# TSearch: Target-Oriented Low-Delay Node Searching in DTNs With Social Network Properties

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***Abstract*— Node searching in delay tolerant networks is of great importance for different applications, in which a locator node finds a target node in person. In the previous distributed node searching method, a locator traces the target along its movement path from its most frequently visited location. For this purpose, nodes leave traces during their movements and also store their long-term movement patterns in their frequently visited locations (i.e., preferred locations). However, such tracing leads to a long delay and high overhead on the locator by long-distance moving. Our trace data study confirms these problems and provides the foundation of our design of a new node searching method, called target-oriented method (TSearch). By leveraging social network properties, TSearch aims to enable a locator to directly move toward the target. Nodes create encounter records (ERs) indicating the locations and times of their encounters and make the ERs easily accessible by locators through message exchanges or a hierarchical structure. In node searching, a locator follows the target's latest ER, the latest ERs of its friends (i.e., frequently meeting nodes), its preferred locations, and the target's possible locations deduced from additional information for node searching. Extensive trace-driven and real-world experiments show that TSearch achieves significantly higher success rate and lower delay in node searching compared with previous methods.**

***Index Terms*— Delay-tolerant networks, node searching, social network properties.**

## I. Introduction

IN RECENT few years, Delay Tolerant Networks (DTNs) attract significant attention from researchers. In such sparsely distributed networks, node searching, in which a *locator* node finds a *target* node in person, is of great value in node management and many applications. For example, in a DTN formed by mobile device holders in a hospital, a campus, a disaster area or a national park, a user needs to find another user in person. In a DTN in battlefield, a node needs to find a node that carries a malfunctioning device in order to fix it. In a DTN formed by vehicles [1], a vehicle may need to find another vehicle to directly communicate with it. The DTN network condition without infrastructures or continuous network connectivity poses a challenge for designing an efficient distributed node searching algorithm.

Some previous object tracking systems [2]–[6] in wireless networks provide high localization accuracy or search efficiency based on the geographical information provided by central base stations or other infrastructures. However, the extra infrastructure requirement is costly and impractical for DTNs (e.g., in battlefields). DTN routing algorithms [7]–[14] can be indirectly used for node searching. In routing, a node forwards the message to the node with a higher probability of meeting the destination. Then, to find a target, a locator can move with the selected message carriers by regarding the target as the message destination. However, since the locator must follow multiple nodes in routing and each node has its own movement path rather than moving directly towards the target, such a node searching method generates a high delay and overhead on the locator by long-distance moving.

Recently, a distributed node searching algorithm (called DSearching) has been proposed [15]. It divides the entire DTN area to sub-areas. During a node's movement, it tells several nodes in its current sub-area its next sub-area (called transient visiting record (VR)) before moving out. Each node also deduces its long-term mobility pattern (MP), which indicates the sub-areas it has high probabilities to move to from each of its frequently visited sub-area (i.e., preferred location). It distributes its MP from sub-area $A_i$ to long-staying nodes in $A_i$. A node's home-area is the sub-area it has the highest staying probability, and this information is stored in all sub-areas. As shown in Figure 1(a), a locator starts from the target's home-area and follows the VRs. When these records are absent in searching, the locator moves to the next sub-area with the highest probability based on the MP. If this information is not available, the locator searches nearby sub-areas for VR and MP.

However, both moving to the target's home-area and tracing along the target's movement path may take a long time. First, as Figures 1(a) and 1(b) show, this tracing process ($A_4 \rightarrow A_{14} \rightarrow A_{10} \rightarrow A_{11} \rightarrow A_7 \rightarrow A_6$) generates high delay. A locator can take a shortcut to directly move towards the target ($A_4 \rightarrow A_7 \rightarrow A_6$). Second, when a locator in a

Manuscript received June 1, 2015; revised January 18, 2016; accepted March 30, 2016; approved by IEEE/ACM Transactions on Networking Editor Y. Yi. This work was supported in part by the U.S. National Science Foundation under Grants NSF-1404981, IIS-1354123, CNS-1254006, and CNS-1249603 and the Microsoft Research Faculty Fellowship 8300751.

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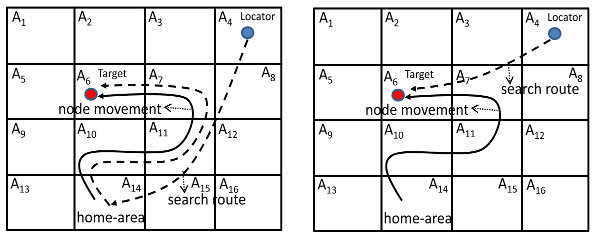
Digital Object Identifier 10.1109/TNET.2016.2586446



(a) (b)

Fig. 1. Node searching in DSearching and TSearch. (a) Node searching in DSearching. (b) Node searching in TSearch.

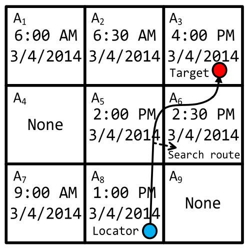


Fig. 2. ER-based node search.

sub-area (say $A_{11}$ in Figure 1(a)) loses trace (i.e., VR), it moves to the predicted next sub-area from $A_{11}$ (i.e., $A_7$), which generates extra search path length. Instead, directly moving to the sub-area that the target frequently visits (i.e., $A_{11} \rightarrow A_6$) generates shorter searching delay and overhead. Also, in this step, the next sub-area with the highest probability may not be the one that the target actually moves to, which leads to high searching delay and even searching failure. Further, storing the target's MP in a very limited number of sub-areas may make it not easily accessible to the locators, which may also increase searching delay.

In this paper, we have conducted trace data [16], [17] study, which confirms the above problems of DSearching and also lays a foundation of our proposed target-oriented method (called TSearch). As DSearching, TSearch is also designed for DTNs with social network properties such as mobility range stability, certain mobility patterns and certain frequently meeting nodes (i.e., friends), and skewed visiting places (i.e., preferred locations) shown in previous works [8], [18], [19]. By leveraging these social network properties, TSearch aims to enable a locator to directly move towards the target.

In TSearch, the information for node searching consists of encounter records (ERs), friends, and preferred locations. Nodes record and disseminate ERs that indicate the locations and times of their encounters. A locator ($N_i$) always directly moves to the sub-area in the latest ER of the target ($N_j$) known by itself (Figure 2). In the absence of $N_j$'s newer ER, $N_i$ relies on the ERs of $N_j$'s friends. In the absence of the friends' ERs, $N_i$ directly moves to the nearest preferred location of $N_j$, and also requests the nodes sharing the common preferred locations with $N_j$ to search $N_j$ simultaneously. If the locator does not have the above information of its target, it relies on additional information (i.e., relation graph, which represents nodes' social relationship based on their mutual friends) to deduce a proper search area. This design is based on our trace study, which shows that this strategy leads to a higher success rate than targeting $N_j$'s most frequently visited preferred location (as in DSearching). To make the information for node searching globally accessible, TSearch adopts the hierarchical structure from [20] and [21], in which each sub-area has a long-staying node (called anchor) to collect the information from nodes, and nodes that frequently transit between two sub-areas (called ambassadors) are responsible for the information updates between anchors. TSearch provides an option for nodes to piggyback ERs on the information exchanged between neighbors in order to expedite the information dissemination. In summary, our contributions are threefold:

1) Our extensive study on two real traces [16], [17] confirms the drawbacks of DSearching and lays the foundation of the strategy design in TSearch.
2) We propose TSearch, which is the first work (to our best knowledge) that aims to enable locators directly move towards the targets with easily accessible information to reduce node searching delay by utilizing social network properties.
3) We have conducted both trace-driven and real-world experiments, which verifies the efficiency and effectiveness of TSearch compared with other previous methods.

The remainder of this paper is organized as follows. Section II presents an overview of related work. Section III presents our trace analysis results. Section IV presents the detailed design of TSearch. Section V presents the experimental results of TSearch. Section VI concludes this paper with remarks on our future work.

## II. Related Work

Object searching in disconnected mobile networks has been paid much attention in research. Juang *et al.* [2] proposed a method that sends the positions of animals to the central station through hop-by-hop broadcasting by configuring tracking collars on animals. By utilizing the flock behavior of sheep in wild areas, Thorstensen *et al.* [3] proposed a system that lets the flock leader monitor and report the positions of other sheep to the server through GPRS [21] or satellite communication. Cenwits [4] and SenSearch [5] provide object searching services in wilderness areas. They utilize the opportunistic encounters among nodes to forward location information to infrastructures. However, these methods need extra infrastructures or central servers, which is not practical for DTNs. Symington and Trigoni [6] proposed a method that centrally models the encounters of sensors as a connected graph and sensors' estimated trajectories. Then, the tracking process is to find a forwarding path to the target that meets its estimated trajectory. However, since the connected graph is generated using a centralized method, it is not suitable for decentralized DTNs. DSearching [15] was proposed specifically for node searching in DTNs. As indicated previously, it provides insufficiently efficient node search by aiming to enable a locator to trace the target along its movement path from its home-area. Routing algorithms [7]–[14] can be indirectly applied for node searching, but the hop-by-hop routing is not efficient for node searching in DTNs. Unlike these previous methods, TSearch does not need an infrastructure or a central server. It is the first work that enables locators to directly move towards targets to achieve low search delay and overhead.

## III. Rationale of TSearch Design

In this section, we present the rationale of the design of TSearch based on trace analysis. We used the DART trace [16] (DART) and the DieselNet AP trace (DNET) [17]. DART is a 119-day record for wireless devices carried by students on Dartmouth College campus. DNET is a 20-day record for WiFi nodes attached to the buses in the downtown area of UMass college town. We filtered out nodes with few occurrences and merged access points (APs) within short ranges to one sub-area. Finally, DART has 320 nodes and 159 sub-areas, DNET has 34 buses and 18 sub-areas.

We set the initial period to 30 days for DART and 2.5 days for DNET, during which nodes collect information for node searching. We randomly selected 70 locators and each locator randomly chose a target to search periodically for 90 times and the average experimental result of each locator is reported. The periodical time was set to 1 day in DART and 4 hours in DNET. The search TTL (Time-To-Live) was set to 24 hours in DART and 4 hours in DNET. Node searches using more than TTL are considered as unsuccessful searches. In each of the following figures, the top figure is for DART and the bottom figure is for DNET.

*1) Leveraging Encounter Records (ERs):* We define *search length* as the number of sub-areas the locator transited in searching. DSearching has three stages: i) a locator moves to the target's home-area, ii) tracks along its moving trail, iii) and may randomly search in neighbor areas. As shown in Figure 1, such searching may generate a long search length. To confirm this drawback, we measured the cumulative distribution function (CDF) of the search lengths of these three searching stages as shown in Figure 3(a). It also includes the locator-target initial direct distance. We see that the direct distance is very short (within 3 sub-areas in DART and 2 sub-areas in DNET). However, 50% of locators need to travel more than 24 and 6 sub-areas to reach the target's home-area, and also travel more than 35 and 8 sub-areas in the tracking stage in DART and DNET, respectively. These results demonstrate that locators must travel many sub-areas in the first two stages in DSearch. Therefore, we aim to design a method that avoids the unnecessary travel and enables a locator to directly move to current location of the target. For this purpose, we propose the concept of encounter record (ER), which records the location and time of a node. The ERs of nodes are disseminated among nodes for locators to access, so they can move directly to the most recent locations of the targets. We measured the search length of this method as shown in Figure 3(a) when we temporarily let nodes piggyback ERs on the messages exchanged between neighbors for dissemination. The result shows that ERs are effective in enhancing the node searching speed of DSearching.

*2) Leveraging Preferred Locations:* In DSearching, by referring the target's MP Table (MPT), the locator always moves to the target's next sub-area with the highest probability. To verify the effectiveness of this method, for each node, we used this method to search the node's next sub-area from its previous sub-area in its entire movement path, and calculated the success rate. Figure 3(b) shows the CDF of the success rate. We see that $20\%$ of the nodes have success rate less than $60\%$ and $50\%$ of the nodes have success rate less than $75\%$ in DART, while $25\%$ of the nodes have success rate less than $55\%$ and $75\%$ of the nodes have success rate less than $70\%$ in DNET. Therefore, a locator should not ignore the other preferred locations that a target has a high probability (though not the highest probability) to move to. When a target stays in a sub-area most recently, it may be on the way to a nearby preferred location. Then, searching the nearest preferred location may lead to a higher success rate. To verify these, we draw Figures 4(a) and 4(b). A node's *preferred locations* are defined as the sub-areas the node frequently visits. We ranked each node's visited sub-areas based on the visiting frequency and consider the top sub-areas that constitute 60% of visiting frequency as its preferred locations.

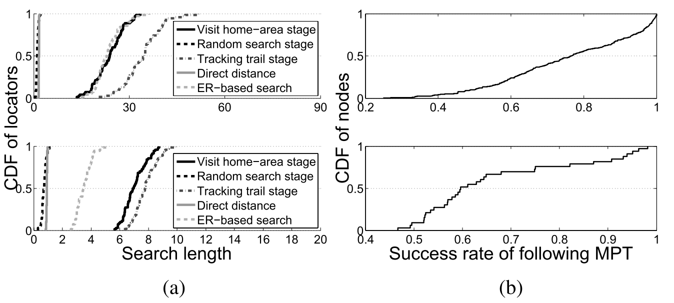


Fig. 3. Drawbacks of DSearching. (a) The number of searched sub-areas. (b) Choosing the top next sub-area.

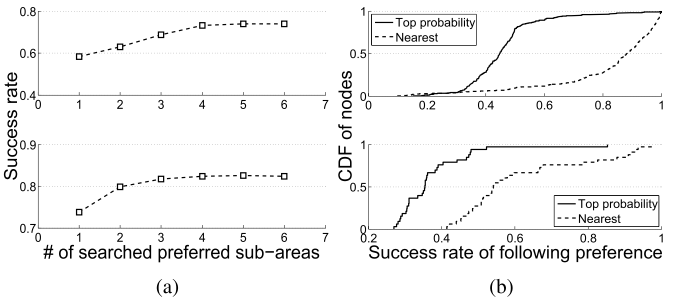


Fig. 4. Node searching based on preferred locations. (a) Searching top preferred locations. (b) Preferred locations to search.

Figure 4(a) shows the average success rate of searching different numbers of preferred locations. We see that searching the top preferred location only leads to 59% and 74% success rates in DART and DNET, respectively. Searching top 4 (in DART) and 3 (in DNET) preferred locations can achieve $73\%$ and $82\%$ success rate, respectively, and then searching additional 1 or 2 preferred locations only generates a very marginal improvement. Figure 4(b) shows the success rates of searching the top and nearest preferred location, respectively. From this figure and Figure 3(b), we can see that selecting the nearest preferred location is more accurate than selecting the top preferred location.

*3) Leveraging Frequently Met Nodes (i.e., Friends):* We define that node $N_i$ and node $N_j$ are friends if their encounter

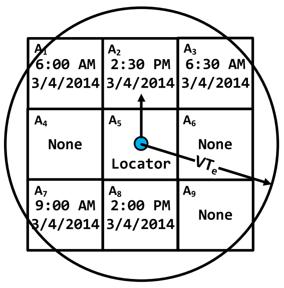


Fig. 5. Constrained search area.

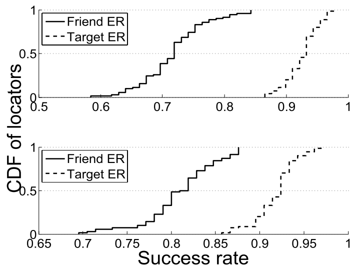


Fig. 6. Following the ERs of the target or its friends.

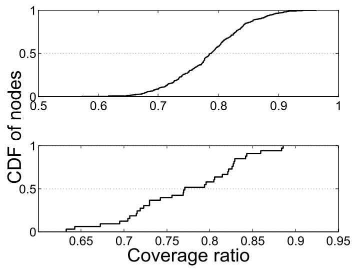


Fig. 7. Constraining searching range.

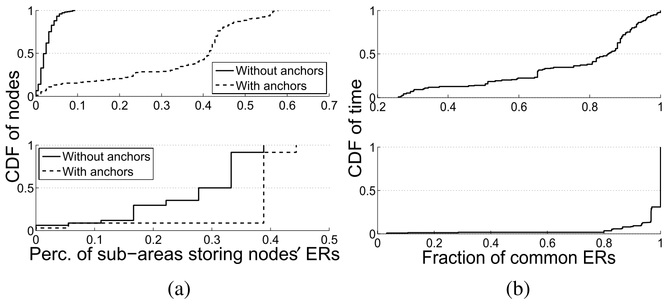


Fig. 8. Role-based information dissemination. (a) Effectiveness of anchors. (b) Effectiveness of ambassadors.

frequency is higher than a threshold. Since each node has certain frequently meeting nodes (i.e., friends) [8], [18], [19], if a locator moves towards the target's friend, it is very likely to meet the target. To verify this conjecture, we draw Figure 6 that shows the CDF of success rate of following the ERs of the target and the target's friends, respectively. We regard a node's friends as the nodes that take up at least a high percentage (60%) of all contacts with the node. We see that following the targets' ERs, about 60% of the locators have success rate higher than 92% in DART and 91% in DNET. Following the ERs of the target's friends, about 60% of the locators have success rate higher than 70% in DART and 80% in DNET. The result confirms that the ERs of the target's friends can be used for node searching as an auxiliary method.

*4) Search Range Constraint:* Based on the normal node velocity $V$ and the time and location in the latest ER of a node, the range of the area that the node possibly stays (called coverage area) can be determined. It is a circle with $VT_e$ as the radius and the ER location as the center, where $T_e$ is the elapsed time since the time in the ER. For example, in Figure 5, based on the $T_e$ indicated in the ER corresponding to sub-area $A_5$ and the velocity $V$, the possible positions of the target are included in the circle determined by the radius $VT_e$. For each node, at each of its locations, we checked whether it is within its coverage area based on its previous location. Figure 7 shows the CDF of the *coverage ratio* defined as the ratio of the number of locations in the coverage areas. We see that 80% of nodes have coverage ratio higher than 70% in DART and DNET. The result shows that the coverage area can be used to limit the searching areas of the locators to reduce search delay and overhead.

*5) Information Dissemination:* Nodes may move locally in only a few sub-areas [8], [18], [19], so a locator may not receive ERs of very distant targets. To make ERs globally accessible, we adopt a hierarchical structure in previous works [19], [20], which verified the existence of long-staying nodes (i.e., anchors) in each sub-area and nodes that frequently transit between two sub-areas (i.e., ambassadors). In our method, nodes report information to anchors and ambassadors are responsible for the record updates between anchors.

In order to see the effectiveness of this method, we measured the percent of sub-areas that have the ERs of a certain percent of nodes at the time point of 120 hours and 20 hours in DART and DNET, respectively. We see that 50% of nodes have their ERs disseminated to less than 2% and less than 40% of all the sub-areas without and with the anchors in DART, and to less than 27% and less than 39% of all the sub-areas without and with the anchors in DNET. The result confirms the importance of using anchors for easy information access.

In order to see the degree of consistency relying on the ambassadors, in each hour during the 120 hours and 20 hours in DART and DNET, respectively, we measured the ratio of common ERs among all anchors. The results are shown in Figure 8(b). We see that about 80% of the time, the ratio of common ERs among anchors is higher than 40% in DART, and higher than 90% in DNET. It confirms that the ambassadors can help maintain a high degree of consistency among anchors.

*6) Stability of the Number of Nodes With Different Roles:* To verify the stability of the number of nodes with these three roles, we draw Figure 9 that shows the number of nodes with each role throughout the time of the two traces. We sampled the number of nodes with each of the three roles every 3 days and 12 hours for DART and DNET, respectively. We see that after an initial time period, the number of nodes with each role becomes steady though they fluctuate within a small range. The number of anchors is around 80 and 9 with fluctuating range of [10, 15] and [2, 3] in DART and DNET, respectively. The number of ambassadors is around

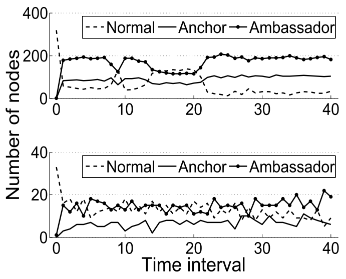


Fig. 9. Stability of number of nodes with different roles.

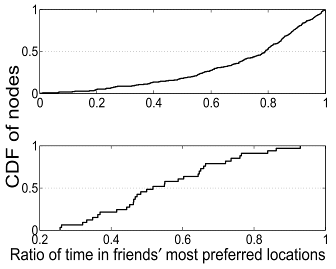


Fig. 10. Ratio of time in friends' most preferred locations.

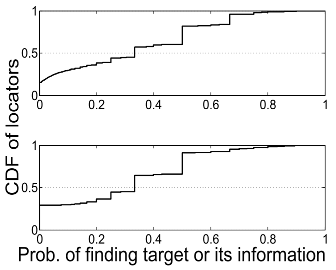


Fig. 11. Following the most preferred sub-areas of target's friends.

200 and 15 with fluctuating range of [10, 60] and [3, 5] in DART and DNET, respectively. The number of ambassadors fluctuates more than that of anchors. This is because some previously qualified ambassadors may change mobility patterns and thus are no longer ambassadors. Compared with DART, the number of nodes that serve different roles in DNET fluctuates more. This is because DNET was generated from the movement of buses while DART was generated from the movement of people. Compared with pedestrians, buses are always moving by scheduled routes. The results verify the constant existence of nodes that stay in certain sub-areas for a long time that can function as anchors, and the constant existence of nodes that frequently transit between two sub-areas that can function as ambassadors. Even though the numbers fluctuate, the fluctuating range is only within 35%. TSearch only needs one anchor in one sub-area and only a few ambassadors (e.g., 3) between each pair of sub-areas, and there are 159 and 18 sub-areas in DART and DNET, respectively. Therefore, the assignment of roles is reasonable.

*7) Leveraging Friends' Preferred Locations:* In a DTN with social network properties, nodes have high meeting probabilities with their friends. It has already been verified in Section III-.2 that nodes have preference in staying at certain sub-areas [15]. In this section, we check whether nodes spend much time staying in the preferred locations of their friends. If it is true, the preferred locations of a node's friend can be the location to search this node.

We call a node's preferred location with the highest visiting frequency its *most preferred location*. We measure the ratio of the total time a node stays in the most preferred locations of its friends over the node's total activity time. It is calculated by $\sum_j T_{p_j}/T_t$, where $T_{p_j}$ is the time the node $N_i$ stays in the most preferred location of its friend $N_j$, and $T_t$ is $N_i$'s total activity time. Figure 10 shows the CDF of this ratio on all nodes. We see that about 75% of nodes spend more than 60% of their time, and about 80% of nodes spend more than 40% of their time staying in their friends' most preferred locations in DART and DNET, respectively. The results confirm that most nodes spend much of their time in the most preferred locations of their friends. Recall that the anchor of a sub-area stores the information for node searching (e.g., ERs, friends and preferred locations) of the nodes in the sub-area. Based on above observation, we conjecture that searching in the most preferred locations of a target's friends can help the locator find the target or its information for node searching.

To confirm our conjecture, we draw Figure 11 that shows the CDF of the probability of finding the target or its information for node searching only through following the most preferred locations of its friends in node searching. We see that about 40% of locators achieve the probability of more than 50%, and about 30% of locators achieve the probability of more than 50% in finding the target or its information through following the most preferred location of the target's closest friend in DART and DNET, respectively. The result confirms that using the most preferred locations of the target's friends as a complementary approach in node searching is effective.

## IV. The Design of TSearch

Using the same method in DSearching, we partition the whole network area into several sub-areas (denoted by $A_i$) to represent node positions (Figure 1). It is obvious that more partitioned sub-areas lead to more accurate node positions but also generate higher overhead on maintenance and management. To achieve a balance for this tradeoff in deciding sub-areas, we consider the fact that nodes usually have "gathering" preference in popular places in a DTN with social network properties [9], [22]–[24]. For example, libraries, department buildings, and dorms are common popular places of a DTN on campus. Then, the sub-area partition is based on the popular places and each sub-area is labeled with a place (e.g., a landmark or building).

The sub-area partition is completed off-line. Each node is configured with the area map when it joins the DTN. Each node in the network has a positioning device (e.g. GPS) that can be used to learn its current sub-area.

TSearch is designed for DTNs with the social properties [8], [18], [19] (mentioned in Section I) and it leverages these properties for efficient node searching.

- Mobility range stability means that the mobility range of each user is significantly smaller than the whole area, and the change of its mobility range is small over time [18], [19]. Therefore, ERs can be used to search

TABLE I
AN ENCOUNTER RECORD (ER) TABLE

| ER creator | Node ID | Sub-area | Time |
|---|---|---|---|
| $N_2$ | $N_3$ | $A_1$ | 1:00pm, 3/4/2014 |
| $N_1$ | $N_7$ | $A_2$ | 2:00pm, 3/4/2014 |
| ... | ... | ... | ... |

targets. Even though a target is no longer in an ER's location, it is very likely to stay nearby (Figure 3(a)).

- Following the ERs of a target's friends (i.e., frequently meeting nodes) can be used as an auxiliary method (Figure 6).
- As each node has preferred locations, moving towards a target's preferred location has a high probability of finding it on the way or at the destination (Figure 4).
- Mobility pattern feature indicates that some nodes are relatively stable while some nodes transit frequently between sub-areas. As previous works [19], [20], we assign different roles (i.e., anchor, ambassador) to nodes with certain mobility features for information dissemination (Figure 8).
- Since most nodes spend much time in the most preferred locations of their friends (Figure 10), searching in the most preferred locations of a target's friends is effective in finding the target or its information (Figure 11).

Accordingly, TSearch has three types of location information of nodes: ERs, friends' ERs and preferred locations, along with additional information for search area determination: relation graph. We first introduce the location information and the additional information in Section IV-A and Section IV-B, respectively. We then present the node searching algorithm in Section IV-C, and finally explain the information dissemination in Section IV-D.

## A. Information for Node Searching

A node generates an ER for each of its neighbors (i.e., the nodes in its transmission range) upon encountering. Node $N_i$ generates ER for neighbor $N_j$ in the form of $< N_i, N_j, L_{ij}, T_{ij} >$, where $L_{ij}$ and $T_{ij}$ denote the current sub-area and current time. If $N_i$ already has $N_j$'s ER, it only needs to update the $L_{ij}$ and $T_{ij}$ in the existing ER. Finally, each node maintains its ER table based on its encounters with other nodes as shown in Table I. To constrain the storage overhead for ERs and ensure their validity in guiding node searching, TSearch sets a TTL for ERs. Each node deletes ERs after TTL upon their creation. Due to the mobility range stability, the number of nodes that node $N_i$ encounters is limited [8], [18], [19], which means that $N_i$'s ERs are created in a limited number of nodes. In Section IV-D, we will introduce methods to enable a locator of $N_i$ to access its ERs.

After a node joins in the system, it accumulates enough records during its movement and calculates its friends and preferred locations as shown in Table II. Because each node has a skewed visiting preference and relatively stable friends, these types of information do not update frequently. Through accessing this table, the locator knows that its target node $N_1$ has the probability of 0.3 to meet $N_3$, probability of 0.2 to meet $N_4$ and probability of 0.1 to meet $N_7$. Meanwhile, it also knows that $N_1$ has the probability of 0.25 to appear in $A_3$, probability of 0.15 to appear in $A_4$ and probability of 0.1 to appear in $A_5$.

TABLE II
FRIENDS AND PREFERRED LOCATIONS OF $N_1$

| Node | Friends | Meeting prob. | Preferred locations | Visiting prob. |
|---|---|---|---|---|
| $N_1$ | $N_3$ | 0.3 | $A_3$ | 0.25 |
| | $N_4$ | 0.2 | $A_4$ | 0.15 |
| | $N_7$ | 0.1 | $A_5$ | 0.1 |

The TTL should be set to a proper value so that the ERs can reflect the most recent position of corresponding nodes. The TTL is determined based on many factors such as the average frequency of encounters, average encounter duration, the total number of nodes in the network and so on. In this paper, we determine the TTLs heuristically based on the encounter of nodes in DART and DNET. We leave the method to accurately determine TTL value as our future work.

## B. Additional Information for Node Searching

In this section, we handle the problem of how a locator uses existing information in an anchor to deduce the next search area when the direct information of the target (i.e., ER, friends and preferred sub-areas) is not available. Section III shows that searching in the most preferred locations of a target's friends is effective in finding the target or its information for node searching. Therefore, in addition to a node's ERs, its friends' ERs and its preferred locations, we additionally consider its friends' preferred locations in node searching.

In Section IV-D, we will introduce role-based information collection and dissemination. Basically, nodes exchange the information for node searching and report the information to the anchor of a sub-area when they enter the sub-area and ambassadors are responsible for information consistency between anchors. Therefore, a locator may or may not know the preferred locations of its target's friends from an anchor, namely additional information for node searching. Below, we introduce the methods to search nodes based on this additional information in two situations. First, the locator knows the most preferred locations of the target's friends. Second, the locator does not know the most preferred locations of the target's friends.

*1) Possible Locations of Nodes:* Based on Figure 10 and Figure 11, we can see that the most preferred location of a target's friend may be the target's location. Therefore, besides the direct information of the target, say $N_i$, the locator can search the most preferred location of $N_i$'s friend to find $N_i$. After anchors and ambassadors collect and disseminate nodes' information, anchors will have a general view of the friends and preferred locations of many nodes. For each friend of $N_i$, the anchor may know its most preferred location. Among the most preferred locations of $N_i$'s friends, the locator needs to choose one location to search $N_i$, which should be the location that $N_i$ has the highest probability to visit among these most preferred locations. We use *weight* to represent the probability that a target visits its friend's most preferred location. It can be calculated by the product of their meeting probability ($P_m$) and the visiting probability of the friend on this location ($P_v$). For each node, an anchor builds a table recording its friends,

TABLE III
POSSIBLE LOCATIONS OF $N_1$

| Node | $N_1$ | | | |
|---|---|---|---|---|
| Friends | Meeting prob. | Most preferred locations | Visiting prob. | Weight |
| $N_3$ | 0.2 | $A_1$ | 0.5 | 0.1 |
| $N_4$ | 0.1 | $A_9$ | 0.4 | 0.04 |
| $N_7$ | 0.3 | $A_3$ | 0.1 | 0.03 |

their most preferred locations, their visiting probabilities to their most preferred locations and the corresponding weights. Finally, the locator chooses the most preferred location with the highest weight to search the target.

Table III shows an example for such a table for $N_1$. From the table, the locator knows that $N_3$'s most preferred location is $A_1$ with corresponding visiting probability of 0.5 and weight of 0.1, $N_4$'s most preferred location is $A_9$ with corresponding visiting probability of 0.4 and weight of 0.04, and $N_7$'s most preferred location is $A_3$ with corresponding visiting probability of 0.1 and weight of 0.03. Then, the locator chooses $A_1$ to search $N_1$, which has the highest weight (i.e., the highest probability that $N_1$ stays among these most preferred locations). If the locator cannot find $N_1$ in $A_1$, it is very likely to find $N_1$'s information for node searching (i.e., ER, friends and preferred sub-areas) from the anchor of $A_1$ since $N_1$ has a high probability of staying in $A_1$. Using this information, the locator can find $N_1$.

*2) Relation Graph Based Search Area Determination:* Searching the most preferred location of the target's friend is based on the assumption that the locator can learn the most preferred locations of the target's friends from the anchor or information exchange. However, the locator may not learn the information of the target's friends. In this case, as long as the locator can approach these possible locations, its probability of finding the target increases. Since nodes report the information to anchors, the locator may be able to find the information of the target's friend or even the information of the target by searching the most preferred location of the friend of the target's friend. To generalize this approach, for the nodes known by an anchor, considering their closenesses (i.e., meeting probability) to the target helps the locator determine which node's information is the most useful in helping the locator approach the target.

For example, $N_i$ and $N_j$ have some mutual friends. Suppose a locator wants to find $N_j$, but it cannot proceed the node searching because it does not know the ERs of $N_j$ or its friends, or the preferred locations of $N_j$ or its friends. However, by searching the most preferred location of $N_i$ for the information of the mutual friends, the locator can have a high probability of finding $N_j$. Specifically, based on Figure 10 and Figure 11, in $N_i$'s most preferred location, the locator is likely to find the mutual friends or their information (e.g., ER, friends, preferred locations). Since $N_j$ also frequently meets with the mutual friends in their most preferred sub-areas, the locator is likely to find $N_j$ or its information on the way approaching the preferred locations of the mutual friends.

To realize this method, each anchor builds a relation graph (as shown in Figure 12) that connects all nodes known by itself. In the relation graph, each vertex represents a node

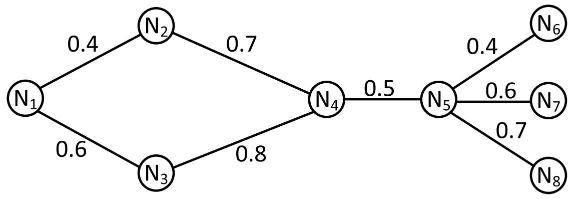


Fig. 12. Relation graph of nodes.

TABLE IV
MOST PREFERRED LOCATIONS OF NODES

| Node | $N_1$ | $N_2$ | $N_3$ | $N_4$ |
|---|---|---|---|---|
| Preferred location | $A_5$ | $A_2$ | $A_1$ | $A_9$ |
| Visiting prob. | 0.3 | 0.5 | 0.7 | 0.6 |

(e.g., $N_1, \ldots, N_8$). Each link in the relation graph is associated with a weight, which is the meeting probability of the two connected nodes. Each path connecting two nodes consists of several links. The weight of a path is calculated as the product of the weights of its composing links. The relation closeness between a pair of nodes equals to the maximum weight among the weights of the paths connecting them.

From the relation graph, the locator firstly determines each node's relation closeness to the target and ranks the nodes by their closeness. Secondly, the locator learns the information of the nodes whose closeness to the target is higher than a threshold. Then, the locator can deduce a collection of nodes that are close to the target. Next, for nodes in the collection, the locator multiplies the relation closeness of each node by the node's visiting probability on its most preferred location to be the node's weight. Finally, the locator chooses the most preferred location of the node with the highest weight to be the next destination.

Figure 12 shows an example of relation graph formed by an anchor. Table IV shows the most preferred locations of nodes known by the anchor. Suppose the locator presently stays in $A_5$, which is the most preferred location of $N_1$, and its target node is $N_6$. However, the anchor only knows the most preferred locations of the nodes shown in Table IV. According to Figure 12, the ranking of the nodes' closeness to the target is: $N_4(0.2) > N_3(0.16) > N_2(0.14) > N_1(0.096)$. Suppose the closeness threshold is 0.1. Thus the most preferred locations of $N_4$, $N_3$ and $N_2$, namely $A_9$, $A_1$ and $A_2$, are candidate destinations. According to Table IV, the weights of these locations are $A_9(0.12) > A_1(0.112) > A_2(0.07)$. Finally, the locator chooses $A_9$ as the next search destination.

## *C. Target-Oriented Node Searching*

The priority to use the three types of information is ordered by ERs, friends' ERs and preferred locations. If above information is unavailable, the additional information is used. The information is collected and disseminated by anchors. A DTN can also choose to piggyback ERs on packets exchanged between neighbors to expedite the information dissemination if it can afford this additional transmission overhead. We will introduce the details for the information dissemination in Section IV-D. In TSearch, if a locator does not have the higher-priority information, it uses the lower-priority information. Specifically, when a locator searches a target, if it has the ER of the target, it moves towards the location in the ER. During the movement, if the locator receives a newer ER (with a more recent time), it moves towards the new location in the ER. In the absence of an ER in searching, the locator finds the ER of the target's friend with the highest meeting probability with the target, and then moves towards the location in this ER. If the ERs of the target's friends are not available, the locator moves towards the nearest preferred location of the target. In order not to miss other frequently visited places of the target, we propose an agent-based simultaneous searching scheme, in which the locator requests a certain number of nodes sharing these preferred locations to search the target simultaneously. For situations that the locator does not have direct information of the target, it uses the additional information maintained by anchors to help determine where to search for the target. In the absence of all the information, the locator searches in the coverage area of the target. In the following, we present the details of each step of the node searching process.

*1) Node Searching Based on ERs:* If a locator has or can access the ER of its target, it directly moves to the location in the ER, say $A_i$. The ER may not provide the current location of the target and the target may move to a sub-area near $A_i$. during searching, if the locator receives a newer ER which represents a more recent appearance place of the target, it moves to this new place.

*2) Node Searching Based on Friends' ERs and Preferred Locations:* It is possible that in the disconnected DTN with sparsely distributed nodes, the most recent ERs of the target are not transmitted to the locator or its local anchor in time. In the absence of the target's ER initially or when the locator arrives at the moving destination but cannot find the target, the locator queries the target's friends and their ERs, and the preferred locations of the target from its local anchor. The locator finds the ER of the friend that has the highest meeting probability with the target and moves towards the location in this ER. As the friend has a high probability of meeting the target, the locator has a high probability of finding the target.

In the case that no newer ER of the target or no ERs of the target's friends can be found, the locator can use the target's visiting preference for node searching. Based on our observations in Section III, the locator itself moves to the nearest preferred location of the target, and relies on $M$ number of nodes (as agents) to search the target in top $M$ preferred locations of the target. $M$ is an empirical parameter determined by the node mobility, the network size and etc. For example, as shown in Figure 4(a), $M = 4$ for DART and $M = 3$ for DNET. The selected agents must have high probabilities of meeting the target and of moving to the $M$ preferred locations. These agents then should be the nodes that have these common preferred locations with the target. The locator queries the local anchor for such nodes in the current sub-area. For each of the $M$ top preferred location $A_k$, the locator queries the nodes that have $A_k$ as their preferred locations about the time they will move to $A_k$, and then chooses the node with the earliest time to search the target. If an agent finds the target, it uses a routing algorithm [7]–[13] to send a notification message with the latest ER to the locator. Then, the locator moves to the new destination in the ER.

Within each sub-area, nodes may not be in the transmission ranges of each other. That is, even if an agent arrives at the target's sub-area, it may not find the target quickly. In order to increase the success rate, multiple agents can be sent to each selected preferred location. The overhead of failing to find the target in a sub-area equals $(1 - P)n_a$, where $P$ is the target's probability of visiting the sub-area and $n_a$ is the number of agents for the sub-area. In order to quickly find the target in a sub-area while constraining the searching overhead, for each selected sub-area, the number of agents should be set to a value proportional to the target's visiting probability in the sub-area. That is, if the target has a higher probability of visiting a sub-area, more agents moving to that sub-area are designated and vice versa.

*3) Node Searching Based on Additional Information:* It is possible that only partial information of the target is available in some sub-areas distant to the target. For example, when the locator only knows the friends of the target, but can find neither the ERs of the friends nor the preferred locations of the target, the node searching based on friends' ERs or target's preferred locations cannot be conducted. In this case, the most preferred locations of the nodes close to the target in the relation graph are used as the next searching locations.

Specifically, when a locator enters a sub-area, it firstly accesses the relation graph from the anchor of the sub-area. For all the nodes known by the anchor, the locator ranks the nodes according to their closeness to the target. The locator then identifies a collection of nodes with closeness higher than a pre-defined threshold. For each node in this collection, the locator calculates the weight on the node's most preferred location and chooses the location with the maximum weight as the next searching location. Then, the locator itself moves to this location to search this target. For other candidate locations, the locator requests ambassadors that are moving to the candidate locations to assist the search.

For example, as shown in Figure 12, suppose the closeness threshold is 0.1, the nodes whose closeness to target $N_6$ is larger than this threshold are $N_4(0.2)$, $N_3(0.16)$ and $N_2(0.14)$. According to Table IV, the weights of the nodes' most preferred locations are $A_9(0.12)$, $A_1(0.112)$ and $A_2(0.07)$, respectively. Thus the locator moves to $A_9$ ($N_4$'s most preferred location). The other two assisting ambassadors move to $A_1$ ($N_3$'s most preferred location) and $A_2$ ($N_2$'s most preferred location), respectively. If an ambassador finds the target or its direct information, it uses a routing algorithm [7]–[13] to send the message to the locator. Then, the locator can switch to other searching methods or determine a better search sub-area.

*4) Node Searching in Coverage Area:* Section III finds the coverage area of a target where the target possibly stays currently. In the absence of all types of information for node searching, the locator then searches the target's coverage area rather than randomly searching the nearby sub-areas as in DSearching. If the locator moves around itself in searching, it generates high overhead on the locator. To handle this problem, the locator then uses the agent-based simultaneous searching scheme to search the coverage area.

### *D. Role-Based Information Collection and Dissemination*

Based on the hierarchical structure in previous works [19], [20], we design a role-based information collection and dissemination scheme to enable the information for node searching to be globally accessed.

*1) Role-Based Scheme:* The role-based scheme selects a relatively stable node with high storage and computing capacity in each sub-area to be "anchor", and selects a number of nodes frequently transiting between two sub-areas as their "ambassadors". Anchors are responsible for collecting the ERs, friends and preferred locations of nodes in different sub-areas. When a node moves into a sub-area, it reports its stored ERs, friends and preferred locations to the sub-area's anchor. An anchor only stores the latest ER of each node. Therefore, once a locator moves into a sub-area, it can quickly access the information of its target from the sub-area's anchor.

An ambassador for sub-areas $A_i$ and $A_j$ are responsible for maintaining the consistency of stored information in the anchors of $A_i$ and $A_j$. When the ambassador moves from $A_i$ to $A_j$, it carries the updated and new information (since the last update) in the anchor of $A_i$ to the anchor of $A_j$. The anchor of $A_j$ then adds the information not in its own storage, and updates the latest ERs. The same applies when the ambassador moves from $A_j$ to $A_i$. Once a new encounter event happens in a sub-area, the ambassador will carry the new ER to other sub-areas. Thus, a locator can access the information of nodes in remote sub-areas from the local anchor for node searching. In the absence of the target's ER, the locator can use the preferred locations, and the ERs of the target's friends for node searching.

In a DTN, nodes always need to exchange packets with neighbors to identify their neighbors. For a DTN that can afford the overhead of transmitting a few more packets, nodes can piggyback ERs on the exchanged packets to expedite the information dissemination. Then, a locator can quickly receive the ERs of nodes in nearby sub-areas.

*2) Role-Based Node Selection:* We next introduce how to select the anchors and ambassadors. We use the nodes' probability of staying in a certain sub-area to determine whether they can be the anchors of this sub-area. The staying probability of a node, say $N_i$, at sub-area $A_k$ is defined as $P_{N_i}(A_k) = T_i/T_u$, where $T_i$ is the total time that $N_i$ has stayed in sub-area $A_k$ during a unit time period $T_u$. If $P_{N_i}(A_k)$ is larger than a high threshold, $N_i$ can be the anchor for $A_k$. By exchanging messages, the node with the highest staying probability becomes the anchor of a sub-area, and all other qualified nodes become anchor backups. Before the current anchor moves out of sub-area $(A_k)$, it chooses the anchor backup with the highest $P_{N_i}(A_k)$ as the new anchor, transfers all of its information to the new anchor and notifies the nodes in the sub-area about this new anchor.

The ambassadors for two sub-areas, say $A_i$ and $A_j$, are the nodes that have high frequency of transiting between $A_i$ and $A_j$. A node records the number of transits between two sub-areas during time period $T_u$. If this transit probability is larger than a threshold, this node can be an ambassador between these two sub-areas. Then, it reports to the anchors of the two sub-areas, which choose a number of nodes that have the highest transiting frequencies as the ambassadors.

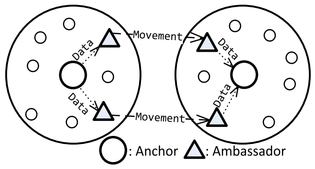


Fig. 13. Information consistency maintenance between sub-areas.

Figure 13 illustrates how information consistency between sub-areas is maintained by the nodes with different roles. The nodes report their stored ERs, their own friends and preferred locations to their local anchors, which maintain the latest ER for each node. When an ambassador for $A_i$ and $A_j$ moves to $A_j$ from $A_i$, it retrieves all the information from the anchor of $A_i$ and sends the information to the anchor of $A_j$. Then, the anchor of $A_j$ updates its information. When the ambassador moves to $A_i$ from $A_j$, the anchor of $A_i$ updates its information. Thus, the information of all nodes is collected and the information consistency is maintained in all sub-areas.

If no node meets the requirement of being an anchor, e.g. all nodes in a community have similarly low staying probabilities, ambassadors or nodes that will transit to other communities will be responsible for collecting and disseminating the information. Specifically, if there's node meeting the requirement of being an ambassador, the node will temporarily fulfill the task of anchors, namely collect the stored ERs, friends and preferred locations of nearby nodes. If even no nodes can play the role of ambassador, e.g. no nodes have frequent transit between two communities, the node that is about to move out of its present community will randomly select $R_m N_c$ nodes and collect their information from their neighbor nodes, where $R_m$ is a ratio constraining the overhead, and $N_c$ is the total number of the neighbor nodes.

## V. Performance Evaluation

We conducted trace-driven experiments based on the DART [16] and DNET [17] traces as introduced in Section III. Unless otherwise specified, the experiment setting is the same as that in Section III. Search rate is defined as the number of locators generated every 24 hours in DART and every 4 hours in DNET and it was set to 40 by default. Since both traces do not provide map information, we assume that the locator needs 10 minutes to move from one sub-area to another neighbor sub-area on average. The expiration TTL for ERs was set to 4 hours and 2 hours in DART and DNET, respectively. The staying probability threshold for determining anchors and the transit probability threshold for determining ambassadors were set to 0.8. The threshold for determining nodes' closeness is 0.2.

We evaluated TSearch in four varieties: TSearch that uses additional information and has ER exchange (*TS**+), TSearch that uses additional information and has no ER exchange (*TS*+), TSearch that doesn't use additional information and has ER exchange (*TS**), TSearch that doesn't use additional information and has no ER exchange (*TS*). The comparison methods are: the *DSearching* distributed node searching method (*DS* in short) [15], and a routing based method (denoted by *Routing*) [25] as explained in Section I. In order to show the effect of ERs in node searching in TSearch, we also evaluated TSearch that only uses ERs without anchors (denoted by *ER*). That is, nodes record the ERs with their encountering nodes and exchange the records. We measured the following metrics in the experiments.

- *Success rate*: The percentage of locators that successfully find their target nodes within searching TTL.
- *Average delay*: The average time (in seconds) used by locators to search for the target nodes. Note that the time spent by unsuccessful locators, which is the searching TTL, is also considered in calculating this metric.
- *Average search length*: The average number of transits between sub-areas that locators move in searching for their target. Note that the transits of unsuccessful locators are also included.
- *Average transmission overhead*: The average number of all packets transmitted among nodes.
- *Average information query*: The average number of information queries received by each node, including the information update caused by encounters. Specifically, the information queries are categorized into request for ER, friend, preferred location and relation graph in TSearch, request for VR, MPT entry in DSearch and request for meeting frequency in Routing.
- *Average node memory usage*: The average number of memory units used by each node. Each piece of information (i.e., VR, MPT entry, ER, friend, preferred location, relation graph) takes one memory unit.
- *Average anchor memory usage*: The average number of memory units used by each anchor or host node. Each piece of information (i.e., VR, MPT entry, ER, friend, preferred location) takes one memory unit.

Since nodes don't share additional information, so additional information creates no transmission overhead. Since nodes just use existing information to generate additional information, so additional information consumes no extra memory. Since locators request additional information along with ER, friends and preferred locations, so additional information won't change the locators' query frequency. Based on above considerations, we only illustrate the improvements of success rate, search delay and search length brought by additional information.

## A. Experiments With Different Search Rates and Search TTLs

We conducted two experiments. In one experiment, we varied the search rate from 20 to 70 with 10 as the step size. In the other experiment, we varied the search TTL from 18 hours to 24 hours in DART and from 2 hours to 7 hours in DNET.

*1) Success Rate:* Figure 14(a) and Figure 15(a) show the success rates of the algorithms under different search rates in DART and DNET, respectively. Figure 16(a) and Figure 17(a) show the success rates under different search TTLs in DART and DNET, respectively. In these figures, we find that in DART, the success rates follow: $TS^{*}+ > TS^{*} \approx TS+ > TS > DS > ER \gg Routing$, while in DNET, the success rates follow: $TS^{*}+ > TS^{*} \approx TS+ \succ TS \succ ER > DS \gg Routing$, where $\approx$ means "approximate", $\succ$ means "slightly higher" and $\gg$ means "significantly higher".

In both traces, *Routing* always produces the lowest success rate. This is because the locators do not move proactively to search the targets, but only adhere to nodes that have the highest probabilities of meeting the targets. Since the nodes in the system have independent mobility patterns, many locators fail to find their targets within TTL. Compared with *Routing*, *DS* and *TS* have remarkably higher success rate. *TS* has higher success rate than *DS* in both traces. Because a locator moves directly to the target's latest location in *TS*, while follows the movement path of the target in *DS*. Also, in *DS*, locators must move to the targets' home-areas first, while in *TS*, the locators search from their current locations. Therefore, *TS* enables locators to search more quickly. Moreover, *TS* relies on multiple agents to search the target in its possible locations, while *DS* only considers the place with the highest visiting probability as the next destination. We also see that *TS** generates a slightly higher success rate than *TS* in both traces, which indicates that ER exchanges can slightly improve success rate. Further, *ER* always generates a higher success rate than *Routing*, which indicates that ERs are effective in guiding node searching.

The success rate shows $DS > ER$ in DART, but shows $ER > DS$ in DNET. DART has much more nodes and sub-areas than DNET. Then, some locators may fail to receive the ERs of their targets in time, leading to lower success rate. This verifies the effectiveness of ERs for node searching in small networks. It also implies the necessity of anchors to facilitate the global information dissemination, especially in a large network area. We see that *TS** always achieves higher success rate than *ER*, which indicates the effectiveness of the anchors, friends and preferred locations. The similar success rates of *TS** in both traces reflect that the number of sub-areas is not the constraint due to the relatively fast dissemination of ERs. Additionally, we find that except for *TS*+*, *TS**, *TS+* and *TS*, the other three algorithms exhibit obvious improvement in success rate as TTL increases. This verifies the performance of *TS*+*, *TS**, *TS+* and *TS* under small TTL.

With the help of additional information, *TS*+* and *TS+* always have higher success rate than *TS** and *TS*, respectively. This shows the benefit of additional information for node searching. On the way to the most preferred locations of the target's friends, the target or its information is often found.

*2) Average Delay:* Figure 14(b) and Figure 15(b) show the average delay for node searching in the algorithms under different search rates in DART and DNET, respectively. Figure 16(b) and Figure 17(b) show the average delay under different search TTLs in DART and DNET, respectively. We find that the average delays follow: $TS^{*}+ < TS^{*} \approx TS+ < DS \approx TS < ER \ll Routing$ in DART, while it follows $TS^{*}+ < TS+ \prec TS^{*} \prec ER < TS < DS \ll Routing$ in DNET, where $\prec$ means "slightly smaller" and $\ll$ means "significantly smaller". The results are caused by the same reasons explained previously. Higher success rate means more node searches are successful during TTL. Recall we used TTL as delay for failed searches. Thus, the methods with higher success rates

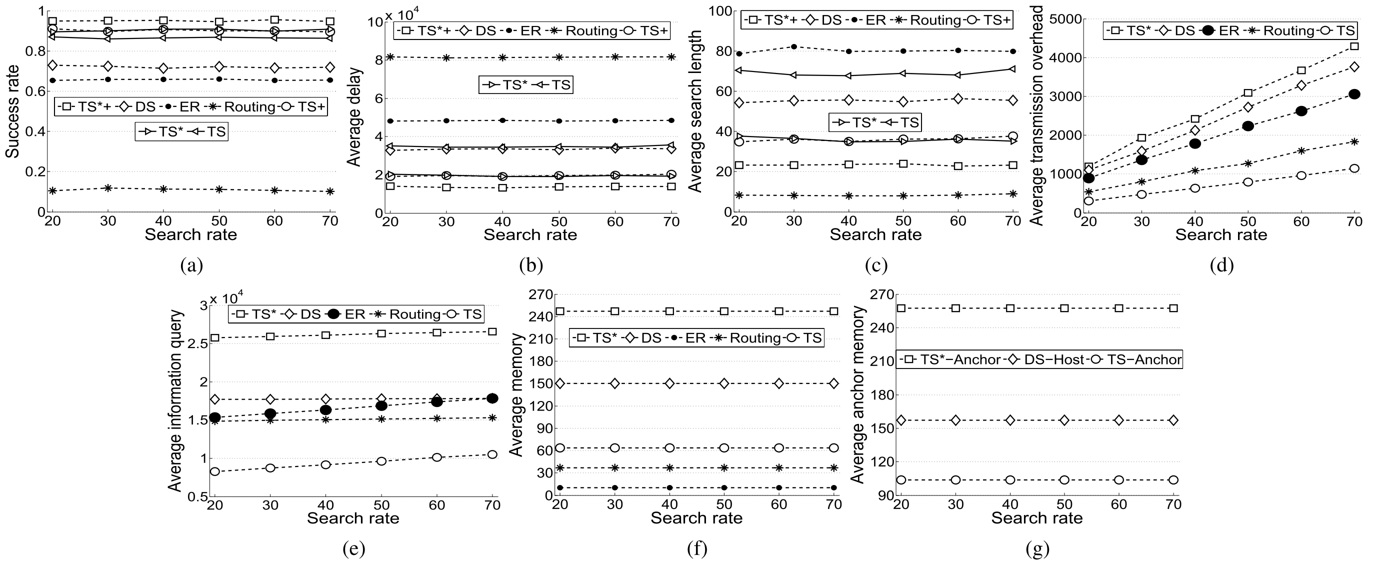


Fig. 14. Performance with different search rates using the DART trace. (a) Success rate. (b) Average delay. (c) Average search length. (d) Average transmission overhead. (e) Average information query. (f) Average node memory usage. (g) Average anchor memory usage.

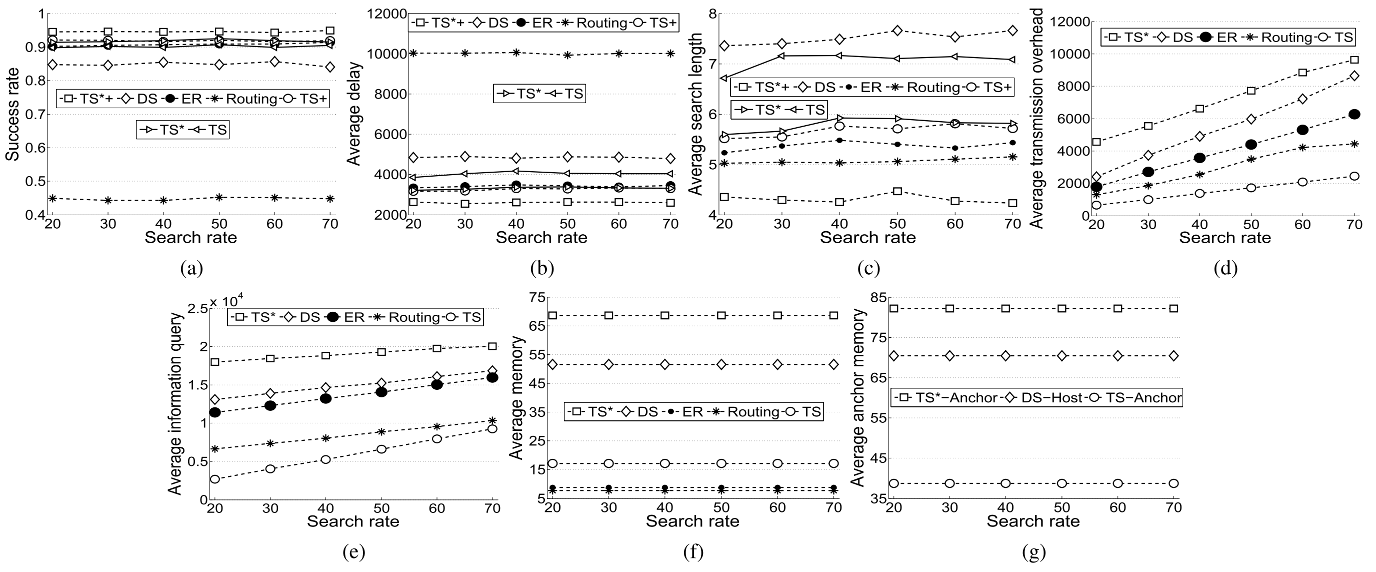


Fig. 15. Performance with different search rates using the DNET trace. (a) Success rate. (b) Average delay. (c) Average search length. (d) Average transmission overhead. (e) Average information query. (f) Average node memory usage. (g) Average anchor memory usage.

produce low searching delay while the methods with lower success rates produce higher searching delay. *TS** generates a lower average delay than *TS* because locators may not need to query ERs from anchors. *TS*+* and *TS+* have lower average delay than *TS** and *TS*, respectively. This is because additional information helps the locator save much time in finding the target and its direct information. On average, *TS** reduces the average delay of *TS* by 30% and 5900 seconds (1.64 hours) in DART, and by 20% and 651 seconds (11 minutes) in DNET. *TS*+* further reduces the average delay of *TS** by 29% and 5869 (1.63 hours) seconds in DART, and by 21% and 708 seconds (12 minutes) in DNET. The results indicate the high efficiency of TSearch in terms of searching delay, and the effectiveness of additional information.

*3) Average Search Length:* Figure 14(c) and Figure 15(c) show the average search lengths of the algorithms under different search rates in DART and DNET, respectively. Figure 16(c) and Figure 17(c) show the average search lengths of the algorithms under different search TTLs in DART and DNET, respectively. From these figures, we can see that the average search lengths follow: *Routing<TS*+<TS+<TS*<DS<TS<ER* in DART, while generally follow: *TS*+<Routing<ER<TS+<TS*<TS<DS* in DNET.

We can see that the search lengths of *TS*+*, *TS+*, *TS**, *TS*, *DS* and *ER* are positively correlated with their delays. This is because the locators in these algorithms are always moving to search their targets. Therefore, their search delay

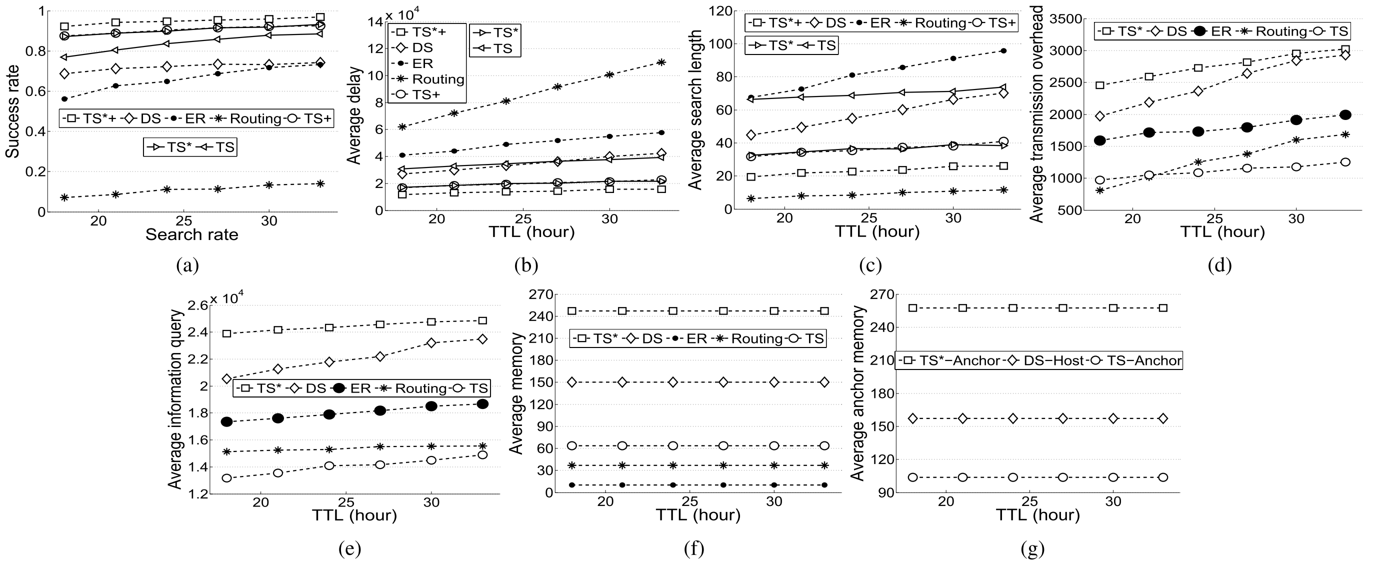


Fig. 16. Performance with different locator TTLs using the DART trace. (a) Success rate. (b) Average delay. (c) Average search length. (d) Average transmission overhead. (e) Average information query. (f) Average node memory usage. (g) Average anchor memory usage.

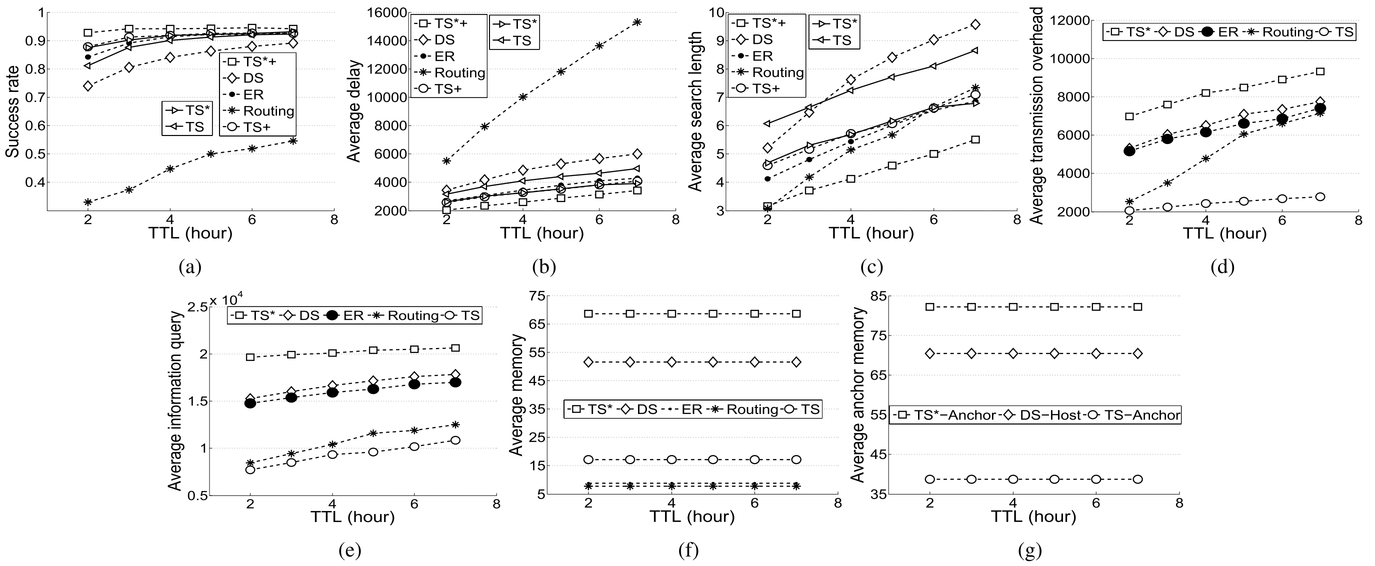


Fig. 17. Performance with different locator TTLs using the DNET trace. (a) Success rate. (b) Average delay. (c) Average search length. (d) Average transmission overhead. (e) Average information query. (f) Average node memory usage. (g) Average anchor memory usage.

is determined by how far they transit. However, the delay of *Routing* is very high but the search length of *Routing* is the lowest or medium. This is because the locators in *Routing* cannot proactively move towards the targets but attach to nodes. Moreover, meeting frequency cannot tell locators the most suitable attaching nodes. Therefore, the locators in *Routing* don't transit much but wait on a few nodes.

*4) Average Transmission Overhead:* Figure 14(d) and Figure 15(d) show the average transmission overhead of the algorithms under different search rates in DART and DNET, respectively. Figure 16(d) and Figure 17(d) show the average transmission overhead of the algorithms under different search TTLs in DART and DNET, respectively. We find that the result follows: *TS<Routing<ER<DS<TS**. *TS* has the least transmission overhead because nodes only need to report ERs to and request ERs from anchors without packet exchange between nodes. Nodes only report their friends and preferred locations once to anchors. Each ambassador carries the information in an anchor only when it moves to another sub-area. *Routing* and *ER* produce higher transmission overheads than *TS* because they require packet exchange between nodes upon entering. In *Routing*, a node keeps its meeting probabilities with other nodes and exchanges this information with its neighbors. In *ER*, a node keeps the ERs, which may or may not involve itself. Therefore, *Routing* produces lower transmission overhead than *ER*. In *DS*, each node tells several neighbors in its current sub-area its transient VR before moving. The node also distributes its MPT from a sub-area to long-staying nodes in this sub-area. Each node's home-area information is stored in all sub-areas. As nodes move around, they transmit many

transient VRs. Therefore, *DS* requires nodes to distribute MPT to host nodes of each sub-area, and the locators access the MPT from the host nodes. The more nodes contact with each other, the larger the average transmission overhead will be. *TS** has the transmission overheads of both *TS* and *ER*, thus nodes exchange ERs upon encountering and also report their ERs, friends and preferred locations to the anchors once. Therefore, it produces the maximum transmission overhead among the algorithms. We also see that the average transmission overhead of each algorithm increases as the TTL increases because more packet transmissions occur during a longer time period. On average, *TS* reduces the average transmission overhead of *TS** by 74% and 2047 packets in DART, and by 78% and 5603 packets in DNET. ER exchanges enable nodes to receive ERs more quickly for faster node searching. Recall that *TS** reduces the average delay of *TS* by 20%-30%. Then, TSearch can activate or inactivate the ER exchange function based on applications. Also, nodes can choose to use ER exchanges based on their individual desires.

*5) Average Information Query:* Figure 14(e) and Figure 15(e) show the average number of information queries of the algorithms under different search rates in DART and DNET, respectively. Figure 16(e) and Figure 17(e) show the average number of information queries of the algorithms under different search TTLs in DART and DNET, respectively. We see that in both traces, the average number of information queries generally follow: *TS*<*Routing*<*ER*<*DS*<*TS**. From the figures, we can find that the average number of information query increases along with the increment of search rate.

In *TS**, every encounter among nodes will create at least one information query. Besides, the anchors and ambassadors will request ERs, friends and preferred sub-areas from the nearby nodes. Since there may be several ambassadors in one sub-area, they may request repeated information from anchor nodes. Therefore, *TS** achieves the highest number of information queries.

In *DS*, each node leaves its transient VR to neighbors before moving out of a sub-area. Meanwhile, nodes report their MPT entries to long-staying nodes in the sub-area, namely host nodes. Compared with *TS**, the occasion of information query is much lower. But once nodes move in or out of sub-areas, information query is possible, rendering *DS* the second highest information query.

In *ER*, each node only needs to record, exchange and report ERs. The number of information query is determined by the encounter among nodes. Therefore, it ranks the third.

In *Routing* and *TS*, each node only records its meeting frequency or ER with other nodes. Therefore, they achieve much less information query than the other algorithms. Since nodes in *Routing* need to find the nodes with the maximum meeting frequency with the target, while nodes in *TS* only checks whether the nodes have the ER of the target, *Routing* has more information query than *TS*.

*6) Average Node Memory Usage:* Figure 14(f) and Figure 15(f) show the average node memory usage of the algorithms under different search rates in DART and DNET, respectively. Figure 16(f) and Figure 17(f) show the average node memory usage of the algorithms under different search

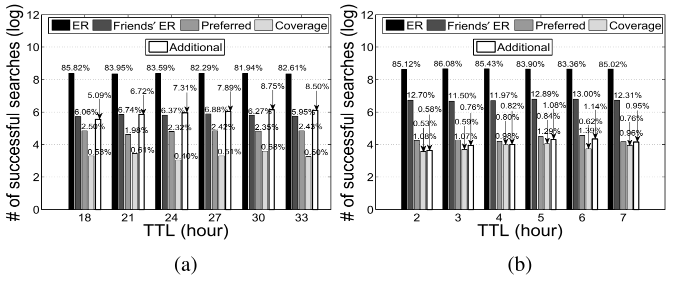
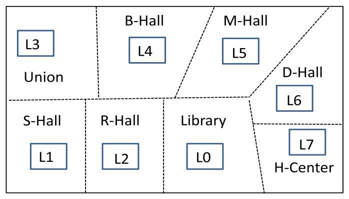


Fig. 18. Breakdown of success rate in different search stages (log). (a) DART. (b) DNET.



(a)

| Item | Value |
|---|---|
| # Sub-areas | 8 |
| # Nodes | 9 |
| # Transits | 147 |
| Duration | 4 days |

(b)

Fig. 19. Configuration in the real environment. (a) Maps for sub-area division. (b) Statistical data.

TTLs in DART and DNET, respectively. We see that the average memory usage follows: *ER*<*Routing*<*TS*<*DS*<*TS** in DART and *ER*≈*Routing*<*TS*<*DS*<*TS** in DNET.

In *ER*, each node stores its received ERs of node pairs and deletes ERs after TTL. In *Routing*, each node stores its meeting probabilities with all other nodes. Therefore, the average memory usage of *ER* is less than *Routing* in DART. DNET has a small network and much fewer sub-areas, which enables a node to meet more nodes and also receive the ERs of most of other nodes. Thus, the average memory usage of *ER* is close to *Routing* in DNET.

In *TS* and *TS**, normal nodes maintain their own ERs, and friend and preferred location lists, and anchors store such information from nodes. In *TS**, nodes additionally need to exchange ERs. Thus, their average memory usage is higher than *ER* and *Routing*. In *DS*, each node needs to store its home-area and its MPT, which records its frequently visited locations and the next locations with visiting probabilities for each frequently visited location. The hosts in each sub-area need to store the home-area of each node, the transient VRs and MPT entries of some nodes. In *TS**, each node records and exchanges the ERs of other nodes, and its own friends and preferred locations. Also, the anchors need to store their received ERs, friends and preferred locations. Since the MPT and VRs are collected and stored in hosts but ERs are generated upon encountering and shared among nodes in *TS**, the memory usage of *TS** is larger than *DS*. The average memory usage of hosts and anchors follows: *TS**>*DS*>*TS* in both traces. *TS**>*DS* is because that one sub-area has several hosts but one anchor, and the information is distributed to hosts in different sub-areas but each anchor needs to store global information of all nodes. In *TS**, due to ER exchange between nodes, anchors can more quickly receive ERs of far-away nodes. In *TS*, an anchor can only quickly receive ERs from the nodes in its sub-area but may not quickly receive

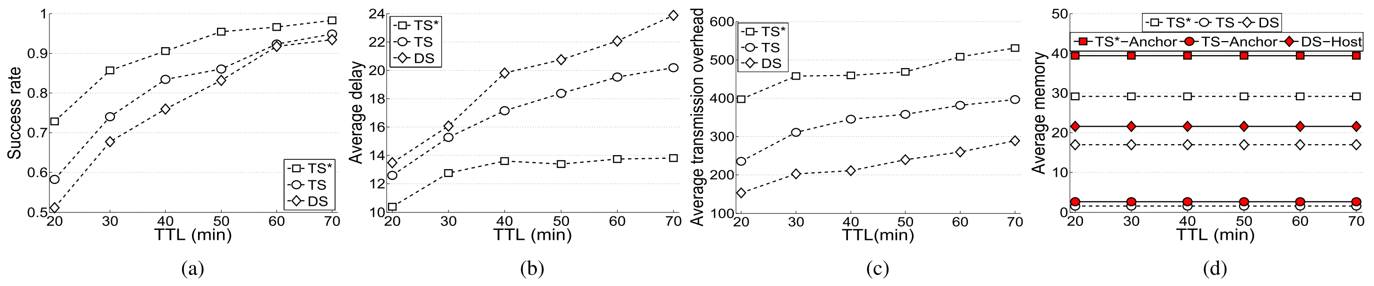


Fig. 20. Performance with different TTLs using real environment data. (a) Success rate. (b) Average delay. (c) Average transmission overhead. (d) Average node memory usage.

the ERs of nodes in other sub-areas, which are carried by ambassadors. Therefore, anchors in *TS** have higher memory than in *TS*.

We use an example to illustrate the memory usage of *TS**. We find the peak number of information entries stored on each node is about 210 and 50 in DART and DNET, respectively. Each memory unit takes about 40 bytes. This means the actual average memory usage on each node is only about 8.4KB and 2KB in the two tests. Based on the average node memory usage and average anchor/host memory usage, we can conclude that *TS** is applicable on modern mobile devices.

*7) Average Anchor Memory Usage:* Figure 14(g) and Figure 15(g) show the average anchor memory usages of the algorithms under different search rates in DART and DNET, respectively. Figure 16(g) and Figure 17(g) show the average anchor memory usages of the algorithms under different search TTLs in DART and DNET, respectively. We see that the average anchor memory usages follow: *TS-Anchor*$<$*DS-Host*$\ll$*TS*-Anchor* in DART, while *TS-Anchor*$\ll$*DS-Host*$<$*TS*-Anchor* and DNET.

In *TS**, anchors can accumulate more global mobility information from other nodes. In *DS*, the host nodes need to store the home-area of other nodes, along with the transient VRs and MPT entries of some nodes. However, there're several host nodes in one sub-area of *DS* but only one anchor in the sub-area of *TS**. Therefore, anchors in *TS** use more average memory than host nodes in *DS*.

In *TS*, since nodes have no exchange, anchor may not quickly collect the ERs of nodes in other sub-areas, which are carried by ambassadors. Moreover, anchors generally stay in their home-area for a long time, leading to limited meeting of nodes. Therefore, anchors in *TS* utilize less memory than the host nodes in *DS*.

*8) Contribution of Different Stages in TSearch:* To better illustrate the respective contribution of different search methods on success rate, we break down the total success rate into 5 stages by using different information in node searching: ERs, friends' ERs, preferred locations, coverage area and additional information. Figure 18 shows the ratio of contribution in log format. We see that most of the successful searches are achieved by following the target's ERs. The ERs of the target's friends have the second highest contribution. The target's preferred location offers complementary contribution to success rate. Searching the coverage area contributes the least, which means this searching stage not launched in most cases. Note that additional information helps in enabling the locator to get the trace of its target. Once the locator finds the target or obtains the information of the target (e.g., ER, friends, preferred locations) by following additional information, we consider this as the contribution from additional information. Results show that additional information is effective in helping locators find the target or its information in node searching. Additional information contributes relatively more in DART than that in DNET, this is because DART has more ambassadors and anchors for each sub-area, the locator in DART is more likely to encounter the target or its information by following additional information.

### *B. Experiment in Real Environment*

To test *TSearch*'s performance in real environment, we deployed *TSearch* on our campus and collected the mobility information of 9 students from 4 departments in our university. We selected 8 buildings frequently visited by the 9 students as the sub-areas. Based on the GPS on mobile phones, each node can determine its location. Compared with the previous two traces, the distance hence the node movement latency between two sub-areas is more accurate in this real-world test. The distribution of sub-areas and the summary of the data are shown in Figure 19(a) and 19(b). Since different search TTLs influence the results of different performance metrics, we varied the search TTL from 20 minutes to 70 minutes and set the search rate to 40. According to our campus map, a locator usually takes about 5 minutes to move from one sub-area to a neighboring sub-area.

The test results for different metrics for *TS**, *TS* and *DS* are shown in Figure 20. The orders of the results between the three algorithms are the same as those in the previous experiments due to the same reasons. When the search TTL increases, the success rate, average delay and average transmission overhead increase. When the TTL increases, more locators can find their targets after a longer delay, and along with higher transmission overhead. We also see that when the TTL was set to 70 minutes, a successful locator takes only about 14 minutes to find the target node on average. Further, each node only needs 7 units of memory on average to support node searching. In conclusion, *TSearch* is effective and efficient in searching nodes.

## VI. Conclusion

Previous node searching method in DTNs cannot achieve low searching delay by tracing a target along its movement path and also cannot guarantee high success rate by targeting the most frequently visited place (i.e., preferred locations) of the target. Our real trace data analysis confirms these drawbacks and also provides foundations for the design of our proposed TSearch node searching method. Rather than tracing along target's moving trail, TSearch aims to enable a locator to directly move towards the target by leveraging social network properties. It enables a locator to always move to the target's latest appearance place known by itself, the latest appearance place of the target's most frequently meeting node, or the preferred locations of the target. Then, the locator can find the target in its movement or destination. Also, to increase the searching success rate, the locator itself moves to the nearest preferred location of the target and asks a limited number of nodes that share other common preferred locations with the target to assist node searching. Even if the locator has no direct information of its target, it can use the additional information maintained by anchor for node searching. Extensive trace-driven and real-world experiments show that TSearch has much higher efficiency and effectiveness in node searching compared with previous methods. In our future work, we plan to further exploit nodes' social network properties to reduce node searching delay and overhead.

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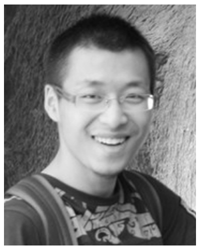

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