average inter-contact time with the nodes of the community C_j is the shortest among the other nodes of its community C_i.

Network. Let the set of all nodes in the environment be given as the set V. Let the set of all communities in the environment be $\mathbb{M} = \{C_i | 1 \leq i \leq k, V = \bigcup_{i=1}^{k} C_i\}$. Edges $e_{i,j}$ and $e_{j,i}$ exist between two communities C_i and C_j (where $1 \leq i \leq k, 1 \leq j \leq k, i \neq j$), if some nodes from the two communities have encountered at least once. The weight of the edge $e_{i,j}$, denoted as $\varpi_{i,j}^{w}$, is the average inter-contact time of the gateway w of community C_i with the nodes of the community C_j. Notice that the gateway from community C_i to the community C_j is not the same node as the gateway from C_j to C_i, so the community graph is a directed graph. Let $E = \{e_{i,j} | 1 \leq i \leq k, 1 \leq j \leq k, i \neq j\}$. We will represent the MDTN formed by all the nodes of the network by their community graph $G(\mathbb{M}, E)$.

Message. A message is represented as a tuple $\langle S, D, I, C, L, T \rangle$, where S is the source node, D is the destination node, I is the intermediate target node, which is a gateway node connecting the current community to another community (or the destination node if the message is yet in the community of the destination node). C is the identifier of the community connected by the gateway node (or null if the intermediate target node is the destination node). L is the number of copies allocated to route the message to the intermediate target node in the current community, T is the message TTL.

3.2. Information maintained by a node

Each node in the network, e.g., node u, maintains six types of information: its node ID u, its community ID C^u (the exponent here indicates the fact that u belongs to this community), a community table, a gateway table, a contact table, and a community graph.

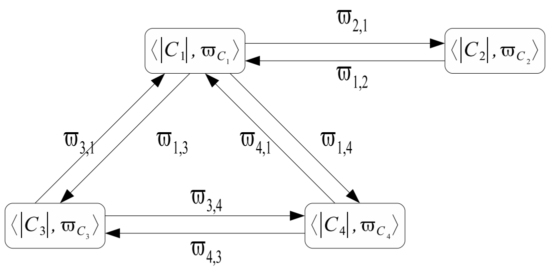

$\langle |C_1|, \varpi_{C_1} \rangle$
$\langle |C_2|, \varpi_{C_2} \rangle$
$\langle |C_3|, \varpi_{C_3} \rangle$
$\langle |C_4|, \varpi_{C_4} \rangle$
$\varpi_{2,1}$
$\varpi_{1,2}$
$\varpi_{3,1}$
$\varpi_{1,3}$
$\varpi_{4,1}$
$\varpi_{1,4}$
$\varpi_{3,4}$
$\varpi_{4,3}$

Figure 1: Community Graph

Community table. The community table of node u holds the node ID and the community ID of all nodes who have encountered the nodes of u's community. Node u also maintains a timestamp which indicates the time when the table was last updated.

Gateway table. The gateway table of node u contains the following fields for each known community C_i and for each gateway w linking C_i to another community C_j: the community ID of C_i, the node ID of the gateway w, the community ID of C_j, and the average inter-contact time between the gateway w and the community C_j given as $\varpi_{i,j}^{w}$. Node u also maintains a timestamp which records the last updated time of this table.

Contact table. The contact table of node u maintains the following fields for each encountered node v: the node ID of v, the sum of inter-contact times between the nodes u and v denoted as $\tau_{u,v}$, the number of encounters $\sigma_{u,v}$ (the latter two quantities are used to compute the average inter-contact time), the end time of the last encounter $t_{u,v}^{e}$, and the start time of the ongoing encounter $t_{u,v}^{b}$ (if there is one).

Community graph. In the community graph of node u, each vertex denotes a known community e.g., community C_i. Each vertex is labeled by a tuple $\langle |C_i|, \varpi_{C_i} \rangle$, where $|C_i|$ is the number of nodes in community C_i, ϖ_{C_i} is the average inter-contact time between the member nodes of the community C_i. The weight of the directed edge e_{ij} denoted by $\varpi_{i,j}$ is the average inter-contact time between the gateway in community C_i and the community C_j. The community graph of node u locally reflects the topology of the communities of the network *as it is known by* u, which is illustrated in Figure 1.

3.3. Maintenance of information

The maintenance of the above information is driven by events. There are three kinds of events in the protocol: 1) *Connect Event*, 2) *Disconnect Event*, and 3) *Update Event*. We assume that nodes in the network honestly synchronize the maintained information.

Connect Event. It happens at the moment when two nodes enter the transmission range of each other. When a connect event takes place, two meeting nodes honestly exchange and update their corresponding values in each field of their community table, community graph, and gateway table, according to the value of their timestamps. They also set the timestamps.

Disconnect Event. It happens at the moment when two nodes u and v go out of the transmission range of each other. Let $t^e_{u,v}$ be the end time that node u encounters node v. Let $t^b_{u,v}$ be the begin time that node u encounters node v of the ongoing encounter. Thus, the last inter-contact time between node u and v is set to $\Delta\tau_{u,v} = t^b_{u,v} - t^e_{u,v}$. The sum of inter-contact time between nodes u and v is $\tau_{u,v} = \tau^{'}_{u,v} + \Delta\tau_{u,v}$, where $\tau^{'}_{u,v}$ is the sum of inter-contact time between node u and v before last encounter. Then, the number of encounters $\sigma_{u,v}$ increases by 1.

Consequently, the average inter-contact time between two nodes u and v is expressed as follows:

$$\varpi_{u,v} = \begin{cases} +\infty, & \sigma_{u,v} = 1 \\ \frac{\tau_{u,v}}{\sigma_{u,v}-1}, & \sigma_{u,v} > 1 \end{cases} \tag{1}$$

The average inter-contact time between two nodes is the major parameter used by methods of community detection. Specifically, a node joins (or leaves) a community if it is (or is not) qualified to be in the community. Since the community detection is out of this paper's scope, the reader is suggested to refer to [16] for further information.

Moreover, as in [25, 24], we assume that the nodes in the same community have the same average inter-contact time. As a consequence $\varpi_{C_i} = \varpi_{u,v}$, for any nodes u and v are in the same community C_i.

Update Event. The update event is periodically invoked synchronously by all nodes every γ time units. Let $C^{'}_j$ be the set of nodes which belong to a community C_j and have met node u by more than once. Then the average inter-contact time between node u and community C_j is computed as follows.

$$\varpi^u_{i,j} = \frac{\sum_{v \in C^{'}_j} \tau_{u,v}}{\sum_{v \in C^{'}_j} (\sigma_{u,v} - 1)} \tag{2}$$

If node u achieves an average inter-contact time with community C_j that is shorter than the one of the current gateway w (that is $\varpi^u_{i,j} \leq \varpi^w_{i,j} - \epsilon$, where ϵ is a threshold), then the relevant fields are updated i.e., the node ID of the gateway from C_i to C_j, the inter-contact time and timestamp are updated to u, $\varpi^u_{i,j}$ and the current time respectively.

4. Protocol design

In this section, we first briefly describe the mechanism of CAS. We then present the design of CAS in detail. Finally, we demonstrate that our protocol is the generalization of several existing routing protocols.

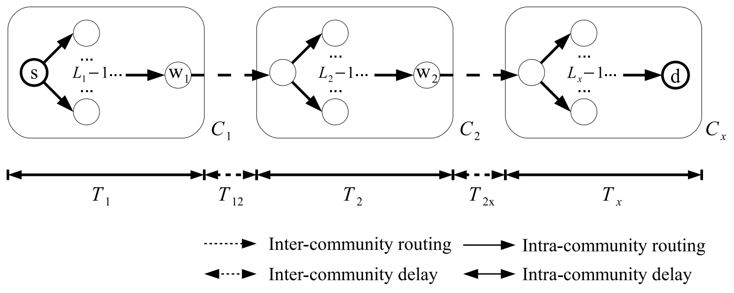


Figure 2: Routing Protocol Overview

4.1. Overview of CAS

In this section, we give an overview of our routing protocol. A routing example is depicted in Figure 2. This figure shows a number of nodes belonging to three communities C_1, C_2, and C_x. A source node s that belongs to the community C_1 wants to send a message to a node d that belongs to the community C_x.

In CAS, the routing process is composed of multiple sub-processes. In each sub-process, a message is routed to an intermediate target node, which is the gateway node bridging two communities or the destination node if the latter belongs to the same community as the source node. At the beginning of each sub-process, the shortest path from the current community to the community of the destination node is computed according to the community graph. For instance, in Figure 2, when the source node s generates a message, it computes the shortest path from its community C_1 to the destination node's community C_x, that is, $C_1C_2C_x$. After that, node s looks up its gateway table to find the gateway node w_1, which connects its community with the community C_2. The node w_1 is then considered as the first intermediate target node to reach. At the same time, the minimum number of message copies needed to route the message to the intermediate target node is computed, based on the message TTL and a predefined corresponding delivery ratio. These message copies are sprayed inside the current community in a binary spraying manner in which a message carrier hands over half of the copies it holds to each node it meets. When the intermediate target node encounters a node in its connecting community (e.g., C_2 in the case of w_1), it forwards the message to it. The above process is repeated until the message reaches the destination node or expires.

4.2. Design of CAS

As explained above, the CAS routing process is divided into multiple sub-processes. Each sub-process consists of the following two phases: 1) optimization of the number of message copies to be distributed and 2) message routing.

4.2.1. Optimization of the number of message copies

According to the analysis of the routing performance presented in [31], if L copies of a message are distributed in the network and the TTL of the message is T, the expected delivery probability of the message can then be calculated as $p_d = 1 - e^{-\lambda LT}$, where λ is the contact rate, that is, the inverse of the average inter-contact time between nodes [3]. Hence, if the expected delivery probability p_d is assigned, the relationship between the number of message copies and the TTL can be expressed as Equation 3. Note that the delivery probability is the delivery ratio from the viewpoint of all generated messages.

$$L \times T = -\frac{ln(1-p_d)}{\lambda} \tag{3}$$

Recall that an MDTN is modeled as a directed graph of communities $G(\mathbb{M}, E)$ (Section 3.1). Let h a path in $G(\mathbb{M}, E)$. Let n be the number of communities in path h. The weight (denoted as $wgt(h)$) of path h is the sum of the weights of the edges that form the path, which is expressed in Equation 4. It represents the sum of the average inter-contact time between the communities in path h. Note: we assume that in the community graph that represents a MDTN every community is reachable (i.e., a non-reachable community constitutes a distinct MDTN).

$$wgt(h) = \begin{cases} \sum_{i=1}^{n-1} \varpi_{i,i+1}^{w}, & \text{if } n > 1 \\ 0, & \text{if } n = 1 \end{cases} \tag{4}$$

Further, let us consider two communities C_1 and C_2. Let $h(C_1, C_2)$ be any path which originates within community C_1 and ends within community C_2. In a network, it is possible that more than one such path exists. Let $H(C_1, C_2)$ be the set of all possible paths $h(C_1, C_2)$. Let $h^*(C_1, C_2)$ be the shortest path from community C_1 to community C_2.

Assume a node u carries a message denoted by $\langle S, D, I, C, L, T\rangle$. Let h^* be the shortest path from the community of node u to the community of the destination node. Let n be the number of communities in the path h^*. Let L_i denote the number of message copies distributed in a community C_i. Let w be the gateway node connecting community C_i to community C_{i+1}. Let p_d be the expected delivery probability of the message. Let λ_i be the contact rate of nodes in community C_i, which is the inverse of the average inter-contact time ϖ_{C_i} of nodes in community C_i. Then the optimization of delivery cost can be expressed as in Equation 5-7.

$$min \sum_{i=1}^{n} L_i \tag{5}$$

$$s.t. \sum_{i=1}^{n-1} \varpi_{i,i+1}^{w} + \sum_{i=1}^{n} \frac{-ln(1-p_d)}{\lambda_i L_i} \leq T \tag{6}$$

$$L_i \leq |C_i|, \text{ where } 1 \leq i \leq n \tag{7}$$

The purpose of the objective function Equation 5 is to minimize the number of message copies utilized to route a message. Equation 6 expresses the fact that the sum of the time spent to route the message in communities and the sum of the average inter-contact time between communities should be less than the TTL of the message. The constraint Equation 7 expresses the fact that the number of message copies allowed in a community should be less than the number of nodes in the community.

All L_i are positive integers and finite; thus Equation 5-7 defines a classical integer optimization problem for which a number of heuristics can be applied. However, in practice, the number of communities in path h^*, n, and the acceptable values for L_i are small, so an exhaustive search, i.e. the enumeration of all the possible values for L_i, is clearly tractable. For instance, there are about 8 communities in the MIT reality mining dataset [15], and most of communities contain less than 10 nodes. The pseudo-code of the solution is illustrated in Figure 3.

Without loss of generality, let's consider that the algorithm is invoked by a node u. Node u has a message m. The shortest path from the community of node u to the community of the destination node of message m is h^*. The algorithm initially gets the community (denoted by C^*) next to the community of nodes u on the path h^* (Line 1); and sets the number of the nodes in node u' community as the default value for L_u, which indicates the number of message copies of message m for node u (Line 2). The algorithm then enumerates all the possible values for the number of copies in each community on the path h^* (Lines 19 to 31). More specifically, the algorithm uses the elements in a vector π to express the number of copies of message m allocated for each community on the path h^*. The algorithm initially sets all the elements in π to be 1. It then starts with the last element in π (Line 19), and selects all possible values for the last element (Lines 21 to 23). The algorithm then uses the values of the elements in π to verify whether (1) the allocated number of message copies can satisfy Equation 6; (2) the sum of these values is smaller than the previous minimal sum, which is initially set as the number of nodes on the path h^* (Line 15). If so, the algorithm updates the minimal sum (Line 16) and L_u (Line 17). The algorithm then resets the value of the last element to be 1 (Line 25), and goes to the element before the last element (Line 26). The above process is repeated until all possible values are enumerated. Finally, the algorithm returns C^* and L_u.

There are two heuristic methods to reduce the computation complexity of algorithm OptimalCost: (1) using a smaller sample to test the values for $L_2, \ldots, L_n$. (2) terminate the computation of the algorithm when the first combination of values in π is found.

4.2.2. Message Routing

In CAS, we distinguish the routing within a community from the routing among communities. In the former case, the allocated message copies are sprayed inside the current community in a binary manner, in order to minimize the time to spray message copies. Specifically, a node hands over half of the number of a message copies to an encountered node, which is in the same community and does not have the message. When the node has just one copy

Algorithm: OptimizeCost
Participants: Node u.
Input: (1) D_m, the destination node of message m. (2) T, the TTL of message m. (3) p_d, a predefined delivery probability of message m. (4) h^*, the shortest path from node u's community to node D_m's community.
Output: (1) C_u^*, the community next to node u's community on the path h^*. (2) L_u, the number of copies of message m carried by node u.
Setup: (1) n, the number of communities in path h^*. (2) ϖ_{sum}, the weight of the shortest path h^*. (3) L_{min}, the minimum number of message copies utilized to route the message. It is initially set to the sum of the number of nodes in each communities in the path h^*. (4), π, $1 \times n$ vector, whose elements are 1 (5) λ_i, the contact rate of nodes in community C_i, where $1 \leq i \leq n$.

```
1: $C_u^* \leftarrow h^*[2]$ {The index of the community $C_u^*$ is 2.}
2: $L_u \leftarrow |h^*[1]|$
3: $j \leftarrow n$ {The index for the vector $\pi$.}
4: while $j \geq 1$ do
5:     $T_{sum} \leftarrow 0$
6:     $L_{sum} \leftarrow 0$
       {Compute the needed number of message copies for a combination of values in $\pi$.}
7:     for $i \leftarrow 1$ to $n$ do
8:         if $\pi[i] \leq |h^*[i]|$ then
9:             $L_i' \leftarrow \pi[i]$
10:        else
11:            $L_i' \leftarrow |h^*[i]|$
12:        end if
13:        $T_{sum} \leftarrow T_{sum} + \frac{-ln(1-p_d)}{\lambda_i L_i'}$
14:        $L_{sum} \leftarrow L_{sum} + L_i'$
15:    end for
       {Find the minimal number of message copies.}
16:    if $T_{sum} + \varpi_{sum} \leq T$ and $L_{sum} < L_{min}$ then
17:        $L_{min} \leftarrow L_{sum}$
18:        $L_u \leftarrow \pi[1]$
19:    end if
       {List all possible combination of values in $\pi$}
20:    $j \leftarrow n$
21:    while $j \geq 1$ do
22:        if $\pi[j] < |h^*[j]|$ then
23:            $\pi[j] \leftarrow \pi[j] + 1$
24:            break
25:        else
26:            $\pi[j] \leftarrow 1$
27:            $j \leftarrow j - 1$
28:        end if
29:    end while
30: end while
31: return $\langle C_u^*, L_u \rangle$
```

Figure 3: Algorithm:OptimizeCost

of the message, the message can only be forwarded to the intermediate target node. As we stated in Section 3, the meeting frequency of nodes in the same community is much higher than that of nodes in different communities. Thus, messages can be delivered to the intermediate target node with a higher probability.

As for the routing among communities, a gateway node forwards a message to an encountered node if it belongs to the next community along the shortest path from the gateway node's community to the community of the destination node. After it gets the message, the receiving node re-computes the shortest path from its community to the community of the destination node, and sets the intermediate target node as the gateway node bridging the next community, or the destination node if it is in the same community as the destination node. After that, it calls the Algorithm *OptimizeCost* to compute the needed number of message copies utilized to route the message to the intermediate target node. The complete mechanism of the routing protocol in CAS is summarized in Figure 4.

4.3. CAS generalizes classes of routing protocols

Another relevant point about CAS is that it represents the generalization of many existing routing protocols, including Direct [34], Spray-and-Wait [31], Epidemic [36], and Clustering routing [5]. Depending on the number of communities in the network and the number of message copies, CAS can dynamically transform to these routing protocols. Let V be the set of all nodes in a network. Let $\mathbb{M}$ be the set of all communities in the network. Let L be the number of allocated copies for a message. The transformation from CAS to these routing protocols is then illustrated in Figure 5.

- Direct ($L = 1$, $|\mathbb{M}| = 1$): The source node of a message can only forward the message to the destination node. Direct is a well known single-copy routing protocol.

- Spray-and-Wait ($1 < L < |V|$, $|\mathbb{M}| = 1$): Each message is associated with some forwarding tokens, which indicates message copies. Each message has two phases: the spray phase and the wait phase. If there is more than one forwarding token left, the message is in the spray phase. During the spray phase, the forwarding tokens of a message can be sprayed to an encountered node without the message. If there is only one forwarding token left, it is in the wait phase. During the wait phase, a message can only be forwarded to the designation node. Spray-and-Wait is a representative routing protocol of quota-based routing.

- Epidemic ($L = |V|$, $|\mathbb{M}| = 1$): Each node stores its messages in its buffer. When two nodes meet, each of them complements the missing messages according to the messages in the other's buffer. It is therefore flooding-based in nature.

Protocol: RouteMessage
Participants: Two encountering nodes u and v.
Input: (1) m, a message carried by node u. (2) D_m, the destination node of message m. (3) I_m, the intermediate target node of message m. (4) L_u, the number of copies of message m for node u. (5) L_v. (6) T, the TTL of message m. (7) p_d, a predefined message delivery probability. (8) C_u^*, the community next to node u's community on the shortest path from node u's community to node D_m's community. (9) C_v^*.
Output: Message m is forwarded to node v, if one of the following conditions is met: (1) node v is the destination; (2) node v is the intermediate target node; (3) nodes u and v are in the same community, and node u has more than one copy of message m; (4) node u is the gateway node bridging community C_u^*, and node v is in community C_u^*, and node u has not yet forwarded message m to another node member of the community C_u^*. Furthermore, the number of copies of message m for node v, L_v, is computed and the intermediate node on the message route is updated.
Events and Associated Actions:

node u initiates the protocol

```
1: if $C^u = C^v$ then
2:     if $v = I_m$ then
3:         node $u$ forwards message $m$ to node $v$.
4:     else if $L_u > 1$ then
5:         node $u$ forwards half number of copies of message $m$ to node $v$, and keeps the
           remaining copies.
6:     end if
7: else
8:     if $v = D_m$ then
9:         node $u$ forwards message $m$ to node $v$
10:    else if $u$ is the gateway node connecting $C_u^*$ and $C_u^* = C^v$ and node $u$ has not
       yet forwarded message $m$ to another node in the community $C_u^*$ then
11:        node $u$ forwards message $m$ to node $v$
12:    end if
13: end if
```

upon node v receives a message m from node u

```
1: if $C^u \neq C^v$ and $v \neq D_m$ then
2:     $\langle C_v^*, L_v \rangle \leftarrow OptimizeCost(D_m, T, p_d)$
3:     if $C^{D_m} = C^v$ then
4:         $I_m \leftarrow D_m$
5:     else
6:         node $v$ looks up its gateway table to find the gateway node $w$ to community
           $C_v^*$
7:         $I_m \leftarrow w$
8:     end if
9: end if
```

Figure 4: Protocol:RouteMessage

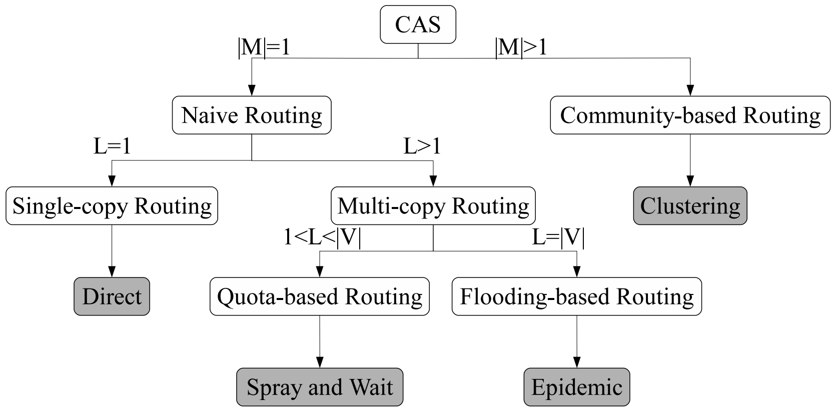


Figure 5: The transformation from CAS to several kinds of routing protocols, where L is the number of allocated copies for a message, V is the set of all nodes in a network, M is the set of all communities in a network.

- Clustering routing ($|\mathbb{M}| > 1$): The encounter information of nodes is synchronized and processed to identify the community structure and the gateway nodes. A gateway node connecting its community to another community is the node that has the highest probability of meeting any node in the latter community. In this protocol, Direct routing is employed to route a message to a gateway node or the destination node if the message is in the destination node's community. Clustering routing is a community-based routing protocol.

It is worth pointing out that Epidemic and Direct achieve the upper and lower bounds of routing performance in terms of delivery ratio and delivery cost [33, 34] respectively. CAS realizes a trade-off by minimizing the delivery cost while maintaining a predefined delivery ratio.

5. Analysis

In this section, we first develop an analytical model for estimating the cover time of the community graph. We then evaluate the accuracy of our analytical model by comparing the theoretical results with the simulation results by using a standard simulator.

5.1. Analytical model

Since our protocol depends on the local community graph to allocate message copies, it is necessary to estimate the cover time of the community graph when the maintained information is changed at a node.

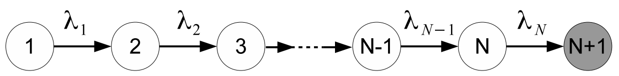


Figure 6: The continuous time Markov chain model for modeling the flooding process in a community. States (1) to (N) are N transition states and state ($N+1$) is the absorbing state.

5.1.1. Cover time of maintained information

In the following sections, we theoretically analyze the cover time of maintained information from the following two aspects: 1) intra-community message exchange and 2) inter-community message exchange.

A. Intra-community message exchange

When the role of a node changes within the network – for instance, when a node becomes the new gateway node – the information about this change is propagated to all the relevant nodes of the community. This process applies to all the information that has to be maintained to grant the correct operation of the network. The cover time of the maintained information inside a community is defined as the difference from the time of the change at a node to the time when all the other nodes in the community are aware of the change.

Let us consider a community C, which has $N+1$ nodes. According to the update mechanism, the modified information (see the case of a message hereafter) is disseminated inside the community through flooding. Let $n(t)$ represent the number of nodes with a given message at time t. We model the flooding process by a one-dimensional continuous time Markov chain (with state $n(t)$). States and transitions of this chain are illustrated in Figure 6. We can observe that this Markov chain starts with state (1) – when a message is generated by a node – and has N transient states and an absorbing state. When all nodes in the community C receive the message, the system enters the absorbing state (i.e., state ($N+1$)). The corresponding infinitesimal generator matrix $\mathbf{Q}$, with dimension of $N+1$, is shown in Equation 8.

$$\mathbf{Q} = \begin{pmatrix} \mathbf{D} & \mathbf{R} \\ \mathbf{0} & \mathbf{0} \end{pmatrix}. \tag{8}$$

where the sub-matrix $\mathbf{D}$ is a $N \times N$ matrix with element $D_{i,j}$ ($1 \leq i,j \leq N$) expresses the transition rate from transient state (i) to transient state (j). $\mathbf{R}$ is a $N \times 1$ matrix with element $R_{i,N+1}$ representing the transition rate from transient the state (i) to the absorbing state ($N+1$). The left $\mathbf{0}$ matrix is a $1 \times N$ vector with all elements 0 representing the transition rates from the absorbing state to transient states. The right $\mathbf{0}$ matrix includes only a single element, 0, representing the negative sum of the left $\mathbf{0}$ vector. Based on the above choice of the message dissemination process, we obtain the transition rate $q_{i,j}$ from state (i) to state (j) as follows.

In the flooding process, each of the nodes with the message can replicate the message to an encountering node without the message. Assume that the system is currently in state $(n)_{n \leq N}$, that is, there are n nodes with the message and $N+1-n$ nodes without the message. When one of the nodes without the message encounters a node with the message, the system state turns to state $(n+1)$. The transition rate from state (n) to state $(n+1)$ is $\lambda_n = (N+1-n)n\lambda$, since there are $(N+1-n)$ nodes that can receive the message from n nodes and meetings take place at rate λ. When the last node receives the message, the system turns to the absorbing state (i.e., state $(N+1)$). Let $D\{(j)|(i)\}$ be the transition rate from state (i) to state (j) and let $R\{(N+1)|(i)\}$ be the transition rate from the state (i) to the absorbing state. The non-zero transition rates in the Markov chain can be expressed as in Equation 9.

$$\begin{cases} D\{(n+1)|(n)\} = (N+1-n)n\lambda, n \in [1, N-1] \\ R\{(N+1)|(n)\} = N\lambda, \text{ if } n = N \\ D\{(n)|(n)\} = -D\{(n+1)|(n)\} - R\{(N+1)|(n)\}, n \in [1, N] \end{cases} \tag{9}$$

B. Inter-community message exchange

The cover time in the inter-community message exchange is defined as the difference between the time when the information to be maintained is changed at a node in a community C_i and the time when all nodes in another given community (e.g., C_j) are aware of the change.

Let us consider two communities C_i and C_j, which have $M+1$ and $N+1$ nodes respectively. Unlike in the single community case, when flooding a message from one community to another one we need to record the number of nodes with the message in each of the two communities. Consequently, as in to [23], we use a two-dimensional continuous time Markov chain to model the flooding process in two communities.

Moreover, as pointed in [14], the distributions of inter-contact time between nodes belonging to the same community and nodes belonging to different communities are different. Thus, we set λ^{intra} and λ^{inter} as the contact rate of the nodes belonging to the same community and different communities respectively.

The Markov chain consists in states which can be indicated by $(m(t), n(t))$, where $m(t)$ (or $n(t)$) represents the number of nodes with the message in community C_i (or C_j) by time t. The state transition is illustrated in Figure 7. We can observe that this Markov chain starts with state $(1, 0)$ when a message is generated by a node in community C_i, and has $F = (M+1)(N+1)$ transient states. When all the nodes in community C_j have received the message, the system enters into the absorbing state, denoted by $(x, (N+1))$, where $1 \leq x \leq M+1$ (in this case, we are considering as final state of the propagation to the second community, the state where all the nodes of the second community have received the message, irrespectively on the number of nodes of the first community who have been informed). Similar to what we did for the model of the flooding of a message inside a single community, we can obtain a generator matrix $\mathbf{Q}$ expressed by Equation 8.

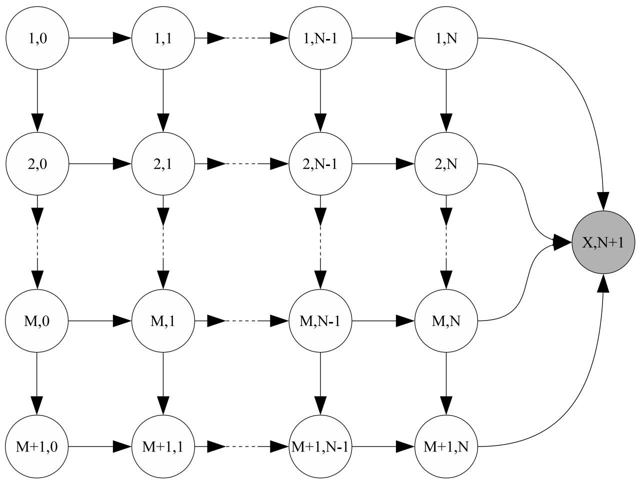


Figure 7: The two-dimensional continuous time Markov chain model for modeling the message dissemination within two communities. States $(1,0)$ to $(M+1,N)$ are $(M+1)(N+1)$ transition states and state $(x,N+1)$ is the absorbing state.

Here, the sub-matrix $\mathbf{D}$ is a $F \times F$ matrix, $\mathbf{R}$ is a $F \times 1$ matrix, the left $\mathbf{0}$ matrix is a $1 \times F$ vector, and the right $\mathbf{0}$ matrix includes a single element 0, which are with the same meanings in the generator matrix utilized to model the flooding of a message inside a single community. Assume the current state is state $(m,n)_{m \le M, n \le N}$ (that is, the number of nodes in community C_i and C_j with the message is m and n respectively). The transmission rate from state (m,n) to state $(m+1,n)$ is $(M+1-m)(m\lambda^{intra}+n\lambda^{inter})$, since $M+1-m$ nodes without the message can receive the message from m nodes inside community C_i with rate of λ^{intra} or from n nodes inside community C_j in rate of λ^{inter}. Similarly, the transmission rate from state (m,n) to state $(m,n+1)$ is $(N+1-n)(m\lambda^{inter}+n\lambda^{intra})$, since $N+1-n$ nodes without the message can receive the message from m nodes inside community C_i in rate of λ^{inter} or from n nodes inside community C_j in rate of λ^{intra}. When the last node in community C_j receives the message, the system turns to the absorbing state (i.e., state $(x,N+1)$), and the transition rate is $m\lambda^{inter}+N\lambda^{intra}$. Thus, the non-zero transition rates in the Markov chain can be expressed as in Equation 10.

$$\begin{cases} D\{(m+1,n)|(m,n)\} = (M+1-m)(m\lambda^{intra}+n\lambda^{inter}), m \in [1,M], n \in [0,N] \\ D\{(m,n+1)|(m,n)\} = (N+1-n)(m\lambda^{inter}+n\lambda^{intra}), m \in [1,M+1], n \in [0,N-1] \\ R\{(x,N+1)|(m,n)\} = (m\lambda^{inter}+N\lambda^{intra}), \text{ if } m \in [1,M+1], n = N \\ D\{(m,n)|(m,n)\} = -D\{(m+1,n)|(m,n)\} - D\{(m,n+1)|(m,n)\} \\ \qquad\qquad -R\{(x,N+1)|(m,n)\}, m \in [1,M+1], n \in [0,N+1] \end{cases} \tag{10}$$

5.1.2. Computation of cover time

Let F be the dimension of the transition matrix $\mathbf{D}$. Based on the transition matrix $\mathbf{D}$, we can derive the cover time of the maintained information in the intra- and in the inter-community case, denoted by $D^d_{(intra)}$ and $D^d_{(inter)}$ respectively, as the following expression [19, 23]:

$$D^d_{(\cdot)} = \mathbf{e}\,(-\mathbf{D}^{-1}_{(\cdot)})\,\mathbf{1} \tag{11}$$

where $\mathbf{e}$ is a $1 \times F$ vector denoting the initial state probability vector $\mathbf{e} = [1, 0, \ldots, 0]$, whereas $\mathbf{1}$ is a $F \times 1$ all-one vector, that is, $\mathbf{1} = [1, 1, \ldots, 1]^T$.

5.2. Model validation

In this section, we evaluate the accuracy of our analytical model by comparing its predictions to the simulation results, which are obtained by simulating message dissemination through a standard simulator.

5.2.1. Evaluation settings

The simulation scenario considers a rectangular area of 2000 m $\times$ 1000 m. This area is equally partitioned into 2 regions, that is, each region is an area of 1000 m $\times$ 1000 m. Initially, a given number of nodes are deployed in each region. Each node considers the region in which it has been deployed as its *local region*. According to the mobility model, which will be further described below, a node is more likely to visit its local region than other regions. This leads to the encounter frequency of nodes deployed in the same region being much higher than the encounter frequency of nodes deployed in different regions. Consequently, nodes associated to one region constitute a community.

Let r be the transmission range. Let v be the speed of nodes. Following [24], the parameters are set as follows: $r = 20$ m, $v = 10$ m/s. The number of nodes is set as variable parameter for the investigation. Let λ^{intra} be the contact rate of nodes in the same community. Let λ^{inter} be the contact rate of nodes belonging to different communities. According to the study in [32], the contact rates λ^{intra} and λ^{inter} are set to 1.703 h^{-1} and 0.672 h^{-1} respectively in the simulation model.

The simulations, in the simulator ONE (Opportunistic Network Environment simulator) [20], also include the settings of the message generation parameters. Every minute, a message is generated with a random node as the source and all other nodes in the community as the destinations. The message generation process lasts for 6 hours. Therefore, there are 360 messages generated in each simulation. Moreover, in order to ensure that each message can eventually reach all destination nodes, the TTL is set to “never expire”.

5.2.2. Mobility model

For the simulations under the ONE simulator, we adopt the community-based mobility model proposed in [32], which has been widely used for the evaluation of community-based routing protocols [11, 5]. In this mobility model, each community is associated with a geographical area. The movement of a

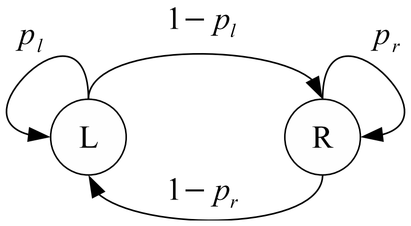


Figure 8: Community-based mobility model

node, which belongs to a community, consists of a sequence of *local* and *roaming* epochs. A local(or roaming) epoch of a node is a movement with a given speed towards a random destination inside the area associated with the community (or the entire network). When the node reaches the destination, it stays there for a certain period of time (i.e, a pause time). When the pause time expires, it starts a new epoch. If the node's previous epoch was a local one, the next epoch is a local one with probability p_l, or a roaming epoch with probability $1 - p_l$. Similarly, if the node's previous epoch was a roaming one, the next epoch is a roaming one with probability p_r, or a local one with probability $1 - p_r$. The state transition between local and roaming epochs is shown in Figure 8.

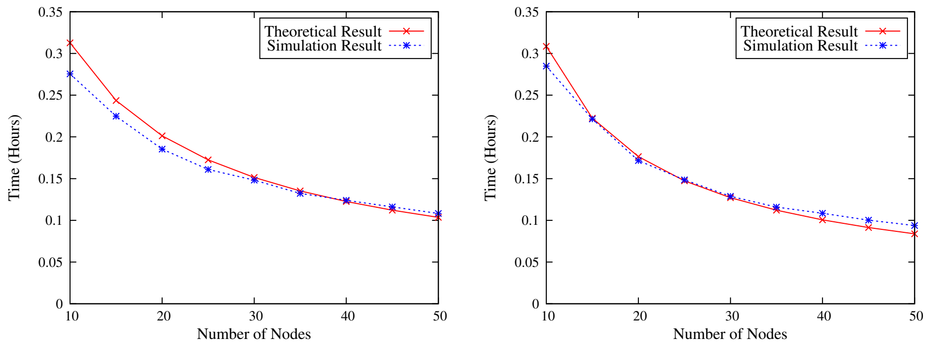
In our case, in order to avoid biasing the cover time by the pause time, we set the pause time in the simulations to zero [25, 27]. Moreover, we assign the same mobility characteristics to the nodes in the network, since our goal is to verify the accuracy of the model. Specifically, the values of p_l and p_r for nodes are set to 0.8 and 0.2 respectively.

5.2.3. Evaluation results

Figs. 9(a) and (b) show the results obtained for the cover time for the case of intra-community and inter-community. It can be seen that the average deviation of the theoretical results from the simulated results is small. Specifically, in the case of intra-community, the minimum, maximum, and average deviations are 1.13%, 13.50%, and 5.64% respectively; while in the case of inter-community, the minimum, maximum, and average deviations are 0.45%, 10.57%, and 4.83% respectively. This demonstrates the accuracy of our analytical model in the evaluation of the cover time.

6. Performance evaluation

In this section, we present the performance evaluation of CAS. We first introduce our simulation settings and the mobility model in Sections 6.1 and 5.2.2 respectively. We then present the routing protocols against which we compare the performance of CAS in Section 6.2 followed by the description of the performance evaluation metrics in Section 6.3. Finally, we present the simulation results in Section 6.4.



(a) Intra-community

(b) Inter-community

Figure 9: Theoretical and simulation result comparison in the case of: (a) intra-community and (b) inter-community message exchange. The contact rates between nodes in the same community and different communities are $\lambda^{intra} = 1.703$ h^{-1} and $\lambda^{inter} = 0.672$ h^{-1} respectively.

6.1. Simulation settings

The simulations have been conducted by the ONE simulator [20]. The simulation scenario considers a rectangular area of 2000 m × 1500 m. This area is equally divided into 12 regions each measuring 500 m × 500 m. Initially, twenty nodes are deployed in each region. Each node considers the region in which it has been deployed as its *local region*. According to the mobility model (see Section 5.2.2), a node is more likely to visit its local region than other regions. This leads to the encounter frequency of nodes deployed in the same region being much higher than that of nodes deployed in different regions. Consequently, nodes associated to one region constitute a community.

In addition, we assign different mobility characteristics to the nodes in a region in order to produce a scenario closer to reality, where there is heterogeneity in mobility among nodes. To achieve this, the nodes in a region are divided into two kinds: *low mobility* nodes and *high mobility* nodes. The low mobility nodes can only roam inside their local regions, while the high mobility nodes may roam among their local region as well as the entire space. Specifically, the values of p_l and p_r for the low mobility nodes are set to 1 and 0 respectively. Whereas, the values of p_l and p_r for the high mobility nodes are set to 0.5.

Moreover, each node is equipped with a radio interface for short-range communication. The transmission range and rate are set as 10 m and 2 Mb/s respectively. This is consistent with contemporary protocols, such as Bluetooth [20]. Additionally, the speed of nodes is set to 1.34 m/s, which is an average human walking speed [20]. Since we find that the routing performance of CAS and the chosen routing protocols converges after about six hours, we set thirteen hours for each simulation in order to achieve statistical confidence. Since CAS depends on the knowledge of the network topology, we specify the first hours as a warm-up period to allow the nodes to setup the community graph. During

Table 1: Parameter Settings

Parameter Name	Value
Simulation area	2000 m $\times$ 1500 m
Transmission range	10 m
Simulation duration	13 hours + TTL
Warm-up period	1 hour
Message generation rate	1 message per minute
Number of communities	12
Number of nodes in a community	20
Node speed	1.34 m/s
p_l (low mobility nodes)	1
p_r (low mobility nodes)	0
p_l (high mobility nodes)	0.5
p_r (high mobility nodes)	0.5
γ	1 hour
p_d	0.8

the warm up period, no message is generated. After this period, every minute, a random node sends a message to a random destination node. The detailed settings are listed in Table 1.

6.2. Routing protocols

Based on the above settings, we have compared the performance of CAS against the following protocols:

Epidemic: Each node forwards a copy of each unexpired message in its buffer to the encountered node that does not have a copy of the message.

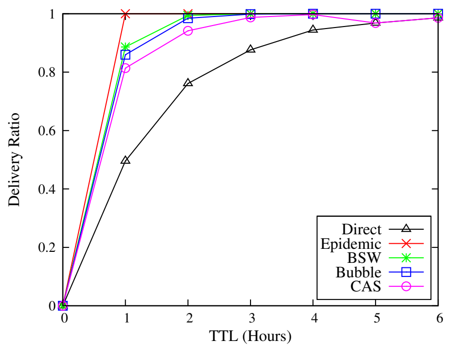
Direct: The source node of a message can only forward the message to the destination node.

Binary Spray-and-Wait (BSW): Each message has L copies. A message carrier forwards half of the message copies to an encountered node, if its $L > 1$ and the latter does not have the message. The message, which has only one message copy left, can only be forwarded to the destination.

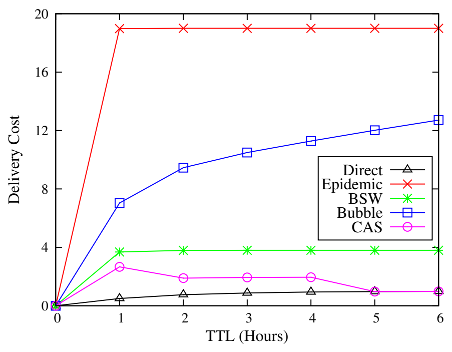
Bubble: It utilizes social information about nodes, such as their centrality and the community to which they belong. In this protocol, a message is forwarded based on the global rankings of two encountering nodes, until it reaches a node in the community of the destination node. After that, the message is forwarded based on the local rankings of two encountering nodes, until it either reaches the destination node or expires. In the experiment, the length of time window is set to 1 hour.

6.3. Metrics

The goal of CAS is to minimize the number of message copies and while maintaining a predefined delivery ratio. Therefore, we have measured the following metrics for the simulations that we have conducted in this work:



(a) Delivery Ratio



(b) Delivery Cost

Figure 10: Comparison of the routing performance of several algorithms in the single-community case.

Delivery ratio: The proportion of messages that have been delivered out of the total unique messages created.

Delivery cost: The total number of message transmissions in the simulation. To normalize this, we divide it by the total number of unique messages created.

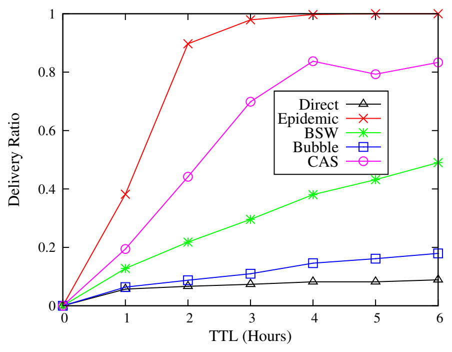
6.4. Simulation results

As mentioned in Section 4.3, CAS includes some basic routing protocols as special cases according to the number of communities in the network and the allocated number of message copies. Therefore, in this section, we compare the routing performance of CAS with the chosen routing protocols in the following two cases: single-community case and multiple-community case.

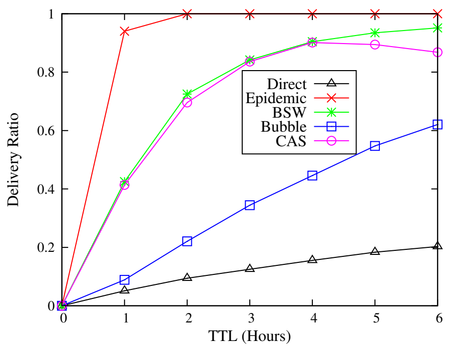
6.4.1. Single-community case

We arbitrarily select one of the twelve regions for this study. The nodes deployed in this region constitute a community. For the Binary Spray-and-Wait protocol, each message is initially associated with 4 copies. Thus, at most 20% nodes can participate in message routing in Binary Spray-and-Wait.

Figure 10(a) shows the delivery ratio of the compared routing protocols. We can observe that Epidemic and Direct always achieve the best and worst delivery ratio respectively, for all values of TTL. We also observe that the delivery ratio of Bubble is very close to that of Binary Spray-and-Wait. Binary Spray-and-Wait achieves a better delivery ratio than CAS. The maximum and minimum difference between CAS and Binary Spray-and-Wait is 7.22% and 0.28%. The delivery ratio of CAS is always higher than the predefined delivery ratio (i.e., 0.8). It is worth noting that CAS achieves the same delivery ratio as Direct when the TTL is greater or equal to 5 hours. This is because CAS allocates the same number of copies for each message as Direct. This indicates that CAS can dynamically transform to Direct.



(a) a



(b) b

Figure 11: Comparison of delivery ratio of several algorithms with different densities of high mobility nodes. 5% and 50% nodes are chosen as the high mobility nodes in (a) and (b) respectively.

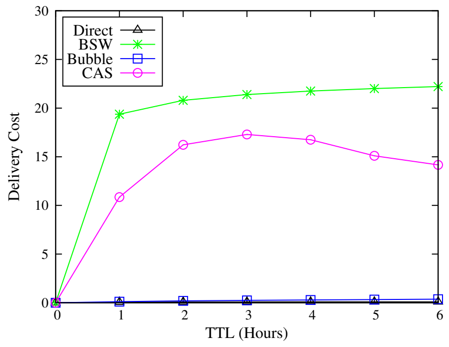
Figure 10(b) shows the delivery cost of the compared routing protocols as a function of the TTL of the generated messages. We observe that Epidemic and Direct have the highest and lowest delivery cost respectively, whatever the value of TTL. The delivery cost of Bubble keeps increasing as the TTL increases. The delivery cost of Binary Spray-and-Wait is lower than that of Bubble and remains stable as the TTL increases. However, it is very close to the allocated number (i.e., 4) of copies for each message in Binary Spray-and-Wait. It is worth noting that unlike other routing protocols, the delivery cost of CAS decreases as the TTL increases. In particular, CAS achieves the same delivery cost as Direct when the TTL is greater or equal to 5 hours. This is because CAS can dynamically allocate copies for a message according to its TTL.

6.4.2. Multiple-community case

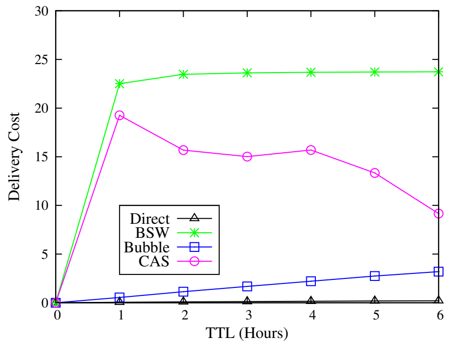
In the multiple-community case, we conduct two experiments to investigate the impact of the density of high mobility nodes and the mobility model settings on the routing performance of our protocol.

A. Impact of the density of high mobility nodes

In this section, we investigate the impact of the density of high mobility nodes on the routing performance of CAS and the chosen routing protocols. The investigation is conducted by two experiments, in which the densities of high mobility nodes are set as 5% and 50% respectively. In order to avoid the impact of the settings for roaming nodes on the routing performance, the values of p_l and p_r for high mobility nodes are set to 0.5. Moreover, for Binary Spray-and-Wait, each message is initially associated with 24 copies. Since there are twenty nodes in each of the twelve regions, at most 10% nodes can participate in message routing in Binary Spray-and-Wait.



(a) a



(b) b

Figure 12: Comparison of delivery ratio of several algorithms with different densities of roaming nodes. 5% and 50% nodes are chosen as the roaming nodes in (a) and (b), respectively.

Figs. 11(a) and (b) show the delivery ratio of the compared routing protocols with different densities of high mobility nodes. As the same as in the single-community case, we can observe that Epidemic and Direct always achieve the best and worst delivery ratio respectively. We also observe that CAS always achieves a much better delivery ratio than Bubble for all values of TTL. Indeed, the maximum difference between the delivery ratio of CAS and Bubble is about 69.17% and 49.17% in Figs. 11(a) and (b) respectively. This is because CAS takes advantage of gateway nodes to steer the forwarding of the messages whose source and destination nodes belong to different communities in the right direction. Figure 11(a) shows that CAS achieves a much better delivery ratio than Binary Spray-and-Wait; while Figure 11(b) shows that Binary Spray-and-Wait even achieves a little better delivery ratio than CAS. This results from that the increasing number of roaming nodes raises the opportunity of message exchange between different communities. This also reflects the shortcoming of Binary Spray-and-Wait, that is, assuming that nodes have the same capability of visiting the entire network. Moreover, It is worth noting that delivery ratio of CAS is a little lower when TTL is 5 hours than that when TTL is 4 hours. This is because CAS allocates less copies for the messages with longer TTLs.

The performance of delivery cost of the compared routing protocols is illustrated in Figs. 12(a) and (b). Since the delivery cost of Epidemic increases much quickly than that of other protocols, we omit the delivery cost of Epidemic to illustrate the delivery cost of other protocols in detail. We can observe that Direct always has the lowest delivery cost. Bubble achieves a close delivery cost as Direct in Figure 12(a) and a little higher delivery cost than Direct in Figure 12(b). Additionally, Binary Spray-and-Wait always consumes the assigned number of message copies. Figure 12(a) shows that the delivery cost of CAS raises as the TTL increases, When the TTL is less than 3 hours. Since the TTL increase, the gateway nodes can reach more communities, which invokes the allocation of message copies. When the TTL is greater than 3 hours, the delivery cost of CAS decreases as the TTL increases. This is because CAS allocates less copies for the messages with longer TTLs. Figure 12(b) shows that the delivery cost of CAS decreases as the TTL increases. The increasing number of high mobility nodes can enhance the successful delivery probability for the messages whose source and destination nodes belong to different communities, which can terminate the allocation of message.

B. Impact of the settings of mobility model

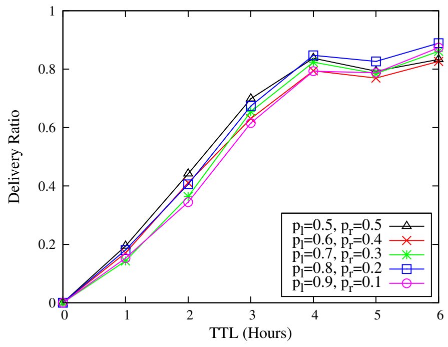
In this section, we investigate the impact of the settings of the chosen mobility model on the routing performance of CAS. As we stated in Section 6.1, a high mobility node is more likely to visit its local region than other regions. Hence, for high mobility nodes, we vary the value of p_l from 0.5 to 0.9 with step by 0.1 and set the value of p_r as $1 - p_l$ in the simulations. Moreover, 5% nodes are chosen as high mobility nodes in order to avoid the impact of the density of high mobility nodes on the routing performance of CAS.

First we look at the delivery ratio. From the results illustrated in Figure 13(a), we can observe that CAS achieves similar results under different settings with respect to p_l and p_r. The settings with $p_l = 0.5, p_r = 0.5$ and $p_l = 0.9, p_r = 0.1$ always achieve the best and worst delivery ratio respectively, when TTL is less than 4 hours. This is because that a higher probability p_r can provide more opportunities to route messages whose source and destination nodes are in different communities. When TTL is greater than 4 hours, the setting with $p_l = 0.8, p_r = 0.2$ achieves the best delivery ratio while the setting with $p_l = 0.6, p_r = 0.4$ achieves the worst delivery ratio. Since as the TTL increases, the higher probability p_l can make the gateway nodes collect more messages whose source and destination nodes are in different communities.

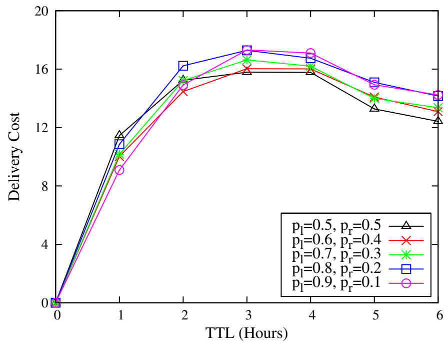
Next we compare the delivery cost of CAS with different settings. As shown in Figure 13(b), we can observe that CAS achieves similar results under different settings with respect to p_l and p_r. When TTL is greater than 3 hours, the setting with $p_l = 0.5, p_r = 0.5$ has the lowest delivery cost. Since, with a higher probability p_r, the gateway nodes collect fewer messages from their community. Additionally, the gateway nodes can forward the messages whose source and destination nodes belong to different communities earlier to the next communities, which in turn results in fewer message copies are allocated in the next communities.

7. Conclusion

In this paper, we presented CAS, the self-regulating protocol for efficient routing in mobile delay tolerant networks. CAS can dynamically control the message replication based on the urgency of messages. We demonstrated that CAS includes some basic routing protocols as special cases. An analytical model that estimates the cover time of the local knowledge maintained in CAS was developed and validated by simulations. Our simulations on a widely used



(a) Delivery Ratio



(b) Delivery Cost

Figure 13: The impact of the settings of the mobility model on the routing performance of CAS

community-based mobility model, demonstrate that CAS can improve the routing performance compared to the quota-based Binary Spray-and-Wait protocol and the community-based Bubble protocol.

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