Delay Tolerant Mobile Sensor Networks: Routing Challenges and Solutions

Eyuphan Bulut

Abstract Delay-Tolerant Mobile Sensor Networks (DTMSN), which have features of both Delay-Tolerant Networks (DTN) and Wireless Sensor Networks (WSN), need to be considered as a different network type due to the unique characteristics. DTMSNs have been getting popular due to the increasing number of applications. As a result, several routing algorithms for the communication between the nodes have been developed recently. In this chapter, we discuss the challenges for routing in the DTMSN environment and present a survey of existing routing algorithms in the literature. We categorize the DTMSNs as terrestrial, underwater and flying DTMSNs and go through the challenges and routing solutions in each of these subcategories. We not only examine the routing algorithms specifically designed for DTMSNs but also examine the routing algorithms designed for DTNs and WSNs from the perspective of DTMSNs. Moreover, we discuss the evaluation metrics used for the performance analysis of developed routing algorithms.

1 Introduction

Wireless Sensor Networks (WSN) have become popular with the advances in wireless communication electronics that enabled the development of low-power and small size sensor nodes. A WSN consists of many sensor nodes deployed in a geographical area. There is a wide range of applications areas of sensor networks including military networks (e.g., battlefield surveillance), environmental monitoring (e.g., habitat exploration, pollution detection) and transportation (e.g., vehicle identification and tracking). WSNs have been broadly studied in the past two decades, with primary focus on routing, energy saving, and topology control. However, when the sensors are located at moving objects such as people, animals and vehicles and

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Eyuphan Bulut
Virginia Commonwealth University, Department of Computer Science, 401 West Main St. Richmond, VA 23284, e-mail: ebulut@vcu.edu

the connectivity between the objects shows DTN characteristics, the developed approaches usually fail to perform properly, requiring the development of new routing algorithms.

It has been more than a decade since Kevin Fall gave a talk about DTNs [1] and initiated the research efforts on the topic. DTN topologies are very sparse and the nodes are connected intermittently. Thus, the network suffers from frequent partitions and the probability that there will be an end-to-end path from a source node to a destination node is very low. DTNs are originally proposed for communication for the interplanetary Internet, however it has been applied in many different challenging environments with similar characteristics such as ad hoc and sensor networks, and vehicular networks.

Recently, DTN concept and technology has been introduced to sensor networks to address the challenges in data gathering and dissemination in mobile sensor networks with occasional connectivity. Delay Tolerant Mobile Sensor Networks (DTMSN) is a new type of sensor network based on DTN communication principles. DTMSNs have been recently studied due to the lack of appropriate mechanisms that can handle their unique characteristics. In a DTMSN, there could be many sensors attached on the mobile devices. For example, smartphones carried by people are a good example of nodes in a DTMSN with multiple sensors (e.g., accelerometer, barometer, camera etc.). Moreover, a group of people in a community with wearable sensor units on their body also forms a DTMSN. The connectivity between nodes can happen only when the devices are within their communication (e.g., WiFi, Bluetooth) range of each other. Thus, a loosely connected mobile sensor network topology is generated. Each sensor on the device generates different type of data and can be delivered to a sink node which can be located at a popular location to increase the likelihood of meeting with other nodes in the network [2]. Such sink nodes are also usually assumed to have no power problem compared to the regular nodes. Therefore, they can perform heavy processing on the collected data (e.g., filtering, aggregation). Moreover, they are usually equipped with powerful communication hardware.

In Fig. 1, a typical architecture for a DTMSN is illustrated. There can be nodes with different mobility behaviors. Some sensor nodes can be static and can only transmit data to mobile nodes that come to the range of them. Within mobile sensor nodes, some of them such as smartphones can be connected to the backbone network (e.g., cellular network) and communicate with each other. On the other hand, some of the mobile nodes such as wearable sensing units on humanbeings or animals [3], can only communicate to other mobile nodes and static nodes. The links between sensor nodes can also show constant and intermittent connectivity patterns. Most of the time, sensor nodes can only communicate with each other when they come to the range of each other. It is possible that some nodes (e.g., smartphones) can communicate with each other through backbone network. These nodes can also be referred to as high-end sink nodes [4]. Such nodes usually have sufficient power in their batteries so that they can collect, store and process the data from other sensor nodes. They also use their power for communication with other nodes through the backbone network with their powerful wireless transceivers they have.

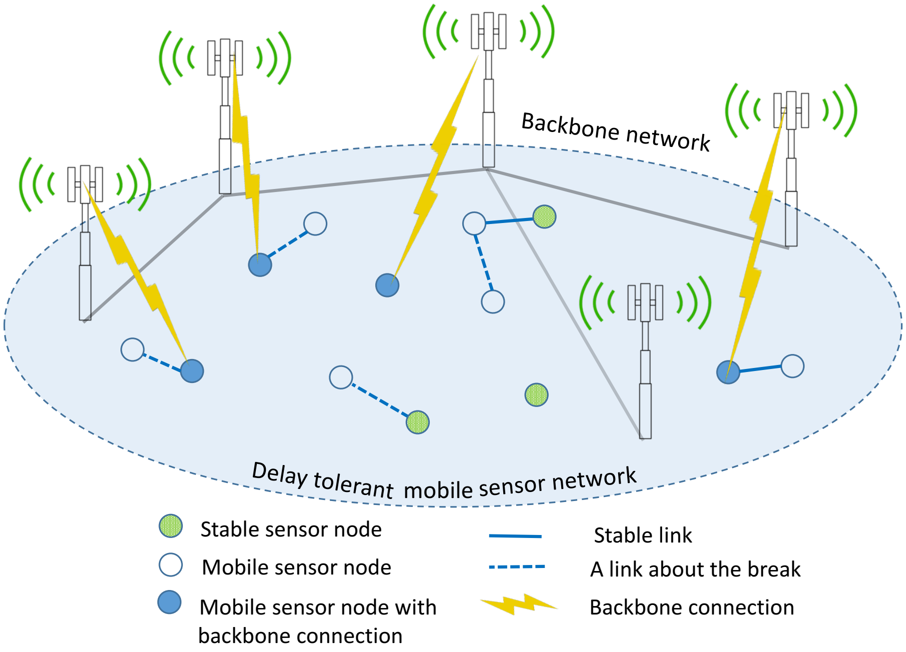

Fig. 1 Delay Tolerant Mobile Sensor Network architecture with different types of sensor nodes and varying links.

DTMSNs show similar properties as sensor networks such as short range of communication, limited computation capability and battery capacity. However, they also have the following features which are different than traditional sensor networks [8]:

- Mobility: The sensors and sinks are carried by the people who have different mobility patterns. This generates a very dynamic network topology and many partitions. Network structure is highly affected by the mobility yielding unstable link quality between nodes. On the other hand, mobility brings opportunities for reaching out other nodes in the network.
- Intermittent connectivity: The connectivity among nodes in a DTMSN is very low, thus a very sparse topology is created. Sensor nodes can only communicate to other nodes when they are in their communication ranges mutually, which occurs very limitedly.
- Delay-tolerant: Loose connectivity between nodes causes high delays in data delivery. However, depending on the requirements of the applications, this can be usually tolerable. Ubiquitous and pervasive data gathering could be exchanged in the expense of delays.
- Fault-tolerant: In order to increase the performance of communication, there can be multiple redundant copies of the same packet in the network. Such a policy

during data acquisition and routing towards the sink makes the network more robust and fault tolerant. Some of the packets can be lost or damaged, but the performance of data gathering and dissemination process does not worsen.

- Limited buffer: There can be multiple sensors on each node in a DTMSN. Similar to the sensor networks, each sensor has usually limited buffer or some sensors can share some limited memory. As the sensed data needs to be communicated to some high-end sink node without being deleted due to buffer problem, queue management is important and challenging in DTMSNs.

Even though DTMSNs show similar characteristics with other networking types, they differ from them in multiple aspects. Table 1 shows the comparison of a DTMSN with other networking types in terms of several features.

Table 1 Comparison of a DTMSN with other network types

	Topology	Mobility	Connectivity	Density	Delay Tolerability
DTMSN	Very dynamic	Various speeds	Intermittently connected	Very sparse	High
WSN	Stable	Static	Mostly connected	Dense	Low
MANET	Slow	Low speeds	Mostly connected	Moderate dense	Low
VANET	Dynamic	High speeds	Mostly connected	High	Moderate

The primary focus of researchers studying on DTMSNs has been the routing problem. Due to the aforementioned characteristics, designing an effective routing algorithm and a data delivery scheme for DTMSNs is challenging. Many studies have been performed on how to handle the sporadic connectivity between the nodes of a DTN and provide a successful and efficient delivery of messages to the destination.

In this chapter, we study the routing challenges and solutions in DTMSNs. There are also other challenges such as developing efficient MAC protocols, queue management and scheduling schemes, which could be found in several surveys [7, 9, 2]. We categorize the routing algorithms developed for DTMSNs based on the deployment space of the network. In some studies [4] DTMSNs are categorized as networks with static sensors, networks with managed mobile nodes and networks with mobile sensors. However, we think that all these sensor types could be present in the same DTMSN at the same time. Thus, we categorize the DTMSNs based on the space they are deployed. In other words, we study terrestrial, underwater and flying DTMSNs with their own routing challenges and solutions.

The rest of the chapter is organized as follows. We discuss the routing challenges and solutions in Terrestrial Delay Tolerant Mobile Sensor Networks (T-DTMSN) in Section 2. Then, we look at the different challenges and solutions in Underwater Delay Tolerant Mobile Sensor Networks (U-DTMSN) in Section 3. As the third category, in Section 4, we discuss the differences in challenges and approaches proposed in Flying Delay Tolerant Mobile Sensor Networks (F-DTMSN). Then, the evaluation metrics used commonly for the performance analysis of routing algorithms in DTMSNs are presented in Section 5. Finally, we discuss the open research issues and provide a conclusion of the study in Section 6.

2 General (Terrestrial) Delay Tolerant Mobile Sensor Networks

In this section, we overview the routing algorithms proposed for DTMSNs. Most of the routing algorithms proposed generally for DTNs also apply to DTMSNs. Thus, we will study a mixed set of routing algorithms that could be applied in DTMSNs. In a DTMSN, at any given time instance, due to the high dynamic and sparse topology, the probability that there is an end-to-end path from a source to destination is low. Most of the nodes in a DTMSN are mobile and the connectivity between nodes is constructed only when the nodes come to the transmission range of each other. In a DTMSN, even though the connectivity of nodes is not constantly maintained, it can be still desirable to send a packet from a node to another node in the network. This requires the development of a routing protocol which aims to route the packets to destination node throughout the times the connections between the nodes are available. However, this cannot be achieved by traditional routing algorithms which assume the network is connected most of the time.

From routing perspective, this requires the usage of store-carry-and-forward paradigm. That is, to deliver a message to a destination (e.g., sink) node, the messages are stored at some nodes and carried until a node with better delivery probability is encountered. The message is then forwarded to the encountered node. Such a mechanism is repeated at each hop until a node with a message copy meets the destination node.

In a standard network, since the nodes are connected most of the time, the routing protocol forwards the packets in a simple way. The cost of links between nodes are mostly known or easily estimated so that the routing protocol computes the best path to the destination in terms of cost and tries to send the packets over this path. Furthermore, the packet is only sent to a single node because the reliability of paths is assumed relatively high and mostly the packets are successfully delivered. However, in DTN like networks, routing becomes challenging because the nodes are mobile and connectivity is rarely maintained. The transient network connectivity needs to be of primary concern in the design of routing algorithms for DTNs. Therefore, routing of the packets is based on store-carry-and-forward paradigm. That is, when a node receives a message but if there is no path to the destination or even a connection to any other node, the message should be buffered in this current node and the upcoming opportunities to meet other nodes should be waited. Moreover, even a node meets with another node, it should carefully decide on whether to forward

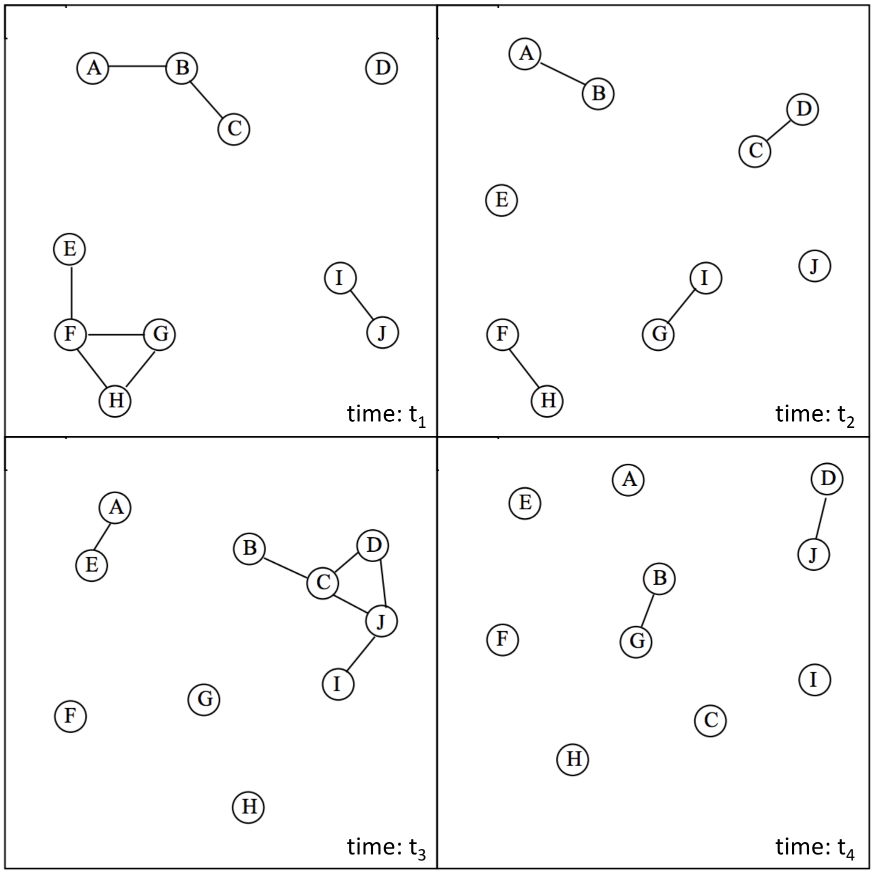

Fig. 2 Snapshots of the topology in a Delay Tolerant Mobile Sensor Network at four different times.

its message to that node. It is obvious that to forward a message to multiple nodes increases the delivery probability of a message. However, this may not be the right choice because it can cause a huge messaging overhead in the network which then causes redundant energy and resource consumption. On the other hand, sending a copy of the message to a few number of nodes uses the network resources efficiently but the message delivery probability becomes lower and the delivery delay gets longer. Consequently, it is clearly seen that there is a tradeoff between the message delivery ratio and the energy consumption and delivery delay in the network.

Hence, in the design of an efficient routing algorithm for DTMSNs, the following parameters need to be carefully considered: (i) the number of copies of each message that will be distributed to the network, and (ii) the determination of next hop nodes to which the message is either replicated or forwarded.

Consider the sample delay tolerant network illustrated in Figure 2. The figure presents different snapshots of the network topology showing connectivity between nodes at four different times. Assume node A has a message destined to node G. Looking at the snapshots, we can easily observe that delivery of the message could be achieved by node B at time t_4 if node A forwards the message to node B at time t_1. However, the key point here is how node A will know that node B will meet the destination node before it meets the destination. What makes routing challenging in a DTMSN environment is to be able to make better decisions at contact times of nodes using only local information available at nodes.

Routing algorithms for T-DTMSNs could be classified based on the number of carriers of the message during routing. In some algorithms (i.e., single-copy) only one node carries the message at all times. In these algorithms, the messages are forwarded to other nodes which are estimated to have higher chance to meet the destination. One other common method used in the design of routing algorithms for T-DTMSNs is using multiple carriers of the message. A number of copies of the same message is generated and distributed to multiple nodes so that the delivery probability of the message is increased. Among these algorithms, while some of them distribute limited number of copies ([11, 12, 13, 14]) to other nodes in the network, some others [5] provide flooding like dissemination of the message copies. Different than replication based algorithms, some algorithms [39, 40] use erasure coding technique for efficient routing of messages. They first process and convert a message of k data blocks into a large set of blocks such that the original message can be constructed from a subset those blocks. Then each of these encoded blocks are distributed to the other nodes in the network and the delivery of sufficient number of blocks is expected to reconstruct the original message. Finally, some routing algorithms that are designed based on social network features of these networks can also be considered as a different category. Table 2 summarizes these categories and highlights their characteristics and comparison. Next we will discuss the details of some of the state-of-the-art algorithms in each category.

Table 2 Routing algorithm categories for T-DTMSNs.

	Number of carriers	Distribution Technique	Pros	Cons
Replication based	Multiple	Copying to met node	Fast delivery	Could be costly
Utility based	Single	Forwarding to met node	Cost-efficient	Could be slow
Erasure Coding based	Multiple	Distributing encoded blocks to met node	More reliable	Computation cost
Social based	Multiple/ Single	Forwarding/Copying to met node	Network structure aware	Human based networks only

2.1 Replication based Routing

The very initial algorithm in this category is Epidemic Routing [5]. This field has attracted considerable attention after this study and other routing algorithms are developed to mitigate the problems of Epidemic Routing. Epidemic Routing protocol works based on principles of spreading of an epidemic. That is, when the nodes in the network come to the range of each other, nodes exchange pair-wise information (i.e., their ids, ids of messages they hold) and the decide which messages to share/exchange to one another. For example, at the meeting of two nodes, a summary vector that holds the index of all messages in the first node is transferred to the second node. Second node then checks its own message ids and detects the messages which are not available in its own buffer and requests the transfer of these messages from the first node. Once the messages are exchanged, two nodes have the same messages (if their contact duration allows to do so). Following this approach at every pairwise node meeting, one of the copies of the message eventually reaches the destination. As the result, the fastest spread of copies is achieved yielding the shortest delivery time and the minimum delay.

The major drawback of this approach is excessive usage of bandwidth, buffer space and energy due to the greedy spreading of copies. Therefore, several algorithms were proposed to limit the distribution of the message copies while still achieving high delivery rates. One of the first examples of controlled flooding based routing algorithms is Spray and Wait [11] algorithm. The idea is to distribute only a limited number of copies of the same message to other nodes in the network and wait for the delivery of one of the copies of the message at the destination. The number of copies of message can be determined based on the tolerance of the application to the delay. A similar algorithm based on controlled flooding is also presented in [6]. These algorithms cannot achieve the same delivery rate as epidemic routing, however they can achieve high delivery rates within the application's expectation, while keeping the cost of routing at very low levels. In [13, 14], Bulut et. al present the spraying based algorithm with multiple periods. That is, the copies that will be sprayed to the network are not given to relay nodes at the beginning. First, a portion of copies are sprayed and delivery with them is waited for some time. If the delivery does not occur, in the second period, more copies are sprayed to the network. The goal is to reduce average copy count sprayed to the network while still achieving a delivery ratio by a delivery deadline. The idea is illustrated in Figure 3.

In replication based routing mainly unicasting is used. In sparse networks like DTMSNs, at a meeting of nodes, there are usually two nodes. Thus, unicasting is sufficient. However, in some scenarios, there can be some group of nodes meeting together and such cases can provide the opportunity to benefit from multicasting. In [22] and [23], multicasting based routing algorithms are presented. It is shown that with sufficient knowledge of network dynamics and topology information, the routing performance can increase with respect to unicasting algorithms.

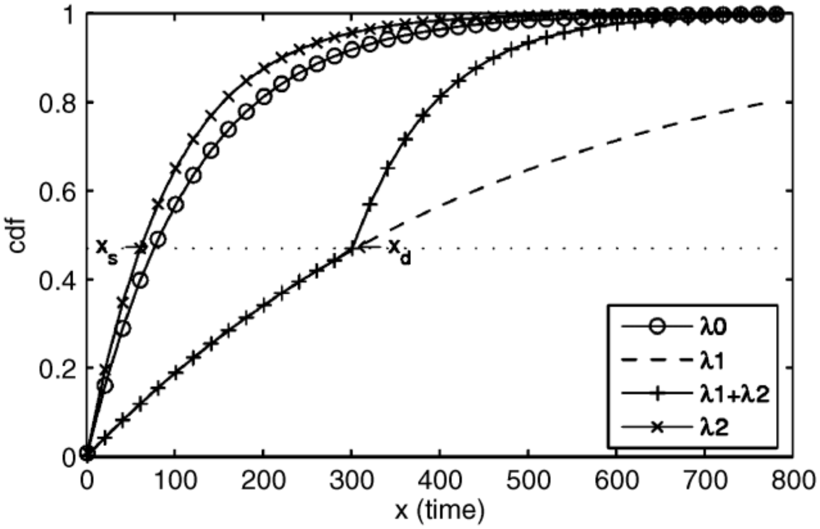

Fig. 3 The cdf of delivery probability of a message when different copies are sprayed in two different periods. [14].

2.2 Utility or Single-copy based Routing

In utility based routing, there is usually one message copy of the message. The delivery of the message is achieved through forwarding of the message between nodes towards the destination or sink node. The utility here is the key factor that determines the forwarding of the message.

One of the first studies that address the weakness of epidemic routing and uses only one copy is Probabilistic ROuting Protocol using History of Encounters and Transitivity (Prophet) [17]. The protocol depends on the observation that the mobility of nodes in a DTMSN is not random and can be predictable based on repeating patterns. For example, if a node has visited a location previously several times, the probability that it will visit that location again is high. A probabilistic routing model is proposed based on this predicted mobility assumption. Each node maintains a vector of delivery predictability which shows the likelihood of meeting with other nodes. The vector is calculated based on historical meetings, and transitivity and aging mechanisms. At the meeting of two nodes the messages are forwarded to nodes with high predictability. The delivery rate increases with the proposed idea compared to epidemic routing while achieving lower communication overhead. However, the overhead is still high, thus, there are many variants of Prophet algorithm [18, 19] have been studied later, some of which include hybrid solutions with replications of the message.

Following the same forwarding idea, several algorithms, mainly differing from each other in terms of delivery probability computation, are proposed. For example, the time passed since the last encounter of nodes with the destination is utilized in some previous work [12, 16] and the messages are forwarded toward nodes with recent meetings with the destination. Moreover, in MaxProp [10] prioritization of the schedule of packets that will be transmitted to other nodes or that will be dropped from the buffer (due to overflow) is also taken into account in the routing decisions, thus better performance results are achieved when the nodes have limited resources (e.g., buffer, bandwidth).

In some of the single copy based routing algorithms, the traditional shortest path based routing idea is also utilized within the DTMSN definition. That is, a virtual graph is constructed with links depending on the quality defined by a utility function. Then the shortest path is determined from the source to the destination node and the message is routed over that path. Two example metrics used to define the link qualities are minimum expected delay (MED [23]) and minimum estimated expected delay (MEED [24]). These metrics computes the expected waiting time plus the transmission delay between each pair of nodes based on historical meetings. The first one uses the future contact schedule, the second one uses only observed contact history. Here, note that, in shortest path based routing, forwarding decisions can be made at three different points: i) at source, ii) at each hop, and iii) at each contact. As the utilization of recent information increases from the first to the last one, better forwarding decisions can be made. On the other hand, maintaining the link qualities with latest information and computing the updated shortest paths require more time. In [25], the impact of correlation between the meetings of a node with other meetings on shortest path based routing is studied. Depending on the condition of meeting with the node at previous hop, the meeting time with the next hop node is calculated, thus, the algorithm is called conditional shortest path routing. Even though such an extended algorithm improves the delivery ratio of shortest path based routing algorithms, there is lots of computation overhead and it may be hard to obtain link quality for each pair of nodes accurately when there is less training data of node meetings in the past. The correlation concept has also been used to develop efficient utility based routing algorithms [45, 46] in different scenarios.

There are also hybrid algorithms that use both the idea of multiple copies of the same message and utility based forwarding. Spray and Focus [12] algorithm is an example of hybrid routing protocols which basically follows the principles of Spray and Wait [11] but improves the process in Wait duration by further forwarding the message copy to nodes that can meet the destination with high likelihood than the current holder. A similar hybrid approach is also presented in [15].

2.3 Erasure Coding based Routing

In order to strengthen the robustness of the routing algorithm against failures and increase its reliability, coding based routing algorithms have been developed. They spread many small size messages and increase the message delivery probability. Erasure coding technique is one of the powerful coding techniques used for that purpose. The approach offers a procedure which first divides a message into k data blocks and then converts these k blocks into a set of ϕ encoded blocks such that the original message can be constructed from any $k+\varepsilon$ subset of ϕ blocks. ϕ is usually set as a multiple of k and $R = \phi/k$ is defined as replication factor of erasure coding. ε is considered as a very small value and can change in different coding algorithms.

Once the source node creates such encoded blocks, it distributes them to different nodes in the network and delivery of at least $k+\varepsilon$ of them to the destination is waited for the delivery of the original message. The benefit of erasure coding based routing is that it will not be affected much if one of the pieces are lost or corrupted as in not-fragmented based routing. Moreover, the large files will be splitted into small blocks and the routing and delivery of them will be conducted separately and over different paths towards destination. All these features make the routing more robust and resilient, which is crucial in several application scenarios such as Virtual Reality (VR).

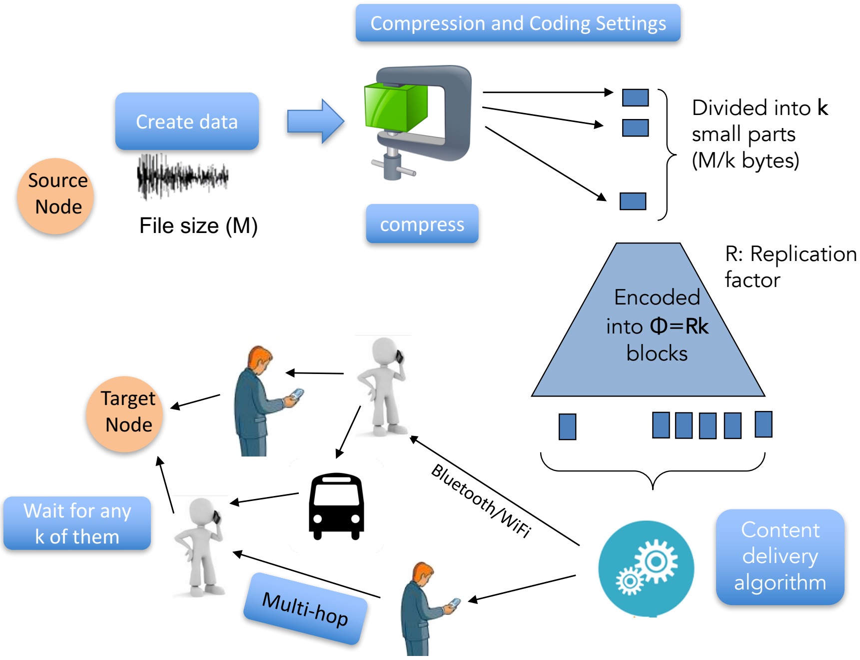

Fig. 4 Erasure coding based content delivery and routing from source to target node.

Let $p(t)$ denote the cdf of a single node's probability of meeting the destination at time t after it is generated at the source device, which will be determined based on the pairwise relations collected. The probability that there are already k messages gathered at the destination node at time t is:

$$P(t,\Phi) = \sum_{i=k}^{\Phi} \binom{\Phi}{i} p(t)^i (1-p(t))^{\Phi-i}$$

Once the source device generates the data, it will first divide the file into small blocks of some fixed size, then with some replication factor, it will encode all these blocks to obtain the set of blocks to be forwarded towards destination. As the device meets other nodes, the blocks will be transmitted to other devices as contact duration permits. Figure 4 shows the summary of this coding and routing process from the data generated at the source device towards the target node.

The idea is introduced in [39], by Wang et. al with extensive discussion on its advantages over multicopy-based routing approach. In later studies, variants of the approach is also presented. In [40, 41], the optimal distribution of the encoded blocks over multiple delivery paths and multiple time frames are studied. In [42], a similar approach with a focus on non-uniform distribution is presented. Its application in a secure routing approach is also discussed in [44].

In [8], Replication-Based Efficient Data Delivery Scheme (RED), which is specifically designed for routing of messages in delay/fault tolerant mobile sensor networks, is presented. The RED scheme uses the erasure coding technique to reach the target data delivery rate with small messaging overhead. There are two phases of the scheme. In the first phase called data transmission, the decision of when and where to transmit the data messages are made depending on the delivery probabilities of nodes. In the second phase called message management, optimal parameters (i.e., number of blocks to encode and the redundancy level) of erasure coding technique are determined depending on the current delivery probability of the node. The RED scheme offers a simple joint message manipulation and queue management at intermediate nodes as the source computes the necessary parameters and intermediate nodes just use them. However, the optimal parameters of erasure coding calculated at the source node based on its own delivery probability to the sink node. This may result in inaccurate optimal results, especially when the source node is away from the sink [8]. To avoid these problems (e.g., increased complexity in message transmission and queue management) of RED scheme, authors propose a better scheme called Message Fault Tolerance-Based Adaptive Data Delivery Scheme (FAD). In FAD scheme, the design is based on the message fault tolerance which is defined as the probability that at least one copy of the message is delivered to the sink by other sensor nodes in the network. Unlike the RED scheme, when a message is transmitted to next hop node, the message copy at the forwarder node is not deleted to increase the redundancy and tolerant to fault of messages. Therefore, FAD scheme can also be considered as a hybrid routing algorithm that benefits from both replication based routing and erasure coding based routing. Similar hybrid approaches are also studied in several other works [43]. The message is not only encoded into small number of multiple message blocks but these blocks are also replicated to further enhance the delivery rate.

Next, we compare the erasure coding based approach to replication based (non-coding) approaches. As Figure 5 shows, erasure coding can increase worst-case delivery ratio compared to replication based routing (where BS stands for binary spraying and SS stands for source spraying of coded blocks). Moreover, it makes the system more reliable as the loss of a packet does not decrease the delivery ratio as it does in replication based routing approach. Thus, each of these routing approaches can show better performance (i.e., high reliability, delivery ratio) in different environments.

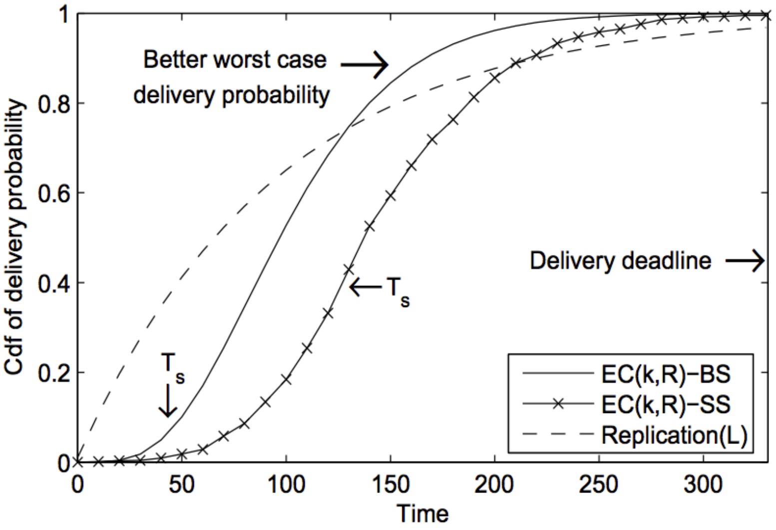

Fig. 5 The cdf of delivery probability with erasure coding compared to replication (non-coding) based approach [14].

2.4 Social based Routing

In some DTMSN applications, the sensor nodes are carried by human beings, thus, a human-oriented data gathering occurs. That is, the sensors on the devices attached to human body collect data related to human body, human movement, or environment in the current location of the person to achieve a goal (e.g., flu tracking, air quality detection) [32]. The data can be sensed through different devices including dedicated wearable sensing units and smartphones with multiple sensor types. With the rise of Internet of Things (IoT) and widespread adoption of smartphones, such an application forms a very large DTMSN network. Thus, designing effective routing algorithms for such networks depends on understanding human mobility and meeting characteristics (see Figure 6 showing the highly varying node encounter patterns). To this end, several studies [35, 36, 37, 38, 45] have been conducted on real mobile user data and identified regularities, repetitions and correlations on these human networks.

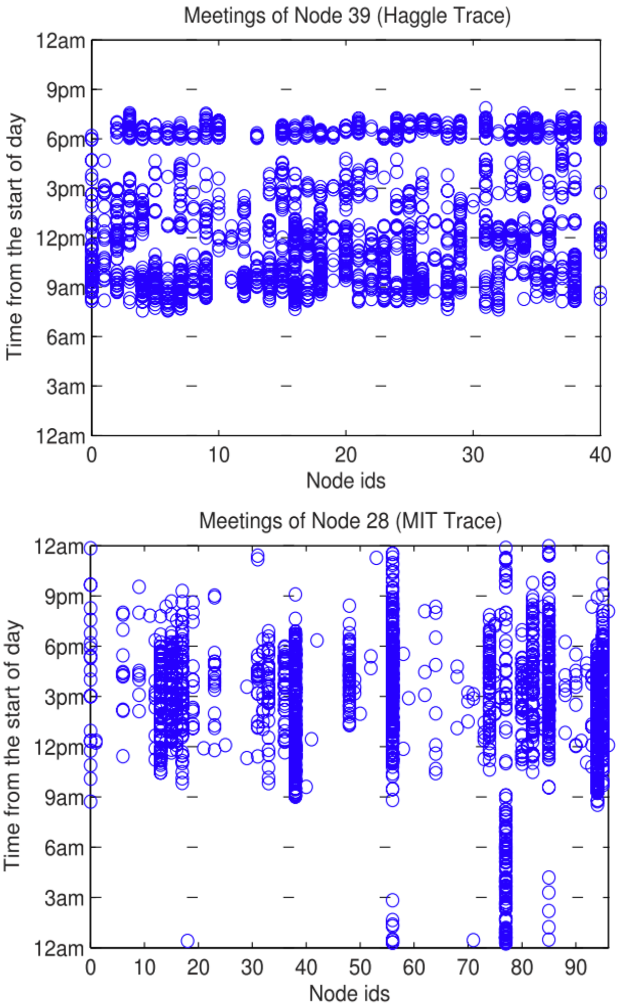

Fig. 6 Encounter distributions of selected nodes with other nodes in two different mobile social network dataset [26].

In [34] a new data gathering approach specifically designed for human-oriented DTMSNs is proposed. The approach estimates the delay of data transmission for each sensor node based on historical relations of humans and selectively replicates the message to sensor nodes with lower estimated delivery delay. Thus, the algorithm can be considered as a hybrid algorithm that uses replications and social relation analysis.

There are also some routing algorithms that aim to improve the routing performance based on social network properties (e.g., betweenness, centrality, degree) of the network topology. In [27], the authors use two different social network metrics to increase routing performance. First, the social similarity metric is used to detect nodes in the same community. Second, they use egocentric betweenness metric to identify the nodes that stay in between different communities and take bridging role. Then, to route a packet towards the destination or sink node, when two nodes meet each other, first a joint utility function comprised of these two metrics is calculated for each destination node. Then, the node with higher value for the message's destination is given the message.

In [33], each node is assumed to have two rankings: global and local. While the former denotes the popularity (i.e., connectivity) of the node in the entire society, the latter denotes its popularity within its own community. Messages are forwarded to nodes having higher global ranking until a node in the destinations community is found. Then, the messages are forwarded to nodes having higher local ranking within destination's community. A distinction between local community members and others is also made in [28] and the distribution of message copies is optimally balanced between these two kinds of encountered nodes. In [29], a community-based epidemic forwarding scheme is introduced. First, the community structure of the network is detected using local information of nodes. Then, the message is forwarded to each community through gateways. An interesting algorithm based on the analysis of friendship relations between nodes is also proposed in [26]. Additionally, in some other studies, several different properties of social networks are considered. In [30], irregular deviations from the habitual activities of nodes are considered and it is shown that the worst case performance of routing can be improved by scattering multiple copies of a message in the network such that even deviant (less frequently encountered) nodes will be close to at least one of these copies. In [31], the effect of socially selfish behavior of nodes on routing is studied.

3 Underwater Delay Tolerant Mobile Sensor Networks

Recently, the area of Underwater Wireless Sensor Networks (UWSNs) has attracted a lot of attention due to high demand and rapid advances in technology. For example, mines in terrestrial areas are getting exhausted and mines in undersea terrains, which could be easier to reach than those in earth, are explored. Therefore, to detect such underwater terrain, sensors are distributed around the field of interest. Designing efficient routing protocols in UWSNs is challenging due to unique characteristics [64, 65, 66]: (i) they rely on acoustic communication (rather than RF) in which the channels offer low bandwidth and long propagation delays [67], (ii) the network topology is very dynamic as the nodes move with water currents and some nodes can be underwater autonomous vehicles, (iii) localization in underwater is difficult [68, 69], thus routing algorithms that need location information may not perform well, and (iv) energy efficiency in the design of routing algorithm should be a priority as the underwater sensor nodes are usually battery powered, and could be hard to recharge or replace them in such challenging environment.

Moreover, even though UWSNs have similar basic functions of sensor networks including sensing, measuring and information collection, they may also show characteristics of delay/disruption-tolerant networks (DTNs). In Figure 7, a sample Underwater Delay Tolerant Mobile Sensor Network (U-DTMSN) is illustrated. The sink node usually floats on the water, while the other sensors are located at different depths of the water. There are also some mobile (e.g., underwater robot) nodes that move around and collect data from other nodes. The links between nodes can be stable and intermittent, thus some delay is tolerable in the communication between nodes. Once the sink node receives the data from other nodes, it can connect to satellite or onshore station via RF link.

Due to the movement of sensors (e.g., triggered by flows in water), the network topology could vary a lot and can be hard to control. Such uncertainty in the network structure makes the routing of information from sensors towards the sink a challenging task. The routing protocols designed for them needs to consider additional constraints compared to the routing algorithms in other DTN types. There is a significant amount of literature on routing protocols for U-DTMSNs. In Table 3, we provide a categorization of them, highlight their characteristics and compare. Next, we will discuss a few routing protocols in each category.

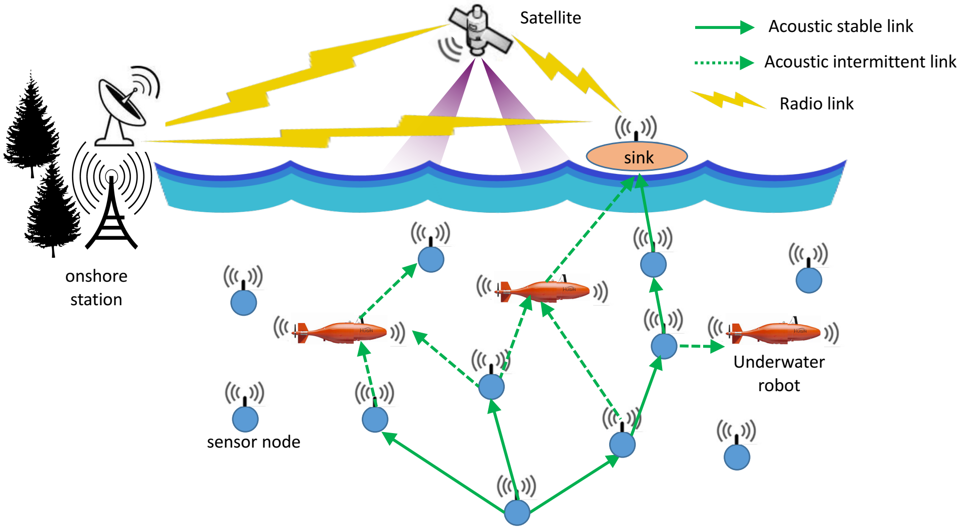

Fig. 7 Underwater Delay Tolerant Mobile Sensor Network ecosystem.

Table 3 Routing algorithm categories for U-DTMSNs.

	Key feature	Pros	Cons
Geographical	Uses locations of sensors	Efficient in dense networks	May not perform well with sparsity
Mobile relays based	Uses autonomous vehicles	Fast delivery	Costly
Clustering based	Cluster heads	Structural	Limited application
Opportunistic and Prediction based	Learning based	Works well with sparsity	Needs warm-up time and training

3.1 Geographical routing

The algorithms in this category utilize location information of the sensors for efficient design. In [49], Depth-based Routing (DBR) is proposed. It only utilizes the two dimensional depth information of sensors. Multiple sink nodes are also considered on the water surface to increase the data collection process. The depth information is exploited to decide the next sensor node (i.e., qualified forwarder) to forward the packets. If the difference between the depth of the nodes is larger than a threshold, the node close to surface is considered as qualified forwarder. Even though such distance based approach help limit the number of forwardings of the packets and reduce the energy consumption, it takes into account only one parameter which leads some drawbacks. For example, with a large depth threshold, delivery ratio can decrease as there will be limited number of forwarders. That's why DBR algorithm will work properly only in dense networks, which may not be the case especially in UWSNs. Pressure routing protocol proposed in [63] is similar to DBR but it uses the pressure levels at the sea floor as the key factor rather than depth. There are also other geographical routing algorithms [52, 53, 54] which use location information of nodes. However, they have either high communication cost or cannot perform well in sparse networks.

3.2 Mobile relays (AUVs) based Routing

Another type of algorithms get benefit from mobile relays in their designs. For example, Delay tolerant Data Dolphin (DDD) algorithm that is proposed in [50] assumes that in addition to many static sensor nodes in the seabed there are also some mobile sensor nodes (or Autonomous Underwater Vehicles (AUVs) [70]) called dolphins. The static sensors collect information from seabed and forward them to the closest dolphin node around. Dolphin nodes move randomly in the area and send beacons to static sensors periodically to notify them about their presence. Receiving the packets from static nodes, dolphin nodes delivers them to the base station once they come to the range of it. Clearly, the performance of this type of routing will depend on the number of dolphin nodes and their characteristics (e.g., speed, range). With smaller number of dolphin nodes, there will be delay in packet delivery to sink node (i.e., base station). On the other hand, with more dolphin nodes, the cost will increase. Thus, such a tradeoff requires careful determination of the number of dolphin nodes based on available resources and performance requirements. There are also other studies [71] which use AUVs to aid the routing.

In [66], a Link-state-based Adaptive Feedback routing (LAFR) algorithm is introduced using the 3D directions of underwater topology. The study analyzes the routing in underwater networks with symmetric and asymmetric links (which is determined by looking at the presence of the same node in downstream and upstream node tables) and proposes an energy-efficient routing mechanism considering this separation. Impact of multiple factors (e.g., angle, radius, interference, beam width) on link states are considered. Once the link states are determined, the routing query proceeds according to the routing information at each node. There is also a feedback mechanism, which is used to update the routing information. As the feedback can take the path with both the symmetric and asymmetric links.

3.3 Clustering based Routing

Classical cluster based routing algorithms are also proposed for U-DTMSNs. In Minimum-Cost Clustering Protocol (MCCP) [55], clusters are formed based on total energy required to send data to cluster heads, residual energy at clusters and the distance between the cluster head and the sink. Even though MCCP can improve energy efficiency and prolong the network life, it does not support routing over multiple hops. Location-based Clustering Algorithm for Data (LCAD) [56] gathering is another clustering based algorithm which divides the entire network into 3D grids and determines the cluster head accordingly. Thus, the performance of LCAD heavily depends on the position of cluster heads, but with optimal locations, it can reduce energy consumption during data transmission phase.

3.4 Opportunistic and Prediction based Routing

There are also several algorithms which focus on opportunistic nature of Delay Tolerant Mobile Sensor Networks. The communication between nodes is predicted based on several parameters. Prediction-Based Delay-Tolerant Protocol (PB-DTP) [57] is one of the algorithms in this category. It uses a unique prediction approach rather than relying on round trip time (RTT), which may not be accurately estimated due to the obstructions and different propagation rates in the underwater environment. The algorithm can show tolerance to long and varying delays, and disruptions between nodes. It predicates a value for a sensor node if its data does not reach to sink node (instead of having the node retransmit the data). Sensors are formed into clusters. If the packet from a node to cluster head is lost, cluster head predicts it based on previous data values of the sensor node, or its neighbor sensor nodes' data values. Once the cluster head node receives actual data from a sensor node, it replaces the predicted value and use the actual data value for accurate predictions in the future. PBDTP reduces data traffic in the network and uses the network resources efficiently. However, if the actual data arrival interval from the nodes becomes large, the accuracy of the proposed approach reduces dramatically.

In order to increase the delivery chance, multiple copies of the same message are sent towards the sink node. However, this can yield high overhead in the network. Thus, in some studies, the tradeoff between high delivery rates and cost are analyzed. In [60, 61], a Redundancy-Based Adaptive Routing (RBAR) protocol is proposed. The essential part of that algorithm is a sensor node is allowed to hold a packet as long as possible until it is necessary to make a copy. By this way, the algorithm aims to control the replication procedure and the copy count in the network, but in the meantime achieving a guaranteed in-time delivery and better resource consumption. Binary tree based copy distribution scheme is utilized, and the packet replication process is modeled as a continuous Markov chain process with an absorbing state. The minimum number of copies required to guarantee a certain level of delay is also calculated. This is similar to the concept of Spray-and-Wait algorithm where only a certain number of copies of the message is delivered. Moreover, in [14], the idea is extended with multiple period concepts. The algorithm can achieve a good trade-off among delivery ratio, delay and energy consumption.

Machine learning techniques are also utilized extensively in some algorithms. In [62], a reinforcement learning based algorithm (i.e., Q-learning) is used to deal with uncertainty dynamics of UWSNs. The states are associated with each packet holding a specific packet and actions are defined based on the forwarding of the packets between nodes. The reward in Q-learning model is defined based on residual energy and density. With increasing density, the forwarding probability increases but also the energy consumption. Thus, a weighted equation is used. A Markov-Decision-Process (MDP) based model is used to define the relationship between the states of Q-learning, then an energy-efficient and adaptive routing protocol is proposed. Even though the algorithm increases performance, the learning algorithm needs some warm-up time to learn and converge, thus there might be unsatisfactory performance in some cases.

Even though multi-copy based algorithms offer improved delivery ratios potentially, due to the inconsistent nature of UWSNs, some copies can be lost and do not provide benefit while increasing the cost. Thus, there are also studies which focus on routing with single copy based messages. In [58, 59], Guo et. al proposes Prediction-Assisted Single-copy Routing (PASR), in which single copy of the message is routed towards the sink over a more reliable route. The concept of aggressive chronological projected graph (ACPG), which basically integrates dynamic topology change in the same graph, is introduced. Once the historical information about links between nodes are collected and ACFG is formed (which could also be considered as mobility pattern of nodes), the optimal routes are determined for the single copy of the message. For example, the nodes with more neighbors are selected to be part of the routes as they can provide more stable connectivity with their neighbors. Other factors considered for optimal route selection include, geographic location, contact periodicity, inter-contact time distribution, and contact probability.

4 Flying Delay Tolerant Mobile Sensor Networks

Delay Tolerant Mobile Sensor Networks (DTMSN) can also consist of flying agents (e.g., unmanned aerial vehicles (UAV) or drones) in some scenarios. UAV systems can be operated remotely by human operators or can fly autonomously without carrying human personnel. Exploiting UAVs offers new flexible ways for many applications including military, search and rescue, public safety [103], transportation, wildfire management [73], wind estimation [74], disaster monitoring [75], remote sensing [76] and traffic monitoring [77]. Missions can be completed with UAVs faster and with less cost. Some example missions could be listed as monitoring of a disaster area and conducting an assessment of the destruction, video dissemination, victim localization through thermal cameras or wireless signals from phones, and providing immediate aid to stranded people in rural areas through video service etc..

Flying DTMSN (F-DTMSN) is a special network type that could be considered as a subtype of Mobile Ad hoc NETworks (MANET), Wireless Sensor Networks (WSN), Delay Tolerant Networks (DTN) and Vehicular Adhoc NETworks (VANET). However, they have unique features which make them different than these networks. As the communication range of UAVs are much higher than the nodes (e.g., smartphone carried by people) in terrestrial DTMSNs, the distances between nodes in a F-DTMSN are very large and the degree of nodes could be much higher than in other networking scenarios. As the drones are agile and can move fast the network topology changes very dynamically. This results in drones that connect intermittently, a characteristic of links between nodes in DTNs.

Figure 8 shows a sample Flying Delay Tolerant Mobile Sensor Network ecosystem. There are ground sensors and UAVs flying. UAVs can carry information from one subnet to another subnet with some delay. UAVs fly around obstacles, thus, the links between UAVs are mostly intermittent. There can also be a ground satellite station which communicates with flying nodes and collects data. UAVs' range is limited thus they can only communicate with the other nodes in their range. Moreover, the communication between UAVs can be achieved over multiple hops.

The nodes need to communicate through peer-to-peer connections (similar to MANETs) for data exchange, synchronization and coordination with each other. They collect data from environment through their sensors and transmit to a sink node (i.e., ground station) similar to the Wireless Sensor Networks (WSN). In a multi-UAV network, there might be many sensors located on UAVs and each sensor may

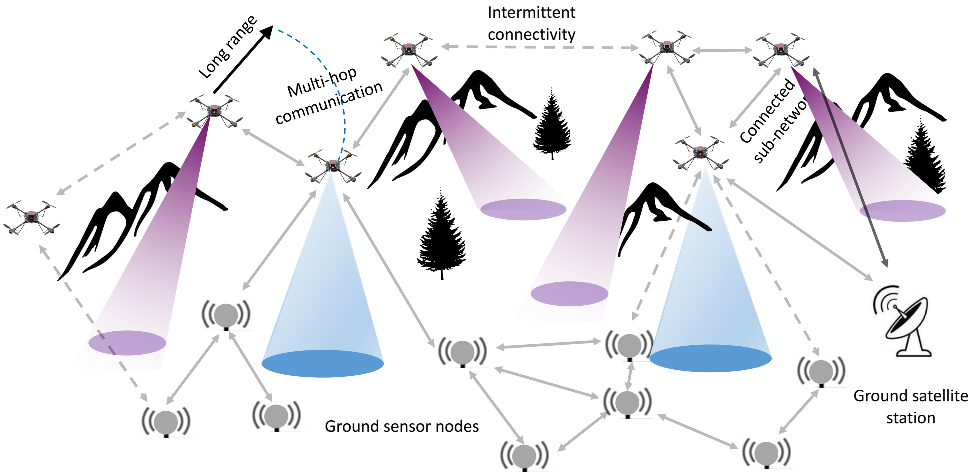

Fig. 8 Flying Delay Tolerant Mobile Sensor Network ecosystem.

have different data dissemination requirements. Moreover, the energy constraints of UAVs are much greater than the energy constraints of nodes in other nodes (e.g., a typical UAV may have battery capacity of 5200mAh, and a flight time of about 25 minutes [84] while for example a smartphone in terrestrial DTMSN can last a day). All these features make them show some similarities with other networking types (DTN, WSN, MANET, VANET), however, the routing protocols developed for these traditional networks do not work well due to their unique aggregate characteristics.

The advantages of F-DTMSNs with multiple UAVs can be summarized as follows [72, 78]:

- Low cost: UAVs involved in such networks are usually small, thus their acquisition and maintenance cost is low compared to other large size flying objects [87].
- High-speed: UAVs can handle missions that human beings cannot handle and as the number of UAVs in the network increases the speed of completing the missions becomes faster [89].
- Large-scalability: UAVs can connect multiple ground sensors and provide communication opportunity with minimum cost. This increases the scalability of the sensor networks and size of coverage area [88].
- High-survivability: When multiple UAVs are involved in a F-DTMSN, failure of one UAV could easily be fixed through the reassignment of tasks to other UAVs and the operation survivability increases.
- Small radar cross-section: Multi-UAV based sensor networks can produce very small radar cross-sections, instead of having one large radar cross-section. This will be critically important especially in military based applications [90].

On the other side, there are some challenges to design routing algorithms for these networks. The initial studies and experiments for flying networks focused on adaptions of existing routing protocols designed originally for other networks types (e.g., MANET). However, most of the such algorithms do not perform well in F-DTMSN due to the unique challenges in these networks (e.g., high mobility and very dynamic link quality). Therefore, recently new algorithms that try to address these challenges are proposed specifically for these networks. Table 4 summarizes a categorization of these algorithms and their comparison. In the rest of this section, we survey over the routing algorithms in each category.

Table 4 Routing algorithm categories for F-DTMSNs.

	Key feature	Pros	Cons
Routing table based	Link quality Predetermined paths	Low latency	May not be scalable
Hierarchical based	Cluster heads	Scalable	May not perform well with high dynamicity
Geographical	Uses locations of nodes	Works well with less dynamicity	May not perform well with high dynamicity

4.1 Routing table based Routing

In routing table based algorithms, there is a routing table maintained to utilize in making forwarding decisions. These algorithms could be proactive and reactive protocols and mainly depend on the rationale used in MANET routing. However, the algorithms are usually adapted to satisfy the requirements of F-DTMSNs. For example, in [95], a novel routing algorithm that promises low latency for F-DTMSN is proposed. The algorithm is the extended version of the well-known Optimized Link State Routing (OLSR) protocol [81]. Directional antennas are utilized to find the next relay node to improve the performance of OLSR. The sensor node chooses a set of multipoint relay (MPR) nodes such that the two hop neighbors can be covered. The proposed Directional OLSR (or D-OLSR) protocol reduces the number of MPRs with directional antennas, thus reduces the messaging overhead and decreases end-to-end latency, which is an important parameter for F-DTMSNs. Another extension of OLSR protocol is proposed in [82], with a name Predictive OLSR (P-OLSR). It uses GPS information available at UAVs and link quality with ETH metric [83]. It is currently the only F-DTMSN-specific routing technique with an available Linux implementation.

There are also different variants of these algorithms proposed. In [91], a time slotted on-demand routing protocol is proposed for F-DTMSNs. It is indeed time-slotted version of well-known Ad-hoc On-demand Distance Vector Routing (AODV) algorithm [92]. In AODV, the nodes send the control packets on random access mode, while in [91] dedicated time slots are used and only one node is allowed to send data packets. The algorithm increases packet delivery ratio and reduces packet collisions, however this happens at the expense of some decrease in usable network bandwidth.

In a UAV network, it is also important to collect data from multiple sensors on UAVs. Thus, data-centric routing algorithms can also be adopted for them (where the routing tables are static). As the UAVs could be developed specifically for some mission, the hardware (e.g., sensor) and capabilities of UAVs could be different at every mission. This makes it difficult to use a routing algorithm for any mission. Data-centric routing algorithms can be used to address this challenge, for example, through a publish-subscribe mechanism [98]. The model links the data producers (i.e., publishers) and data consumers (i.e., subscribers). The data collected from nodes towards the sink node are aggregated at intermediate nodes. Contrary to flooding like algorithms, only the registered data types are dispatched to the data consumers. Thus, rather than point-to-point transmission, point-to-multi-point data transmission model can be utilized. Data-centric communications are usually preferred on a network with smaller number of UAVs and with predetermined path plans. Thus, a very small portion of F-DTMSN scenarios may benefit from it.

4.2 Hierarchical/Clustering based Routing

There are several studies that target scalable routing for any network size of F-DTMSN. They basically use hierarchical structure consisting of clusters. Each cluster has a cluster head and all the nodes in its cluster communicate with that cluster head through direct communication link. The cluster head communicates with upper layer UAVs or satellites directly or indirectly. When a cluster head receives data from upper layers, it disseminates them to cluster members by broadcasting. Hierachical routing algorithms provide better performance when the target area and the number of nodes in the mission are high. However, there are critical design issues such as effective cluster formation in such dynamic networks. In [94], a mobility prediction based cluster formation algorithm is presented. As the UAVs are fast, the high mobility of nodes requires frequent updates to clusters. In [94], authors aim to address this challenge through a mechanism that predicts the topology updates of the network. Utilizing a dictionary trie structure prediction algorithm [96] and link expiration time mobility model, they model and predict the mobility of UAVs. The cluster head is selected as the node with the highest weighted sum of all models used. The results presented show that such a cluster head selection scheme increases the robustness of the cluster and cluster heads.

Another clustering algorithm for flying UAV networks is also proposed in [97]. The clusters are first formed on the ground station using geographical information of nodes and updated during the operation of the network. Cluster heads are selected from the nodes with high degree and long connection endurance. The cluster structure is updated based on the mission information. The simulation results presented in the study show that the stability of the network increases with the proposed clustering method and routing.

4.3 Geographical Routing

If the physical position of the nodes in the network could be retrieved via GPS sensors or other type of positioning techniques, geographical routing algorithms can also be utilized for F-DTMSNs. The algorithm uses the position of the source node and the destination to decide the forwarding strategy. There are some geographical or position based routing algorithms developed specifically for F-DTMSNs. In [93], Lin et. al propose Geographic Position Mobility Oriented Routing (GPMOR) algorithm. In GPMOR, the node movements of UAVs are predicted with a Gaussian-Markov mobility model and this information is exploited in determining the forwarding of packets. The results presented show that this algorithm can provide better latency and high packet delivery ratio compared to existing location based routing algorithms proposed for MANETs. While some studies claim the benefit of geographical routing for F-DTMNs, some also recommend to be cautious in applying them in F-DTMSNs. In [99], authors develop a simulation framework to study geographic routing algorithms in F-DTMSNs. Their simulation results illustrate that using only greedy geographic forwarding (such as Greedy Perimeter Stateless Routing (GPSR) [100]) is not fully reliable and a combination of other methods is necessary. In [101], the power of geographical routing is combined with routing table based (reactive) routing. A combined algorithm called Reactive-Greedy-Reactive (RGR) routing is presented to increase the performance further. The proposed RGR algorithm basically used both the location information of UAVs and reactive end-to-end paths in the decision process.

Designing efficient routing algorithms for F-DTMSNs is very challenging due to the unique features of them. Existing algorithms can only address some aspect of these networks and propose some adaptions to existing protocols to support routing in UAV networks. Thus, thorough and stable routing algorithms are still needed.

A F-DTMSN can be used to collect information from the sensors on UAVs. However, the data generation rates at these sensors together with their priority of collection at the sink node could be different. All the data collected from all these sensors needs to be routed towards the ground station (i.e., sink) over UAVs in multi-hop manner. Thus, collaboration between UAVs is important for coordination and collision avoidance. Designing new routing algorithms that can converge quickly in the highly dynamic F-DTMSN environment and can satisfy the needs of different data collection requirements is still an open research issue. In [78], authors discusses the potential of data-centric routing algorithms which can support multiple application scenarios simultaneously. However, it is not yet explored for F-DTMSNs.

Considering the characteristics of such networks, in the design of a routing algorithm, the following guidelines can also be considered. Routing tables can be hard to maintain in dynamic network topology environment, thus, an efficient and quickly adapting routing algorithm should not use routing tables in traditional manner. It should also need to consider the requirements of different sensors at UAVs and also intermittent connectivity patterns between UAVs. Thus, limited replication based routing algorithms whose benefit have been shown in DTN settings, can increase the performance of routing in F-DTMSNs. However, number of copies should be determined efficiently depending on the pairwise node relations [26, 14] and mechanisms that will stop copying somehow (through ACKs from destination node or with self-stopping mechanisms [104, 105]) should be developed. As UAVs can carry GPS devices, the location information of nodes is most of the time available. Thus, routing algorithm can be geographical. Finally, the remaining energy levels of the UAVs should be considered while assigning routing related tasks to UAVs. For example, a UAV with a packet to deliver to ground station will give preference to a neighbor UAV with more energy, however a UAV with less energy which is getting ready to visit ground station to be recharged can be preferable rather than another UAV that can provide multi-hop connectivity to ground station.

5 Performance Evaluation Metrics

In this part, we discuss the evaluation metrics utilized in assessing the performance of routing algorithms in Delay Tolerant Mobile Sensor Networks. At the end of this section, we also provide an overview of the performance of the algorithms presented in previous sections with respect to these metrics.

5.1 Average delivery ratio

Average delivery ratio is the ratio of packets received successfully at the sink node to the total number of packets originated from all source nodes. Since the network topology in a DTMSN could be very dynamic and there could be uncertainties about the links between the nodes, it is challenging to find the next sensor node that will lead the packets to the sink. There may not be a connection between the source and sink node at all. The routing (i.e., forwarding) decisions are made through current neighbors of the packet carrying node, however, the connection between neighbor nodes may be interrupted as they move and tranmission of the packets may fail. Thus, some of the packets may not arrive to the destination sink node and average delivery ratio for all messages can decrease. Average delivery ratio metric is used to ensure that the desired number of packets (i.e., information) is delivered to the sink, so that sensor network can function properly. Delivery ratio sometimes linked with some delivery deadline. Even though these networks are tolerant to delays, there is sometimes a deadline [13, 14] considered for the successful delivery of certain ratio of packets. In that case, the packets arriving to the sink node before the deadline needs to achieve a certain delivery ratio required by the application.

5.2 Average end-to-end delivery delay

The average end-to-end delay is another significant metric used in the evaluation of routing protocols. There can be multiple services in DTMSNs and an immediate demand can emerge for these services or applications at the sink nodes or between the sensor nodes. The communication between nodes is achieved via intermittently connected links. Thus, a delay occurs when a message from a sensor node to another node needs to be transferred. If there will be multiple hop communication, then the delays at each hop will accumulate and constitute the end-to-end delay. For all messages through the network, this will then be averaged to find the delay performance of the routing algorithm. End-to-end delay is critical metric that can also affect other factors in the network such as power consumption, and buffer utilization. As the network environment is challenging due to intermittently connected links, some messages can stuck at some nodes and new messages arriving to these nodes can cause dropping of messages.

5.3 Average delivery cost or messaging overhead

Delivery cost is usually defined as the number of copies of the message distributed during routing and/or the number of forwardings of the message copy happened between nodes. Whatever the mechanism used in the routing algorithm design (e.g., single copy, multiple copy), the delivery cost covers the communication cost between the nodes. This is also directly related to the energy consumption at nodes as the tranmission of a message and receiving at the other node requires energy. Thus, this metric also can be used to understand how energy efficient is the routing algorithm is. Routing algorithms should also be designed such that the energy consumption due to the routing is balanced among all nodes in the network. Fair routing [102] is one example algorithm designed primarily with this goal.

5.4 Routing Efficiency

In some studies [26], there is also a metric called routing efficiency used to evaluate the performance of routing algorithms and compare with others. Basically, this metric measures the ratio of delivery ratio to the number of copies or forwardings made throughout the routing of a packet. This gives the contribution of each copies or forwardings to the delivery ratio. For example, direct delivery method tries to achieve delivery with the copy at the source, so the cost is only one and happens at the time of delivery to destination. But the delivery ratio with direct delivery within a deadline can be very small as some node pairs may not even meet. Thus, routing efficiency of the direct delivery method will be equal to the delivery ratio, which is small. On the other hand, in epidemic routing, the delivery ratio will be very high and best possible among all algorithms. However, the cost will be very large too, as many message copies are generated and transferred over the radio between the nodes. Thus, the routing efficiency will be small too. However, there are algorithms which can provide high delivery ratios and low overheads. The routing efficiency for them will be high.

5.5 Network Lifetime

In any type of sensor networks, one of the important metrics regarding the network performance is its lifetime. Energy is consumed by different operations of the sensor network including the copying and forwarding of the messages during routing. Thus, routing algorithms should be designed in a way that it will contribute to the goal of prolonging the network lifetime. In Wireless Sensor Networks (WSN), network lifetime sometimes considered as the time until the first node dies or the time when the network is partitioned. However, in DTMSN systems, the nodes are not always connected, and death of one node does not cause a problem in the functioning of the routing algorithm as it is designed opportunistically. Thus, the network lifetime in DTMSN environment can be defined as the time after which there will not be any communication opportunity between nodes. In other words, there can be nodes moving around but they may not come to the range of each other at all, thus, such nodes cannot send their messages to other nodes.

Comparing the performance of the algorithms presented in previous sections in terms of the presented metrics, we observe a very broad range of performance. For example, the algorithms in each category may achieve a better average delivery ratio than the algorithms in other categories depending on the application scenario and network characteristics. A general observation is that the algorithms in which the messages are carried by many carriers provides faster delivery, yielding higher average delivery ratios and shorter end-to-end delivery delays. Moreover, hybrid algorithms that utilize multiple information about nodes can overcome the other algorithms in terms of average delivery ratio and delay. On the other hand, these algorithms may generate high delivery cost, thus routing efficiency can reduce dramatically. If the buffer space of nodes is limited and the generated message traffic is very high, due to the drops at nodes, this may even yield lower delivery ratios and longer delays. Therefore, the algorithms that aim a delivery with single carriers of the message may overcome these multi-carrier algorithms in such environments in terms of all metrics. Network lifetime, which is basically defined by other performance metrics, could also be very different for the algorithms in each category depending on the application.

6 Conclusion

In this chapter, we give a survey of Delay Tolerant Mobile Sensor Networks (DTMSN) and the routing algorithms proposed for them. The challenges in a DTMSN, which is a sensor network with low connectivity among nodes and sparse topology, is different than the challenges in traditional WSNs. Thus, to address the requirements, several routing algorithms are proposed or traditional ones are adapted. After summarizing the characteristics of DTMSNs and their unique features and differences from other network types, we present the routing algorithms proposed for them under three categories. We classify such networks as terrestrial, underwater and flying DTMSNs and discuss their specific constraints and challenges. Finally, we present the performance metrics used in the evaluation of routing algorithms proposed for DTMSNs.

We believe that the following issues are still open research questions and worth studying.

- A DTMSN may have different performance requirements based on the application. High delivery ratio of packets with low messaging overhead has been considered as the most significant parameter in routing performance. However, in some applications, there might be other concerns such as prioritized delivery for some significant (e.g., emergency related, keyframes in a video file) messages. There is very less focus on routing with such special requirements and needs further study.
- The key factor that defines the routing performance is the ability to select the next hop nodes properly. Different mechanisms that analyze and model the relations between nodes and mobility of nodes are utilized to be able to predict nodes' future encounter patterns accurately and give reasonable forwarding decisions. However, the behavior of mobile agents carrying the sensor nodes can be very different depending on the type of agent (e.g., human, animal). Thus, efficient routing algorithms in heterogeneous environments have still need to be studied.
- Most of the research results have been obtained through specific mobility model based or real-trace driven simulations. There is a lack of real DTMSN testbeds for real world evaluation of proposed systems. In such a testbed, there should be heterogeneous nodes (static, mobile) and the number of nodes should be easily updatable.

References

1. Fall, K. (2003, August). A delay-tolerant network architecture for challenged internets. In Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications (pp. 27-34). ACM.
2. Wang, Y., Dang, H., and Wu, H. (2007). A survey on analytic studies of DelayTolerant Mobile Sensor Networks. Wireless Communications and Mobile Computing, 7(10), 1197-1208.

3. Juang, P., Oki, H., Wang, Y., Martonosi, M., Peh, L. S., and Rubenstein, D. (2002, October). Energy-efficient computing for wildlife tracking: Design tradeoffs and early experiences with ZebraNet. In ACM Sigplan Notices (Vol. 37, No. 10, pp. 96-107). ACM.
4. Wang, Y., and Wu, H. (2010). Delay-Tolerant Mobile Sensor Networks. In Encyclopedia On Ad Hoc And Ubiquitous Computing: Theory and Design of Wireless Ad Hoc, Sensor, and Mesh Networks (pp. 303-318).
5. Vahdat, A., and Becker, D. (2000). Epidemic routing for partially connected ad hoc networks, Technical Report CS-200006, Duke Univ., 2000.
6. Harras, K. A., Almeroth, K. C., and Belding-Royer, E. M. (2005, May). Delay tolerant mobile networks (dtmns): Controlled flooding in sparse mobile networks. In International Conference on Research in Networking (pp. 1180-1192). Springer Berlin Heidelberg.
7. Psaras, I., Wood, L., and Tafazolli, R. (2010). Delay-/disruption-tolerant networking: State of the art and future challenges. University of Surrey, Technical Report.
8. Wang, Y., and Wu, H. (2007). Delay/fault-tolerant mobile sensor network (dft-msn): A new paradigm for pervasive information gathering. IEEE Transactions on mobile computing, 6(9), 1021-1034.
9. Li, Y., and Bartos, R. (2014). A survey of protocols for intermittently connected delay-tolerant wireless sensor networks. Journal of Network and Computer Applications, 41, 411-423.
10. Burgess, J., Gallagher, B., Jensen, D., and Levine, B. N. (2006, April). MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks. In INFOCOM (Vol. 6, pp. 1-11).
11. Spyropoulos, T., Psounis, K., and Raghavendra, C. S. (2008). Efficient routing in intermittently connected mobile networks: the multiple-copy case. IEEE/ACM transactions on networking, 16(1), 77-90.
12. Spyropoulos, T., Psounis, K., and Raghavendra, C. S. (2008). Efficient routing in intermittently connected mobile networks: The single-copy case. IEEE/ACM Transactions on Networking (ToN), 16(1), 63-76.
13. Bulut, E., Wang, Z., and Szymanski, B. K. (2008, November). Time dependent message spraying for routing in intermittently connected networks. In IEEE GLOBECOM 2008-2008 IEEE Global Telecommunications Conference (pp. 1-6). IEEE.
14. Bulut, E., Wang, Z., and Szymanski, B. K. (2010). Cost-effective multiperiod spraying for routing in delay-tolerant networks. IEEE/ACM Transactions on Networking (ToN), 18(5), 1530-1543.
15. Chen, L. J., Yu, C. H., Sun, T., Chen, Y. C., and Chu, H. H. (2006, September). A hybrid routing approach for opportunistic networks. In Proceedings of the 2006 SIGCOMM workshop on Challenged networks (pp. 213-220). ACM.
16. Dubois-Ferriere, H., Grossglauser, M., and Vetterli, M. (2003, June). Age matters: efficient route discovery in mobile ad hoc networks using encounter ages. In Proceedings of the 4th ACM international symposium on Mobile ad hoc networking and computing (pp. 257-266). ACM.
17. Lindgren, A., Doria, A., and Scheln, O. (2003). Probabilistic routing in intermittently connected networks. ACM SIGMOBILE mobile computing and communications review, 7(3), 19-20.
18. Xue, J., Li, J., Cao, Y., and Fang, J. (2009, February). Advanced PROPHET routing in delay tolerant network. In Communication Software and Networks, 2009. ICCSN'09. International Conference on (pp. 411-413). IEEE.
19. Sok, P., and Kim, K. (2013, October). Distance-based PRoPHET routing protocol in disruption tolerant network. In 2013 International Conference on ICT Convergence (ICTC) (pp. 159-164). IEEE.
20. Erramilli, V., Crovella, M., Chaintreau, A., and Diot, C. (2008, May). Delegation forwarding. In Proceedings of the 9th ACM international symposium on Mobile ad hoc networking and computing (pp. 251-260). ACM.
21. Chen, X., Shen, J., Groves, T., and Wu, J. (2009, August). Probability delegation forwarding in delay tolerant networks. In Computer Communications and Networks, 2009. ICCCN 2009. Proceedings of 18th Internatonal Conference on (pp. 1-6). IEEE.

22. Zhao, W., Ammar, M., and Zegura, E. (2005, August). Multicasting in delay tolerant networks: semantic models and routing algorithms. In Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking (pp. 268-275). ACM.
23. Jain, S., Fall, K., and Patra, R. (2004). Routing in a delay tolerant network (Vol. 34, No. 4, pp. 145-158). ACM.
24. Jones, E. P., Li, L., Schmidtke, J. K., and Ward, P. A. (2007). Practical routing in delay-tolerant networks. IEEE Transactions on Mobile Computing, 6(8), 943-959.
25. Bulut, E., Geyik, S. C., and Szymanski, B. K. (2010, June). Conditional shortest path routing in delay tolerant networks. In World of Wireless Mobile and Multimedia Networks (WoWMoM), 2010 IEEE International Symposium on a (pp. 1-6). IEEE.
26. Bulut, E., and Szymanski, B. K. (2012). Exploiting friendship relations for efficient routing in mobile social networks. IEEE Transactions on Parallel and Distributed Systems, 23(12), 2254-2265.
27. Daly, E. M., and Haahr, M. (2007, September). Social network analysis for routing in disconnected delay-tolerant manets. In Proceedings of the 8th ACM international symposium on Mobile ad hoc networking and computing (pp. 32-40). ACM.
28. Bulut, E., Wang, Z., and Szymanski, B. K. (2009, November). Impact of social networks on delay tolerant routing. In Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE (pp. 1-6). IEEE.
29. Li, F., and Wu, J. (2009, June). LocalCom: a community-based epidemic forwarding scheme in disruption-tolerant networks. In 2009 6th annual IEEE communications society conference on sensor, mesh and ad hoc communications and networks (pp. 1-9). IEEE.
30. Zhou, T., Choudhury, R. R., and Chakrabarty, K. (2009, August). Diverse routing: Exploiting social behavior for routing in delay-tolerant networks. In Computational Science and Engineering, 2009. CSE'09. International Conference on (Vol. 4, pp. 1115-1122). IEEE.
31. Li, Q., Zhu, S., and Cao, G. (2010, March). Routing in socially selfish delay tolerant networks. In INFOCOM, 2010 Proceedings IEEE (pp. 1-9). IEEE.
32. Wu, H., Wang, Y., Dang, H., and Lin, F. (2007). Analytic, simulation, and empirical evaluation of delay/fault-tolerant mobile sensor networks. IEEE Transactions on Wireless Communications, 6(9), 3287-3296.
33. Hui, P., Crowcroft, J., and Yoneki, E. (2011). Bubble rap: Social-based forwarding in delay-tolerant networks. IEEE Transactions on Mobile Computing, 10(11), 1576-1589.
34. Zhao, H., and Liu, M. (2012, June). A Delay-Based Routing Protocol for Human-Oriented Delay Tolerant Mobile Sensor Network (DTMSN). In 2012 32nd International Conference on Distributed Computing Systems Workshops (pp. 201-208). IEEE.
35. Song, C., Qu, Z., Blumm, N., and Barabsi, A. L. (2010). Limits of predictability in human mobility. Science, 327(5968), 1018-1021.
36. Song, C., Koren, T., Wang, P., and Barabsi, A. L. (2010). Modelling the scaling properties of human mobility. Nature Physics, 6(10), 818-823.
37. Becker, R., Cceres, R., Hanson, K., Isaacman, S., Loh, J. M., Martonosi, M., ... and Volinsky, C. (2013). Human mobility characterization from cellular network data. Communications of the ACM, 56(1), 74-82.
38. Bulut, E., and Szymanski, B. K. (2015, June). Understanding user behavior via mobile data analysis. In 2015 IEEE International Conference on Communication Workshop (ICCW) (pp. 1563-1568). IEEE.
39. Wang, Y., Jain, S., Martonosi, M., and Fall, K. (2005, August). Erasure-coding based routing for opportunistic networks. In Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking (pp. 229-236). ACM.
40. Jain, S., Demmer, M., Patra, R. and Fall, K. (2005, August). Using redundancy to cope with failures in a delay tolerant network. In ACM SIGCOMM Computer Communication Review (Vol. 35, No. 4, pp. 109-120). ACM.
41. Bulut, E., Wang, Z., and Szymanski, B. K. (2010, May). Cost efficient erasure coding based routing in delay tolerant networks. In Communications (ICC), 2010 IEEE International Conference on (pp. 1-5). IEEE.

42. Liao, Y., Tan, K., Zhang, Z., and Gao, L. (2006, July). Estimation based erasure-coding routing in delay tolerant networks. In Proceedings of the 2006 international conference on Wireless communications and mobile computing (pp. 557-562). ACM.
43. Chen, L. J., Yu, C. H., Sun, T., Chen, Y. C., and Chu, H. H. (2006, September). A hybrid routing approach for opportunistic networks. In Proceedings of the 2006 SIGCOMM workshop on Challenged networks (pp. 213-220). ACM.
44. Bulut, E., and Szymanski, B. K. (2013). Secure Multi-copy Routing in Compromised Delay Tolerant Networks. In Wireless Personal Communications. Springer.
45. Bulut, E., Geyik, S. and Szymanski, B. K. (2014). Utilizing Correlated Node Mobility for Efficient Routing in DTNs. In Elsevier Pervasive and Mobile Computing (PMC), pp 150-163, August, 2014.
46. Bulut, E., Geyik, S. and Szymanski, B. K. (2010). Efficient Routing in Delay Tolerant Networks with Correlated Node Mobility. In Proceedings of 7th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS), Nov, 2010.
47. Li, J., Li, Q., Qu, Y., and Zhao, B. (2011). An energy-efficient MAC protocol using dynamic queue management for delay-tolerant mobile sensor networks. Sensors, 11(2), 1847-1864.
48. Wang, Y., Dang, H., and Wu, H. (2007). A survey on analytic studies of DelayTolerant Mobile Sensor Networks. Wireless Communications and Mobile Computing, 7(10), 1197-1208.
49. Yan, H., Shi, Z. J., and Cui, J. H. (2008, May). DBR: depth-based routing for underwater sensor networks. In International Conference on Research in Networking (pp. 72-86). Springer Berlin Heidelberg.
50. Magistretti, E., Kong, J., Lee, U., Gerla, M., Bellavista, P., and Corradi, A. (2007, March). A mobile delay-tolerant approach to long-term energy-efficient underwater sensor networking. In 2007 IEEE Wireless Communications and Networking Conference (pp. 2866-2871). IEEE.
51. Vieira, L. F. M., Kong, J., Lee, U., and Gerla, M. (2006). Analysis of aloha protocols for underwater acoustic sensor networks. Extended abstract from WUWNet, 6.
52. Xie, P., Cui, J. H., and Lao, L. (2006, May). VBF: vector-based forwarding protocol for underwater sensor networks. In International Conference on Research in Networking (pp. 1216-1221). Springer Berlin Heidelberg.
53. Jornet, J. M., Stojanovic, M., and Zorzi, M. (2008, September). Focused beam routing protocol for underwater acoustic networks. In Proceedings of the third ACM international workshop on Underwater Networks (pp. 75-82). ACM.
54. Chirdchoo, N., Soh, W. S., and Chua, K. C. (2009, May). Sector-based routing with destination location prediction for underwater mobile networks. In Advanced Information Networking and Applications Workshops, 2009. WAINA'09. International Conference on (pp. 1148-1153). IEEE.
55. Wang, P., Li, C., and Zheng, J. (2007, June). Distributed minimum-cost clustering protocol for underwater sensor networks (UWSNs). In 2007 IEEE International Conference on Communications (pp. 3510-3515). IEEE.
56. Anupama, K. R., Sasidharan, A., and Vadlamani, S. (2008, August). A location-based clustering algorithm for data gathering in 3D underwater wireless sensor networks. In 2008 International Symposium on Telecommunications.
57. Zhang, Z., Lin, S. L., and Sung, K. T. (2010, October). A prediction-based delay-tolerant protocol for underwater wireless sensor networks. In Wireless Communications and Signal Processing (WCSP), 2010 International Conference on (pp. 1-6). IEEE.
58. Guo, Z., Wang, B., and Cui, J. H. (2010, December). Prediction assisted single-copy routing in underwater delay tolerant networks. In Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE (pp. 1-6). IEEE.
59. Guo, Z., Wang, B., and Cui, J. H. (2013). Generic prediction assisted single-copy routing in underwater delay tolerant sensor networks. Ad hoc networks, 11(3), 1136-1149.
60. Guo, Z., Colombi, G., Wang, B., Cui, J. H., Maggiorini, D., and Rossi, G. P. (2008, January). Adaptive routing in underwater delay/disruption tolerant sensor networks. In Wireless on Demand Network Systems and Services, 2008. WONS 2008. Fifth Annual Conference on (pp. 31-39). IEEE.

61. Guo, Z., Peng, Z., Wang, B., Cui, J. H., and Wu, J. (2011, August). Adaptive routing in underwater delay tolerant sensor networks. In Communications and Networking in China (CHINACOM), 2011 6th International ICST Conference on (pp. 1044-1051). IEEE.
62. Hu, T., and Fei, Y. (2010, August). An adaptive and energy-efficient routing protocol based on machine learning for underwater delay tolerant networks. In 2010 IEEE International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (pp. 381-384). IEEE.
63. Lee, U., Wang, P., Noh, Y., Vieira, L. F. M., Gerla, M., and Cui, J. H. (2010, March). Pressure Routing for Underwater Sensor Networks. In INFOCOM (pp. 1676-1684).
64. Akyildiz, I. F., Pompili, D., and Melodia, T. (2005). Underwater acoustic sensor networks: research challenges. Ad hoc networks, 3(3), 257-279.
65. Chitre, M., Shahabudeen, S., and Stojanovic, M. (2008). Underwater acoustic communications and networking: Recent advances and future challenges. Marine technology society journal, 42(1), 103-116.
66. Zhang, S., Li, D., and Chen, J. (2013). A link-state based adaptive feedback routing for underwater acoustic sensor networks. IEEE Sensors Journal, 13(11), 4402-4412.
67. Partan, J., Kurose, J., and Levine, B. N. (2007). A survey of practical issues in underwater networks. ACM SIGMOBILE Mobile Computing and Communications Review, 11(4), 23-33.
68. Erol-Kantarci, M., Mouftah, H. T., and Oktug, S. (2010). Localization techniques for underwater acoustic sensor networks. IEEE Communications Magazine, 48(12), 152-158.
69. Chandrasekhar, V., Seah, W. K., Choo, Y. S., an Ee, H. V. (2006, September). Localization in underwater sensor networks: survey and challenges. In Proceedings of the 1st ACM international workshop on Underwater networks (pp. 33-40). ACM.
70. Seah, W. K., Tan, H. X., Liu, Z., and Ang, M. H. (2005). Multiple-UUV approach for enhancing connectivity in underwater ad-hoc sensor networks. In Proceedings of OCEANS 2005 MTS/IEEE (pp. 2263-2268). IEEE.
71. Yoon, S., Azad, A. K., Oh, H., and Kim, S. (2012). AURP: An AUV-aided underwater routing protocol for underwater acoustic sensor networks. Sensors, 12(2), 1827-1845.
72. Tareque, M. H., Hossain, M. S., and Atiquzzaman, M. (2015, September). On the Routing in Flying Ad hoc Networks. In Computer Science and Information Systems (FedCSIS), 2015 Federated Conference on (pp. 1-9). IEEE.
73. Barrado, C., Messeguer, R., Lpez, J., Pastor, E., Santamaria, E., and Royo, P. (2010). Wildfire monitoring using a mixed air-ground mobile network. IEEE Pervasive Computing, 9(4), 24-32.
74. Cho, A., Kim, J., Lee, S., and Kee, C. (2011). Wind estimation and airspeed calibration using a UAV with a single-antenna GPS receiver and pitot tube. IEEE transactions on aerospace and electronic systems, 47(1), 109-117.
75. Maza, I., Caballero, F., Capitn, J., Martnez-de-Dios, J. R., and Ollero, A. (2011). Experimental results in multi-UAV coordination for disaster management and civil security applications. Journal of intelligent and robotic systems, 61(1-4), 563-585.
76. Xiang, H., and Tian, L. (2011). Development of a low-cost agricultural remote sensing system based on an autonomous unmanned aerial vehicle (UAV). Biosystems engineering, 108(2), 174-190.
77. Semsch, E., Jakob, M., Pavlicek, D., and Pechoucek, M. (2009, September). Autonomous UAV surveillance in complex urban environments. In Web Intelligence and Intelligent Agent Technologies, 2009. WI-IAT'09. IEEE/WIC/ACM International Joint Conferences on (Vol. 2, pp. 82-85). IET.
78. Bekmezci, I., Sahingoz, O. K., and Temel, . (2013). Flying ad-hoc networks (FANETs): A survey. Ad Hoc Networks, 11(3), 1254-1270.
79. Cheng, C. M., Hsiao, P. H., Kung, H. T., and Vlah, D. (2007, March). Maximizing throughput of UAV-relaying networks with the load-carry-and-deliver paradigm. In 2007 IEEE Wireless Communications and Networking Conference (pp. 4417-4424). IEEE.
80. Rosati, S., Kruelecki, K., and Traynard, L. (2013, December). Speed-aware routing for UAV ad-hoc networks. In 2013 IEEE Globecom Workshops (GC Wkshps) (pp. 1367-1373). IEEE.

81. Clausen, T., and Jacquet, P. (2003). Optimized link state routing protocol (OLSR) (No. RFC 3626).
82. Rosati, S., Kruelecki, K., Heitz, G., Floreano, D., and Rimoldi, B. (2016). Dynamic routing for flying ad hoc networks. IEEE Transactions on Vehicular Technology, 65(3), 1690-1700.
83. De Couto, D. S., Aguayo, D., Bicket, J., and Morris, R. (2005). A high-throughput path metric for multi-hop wireless routing. Wireless Networks, 11(4), 419-434.
84. Gupta, L., Jain, R., and Vaszkun, G. (2015). Survey of important Issues in UAV communication networks. IEEE Communications Surveys and Tutorials, 18(2), 1123-1152.
85. de Freitas, E. P., Heimfarth, T., Netto, I. F., Lino, C. E., Pereira, C. E., Ferreira, A. M., ... and Larsson, T. (2010, October). UAV relay network to support WSN connectivity. In Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2010 International Congress on (pp. 309-314). IEEE.
86. Futahp, A., Koucheryavy, A., Paramonov, A., and Prokopiev, A. (2015, July). Ubiquitous sensor networks in the heterogeneous LTE network. In 2015 17th International Conference on Advanced Communication Technology (ICACT) (pp. 28-32). IEEE.
87. Chao, H., Cao, Y., and Chen, Y. (2007, August). Autopilots for small fixed-wing unmanned air vehicles: A survey. In 2007 International Conference on Mechatronics and Automation (pp. 3144-3149). IEEE.
88. Morse, B. S., Engh, C. H., and Goodrich, M. A. (2010, March). UAV video coverage quality maps and prioritized indexing for wilderness search and rescue. In Proceedings of the 5th ACM/IEEE international conference on Human-robot interaction (pp. 227-234). IEEE Press.
89. Yanmaz, E., Costanzo, C., Bettstetter, C., and Elmenreich, W. (2010, December). A discrete stochastic process for coverage analysis of autonomous UAV networks. In 2010 IEEE Globecom Workshops (pp. 1777-1782). IEEE.
90. To, L., Bati, A., and Hilliard, D. (2009, March). Radar Cross Section measurements of small Unmanned Air Vehicle Systems in non-cooperative field environments. In 2009 3rd European Conference on Antennas and Propagation (pp. 3637-3641). IEEE.
91. Forsmann, J. H., Hiromoto, R. E., and Svoboda, J. (2007, April). A time-slotted on-demand routing protocol for mobile ad hoc unmanned vehicle systems. In Defense and Security Symposium (pp. 65611P-65611P). International Society for Optics and Photonics.
92. Perkins, C., Belding-Royer, E., and Das, S. (2003). Ad hoc on-demand distance vector (AODV) routing (No. RFC 3561).
93. Lin, L., Sun, Q., Li, J., and Yang, F. (2012). A novel geographic position mobility oriented routing strategy for UAVs. Journal of Computational Information Systems, 8(2), 709-716.
94. Zang, C., and Zang, S. (2011, December). Mobility prediction clustering algorithm for UAV networking. In 2011 IEEE GLOBECOM Workshops (GC Wkshps) (pp. 1158-1161). IEEE.
95. Alshabtat, A. I., Dong, L., Li, J., and Yang, F. (2010). Low latency routing algorithm for unmanned aerial vehicles ad-hoc networks. International Journal of Electrical and Computer Engineering, 6(1), 48-54.
96. Konstantopoulos, C., Gavalas, D., and Pantziou, G. (2006, December). A mobility aware technique for clustering on mobile ad-hoc networks. In International Conference on Distributed Computing and Networking (pp. 397-408). Springer Berlin Heidelberg.
97. Liu, K., Zhang, J., and Zhang, T. (2008, November). The clustering algorithm of UAV networking in near-space. In Antennas, Propagation and EM Theory, 2008. ISAPE 2008. 8th International Symposium on (pp. 1550-1553). IEEE.
98. Ko, J., Mahajan, A., and Sengupta, R. (2002). A network-centric UAV organization for search and pursuit operations. In Aerospace Conference Proceedings, 2002. IEEE (Vol. 6, pp. 6-2697). IEEE.
99. Shirani, R., St-Hilaire, M. Kunz, T., Zhou, Y., Li, J., and Lamont, L. (2011). The performance of greedy geographic forwarding in unmanned aeronautical ad-hoc networks. In Communication Networks and Services Research Conference (CNSR). 2011 Ninth Annual. IEEE.
100. Karp, B., and Hsiang-Tsung K. GPSR: Greedy perimeter stateless routing for wireless networks. Proceedings of the 6th annual international conference on Mobile computing and networking. ACM, 2000.

101. Shirani, R., et al. Combined reactive-geographic routing for unmanned aeronautical ad-hoc networks. Wireless Communications and Mobile Computing Conference (IWCMC), 2012 8th International. IEEE, 2012.
102. Pujol, J. M., Lopez, T., and Rodriguez, P. Fair routing in delay tolerant networks. INFOCOM 2009, IEEE. IEEE, 2009.
103. Merwaday, A. and Guvenc, I. UAV assisted heterogeneous networks for public safety communications. Wireless Communications and Networking Conference Workshops (WCNCW), pp. 329-334, 2015. IEEE.
104. Chen, Z., and Chao C. Self-stopping epidemic routing in cooperative wireless mobile sensor networks. Wireless and Mobile Computing, Networking and Communications (WiMob), 2016 IEEE 12th International Conference on. pp. 1-7, 2016. IEEE.
105. Dhungana, A. and Bulut, E. (2017). Timely Information Dissemination with Distributed Storage in Delay Tolerant Mobile Sensor Networks, in INFOCOM MiseNet Workshop 2017, Atlanta, May, 2017. IEEE.