ROUTING IN POCKET SWITCHED NETWORKS

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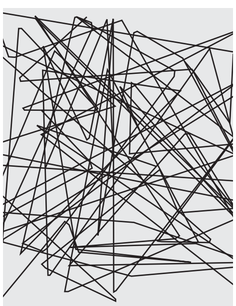

Pocket switched networks provide a new networking paradigm that takes advantage of human mobility to distribute data. Due to the frequent and long-duration disruptions of network links, routing in PSNs is nontrivial.

ABSTRACT

Pocket switched networks (PSNs) provide a new networking paradigm that takes advantage of human mobility to distribute data. Due to the frequent and long-duration disruptions of network links, routing in PSNs is nontrivial. In this article, we first outline the challenges of PSN routing. After that, we summarize the behavioral traits of human beings employed by existing PSN routing schemes and give a brief survey on the state-of-the-art PSN routing techniques. Finally, we analyze the characteristics of existing PSN routing protocols and present some open problems that may foster future research on PSN routing.

INTRODUCTION

Opportunistic networking via pocket switched networks (PSNs) is a new mobile computing paradigm that takes advantage of human mobility to provide occasional communication opportunities among mobile devices for disseminating data. As PSNs do not require the assistance of infrastructures, they are applicable in rural and developing regions to realize low cost communications or to connect the islands of various IP-centric networks when infrastructures fail due to nature disasters or other failures. In addition, PSNs can be exploited as an efficient communication mechanism to complement infrastructure-based wireless networks because they usually have limited coverage.

PSN falls into the category of delay-/disruption-tolerant networks (DTNs). These two types of networks mainly differ in their information carriers as the former employs human beings for data forwarding, while the latter can utilize any possible carrier, including human beings, to disseminate data. Although human mobility brings occasional communication opportunities, it also brings frequent long-duration disruptions for network links, which makes routing a challenge in PSNs. Accordingly, the routing objective of PSNs is quite different from that of wired networks or mobile ad hoc networks (MANETs).

In wired networks, end-to-end paths always exist, and the objective of routing is to find the shortest path or path(s) satisfying some quality of service (QoS) constraints. On theother hand, while links in a MANET may be broken from time to time, the disruption duration is usually short. Hence, end-to end paths may exist with a probability near one in MANETs. Thus, the routing objective for a MANET is to find the best available path. In PSNs, network links may be disrupted for a long time; therefore, end-to-end paths are assumed not to exist. In such a network, *store-carry-forward* is the main mechanism for data delivery, and the routing objective is to maximize the delivery ratio.

Routing is a key issue in a PSN. In this article, we summarize the state-of-the-art research and discuss several related issues on PSN routing. The rest of the article is organized as follows. The next section identifies the challenges of PSN routing, followed by a summary of the characteristics of human behaviors exploited by current PSN routing schemes to enhance the routing efficiency. After that, the state-of-theart PSN routing techniques are overviewed and their cons and pros are analyzed based on three categories: encounterbased, social-based, and location-based. At last, we present the open research issues that might foster future research on PSN routing.

CHALLENGES OF PSN ROUTING

PSNs are formed by human beings. The human behaviors, including their mobility and sociality, bring challenges to PSN routing. Generally speaking, there mainly exist five major challenges:

CHALLENGE 1: SCALABILITY

A PSN is featured by the very limited wireless spectrum and onboard resources (storage, computation capability, battery power, etc.), as well as the rapidly growing number of portable devices and amount of transmitted data. Therefore, PSN routing must be scalable in a sense

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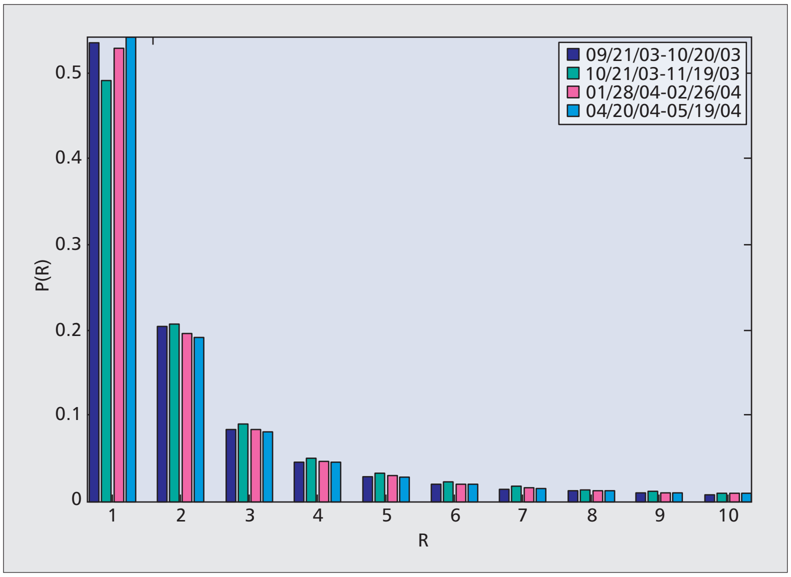

Figure 1. *A Zipf plot showing the average probabilities of all nodes visiting their corresponding 10 most frequently visited APs in four one-month periods [2].*

that the volume of the routing information stored at each node and exchanged among the nodes should not increase rapidly with the increasing number of nodes in the network.

Challenge 2: Selfish Nodes

In the real world, human beings are selfish in nature. As a result, people may not be willing to forward data for others except their acquaintances. A selfish node may not forward data for anybody. In such a case, incentive mechanisms should be employed to encourage nodes to forward data for others and to prevent or punish selfish behaviors.

Challenge 3: Security

The efficiency and effectiveness of PSN routing usually relies on the cooperation among multiple nodes, which requires them to constantly collect or exchange relevant information. On one hand, a node may face the privacy exposure problem. In many cases, the node might need to tell others some information to show its capacity of being a relay. For example, a node might need to tell its neighbors which person it has met, how long their contact usually lasts, how often it meets the same person, and how many times it visits each region. Such information somewhat exposes the privacy of the node. On the other hand, the human behaviors exploited for PSN routing (outlined later) make launching typical security attacks a much easy job. A message may be altered or forged by a malicious relay, or eavesdropped by attackers. The identity of a legitimate node may be spoofed, leading to symbol or clone attacks. Greedy nodes may inject a large volume of data, resulting in denial of service attacks. The routing information may be distorted such that legitimate nodes can be successfully fooled to believe that an attacker has a high chance of delivering their data to the destinations, causing sinkhole or loophole attacks. Nevertheless, human mobility and sociality make the detection of the attackers a very challenging problem. Therefore, typical security services such as confidentiality, authentication, authorization, and data integrity all need to be carefully addressed for PSN routing.

Challenge 4: Emergency Routing

One killer PSN application is to provide emergency communications when infrastructures fail due to natural disasters such as earthquakes and conflagration. In such a scenario, useful prior knowledge is hardly available for routing decisions as human behaviors deviate significantly from their normal conditions, leaving flooding the only effective policy in some cases. However, flooding leads to the broadcast storm problem, which wastes network resources and results in a high collision probability and a low network throughput. Thus flooding does not scale well. Therefore restricted flooding or adaptive routing algorithms should be sought for effective PSN routing in emergency applications.

Challenge 5: Multicasting

Multicast in a PSN is challenging because the time at which the multicast group membership changes can not be ignored compared to the long data delivery latency. In PSNs, a nodemay leave or join a multicast group when a data is in transit, causing the node to receive a data that it does not want, or fail to receive the data it should get. Hence, traditional multicast mechanisms proposed for the Internet or MANET, which first determine the multicast group membership and then transfer the data, may not be applicable. Thus novel research is needed to address such problems in PSN routing.

In fact, human behavior is a double-edged sword, which brings not only the above challenges but also chances to enhance the efficiency of PSN routing. In the next section, we summarize typical human mobility and sociality characteristics exploited by the current PSN routing mechanisms.

Characteristics of Human Behaviors Exploited in PSN Routing

In this section, the five most exploited characteristics of human behaviors by the current PSN routing mechanisms are summarized.

Human Beings Usually Visit One or a Few Place(s)

Each node has a significant probability of returning to one or a few highly frequently visited places. We use the mobility trace data [1] from Dartmouth College's wireless local area network (WLAN) to explain this phenomenon. The trace records when each node connects to or disconnects from which access point (AP) in Dartmouth College. This trace data is very useful for analyzing human mobility patterns because it has a sufficient number of observed targets (about 13888 mobile nodes and 602 APs) over a sufficiently long observation duration (from 2001 to 2004).

We count the probabilities that each node visits its first, second, …, and 10th most frequently visited APs in four onemonth periods of 2003 and 2004. These four months are selected because their records are integral and the behaviors of the students are regular (no vacations). There are about 5346~6052 mobile nodes roaming among 532~543 APs at each month. Figure 1 [2] illustrates the average probabilities of all nodes visiting their own top-ten most frequently visited APs. The *X* label (*R*) is the rank of the APs listed in the order of decreasing visiting frequencies, and the *Y* label is the probability of *R*. From Fig. 1, we observe that the nodes visit their first two preferred APs at a probability over 70 percent. Thus we conclude that human beings usually visit one or a few place(s).

Because of the high probability that a node comes back to the places where it usually visits, with a high frequency the node can successfully relay the data for a destination that resides in one of these places. If a routing scheme selects such nodes as relays, it can achieve a high delivery ratio.

Human Mobility Exhibits Spatial Locality

People usually move within a local region. To reveal this characteristic, we employ the Dartmouth College trace data again and consider the same four one-month periods. The most frequently visited AP is designated as the center place of a node, and the probability of the node's displacement (Δr) from its center is computed. Figure 2 illustrates the probability density function ($P(\Delta r)$) of the average displacement. We found that $P(\Delta r)$ can be approximated by

$$P(\Delta r) = \alpha \cdot (\Delta r + \Delta r_0)^{-(1+\beta)} \quad (1)$$

with $\alpha = 0.3667 \pm 0.0402$, $\Delta r_0 = 57.1875 \pm 13.7978$, and $\beta = 0.2043 \pm 0.0343$. According to Fig. 2, when the displacement increases, the corresponding probability decreases sharply, demonstrating that human mobility exhibits a spacial locality.

Because human mobility exhibits spatial locality, if one of the places where a node frequently visits is close to the place where the destination resides, the node can relay the data for the destination with a high probability. Hence, a routing scheme selecting such nodes as relays can achieve a high delivery ratio.

Human Mobility Activities are Heterogeneous

Some nodes may visit many places within a short duration while some others may stay at a place for a long time. We employ the same subset of the Dartmouth College trace data to illustrate this characteristic. Figure 3 plots how many nodes visit how many different APs in the four one-month periods. From Fig. 3, we obtain the following observations: most nodes (about 52 percent~58 percent) visit less than 10 APs; about 20 percent of the nodes visit 10~20 APs; in average 136 nodes (about 2 percent~3 percent) visit 40~50 APs; some nodes visit more than 80 APs; and one or a few nodes even visit more than 200 APs.

Different mobility activities result in different chances of contacting other nodes. Figure 4 indicates that with the increase of the mobility activities, which is characterized by the number of different APs visited within a 30-day period, the average number of nodes one may contact rapidly increases. Let x represent the number of different APs visited by a node and $f(x)$ be the average number of nodes it meets, then the relationship between x and $f(x)$ can be approximated by:

$$f(x) = a \ln(x) + be^{cx} \quad (2)$$

where a takes the value of 85.91, 95.62, 94.67 or 96.5, b takes the value of 0.333, 0.3149, 0.3422 or 0.3989, and c takes the value of 0.05 0.04518, 0.03974 or 0.04474 for the four onemonth data sets, respectively.

Due to the heterogeneous mobility of nodes, a routing scheme selects the nodes with high mobility activity can achieve a high delivery ratio because such nodes have high chances to contact with others, and thus the probability that it meets the destination or meets a better relay is high.

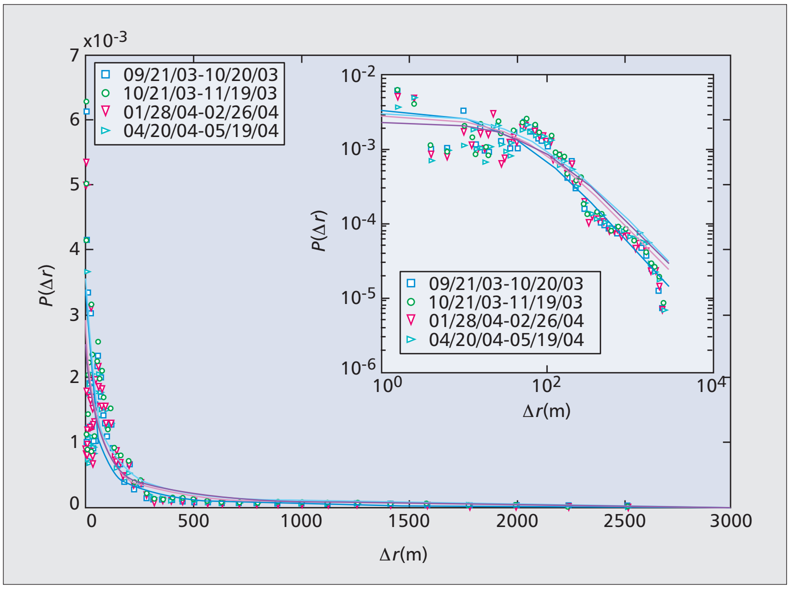

Figure 2. *The probability density function of the average displacement for all nodes over the four one-month periods. The axes graph is the logarithmic plot for clear illustration.*

Sociality

A PSN is formed by people. The social relationships among human beings exhibit the small world phenomenon, which comes from the observation that individuals are often linked by a short chain of acquaintances.

In a society, people with similar interests or having social bonds such as friends, colleagues, and family members often contact each other more frequently than others. These people form a community or a cluster. Within each community, some people may be more popular than others. Taking advantage of these social characteristics, some PSN routing schemes can make better forwarding decisions. Such kind of research usually focuses on how to detect a community and how to determine the popularity of a node. The relays are selected according to their popularity and whether they are belonging to the same community with the destination node.

Human Mobility Has the Levy-Walk Nature

Many simulation and theoretical studies of PSN routing adopt the Random WayPoint (RWP) or the Random Direction (RD) as human mobility models. These two models vary in their movement characteristics.

As shown in Fig. 5a, in RWP model, a node randomly chooses a point in the network and moves toward that point with a random speed. Once arriving at the point, it pauses for a random time and repeats the above process. This indicates that in RWP model, each node moves

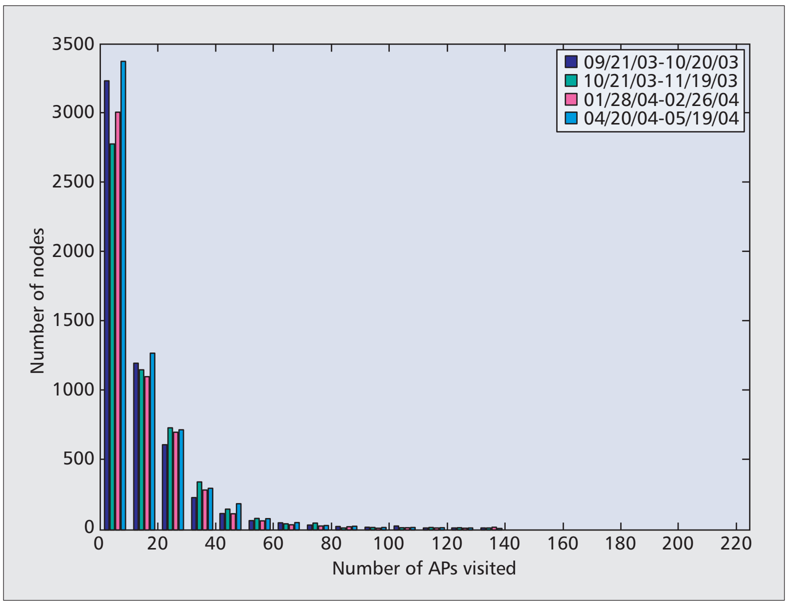

Figure 3. *Heterogeneous mobility activities.*

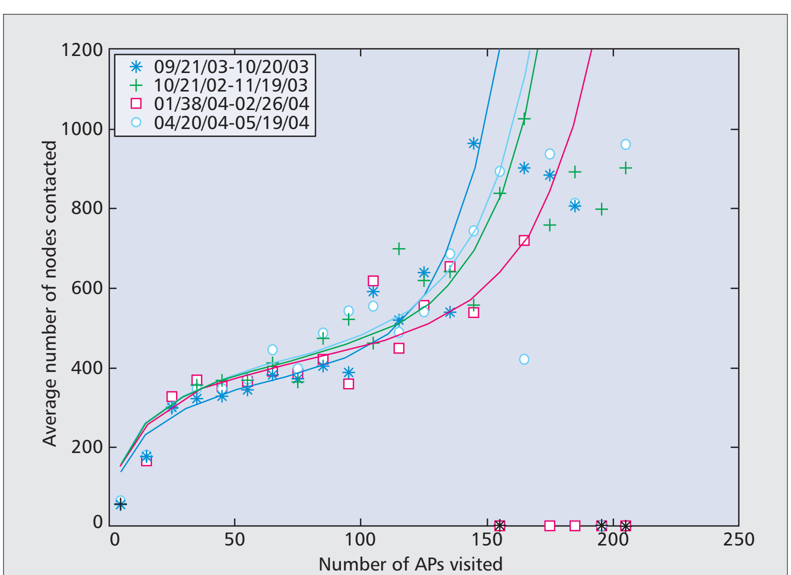

Figure 4. *The impact of mobility activities on the chance of meeting with other nodes.*

along a zigzag line from one point to another. As shown in Fig. 5b, in the RD model, a node randomly selects a starting direction to walk. Once it reaches the network boundary, the node pauses for a random time and then continues the above process.

The popularity of these two mobility models results from their simplicity. However, recent empirical studies [3], [4] indicate that human mobility accords with the more suitable Levy-Walk (LW) model. As shown in Fig. 5(c), Levy walks consist of a large number of short flights and a small number of exceptionally long flights, and the long flights eliminate the distance effect of the short ones. A flight refers to the longest straight line from one location to another that a node walks without a directional change or pause.

The main difference of LW from RWP and RD lies in that the distribution of the inter-contact duration, which is defined to be the time interval separating two contacts between the same pair of nodes. The distribution of the inter-contact duration follows an exponential distribution in RWP and RD while that in LW has a power law tendency. The inter-contact duration is key to the performance of PSN routing. Since the LW model is easy to control the level of diffusivity using the power law exponent, it is a very useful tool to describe a variety of data delivery natures in PSNs, including the delivery ratio and latency.

Routing in PSNs

In this section, we classify and summarize the existing routing schemes proposed for PSNs. Note that PSN falls into the DTN category. Though some DTN routing schemes do not explicitly indicate that they are applicable to PSNs, their design does take the human behaviors into consideration. Therefore we include such protocols in this overview.

PSN routing can be classified into unicast and multicast according to the number of destinations a data needs to be delivered. If the number of copies of the same data allowed in the network simultaneously is used as a metric, PSN routing can be classified into *single-copy-based* and *multi-copy-based*. Based on the relay selection techniques, PSN routing can be classified into *encounter-based*, social-based and *location-based*. In this study, we adopt the third classification criterion and present the major relevant research in the following subsections. After that, we give the analysis about the existing schemes.

Encounter-Based Approach

Encounter or *contact* is an event that two nodes move into a radio range within which they are able to directly communicate. Encounter-based approach is also called *per-contact-based approach*. It exploits the encounter-related information, such as the number of encounters, the encounter time, and the inter-contact duration, to select the appropriate relays.

The transit-contact approach [5] and the approach proposed by Jones *et al.* [6] are typical encounter-based ones. In the transit-contact approach [5], the data forwarding metric of a

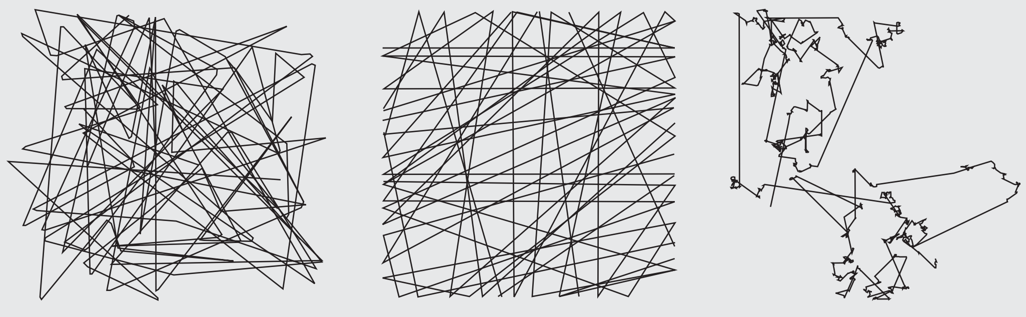

Figure 5. *Human mobility models: a) RW [3]; b) RD; c) LW [3].*

Sociality is the major trait that makes human beings, the information carriers in a PSN, different from the carriers in other networks. Human sociality has been employed to enhance the PSN routing performance, which forms the category of social-based approaches.

mobile node is its capacity of contacting others, measured by the expected number of nodes that it can contact directly or indirectly (through its direct neighbors) within a given time constraint for data forwarding. The higher the data forwarding metric a node has, the higher the probability it can be selected as a relay.

Jones *et al.* [6] propose three methods for a node to estimate the cost of a link between itself and another node based on the observed contact history information such as the average contact duration and the disconnect duration between any two nodes. Once the costs for individual links are estimated, the information is distributed through a link-state routing algorithm, based on which each node can compute a global routing table for data forwarding.

In the encounter-based approach, each node needs to record its encounter information with others for selecting the appropriate relays. Therefore, the record at each node is proportional to the number of nodes in the network, which makes the encounter-based approach scale badly.

Social-Based Approach

Sociality is the major trait that makes human beings, the information carriers in a PSN, different from the carriers in other networks. Human sociality has been employed to enhance the PSN routing performance, which forms the category of social-based approaches.

BUBBLE [7] and SimBet [8] are typical social-based approaches. Hui *et al.* [7] claim that human society owns two traits: *community* and *centrality*. The former refers to the set of human beings with common social attributes while the latter indicates that some popular human beings in a community interact with more people than others. This motivates the design of the BUBBLE scheme [7], which combines the knowledge of the community structure and the node centrality to make forwarding decisions. If a node carrying the data and the destination belong to the same community, the node selects the one that is more popular as the relay; otherwise, it transfers the data to the one that belongs to the same community as the destination or the one that has a more global popularity.

In SimBet [8], two nodes should compare and determine which one of them is more appropriate for relaying the data for a given destination when they meet. A node with a higher *SimBet utility* has a higher chance to be a relay. The SimBet utility is the linear combination of the *similarity utility* and the *betweentimes utility*. The former is defined as the number of common neighbors between a node and the destination while the latter measures the extent to which a node lies on the paths linking together other nodes, capturing how many indirectly connected nodes one can link.

SimBet routing [8] requires each node to estimate its similarity utility and betweentimes utility according to the statistics of the direct links between itself and other nodes in the network. Once two nodes meet, they exchange their contact information with others and then locally determine their SimBet utilities to the destination node. In this scheme, as the number of nodes increases in the network, the volume of the exchanged data between any two contact nodes is linearly increased.

Note that BUBBLE and SimBet both require the central nodes or nodes with high SimBet utility, i.e., popular nodes, to act as bridges. In reality, these nodes usually do not have special capabilities, which makes them easily become the network bottlenecks when the volume of traffic is increased.

Location-Based Approach

Location-based approach takes into account the spatial characteristics of human mobility to select relays.

MobySpace [9] and HERO [2] are typical location-based approaches. MobySpace [9] assumes that two human beings having similar mobility patterns are more likely to meet each other and communicate. The mobility pattern of a node is defined by its MobyPoint characterized by the probabilities of visiting all locations in the network. The MobyPoint of node k is denoted by $m_k = (c_{1k}, \ldots, c_{nk})$, where c_{ik}, $i \in \{1, 2, \ldots, n\}$, is the probability that node k visits location i and n is the total number of locations in the network. In MobySpace, the similarity of the mobility patterns between two nodes is measured by the Euclidean distance of their MobyPoints. Hence, if the MobyPoint of a node has a smaller Euclidean distance to that of the destination compared with the current relay, the node should be selected as the new relay.

The human mobility behaviors exploited in the encounter-based and location-based approaches directly determine the data diffusion in both the time and the space domains because human beings are the data carriers in PSNs.

Type	Scheme	Number of copies	Scalability	Bottleneck problem
Encounter-based	Transit-contact [5] Practice routing [6]	Single-copy/Multi-copy Single-copy	Bad Bad	No No
Social-based	BUBBLE [7] SimBet [8]	Single-copy Single-copy	Good Bad	Yes Yes
Location-based	MobySpace [9] HERO [2]	Single-copy/Multi-copy Single-Copy/Multi-Copy	Good Good	No Yes

Table 1. *Existing PSN routing scheme comparison.*

In the HERO framework [2], the whole PSN area is divided into multiple non-overlapping zones and each zone is identified by its center coordinates. HERO introduces a concept of *home*. The home of a node is the set of zones where the node frequently visits. According to the first trait described earlier, the probability that a node comes back to its home is high. Hence a node can deliver the data to the destination at a high probability if its home includes the zone where the destination resides. Such a node is called a *home node* of the data packet.

The HERO algorithms in [2] select only the home nodes as relays. By exploiting other traits of the human behaviors outlined earlier, HERO accepts a variety of algorithms with better routing efficiency. For example, one can select not only the home nodes but also the nodes whose homes are close to the destination zone because human mobility exhibits spatial locality. On the other hand, nodes with more active mobility are good relay candidates because they have high probabilities to encounter the destination or better relays. Moreover, relays can be selected by exploiting the traits of human mobility and sociality simultaneously: nodes whose friends are home nodes or have active mobility, or whose friends' homes are close to the destination zone, are selected as relays.

The main differences between HERO and MobySpace lie in two aspects. First, MobySpace requires each node to compute and carry the exact probability of visiting each place while HERO only needs to indicate the frequently visited place(s) of a node, i.e. its home information. Since the home information is relatively stable in a dynamic network environment, the volume of information each node exchanges with others does not increase when the number of nodes in the network increases. Even for the HERO variant that needs the friend information to select relays, the information a node needs to maintain and exchange increases slowly when the number of nodes in the network increases because a node usually has a limited number of friends. Therefore, we claim that HERO incurs little communication overhead and it is scalable. Second, MobySpace utilizes the similarity of nodes' mobility patterns while HERO employs the traits of human behaviors such as the spatial regularity, spatial locality, heterogeneous mobility activity, and sociality. As the similarity of mobility patterns is hard to characterize compared to the direct mobility behaviors, HERO is more practical.

Analysis

Since the PSN routing efficiency is closely related to the data diffusion in both the time and the space domains, the objective of investigating encounters, social relationships, or visited locations in existing research is actually to infer the directions and speed of data diffusion. However, such an inference is performed indirectly in the social-based approach because it needs to analyze the human mobility behaviors from their social relationships. On the other hand, the human mobility behaviors exploited in the encounter-based and location-based approaches directly determine the data diffusion in both the time and the space domains because human beings are the data carriers in PSNs. This direct inference could make the routing information in the encounter-based and the locationbased approaches more precise than that in the social-based approaches.

From the mechanisms introduced in Section 4, the locationbased approaches exploits individuals' spacial characteristics to design PSN routing protocols while the encounter-based or the social-based approaches investigates the inter-individual contact or social relationships. Hence, when the number of nodes in the network increases, the overhead of the locationbased approaches remain almost unchanged while those of the encounter-based and social-based approaches increase rapidly. This makes the location-based approaches more scalable than the encounter-based and social-based approaches.

Moreover, most social-based approaches suffer from the bottleneck problem because they prefer a popular people to act as the relay. In reality, these popular nodes usually do not have special capabilities, which makes them easily become the network bottlenecks when the volume of traffic is increased. On the other hand, in the encounter-based and location-based approaches, every node can serve as a relay and therefore no central node is needed. Thus there is no bottleneck problem. The performance comparison among existing PSN routing schemes are summarized in Table 1. It is worth noting that the delivery ratio and the delivery latency are two important metrics to evaluate routing performance. Here, we do not study them because these two quantitative metrics are largely dependent on the network status including the number of nodes and the node behaviors such as the probability that a node visits a location, the number of its friends, the node's mobility activity, and so on. Different routing schemes have different performance under different network statuses. Hence, in Table 1, we only list some qualitative metrics through analyzing the properties and natures of different kinds of routing approaches.

Open Issues

To the best of our knowledge, almost all existing PSN routing schemes care about how to improve the delivery ratio and delivery latency; very few or none of them tackles the challenges of scalability, security, multicasting, and emergency routing. In the following we detail a few open problems that are seldom addressed:

- None of the existing PSN routing schemes considers the *low storage* and *low energy consumption* as design objectives. Because mobile devices carried by human beings have very limited storage and energy, it might be unreasonable to utilize a large amount of storage or energy for a rapid and reliable transmission. Thus *storage* and *energy* should also be the metrics to evaluate PSN routing.
- Few PSN routing schemes address the impact of the contact duration on routing efficiency. The contact duration is defined to be the time interval in which two nodes communicate. It is a key factor because it affects the amount of data that can be transferred between the two contact nodes. If contact duration is considered when selecting relays, a "good" relay based on other metrics might not be good any more. For example, if a node contacts the destination frequentlybut all contacts last very shortly, the node might not be a good relay because the data transmission might not be able to complete during the contacts interval, which actually reduces the delivery ratio and network throughput.
- Almost all existing PSN routing algorithms ignore the temporal locality of human behaviors, which states that human beings prefer to stay at some zones for long time. This trait is very useful to enhance the delivery ratio in PSN routing because such a node in a zone can act as the data anchor for the zone to support others that frequently visit the zone: the data can be retrieved from the anchor node once the frequently visiting nodes come back to the zone.

Conclusion

Routing in PSNs is quite different from that in other networks because the PSN routing efficiency is largely dependent on the behavioral traits of human beings. In this article, we outline the challenges of PSN routing and summarize the characteristics of human behaviors exploited by the existing PSN routing schemes. The state-of-the-art PSN routing techniques are overviewed based on three categories: encounter-based, socialbased, and location-based, following which, we analyze the cons and pros of the existing PSN routing schemes. Finally, we present some open issues that might foster future research on PSN routing.

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Almost all existing PSN routing algorithms ignore the temporal locality of human behaviors, which states that human beings prefer to stay at some zones for long time. This trait is very useful to enhance the delivery ratio in PSN routing.