Hindawi Publishing Corporation
International Journal of Distributed Sensor Networks
Volume 2013, Article ID 145727, 16 pages
http://dx.doi.org/10.1155/2013/145727

Review Article

Study on Routing Protocols for Delay Tolerant Mobile Networks

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Received 11 October 2012; Accepted 6 December 2012

Academic Editor: Nianbo Liu

Delay tolerant mobile networks feature with intermittent connectivity, huge transmission delay, nodal mobility, and so forth. There is usually no end-to-end path in the networks and it poses great challenges for routing in DTMNs. In this paper, the architecture of DTMNs is introduced at first, including the characteristics of DTMNs, routing challenges, and metric and mobility models. And then, the state-of-the-art routing protocols for DTMNs are discussed and analyzed. Routing strategies are classified into three categories: nonknowledge-based approach, knowledge-based approach, and social-based approach. Finally, some research issues about DTMNs are presented.

1. Introduction

With the rapid development of low-power wireless communication technology and integrated circuit technology, there emerge a large number of low-cost, portable wireless devices. These devices are organized into a wireless ad hoc network and communicate with each other by multihop transmissions, which have great potential for many applications. For example, wireless sensor networks (WSNs) [1], composed of densely deployed low-power, low-cost sensor nodes, could be applied in scenarios such as military surveillance [2], disaster relief [3], health monitoring [4], environment monitoring [5], and smart home [6]. Another example is vehicular ad hoc networks (VANETs), in which vehicles equip with short range RF modules and exchange data when they meet, widely used in traffic safety [7], traffic efficiency [8], and information service [9].

Data gathering and routing is one of the fundamental functions of the low-power wireless ad hoc network and there have been lots of research works on routing issues [10–14]. However, authors assume that the network is full connected in these works, that is to say, there exists an end-to-end path between the source node and destination node, which is unreasonable in the real environment. In fact, if nodes are deployed randomly in the region, the density of nodes in some subregions would be higher than other subregions, leading to the phenomena of network partition, as shown in Figure 1. Once the network is partitioned, it is not fully connected any more. Secondly, the environment often has great impacts on the low-power communication. For instance, if there are electromagnetic fields or some obstacles, nodes will not communicate with each other even if they are within the transmission range, disconnecting the network. Thirdly, nodes are often powered by batteries, which is hard to rechargeable. When the energy of the battery exhausts, nodes cannot transmit data any more, degrading the network connectivity. Moreover, if nodes move with animals such as ZebraNet [15] and SWIM [16], data transmission only occurs when nodes meet each other. The mobility of nodes introduces opportunistic connectivity and there is not a stable end-to-end path in the network, leading to partially connected network.

Above all, the network is often not fully connected in the real environments and the network connectivity is intermittent and opportunistic, which is the characteristic of delay tolerant networks (DTNs) [17]. DTNs feature with sparse and intermittent connectivity, long and variable delay, high latency, high error rates, highly asymmetric data rate, and no stable end-to-end path. Obviously, traditional routing protocols are not well suitable for DTNs. For example, on-demand routing protocols such as AODV [18] and DSR [19] for MANET try to find an end-to-end path and table-driven routing protocols such as DSDV [20] and WRP [21] need to build route table. They are both hard to be adaptive to

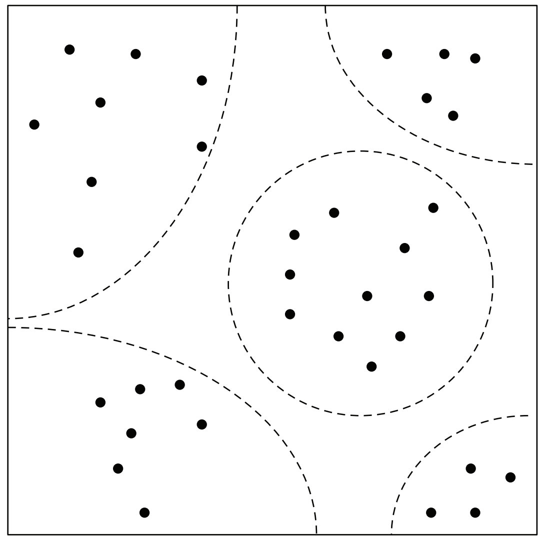

Figure 1: The phenomena of network partition.

the intermittent connectivity and dynamic network topology. New protocols must be designed for delay tolerant networks.

With the improvement of the portability of the wireless nodes, the mobility of nodes has been greatly improved. The enhanced mobility deteriorates the network connectivity further and challenges network routing. Harras et al. discuss the characteristics of delay tolerant mobile networks (DTMNs) and present routing issues of DTMNs in [22]. However, DTMNs are application specific and there are different types of DTMNs such as delay tolerant mobile sensor networks (DTMSNs) [23] composed of tiny sensor nodes, mobile social networks (MSNs) [24] when nodes attached to the human, and vehicular delay tolerant networks (VDTNs) [25]. Undoubtedly, there is not a universal routing protocol running in different types of DTMNs and routing protocols should be application specific, too.

The key issue of routing for DTMNs is to find an opportunistic connectivity between the nodes and transmit data to the nodes when they meet with each other if possible. Some methods have been proposed to achieve opportunistic communication in such challenged networks, trying to achieve the higher delivery ratio with the shorter delivery delay. Each of them has its own pros and cons and is just suitable in certain domains. Flooding is the simplest approach to transmit data to the destination but it wastes network resources extremely. In order to reduce the network overheads, some of them employ the history of contacts made by the nodes to route the data. Some other schemes try to forward messages to the neighbor node with the higher probability to communicate with the destination node. There are also some approaches that predict the behavior of the nodes and assist to route messages by the prediction knowledges. In addition, some other mechanisms are proposed, including infrastructure assisted method, that is, placement of stationary waypoint stores, using some mobile nodes to bridge the disconnection in the network, message replication, network coding, and leveraging prior knowledge of mobility patterns. Authors classify the routing protocols for delay tolerant networks into two categories: flooding-based approach and forwarding-based approach [26–28]. In [29], authors categorize the routing protocols into flooding-based method, history-based method, and special device-based method. In our opinions, the routing protocols should be divided into two categories: nonknowledge-based protocols and knowledge-based protocols. The former is to transmit messages to the next hop without any information indicating whether the next hop is an appropriate relay node. The latter relays messages with the assistance of the collected information about the network state and chooses a suitable next hop based on the knowledge. Moreover, social behavior analysis has been introduced to resolve the routing issues when the nodes are attached to the human and could achieve better performance by using social relationship or human mobility in real life environment, in which the routing schemes are called social-based protocols. In fact, the social-based protocols often utilize the knowledge of the social structure of the network and should be classified into the knowledge-based protocols. However, we discuss them separately from the former two categories in order to present routing schemes by using the social interaction of the nodes more clearly. In this paper, we study the existing routing protocols for DTMNs and give an analysis of them with respect to the important challenging issues and performance metrics.

The rest of the paper is organized as follows. Section 2 presents the architecture of DTMNs, including the characteristics of the DTMNs, routing challenges for the DTMNs, evaluation metrics of routing protocols for the DTMNs, and mobility model of the nodes. In Section 3, the states-of-the-arts of previous routing protocol for DTMNs are introduced and the existing problems are discussed. Section 4 presents some open issues about the DTMNs and Section 5 concludes the paper.

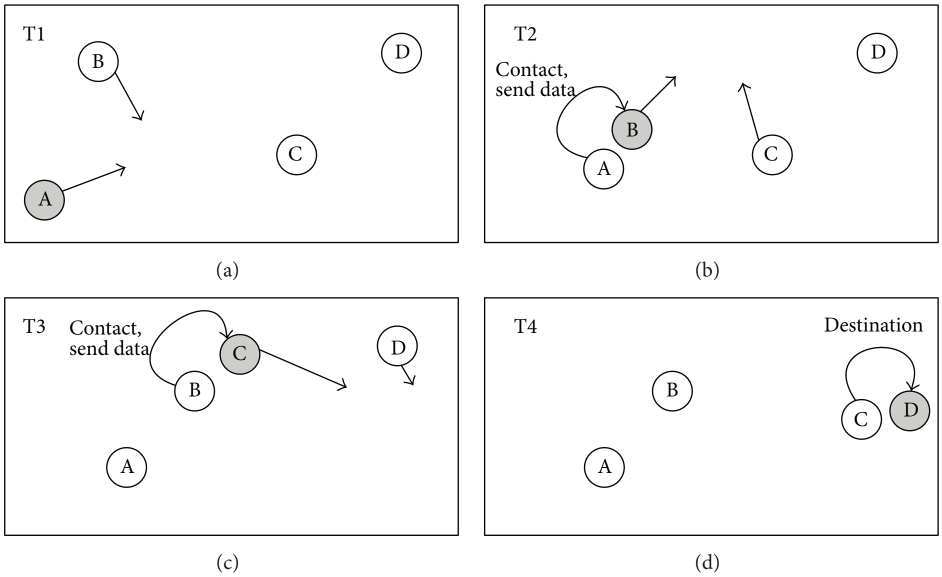

Figure 2: Data transmission in DTMNs.

2. Network Architecture

The concept of delay tolerant networking was initially proposed as an approach for the interplanetary Internet (IPN) [30]. Deep space communication suffers from very long latencies, low bandwidth, and intermittent scheduled connectivity. Fall proposes an overall architecture of DTN in [17], and it operates as an overlay above the transport layer to provide services such as in-network data storage and retransmission, and data forwarding. DTN technology has been introduced into wireless ad hoc network in the past few years. According to the mobility of the nodes, the network can be classified into two categories. (1) Network with some controllable nodes. In the network, most of the nodes are static and only a few movable nodes. The managed mobile nodes bridge the sparse disconnected network, store data from static nodes, and carry data to the destination. This method substantially saves the energy of the nodes as they only transmit over a short range. (2) Network with mobile nodes. In the second category, most of the nodes are movable and they have to transmit data occasionally when they contact with each other, introducing more challenges for routing messages. In this section, we firstly describe the characteristics of DTMNs, then analyze the routing challenges in DTMNs and metrics to evaluate the performance of the routing protocols, and finally discuss some mobility models, which have great influence on the network performance.

2.1. Characteristics of DTMNs. DTMN distinguishes itself from conventional networks by the following characteristics. (1) Intermittent connectivity. The connectivity of DTMNs is very poor. In most cases, it is impossible to have an end-to-end path. A node connects to other nodes only occasionally and the link is the scarcest resource in the network. (2) Delay tolerable. The end-to-end transmission latency is dominated by the queuing delay. Messages have to be stored in the message queue until the node meets a neighbor node. Obviously, opportunistic connection will lead to long latency so that applications have to tolerate the large transmission delay. (3) Sparse density. Node density is normally much lower in DTMNs compared with the traditional densely deployed networks, which further deteriorates network connectivity. (4) Node mobility. Since the nodes are attached to randomly moving objects, the network topology changes frequently. Besides, the buffer size of sensor nodes is usually limited. Since data messages may be stored in the buffer queue for quite a long time before being sent out, queue management is a challenge.

Clearly, a node only transmits its messages to the next hop when it meets other nodes and chooses an appropriate neighbor. As shown in Figure 2, node A wants to send message to node D at T1 but there is no connection between them. Node A has to store the messages and carries them while moving. Then node A contacts node B at T2 and node A will send the messages to node B because node B moves to node D. And then, node B meets node C at T3 and relays the messages to node C. Node C carries the messages and meets node D at T4, then the messages are sent to the destination node.

2.2. Routing Challenges. One of the main design goals of DTMNs is to exchange data between the nodes and employ the opportunistic links among the nodes for transmission. Clearly, the design of routing protocols in DTMNs is influenced by many challenging factors. In the following, we summarize some of the routing challenges that affect routing and forwarding in DTMNs.

2.2.1. Intermittent Connectivity. As mentioned before, intermittent connectivity is the inherent property of DTMNs. DTMN is a partially connected network because of node mobility, sparse deployment, and poor communication quality. The network connectivity varies with time. Consequently, it is hard to find an end-to-end connection between the source node and the destination node so that routing techniques in conventional network are not well suitable for DTMNs. Intermittent connectivity means that the links between the nodes are opportunistic. How to get an opportunistic link and transmit a message is a challenging issue in DTMNs.

2.2.2. High Latency. High latency is also a fundamental property of DTMNs. In general, the transmission delay from a source node to a destination node is composed of four components: waiting time, queuing time, transmission delay, and propagation delay [31]. The waiting time is the interval that a message carried by node until it meets another node, depending on the contact time and the message arrival time. The queuing time is the time it waits for the higher priority messages to be sent out. This depends on the data rate and the traffics in the network. The transmission delay is the time it takes for all the bits of the message to be transmitted, which is determined by data rate and the length of message. The propagation delay is the time a bit takes to propagate across the connection, which depends on the distance between two nodes. Obviously, messages have to be buffered in the queue of the nodes due to intermittent connectivity, incurring more waiting time and queuing time. Moreover, the low data rate of DTMNs introduces more transmission delay. The design of routing protocols for DTMNs should reduce the delivery latency as shorter as possible.

2.2.3. Limited Resources. The nodes in DTMNs are often equipped with low-power RF module, limited buffer size, irreplaceable battery, and low computation capacity, that is to say, the resources of the nodes are limited. The scarce of resources degrades the performance of the routing protocols.

(1) Buffer Size. When a message is generated, the message is buffered in the message queue of the node. Once the node contacts other nodes, it chooses the next hop and delivers the messages in its queue. However, the node usually waits a long periods of time until it meets another node so that the messages have to be buffered in the queue. If the queue is full, some messages would be dropped off, which decreases the delivery ratio. Routing strategies might need to consider the limited buffer space when making routing decisions. In addition, there must be a scheme to manage buffer.

(2) Energy Efficiency. Nodes in delay tolerant mobile networks are usually powered by the battery, which cannot be replaced easily. Lots of energy will be consumed for sending, receiving, and computing. While researchers have investigated general techniques for saving power in delay tolerant networks [32], none of the routing strategies has incorporated energy-aware optimizations. In fact, most of the previous routing techniques do not consider the energy efficiency. In these works, the RF module of the nodes has to work all the time so as to find the possible links (opportunistic connectivity) to their potential neighbors. Then, the nodes will drain off their battery quickly and cannot contribute any more for routing, while degrading the performance of DTMNs. Therefore, there is a tradeoff between the energy consumption and network connectivity. How to maintain an acceptable connectivity while keeping the energy consumption slowly is a challenging routing issue for DTMNs.

(3) Process Capability. The nodes in DTMNs may be very small and have small processing capability, in terms of CPU and memory. These nodes will not be capable of running complex routing protocols. To design routing protocols for DTMSN, we must consider the computing capability of the nodes.

2.2.4. Replication Management. Since the connectivity between mobile nodes is poor, it is difficult to form a well-connected network for data transmission. The nodes deliver the message to their neighbors opportunistically when they contact. In order to achieve certain success delivery ratio in such an opportunistic network, data replication is necessary [33]. However, multiple copies of messages will increase transmission overhead, which is a substantial disadvantage for energy limited sensor networks. Replication management mechanism is necessary to control the number of message copies in order to reduce the overhead caused by redundant copies.

2.2.5. Network Topology. Due to nodal mobility or link quality, the network topology of DTMNs may change dynamically and randomly. It is impossible to maintain a stable end-to-end path in the networks, and routing in DTMNs is often on demand. Routing strategies designed for delay tolerant networks must be adaptive to the frequent change of network topology.

2.3. Routing Metrics. To evaluate the performance of the routing protocols for DTMNs, there are two main metrics: data delivery ratio and data delivery delay. Moreover, there are some other metrics to evaluate the performance of the routing strategies for application of specific DTMNs such as energy consumption, the number of replications, and network overhead.

2.3.1. Delivery Ratio. The most important performance metric is the data delivery ratio. Delivery ratio is defined as the fraction of all generated messages that are successfully transmitted to the destination within a specific time interval. In DTMNs, there are two factors to cause data loss. One is that the TTL of message exceeds the tolerable delay of the application. The network is unable to deliver messages within an acceptable amount of time. The second factor is that the queue of the node is full and some messages have to be dropped. If there are no any other copies of the dropped messages, these messages will not arrive at the destination forever. Routing protocols should achieve higher data delivery ratio.

2.3.2. Delivery Delay. Data delivery delay is another metric to evaluate the performance of routing strategies of DTMNs, which is the time interval between when data is generated by the source node and when it is received by the destination. Due to the intermittent connectivity, the delivery delay of DTMNs is much longer than that of the conventional networks. Though applications in DTMNs can tolerate high latency, they can benefit from a short delivery delay. Some applications also have some time window where the data is useful. For example, if a DTN is used to deliver e-mail to a mobile user, the messages must be delivered before the user moves out of the network.

2.3.3. Energy Consumption. As described before, most of the existing routing protocols for DTMNs do not consider the energy efficiency. The RF module of node works all the time to search the possible links to other nodes, which exhausts the battery energy quickly. Once the battery is exhausted, the node is dead and cannot deliver any more data. However, for some data-centric applications, they want to gather data from the network as much as possible. That is to say, energy consumption of the node must be considered to design routing protocols in order to achieve longer network lifetime. The longer the network lifetime is, the more data the network collects. Routing techniques should make a tradeoff between the energy consumption and data delivery ratio.

2.3.4. Number of Replications. In order to get higher data delivery ratio, some routing protocols employ replication strategies and they transit more messages than others. The intuition is that having more copies of the message increases the probability that one of them will find its way to the destination and decreases the average time for one to be delivered. Unfortunately, the redundant replications waste a number of network resources such as buffer, bandwidth, and energy. The more the number of replications is, the more the wasted resources are. Routing protocols should achieve higher data delivery ratio with less replications.

2.3.5. Network Overhead. Usually, there are some control messages to assist in forwarding messages efficiently. These messages are network overheads. A good routing protocol should create little network overhead and it makes tradeoff between the data delivery ratio/delay and the delivery overhead.

2.4. Mobility Model. The mobility model is designed to describe the movement pattern of mobile users, and how their location, velocity, and acceleration change over time. Since mobility patterns may play a significant role in determining the performance of the routing protocols, it is desirable for mobility models to emulate the movement pattern of targeted real life applications in a reasonable way [34]. We classify the mobility models into four categories: random-based mobility model, social mobility model, map-based mobility model, and real dataset-based mobility model.

2.4.1. Random-Based Mobility Model. In random-based mobility models, the nodes move randomly without any restrictions. More specifically, the nodes choose their destination, speed, and direction randomly and independently of other nodes.

The simplest mobility model is the random walk mobility model [35], also called Brownian motion; it is a widely used model to represent purely random movements of the entities of a system in various disciplines from physics to meteorology. However, it cannot be considered as a suitable model to simulate wireless environments, since human movements do not present the continuous changes of direction that characterize this mobility model.

Another example of random mobility model is the random waypoint mobility model [36]. This can be considered as an extension of the random walk mobility model, with the addition of pauses between changes in direction or speed. When the simulation begins, each node randomly chooses a location in the field as the destination. It then moves towards the destination with constant velocity chosen randomly from $[0, V]$. The velocity and direction of the nodes are chosen independently of each other. On arriving at the destination, the node stops for a period of time and then chooses another random destination in the simulation field and moves towards it, as shown in Figure 3. The whole process is repeated again and again until the simulation ends.

The random waypoint model and its variants are designed to emulate the movement of mobile nodes in a simplified way. They are widely used due to their simplicity. However, they may not adequately capture certain mobility characteristics of some realistic scenarios, including temporal dependency, spatial dependency, and geographic restriction.

2.4.2. Social Mobility Model. In some types of DTMNs such as mobile social networks, the nodes are usually attached to the humans and carried by them. Apparently, the mobility of the nodes is determined by human decisions and social behavior. In order to emulate the social behavior, researchers propose social mobility model which is dependent on the structure of the relationships among people carrying the node.

Musolesi and Mascolo propose the community-based mobility model based on social network theory [37]. They think that a network consists of several communities, and the nodes are grouped into one community according to their social relationships among the individuals. The mobility of the nodes is also based on the social relationships. The model also allows for the definition of different types of relationships during a certain period of time (i.e., a day or a week). For instance, it might be important to be able to describe that in the morning and in the afternoon of weekdays, relationships at the workplace are more important than friendships and family ones, whereas the opposite is true during the evenings and weekends.

The idea of using communities to represent group movements in an infrastructure-based WiFi network has also been exploited in [38] and in its time-variant extension is presented in [39]. More specifically, this model preserves two fundamental characteristics, the skewed location visiting preferences and the periodical reappearance of nodes in the same location.

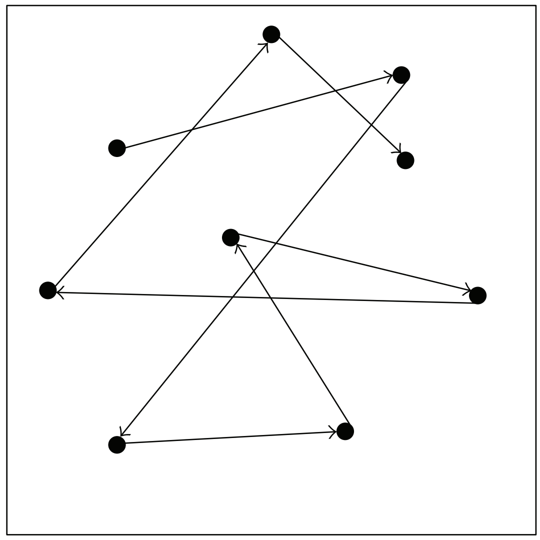

Figure 3: Random waypoint mobility model.

An agenda-based mobility model is proposed in [40], in which authors predict the movement of humans based on the trace of the people in the city. Then routing decision is made according to these information.

2.4.3. Map-Based Mobility Model. Map-based mobility model is designed for a specific type of DTMNs, vehicular delay tolerant networks. Different from the random-based mobility model, the movement of the nodes in vehicular delay tolerant networks is not random. The mobility is restricted by the road in the map and the nodes move regularly.

Freeway mobility model is proposed in [41] to emulate the motion behavior of mobile nodes on a freeway. It can be used in exchanging traffic status or tracking a vehicle on a freeway. The freeway mobility pattern is expected to have spatial dependence and high temporal dependence. It also imposes strict geographic restrictions on the node movement by not allowing a node to change its lane.

Manhattan mobility model is also introduced in [41] to emulate the movement pattern of mobile nodes on streets defined by maps in the city. The map is composed of a number of horizontal and vertical streets. Each street has two lanes for each direction. The mobile node is allowed to move along the grid of horizontal and vertical streets on the map. At an intersection of a horizontal and a vertical street, the mobile node can turn left, right, or go straight. The Manhattan mobility model is also expected to have high spatial dependence and high temporal dependence, but differs from the freeway model in giving a node some freedom to change its direction.

The obstacle mobility Model [42] takes a different approach in the objective to obtain a realistic urban network in presence of building constellations. Instead of extracting data from TIGER files, the simulator uses random building corners and Voronoi tessellations in order to define movement paths between buildings. It also includes a radio propagation model based on the constellation of obstacles. According to this model, movements are restricted to paths defined by the Voronoi graph.

2.4.4. Real Dataset-Based Mobility Model. In order to reflect the node behavior in real environment, some institutes try to collect a large number of real data reflecting the mobility of the nodes and their behavior. Based on these data, a real life mobility model could be built. For example, the reality mining project proposed by MIT [43] builds a system for sensing complex social systems with data collected from 100 mobile phones over the duration of 9 months. The collected data can be used to recognize social patterns in daily user activity, infer relationships, identify socially significant locations, and model organizational rhythms.

Haggle project proposed by Cambridge University [44] is an innovative paradigm for autonomic opportunistic communication. Students carry a tiny iMote with Bluetooth to record the contact history. Similarly, Hui and Crowcroft [45] created a human mobility experiment during IEEE Infocom 2006, with the participants labelled according to their academic affiliations. After collecting 4 days of data during the conference period, they replay traces using an emulator and discover that a small label indicating affiliation can indeed effectively reduce the delivery cost, without trading off much against delivery ratio. The intuition that simply identifying community can improve message delivery turns out to be true even during a conference where the people from different subcommunities tend to mix together.

3. Nonknowledge-Based Routing Protocols

In the nonknowledge-based routing approach, it tries to relay messages to the neighboring node without any information about the next hop. For example, the node does not know the likelihood that the next hop meets with the destination node, and the node chooses the next hop randomly or broadcasts.

Flooding is a mechanism which needs relay nodes to store and forward message copies independently through creating multiple duplications of a message in the network. This method could dramatically enhance delivery ratio and reduce average delivery delays at the cost of huge network resource consumption. Numerous optimization approaches have been presented based on flooding striving for reasonable resource consumption.

Direct transmission [46] is a typical nonknowledge-based routing technique. When source node generates messages, it carries the messages moving in the field. Once it contacts with the destination node, the messages are directly sent to the destination. Direct transmission is very simple and there is only one message copy and one transmission. However, the scheme does not employ the opportunistic links and suffers long delivery ratio due to the long waiting time in the buffer, especially when the source node is hard to meet the destination node.

In two-hop relay mechanism [27], the source node will send a message copy to the first n nodes it contacts. Then there is $n + 1$ node carrying the message and moving on. If any node holding the message encounters the destination node, the message will be delivered to the destination. Obviously, this method consumes more network resources, but it achieves better performance than direct transmission since it has better chance to communicate with the destination. For example, assuming that each node has an independent probability P to contact with the destination, then two-hop relay mechanism will deliver the message to the destination node with the probability $1 - (1 - P)^{n+1}$, which is far more than the probability of direct transmission when P is small. Moreover, it can choose the number of copies to control the resources consumption. However, two-hop relay mechanism has the same disadvantage as direct transmission, that is, if all the $n + 1$ nodes cannot encounter the destination node, the message cannot be transmitted.

Tree-based flooding method [27] improves two-hop relay by distributing the task of making copies to other nodes. When a message copy is transferred to a relay node, it will tell the relay node the number of copies it will generate. Because the relay nodes form a tree rooted at the source, the method is called tree-based routing. There are many ways to decide the number of copies the relay node will make. A simple scheme is to allow each node to make unlimited copies, but to restrict the message to travel a maximum of n hops from the source. Tree-based flooding can deliver messages to destinations that are multiple hops away, unlike direct contact or two-hop relay. However, tuning the parameters is a challenging problem.

Vahdat and Becker present epidemic routing in [47]. Epidemic routing works as follows. When a message is sent, it is still in the buffer with a unique ID. Once two nodes contact with each other, they exchange a summary vector including the list of all the messages IDs they have in their buffers. Then they exchange the message they do not have. Though Epidemic Routing uses the knowledge of summary vector, the knowledge does not indicate whether the next hop is the appropriate relay node. So we classify it into nonknowledge-based category. Epidemic Routing relies upon carriers coming into contact with another connected portion of the network through node mobility. At this point, the message spreads to an additional island of nodes. Through such transitive transmission of data, messages have a high probability of eventually reaching their destination. If the buffer size is large enough, the message will be distributed over the network like epidemic viruses until it arrives at the destination node. Epidemic Routing is relatively simple because it requires no knowledge about the network. Similarly to flooding, the disadvantage of Epidemic Routing is that a great amount of resources are consumed due to the large number of copies and requires large amount of buffer space, bandwidth, and energy.

Authors introduce the idea of immunity to improve the basic Epidemic Routing strategy in [48]. Each node maintains a list of delivered messages, called the immunity list. When two nodes contact with each other, they exchange their immunity lists at first, and then those messages in the immunity lists will not exchange in the future. It is expected to increase the number of delivered messages due to improved buffer and network utilization. Simulation shows statistically significant performance improvement both in delivery ratio and delay for immunity-based epidemic as compared to the basic epidemic protocol.

PREP is another improvement of Epidemic Routing proposed in [49]. The key idea of PREP is to impose a partial priority on the messages for transmission and dropping. The priority calculation is based upon four inputs: the current cost to destination, current cost from source, expiry time and generation time. Each link's average availability is epidemically disseminated to all nodes. As a result of this priority scheme, PREP maintains a gradient of replication density that roughly decreases with increasing distance from the destination. PREP is derived from the recognition that Epidemic routing is unbeatable from the point of view of successful delivery as long as the load does not stress the resources (bandwidth, storage).

Gossip [50] is also nonknowledge-based routing technique. Compared with flooding, Gossip tries to reduce network resources consumption by randomly choosing the relay node rather than delivering message to all nodes it meets. Clearly, the number of message copies is controlled and the resource consumptions decrease. However, randomly selected next hop might not be a suitable relay node and would make negative influence on the performance.

To significantly reduce the overhead of flooding-based schemes, Spyropoulos et al. propose spray and wait (SW) [51], which "sprays" a number of copies into the network at first, and then "waits" till one of these nodes meets the destination. SW routing strategy consists of two phases: spray phase and wait phase. In the spray phase, once a message is generated at source node, the number of message copies is confined by L. L message copies are forwarded by the source node and other relay nodes. If the L nodes with the message copies do not encounter the destination, then enter in to the wait phase. In the wait phase, the L nodes with the message copies performs direct transmission, that is to say, the L nodes carry the message copy till one of them contacts with the destination. SW combines the speed of epidemic routing with the simplicity and thriftiness of direct transmission. At first, it spreads message copies in a manner similar to epidemic routing. When there are enough copies that at least one of them will find the destination quickly with high probability, it stops flooding and performs direct transmission.

Besides flooding-based routing techniques, there are other two types of nonknowledge-based routing strategies: special node-based approach such as SWIM [16] and data MULE [52], and coding based approach [53, 54].

The Shared Wireless Infostation Model (SWIM) architecture proposed by Small and Haas [16] employs the special node called Infostations at various locations. The Infostations are static, and the nodes are attached to moveable whales. Each Infostation is considered as a destination and they are connected. The mobile nodes forward data to the Infostations when they contact with any of the Infostations. So in effect, SWIM is similar to the epidemic scheme, except that in the SWIM, each Infostation is a destination.

Shah et al. [52] present a system called Data MULE. The special node in the system is called MULEs. The MULEs are mobile nodes and move around the sensor area randomly. The MULES try to collect data from the static sensor nodes and carry data back to the base station. Furthermore, there are some other routing schemes using special node to assist in forwarding message [55–61].

There are two types of coding-based strategies: network coding [53] and erasure coding [62]. The former embeds the decoding algorithms into the coded message blocks and the latter adds redundancy into the message blocks. In network coding-based strategies [53, 54], fragmentation and network coding taken are used to reduce resource consumption. In these strategies, each message is partitioned into K fragment packets when it is originated. Those fragments are flooded in the network, and relay nodes firstly combine the fragments and encode them into a new packet then forwarding. At last, when the destination obtains coded packets which collect all the K fragments, it attempts to decode the K source packets and the message is delivered. This method reduces the buffer and transmission consumption at the cost of long time waiting for the destination to receive a sufficient number of coded packets.

Chen et al. [62] apply erasure coding, but combine it with some replication techniques. Liao et al. [63] also propose a method where the message is erasure coded and then routed using estimation-based routing. The same authors further improve this approach in [64] by utilizing the knowledge of the mobility pattern of the network to route the erasure coded blocks.

4. Knowledge-Based Routing Protocols

Nonknowledge-based routing strategies relay message blindly and consume huge network resources. To forward messages efficiently, knowledge about the network could be used to optimize routing strategies and improve the performance. Knowledge about the network include link metric, history contact, mobility pattern, and network topology. According to the knowledge, a node can select the next hop which has the highest likelihood to communicate with the destination node.

4.1. Link Metric-Based Approach. Similarly to traditional networks, DTMNs can be considered as a graph and each link is assigned a weight. Then the shortest path algorithm such as Dijsktra's algorithm is run to get a best route. Link weights are based on some performance metric: the highest bandwidth, lowest latency, and the highest delivery ratio. In DTMNs, the most important metric is the delivery ratio, since the network must be able to reliably deliver data. A secondary metric is the delivery latency. Thus, the challenge is to determine a system for assigning link metrics that maximize the delivery ratio and minimize the delivery latency. Some metrics may also attempt to minimize resource consumption, such as buffer space or power.

Jain et al. utilize link metrics for routing in delay tolerant networks in [65]. Their object is to minimize the end-to-end delivery latency. The intuition is that this minimizes the amount of time that a message consumes to buffer space, and thus it should also maximize the delivery ratio since there is more space available for other messages. Their work uses a metric, that is, the time it will take for a message to be sent over each link. Since this value may depend on the time a message arrives at a node, the authors present a time-varying version of Dijkstra's shortest path algorithm.

Feng et al. propose minimum expected delay-based routing (MEDR) [66] protocols for delay tolerant mobile sensor networks. In MEDR, each sensor maintains two important parameters: minimum expected delay (MED) and its expiration time. According to MED, messages will be delivered to the sensor that has at least a connected path with their hosting nodes and has the shortest expected delay to communicate directly with the sink node. Because of the changing network topology, the path is fragile and volatile, so MEDR uses the expiration time of MED to indicate the time of the path and avoid wrong transmissions.

Jones et al. present a metric called the minimum estimated expected delay (MEED), where the weights are based purely on the history contact record [67]. MEED estimates the transmission delay to the next hop and assumes that the future delay will be similar to the past. The delay metrics are distributed over the network by an epidemic protocol. The node computes the shortest path based on all received link states of the network. MEED maintains a single message copy and selects the next hop with the shortest delay to the destination. Compared to direct transmission, MEED reduces the delivery delay efficiently. But MEED introduces more network overheads when distributing the link states over the network, especially when the network topology changes frequently.

Tan et al. [68] present a shortest expected path routing (SEPR) for DTN scenario. The forwarding probability of the link is calculated from the history of encounters. Based on this, the shortest expected path is calculated. The meet and visit routing (MV routing) proposed by Burns et al. [69] improves SEPR by using only the frequency of node contacts. It uses the frequency of the past contacts of nodes and also the visit to certain regions.

Moreover, Wang and Song propose a distributed real-time data traffic statistics assisted routing protocol (DRTAR) [70] for vehicular ad hoc network. In DRTAR, each vehicle estimates the state of the partitioned network of each road by the real-time statistics of records of neighbors. Based on the estimated delay of all roads, each vehicle can compute the appropriate routing path for message forwarding.

4.2. Prediction-Based Approach. To improve routing performance in opportunistic scenarios, prediction-based approaches have been designed for DTMNs. These approaches calculate and predict the state of network (i.e., message delivery probability, nodes' contact schedule, etc.) based on history information.

ZebraNet [71] is one of the earliest schemes to make routing decisions by the history of encounters. The object of the project is to monitor zebra movement in their habitat and wireless nodes are attached to the zebras. Each mobile node has a hierarchy level, which is calculated from the frequency of its contact with the base station. The hierarchy level of each node varies with time, depending on its frequency of contact with the base station. When a node encounters other nodes, it transmits the messages to another node with higher hierarchy level. In this way, the history of the node's encounter with the base station becomes the metric for data forwarding.

PRoPHET is probabilistic routing protocol proposed by Lindgren et al. [72]. PRoPHET uses the history of encounters to compute the delivery predictability of the nodes. The delivery predictability indicates the likelihood to meet the destination node. Each node maintains the delivery predictability of every other node for all known destinations. When nodes meet each other, they exchange the information of delivery predictability. Moreover, it also incorporates transitivity information to decide the next hop. PRoPHET has a higher delivery ratio than epidemic, with much lower communication overhead.

Spray and focus (SF) proposed in [73] improves spray and wait by substituting wait phase for focus phrase. The works of SF in the spray phase are the same as that of SW. In the focus phase, message carriers would select appropriate relay node based on predicted utility and then forward it. Spray and focus are demonstrated to achieve both good latency and low bandwidth overhead, thereby significantly reducing resource consumption in flooding routing.

PER proposed by Yuan et al. [74] predicts messages' delivery on the ground of probability distribution of future contact schedules and chooses a suitable next hop in order to improve the end-to-end delivery probability. In PER, a model based on a time-homogeneous semi-Markov process is designed to predict the probability distribution of the time of contact and the probability that the two nodes encounters in the future. When making decision, there are three metric functions for nodes in PER, which means nodes could select one of them to choose relay nodes.

Wang and Wu [75] present a replication-based efficient data delivery called RED, which consists of two components for data delivery and message management. Firstly, data delivery uses a history-based method like ZebraNet to calculate the delivery probabilities of sensor nodes. Secondly, the message management algorithm decides the optimal erasure coding parameters based on sensor's current delivery probability to improve the data delivery ratio. However, the optimization of erasure coding parameters used in [75] is usually inaccurate, especially when the source is very far away from the sinks. They also propose a FAD protocol in [76] to increase the data delivery ratio in DTMSNs. Besides using the same delivery probability calculation method as RED, FAD further discusses how to constrain the number of data replications in the sensor network by using a fault tolerance value associated with each data message. However, that protocol still has a quite high transmission overhead.

Xu et al. present a novel data gathering method named relative distance-aware data delivery scheme (RDAD) in [77]. RDAD introduces a simple non-GPS method with small overhead to gain the relative distance from a node to sink and then to calculate the node delivery probability which gives a guidance to message transmission. RDAD also employs the message survival time and message maximal replication to decide message's transmission and dropping for minimizing transmission overhead. Simulation results have shown that RDAD does not only achieve a relatively long network lifetime but also gets the higher message delivery ratio with lower transmission overhead and data delivery delay than FAD approach.

Similarly, a distance-aware replica adaptive data gathering protocol (DRADG) is proposed in [78]. DRADG economizes network resource consumption through making use of a self-adapting algorithm to cut down the number of redundant replicas of messages and achieves a good network performance by leveraging the delivery probabilities of the mobile sensors as main routing metrics.

So far, the routing techniques we discussed do not consider the energy efficiency of the network. However, for some data-centric applications, they want to gather data from the network as much as possible. That is to say, energy consumption of the node must be considered to design routing protocols in order to achieve longer network lifetime. The longer the network lifetime is, the more data the network collects. Routing techniques should make a tradeoff between the energy consumption and data delivery ratio.

Wang et al. develop a cross-layer data delivery protocol for DFT-MSN in [79]. They think that there is a tradeoff between link utilization and energy efficiency. The goal is to make efficient use of the transmission opportunities whenever they are available, while keeping the energy consumption at the lowest possible level. But the sleeping period of sensor nodes is determined by their working cycles and their buffered message. If a node moves around the sink and its sleeping period is too long according to [79], it will not deliver any data to the sink.

To make tradeoff between opportunistic connectivity and energy consumption, a data delivery protocol with periodic sleep (DPS) tailored for DTMSN is proposed in [80]. Based on their delivery probability and their distance to the sink, sensor nodes choose their sleep schedule to save the energy. The higher the delivery probability and the shorter the distance to the sink, the less the time they sleep in order to improve the connectivity around the sink. Simulation results show that DPS achieves acceptable delivery ratio and delay with a very long network lifetime. In the long lifetime, the network can gather more data from sensor nodes than other approaches.

4.3. Context-Aware Approach. Some other protocols use the context information to aid in data forwarding. Musolesi et al. propose a context-aware adaptive routing (CAR) in [81], in which some context information such as the energy, moving speed, location, and communication probability are used to calculate utility. The node chooses the next hop that has the highest utility to transfer the messages. Based on CAR, Mascolo et al. present SCAR (sensor context-aware routing) [82], a routing approach which uses the context of the sensor node (history neighbors, battery level, etc.) to foresee which of the neighbors are the best relay nodes for data forwarding. In addition, SCAR controls the number of message copies like spray and wait.

Leguay et al. propose MobySpace [83], which utilizes the mobility pattern of nodes as context information. A MobySpace consists of Mobypoints. Each Mobypoint summarizes some characteristics of a node's mobility pattern. Nodes with similar mobility patterns are close in MobySpace. They are the optimum carriers of messages. The same concept on multicopy routing schemes is presented in [84].

Opportunistic routing with window-aware replication (ORWAR) is a resource-efficient protocol for opportunistic routing in delay-tolerant networks presented by Sandulescu and Nadjm-Tehrani [85]. ORWAR exploits the context of mobile nodes (speed, direction of movement, and radio range) to estimate the size of a contact window. This knowledge is exploited to make better forwarding decisions and to minimize the probability of partially transmitted messages. As well as optimizing the use of bandwidth during overloads, it helps to reduce energy consumption since partially transmitted messages are useless and waste transmission power. Another feature of the algorithm is the use of a differentiation mechanism based on message utility. This allows allocating more resources for high utility messages. More precisely, messages are replicated in the order of the highest utility first and removed from the buffers in the reverse order.

Grossglauser and Vetterli [86] propose another algorithm that was based on context information. Here the context information was the time lag between the last encounter with the destination. The main purpose of the work is to show that node mobility can be exploited to disseminate destination location information without incurring any communication overhead. To achieve this, each node maintains a local database of the time and location of its last encounter with every other node in the network. The database is consulted by packets to obtain estimates of their destination's current location. As a packet travels towards its destination, it is able to successively refine an estimate of the destination's precise location, because node mobility has "diffused" estimates of that location.

4.4. Position-Based Approach. Position-based routing (also called geographic routing) is a routing principle that relies on geographic position information, which is based on the idea that the source sends a message to the geographic location of the destination instead of using the network address. Position-based routing requires that each node can determine its own location and that the source is aware of the location of the destination. With this information, a message can be routed to the destination without knowledge of the network topology or a prior route discovery.

Greedy perimeter stateless routing (GPSR) presented by Karp and Kung [87] is a typical routing protocol for wireless ad hoc networks that uses the positions of routers and a packet's destination to make packet forwarding decisions. GPSR makes greedy forwarding decisions using only information about a router's immediate neighbors in the network topology. When a packet reaches a region where greedy forwarding is impossible, the algorithm recovers by routing around the perimeter of the region.

Geographic source routing (GSR) [88] combines position-based routing with topological knowledge, as a promising routing strategy for vehicular ad hoc networks in city environments. Greedy perimeter coordinator routing (GPCR) [89] is a position-based routing protocol. The main idea of GPCR is to take advantage of the fact that streets and junctions form a natural planar graph, without using any global or external information such as a static street map. GPCR consists of two parts: a restricted greedy forwarding procedure and a repair strategy which is based on the topology of real-world streets and junctions and hence does not require a graph planarization algorithm.

5. Social-Based Routing Protocols

In the recent years, social structures have been used to help forwarding in intermittently connected networks. Social behavior analysis has been introduced to resolve the routing issues when the nodes are attached to the human and could achieve better performance by using social relationship or human behavior in real-life environment.

5.1. Social Relationship-Based Approach. In society, there are inherent social relationships between people such as relatives, friends, colleagues, and schoolmates. The relationships usually remain stable in a long period of time. Based on the social relationships, message could be forwarded efficiently.

Hui and Crowcroft have proposed a routing algorithm called LABEL which takes advantage of communities for routing messages [45]. LABEL partitions nodes into communities based on only affiliation information. Then ach node in the network has a label telling others about its affiliation. A node only chooses to forward messages to destinations, or to the next-hop nodes belonging to the same group (same label) as the destinations. LABEL significantly improves forwarding efficiency over oblivious forwarding using their dataset, but it lacks a mechanism to move messages away from the source when the destinations are socially far away.

BUBBLE combines knowledge of the community structure with knowledge of node centrality to make forwarding decisions [90]. Centrality in BUBBLE is equivalent to popularity in real life, which is defined as how frequently a node interacts with other nodes. People have different popularities in the real life so that the nodes have different centralities in the network. Moreover, people belong to small communities like in LABEL. When two nodes encounter, the node forwards the message up to the node with higher centrality (more popular node) in the community until it reaches the same level of centrality as the destination node. Then, the message can be forwarded to the destination community at the same ranking (centrality) level. BUBBLE reduces the resource consumption compared to epidemic and PRoPHET. However, this reduction may not be large since the ranking process creates significant communication overhead. In addition, this protocol still uses multicopy forwarding which means that it is not efficient in terms of resource consumption.

SimBet presented in [91] makes routing decisions by centrality (betweenness) and similarity of nodes. Centrality means popularity as in BUBBLE. More specifically, the centrality value captures how often a node connects nodes that are themselves not directly connected [7]. Similarity is calculated based on the number of common neighbors of each node. SimBet routing exchanges the preestimated centrality and locally determined similarity of each node in order to make a forwarding decision. The forwarding decision is taken based on the similarity utility function (SimUtil) and betweenness utility unction (BetUtil). When the nodes contact with each other, the node selects the relay node with higher SimBet utility for a given destination.

SimBetAge [92] improves SimBet by introducing a new parameter, freshness. Routing decision is made based on freshness, betweenness, and similarity. Betweenness and similarity are the same as in SimBet and they are proportional to the freshness in SimBetAge. SimBetAge employs a weighted time-dependent graph, in which the weight of an edge is called the edge freshness, where $w(e,t) = 0$, $e = (A, B)$ means that nodes A and B have not been connected from the initial time t_0 to time t and $w(e,t) = 1$ represents a permanent connection between A and B. The similarity of two nodes in SimBetAge is proportional to the freshness of a common neighbor between the two nodes. In order to have a more accurate calculation of betweenness compared to SimBet, SimBetAge takes all possible paths in a network into account, whereas SimBet only uses the shortest path between nodes.

LocalCom proposed by Li and Wu [93] is a community-based epidemic forwarding scheme in disruption tolerant network. LocalCom detects the community structure using limited local information and improves the forwarding efficiency based on the community structure. It defines similarity metrics according to nodes' encounter history to depict the neighboring relationship between each pair of nodes. A distributed algorithm, which only utilizes local information, is then applied to detect communities and the formed communities have strong intracommunity connections.

In social greedy [94], forwarding decision is made by the closeness and social distance. Closeness is calculated by the common attributes (address, affiliation, school, major, city, country, etc.) of the two nodes. The more common the attributes, the closer the two nodes. Social greedy forwards a message to the next node if it is socially closer to the destination. Social greedy outperforms the LABEL protocol. However, the delivery ratio of Epidemic and BUBBLE is better than social greedy.

PeopleRank approach [95] uses a tunable weighted social information to rank the nodes. PeopleRank is inspired by the PageRank [96] algorithm employed by Google to rank web pages. By crawling the entire web, the algorithm measures the relative importance of a page within a graph (web). Similar to the PageRank idea, PeopleRank gives higher weight to nodes if they are socially connected to other important nodes of the network. With the emergence of Online Social Network platforms and applications such as Facebook, Orkut, or MySpace, information about the social interaction of users has become readily available. Moreover, while opportunistic contact information is changing constantly, the links and nodes in a social network remain rather stable. The idea of PeopleRank is to use this more stable social information to augment available partial contact information in order to provide efficient data routing in opportunistic networks.

5.2. Human Behavior-Based Approach. Another social-based routing strategy employs the regularity of human behavior to aid in routing decision.

Liu and Wu present a cyclic MobiSpace [97], which is a MobiSapce where the mobility of the node exhibits a regular cyclic pattern as there exists a common motion cycle for all nodes. In a cyclic MobiSpace, if two nodes were often in contact at a particular time in previous cycles, then the probability that they will be in contact around the same time in the next cycle is high. Cyclic MobiSpace is common in the real world: (1) most objects' motions exhibit regularity as they are repetitive, time sensitive, and location related; (2) a common motion cycle usually exists because most objects' motions are based on human-defined or natural cycles of time such as hour, day, and week nodes. Based on this phenomenon, routing in cyclic MobiSpace (RCM) scheme is proposed. Routing decision is made by the expected minimum delay (EMD), which is the expected time that an optimal forwarding scheme takes to deliver a message at a specific time from a source to a destination, in a network with cyclic and uncertain connectivity. When nodes contact, messages would be relayed to the next hop with minimum EMD.

Liu et al. consider that there are preference locations that people visit frequently and they propose preference location-based routing strategy (PLBR) [98]. Firstly, PLBR provides the approach of acquiring one's preference locations and then calculates the closeness metric which is used to measure the degree of proximity of any two nodes proposed. On the basis of that, the data forwarding algorithm is presented. The closeness is defined to indicate the similarity of the preference locations that the two nodes visit. The higher the closeness of the two nodes, the more the common preference locations. If the closeness of the two nodes is high, the probability of the two nodes to contact is high. The messages would be forwarded to the next hop with the highest closeness. However, the calculation of the closeness requires the preference locations of the destination node, introducing large network overheads.

An expected shortest path routing (ESPR) [99] scheme improves PLBR by utilizing the stable property of human that they have preference locations in their mobility traces, and the direct distance between node pairs can be calculated according to the similarity of their location visiting preferences. Then an expected shortest path length (ESPL) can be achieved by Dijkstra algorithm. Messages are forwarded to nodes which are closer to the destination than the previous nodes in the message delivery history. In addition, ESPR also employs the priority of message in the queue management.

CSI [100] is a behavior-oriented service as a new paradigm of communication in mobile human networks, which is motivated by the tight user-network coupling in future mobile societies. In such a scenario, messages are sent to the inferred behavioral profiles, instead of explicit IDs. At first, user behavioral profiles are constructed based on traces collected from two large wireless networks, and their spatiotemporal stability is analyzed. The implicit relationship discovered between mobile users could be utilized to provide a service for message delivery and discovery in various network environments. CSI shows that user behavioral profiles are surprisingly stable. Leveraging such stability in user behaviors, the CSI service achieves delivery rate very close to the delay-optimal strategy with minimal overhead.

Hot area-based routing protocol (HARP) scheme presented in [101] is based on the observation that there are some hot areas with higher nodal density and the node in the hot area has higher delivery probability to the destination. In HARP, the delivery probability is determined by the transmission ranking and the popular degree. Transmission ranking indicates the likelihood that sensor nodes communicate with the sink nodes. And popular degree reflects the popularity of sensor nodes. In the real world, some nodes may be more popular and interact with sink nodes more often than others in the network. The more hot areas a sensor node visits, the higher its popular degree is.

6. Open Issues

6.1. Energy Efficiency. Energy efficiency is an important issue for wireless ad hoc networks and there are lots of researches on energy efficiency in traditional wireless ad hoc networks such as WSNs. However, the existing routing strategies for delay tolerant networks seldom consider the energy consumptions of the nodes, shortening the network life time. In the previous works for DTMNs, the RF module of nodes has to work all the time so as to find the possible links (opportunistic connectivity) to their potential neighbors. Then, the nodes will drain off their battery quickly and cannot contribute any more for data gathering. Therefore, routing protocol should make a tradeoff between the energy consumption and data delivery ratio. In DTMNs with intermittent connectivity, it is helpful to find the link to keep the radio working all the time at the cost of rapidly exhausted battery. On the contrary, periodically working of the RF module saves energy but leads to lower connectivity. How to maintain an acceptable connectivity while keeping the energy consumption slowly is a challenging issue for DTMNs.

6.2. Security Routing. Existing routing protocols for DTMNs focus on improving the delivery ratio and reducing the delivery delay, but do not consider security issue. To our knowledge, there is little study on the security of data delivery in DTMNs. In DTMNs with intermittently connectivity, it is argued that the issue of security and privacy is not so important. In fact, DTMNs face all the security threats that a traditional network faces. Just like PC, the nodes in DTMNs are often controlled by people. There might be some malicious attackers using the nodes to transmit bad data in the network. So, security routing is a promising issue for DTMNs.

6.3. Selfish Routing. In the previous routing techniques, there is a common assumption that all nodes in the network are unselfish and coordinated. Each node is willing to receive and relay the messages sent by other nodes. In fact, there would be some selfish nodes, which want to preserve their own resources while using the services of others and consuming the resources of others, especially in social network. In the real world, most people are socially selfish, that is, they are willing to forward packets for nodes with whom they have social ties but not others, and such willingness varies with the strength of the social tie. Social selfishness will affect node behaviors. As a forwarding service provider, a node will not forward packets received from those with whom it has no social ties, and it gives preference to packets received from nodes with stronger ties when the resource is limited. Thus, a DTMNs routing algorithm should take the social selfishness into consideration.

6.4. Social Routing. Utilizing the social behavior and relationship of humans is still a very promising research area. In fact, the handheld devices are more and more popular today so that most of people carry some handheld devices. Knowledge of the social structure of people can enable these devices to be the bridge between the disconnectedness and to forward message more efficiently.

6.5. Cross-Layer Design. Generally speaking, cross-layer design refers to protocol design done by actively exploiting the dependence between protocol layers to obtain performance gains. This is unlike layering, where the protocols at the different layers are designed independently. Knowledge has to be shared between layers to obtain the highest possible adaptivity. So, how to use the information of other layers to assist in routing decision and optimizing forwarding is an interesting topic.

7. Conclusion

In this paper, we introduce delay tolerant mobile networks and discuss the characteristics of the DTMNs. The intermittent connectivity of DTMNs influences the routing performance significantly. Then routing challenges and routing metrics are analyzed. Moreover, mobility models are also discussed because they affect the forwarding efficiency directly. Then we study the existing routing protocols for delay tolerant mobile networks in depth. The routing strategies for DTMNs are categorized into nonknowledge based, knowledge based, and social based. In fact, it is not possible to classify each of the schemes into exactly one of the many classes. More and more routing techniques are hybrid in nature and may be categorized into more than one category. Finally, we give some research issues about routing for DTMNs, including energy efficiency, security routing, selfish routing, social routing, and cross-layer design.

Acknowledgments

This work is supported by National Science Foundation under Grant no. 60903158, 61003229, 61103226, 61170256, 61173172 and the Fundamental Research Funds for the Central Universities under Grant no. ZYGX2010J074 and ZYGX2011J073.

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