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Delay/disruption tolerant mobile *ad hoc* networks: latest developments

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Summary

There is much research activity in the emerging area of delay/disruption tolerant networks (DTN) in the past few years. DTNs pose many new challenges, and protocols designed for wired Internet or wireless mobile *ad hoc* networks do not work properly in DTNs. Routing is one of the key components in DTNs and the message ferry (MF) approach has been drawn a lot of attention to support routing in DTNs. Besides the underlying routing protocols, issues in transport layer are also very important and need to be addressed for DTNs. Recently, many new routing protocols, including unicast using the MF approach, inter-region routing and multicast, have appeared in the literature. There are also a few works addressing issues in the transport layer. This paper provides an overview on recent developments including message ferrying, multicast support, inter-region routing, and transport layer issues. It also points out some open research issues and intends to motivate new research and development in this area.

KEY WORDS: delay tolerant networks; multicasting; inter-region routing; message ferrying; unicast; anycast; DTN

1. Introduction

In mobile ad hoc networks (MANETs), the constant movement of nodes often results in network partitions. In these disconnected networks, applications must tolerate delays beyond conventional IP forwarding delays and these networks are referred to as delay/disruption tolerant networks (DTN). Due to the unique characteristics of the DTNs, protocols developed for wired Internet and MANETs do not work properly and sometimes do not work at all. New protocols must be developed for DTNs. In Reference [1], routing protocols for unicast in DTNs have been reviewed and since its publication, many new routing protocols have appeared in the literature. There are still many open issues that need to be resolved for DTNs to be successful. Due to space limitation, in this paper, we discuss the following four areas and review related works addressing these issues.

(a) When networks become disconnected, extra nodes, referred to as message ferry (MF), can be

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added to facilitate message delivery. The main challenge in MF-based approaches is determining how many ferries should be used and determining the ferry's route so that a certain objective function is optimized.

(b) In many application scenarios, nodes form cluster, referred to as region, and these clusters are sometimes disconnected. In inter-region routing for DTNs, major issues such as naming, name-binding, path selection, protocol translation, and reliability control must be addressed.

(c) Multicasting in DTNs is a considerably different and challenging problem. The multicast semantics (group membership management) should be redefined for DTNs. The design of multicast routing algorithms (when and where to forward) in DTNs also faces new challenges.

(d) In DTNs, for end-to-end communication, the Transmission Control Protocol/Internet Protocol (TCP/IP) does not work well because of long link latency and often lack of end-to-end connectivity. User Datagram Protocol (UDP) provides no reliability service and cannot 'hold and forward'. For a source-to-destination data delivery, the intermediate nodes must be involved in the transport layer control. With the absence of an end-to-end connectivity, the key focuses on transport protocol design are congestion control and reliability.

In Tables I–IV, we compare and summarize recent papers to address these four issues and detailed description of the protocols are discussed in the paper.

The rest of the paper is organized as follows. In Section 2, we review several unicast routing approaches using MF. In Section 3, several inter-regional routing protocols are discussed. Routing protocols for multicast are presented in Section 4. We present work on related issues in the transport layer in Section 5. Section 6 concludes the paper with some discussion on potential open research topics.

2. Message Ferrying for Unicast

In wireless MANETs, there usually are mismatches between available capacity and demand. When such a mismatch occurs, one way to add capacity is to increase the number of extra nodes carrying bundles in the network. In certain cases, the network consists of several islands which are not connected; special nodes are needed to deliver messages between islands. These extra nodes are referred to as *Message Ferries* (MFs). Similar to their real-life analogs, MFs move around the deployment area and take responsibility for carrying data between nodes. The main idea behind the Message Ferrying approach is to introduce non-randomness in the movement of nodes and exploit such non-randomness to help deliver data. The main challenge in MF-based approaches is determining how many ferries should be used and the route that ferry traverses so that a certain objective function is optimized. In the following, we review several message forwarding mechanisms using message ferrying in DTNs.

2.1. Ferry Route is Fixed and Known

In Reference [2], the authors describe an MF approach for data delivery in sparse networks. It is assumed that the ferry moves faster than nodes. In addition, it is

Table I. Summary of protocols developed based on the message ferry approach.

	Ferry route	Main features	Remarks
NIMF [2]	Fixed, and known by all the nodes	Nodes proactively move close to ferry to communicate	—
FIMF [2]	Default is fixed, but adjustable	Ferry adjusts its route to meet nodes	—
ED [4]	To be determined	Ferry visits nodes according to message's deadlines	Single ferry
EZF [4]	To be determined	Nodes make reservations to ferry, ferry visits nodes according QoS requirements	Single ferry
FKLAS [5]	To be determined	Fixed *k*-look ahead, after there are *k* or more packets waiting, the ferry will determine a route to visit these nodes	Single ferry
DLAS [5]	To be determined	Dynamic look ahead, similar to FKLAS, but the ferry also visits nodes with deadlines	Single ferry
SIRA [6]	To be determined	All ferries follow the same route, with different timing, the route is obtained using a solution for TSP and an iterative refinement method	Multiple ferries
MURA [6]	To be determined	It first determines the number of ferries needed, then each ferry's route is determined using SIRA	Multiple ferries

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Table II. Summary of protocols for inter-region routing.

	Scenario	Identifier	Name binding	Main features
Generic DTN [15]	Stationary DTN	*Name tuples* {Region Name, Entity Name}	*Late binding*	Routes are comprised of a cascade of time-dependent *contacts*
EDIFY [16]	Mobile DTN	Tuple (GID, PID)	Role-based addressing and multiple namespaces	Supports policy-based routing
Tetherless computing [17]	Mobile DTN	GUID	HLR, VLR, and LLR	*Custodian* acts as always-available proxy for intermittently connected mobile hosts
Messenger scheduling [14]	Mobile DTN	—	—	Use a dedicated set of messengers to relay messages between regions

assumed that nodes are equipped with a long-range radio which is used for transmitting control messages. Note that while the ferry is able to broadcast data to all nodes in the area, the transmission range of nodes' long-range radios may not necessarily cover the whole deployment area due to power constraints. Two variations of the MF schemes are developed, depending on whether ferries or nodes initiate non-random proactive movement. In both schemes, nodes can communicate with distant nodes that are out of range by using ferries as relays.

In the Node-Initiated MF (NIMF) scheme, ferries move around the deployed area according to specific routes and communicate with other nodes they meet. The ferry route is known by nodes, for example, periodically broadcast by the ferry or conveyed by other out-of-band means. With knowledge of ferry routes, nodes periodically and proactively move close to a ferry and communicate with that ferry. As the sending node approaches the ferry, it forwards its messages to the ferry which will be responsible for delivery. The trajectory control mechanism of the node determines when it should proactively move to meet the ferry for sending or receiving messages. In the Ferry-Initiated MF (FIMF) scheme [2], ferries move proactively to meet nodes. Initially the ferry follows a specific default route and periodically broadcasts its location to nodes using a long-range radio. When a node finds the ferry is nearby and wants to send or receive messages *via* the ferry, it sends a Service Request message to the ferry using its long-range radio. This message contains the node's location information. Upon reception of a request message, the ferry adjusts its trajectory to meet the node. To guide the ferry movement, the node occasionally transmits location update messages to notify the ferry of its new location. When the ferry and the node are close enough, they exchange messages *via* short range radios. After completing the message exchange with the node, the ferry moves back to its *default route*. They also specify the node notification protocol and ferry trajectory control heuristics.

2.2. Determination of the 'Optimal' Route for the Ferries

In the work mentioned above, it is assumed that the ferry route and the number of ferries are fixed and

Table III. Summary of protocols for multicasting in DTNs.

	Semantics model	Main features	Remarks
UBR [18]	TM, TD, and CMD	Using unicast service	Less efficient
BBR [18]	TM, TD, and CMD	Flood the messages into the network	—
TBR [18]	TM, TD, and CMD	Using a tree to forward messages	Tree can be static or dynamic
GBR [18]	TM, TD, and CMD	Using a set of forwarding group	—
OS-multicast [20]	TM	Dynamic tree-based multicast	A receiver may receive multiple copies
CAMR [21]	Static or dynamic join/leave	Context aware, using node location and velocities	—
MFER [12]	If a node belongs to a group	Ferry broadcasts the message, all nodes relay the message	—
MFGR [12]	when a message is generated,	Only nodes in a group can relay	—
Dynamic [12]	it is the destination	Dynamically switch between MFER and MFGR	—

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Table IV. Summary of transport layer protocols.

	Scenario	Main features
Custody transfer [15]	Generic DTN	Utilizes hop-by-hop transfer of reliable delivery responsibility
LTP [26]	Generic DTN	Provides retransmission-based reliability over links characterized by extremely long RTTs and/or frequent interruptions in connectivity. LTP is a point-to-point protocol
LTP-T [27]	Generic DTN	Carry a destination identifier, consider fragmentation and congestion at intermediate nodes on a path
Autonomous congestion control [28]	Generic DTN	Use an economic pricing model and propose a rule-based congestion control mechanism
Transport over DTMN [29]	Mobile DTN	Four different reliability approaches: *hop-by-hop, active receipt, passive receipt*, and *network-bridged receipt* are introduced

known. Determining the ferry route and how many ferries should be used is important topic in MF-based approaches. In the following, we review some of the ferry route selection methods.

2.2.1. Single ferry case

When there is a single ferry, one problem is how to design good or optimal ferry routes, given the node positions (stationary nodes) and their communication requirements. The ferry route problem consists of finding an optimal route such that the bandwidth requirements are met and the average delay is minimized. A heuristic to solve this problem is proposed in Reference [3] by breaking it into two subproblems. The first one seeks to find a route that minimizes the average delay for the expected traffic matrix without considering the bandwidth requirements. Well-known approaches for the Traveling Salesman Problem (TSP) are used. The second subproblem extends the route generated in the first subproblem, if necessary, to meet the bandwidth requirements. More detailed description of the algorithms is given in the paper.

In Reference [4], two ferry route schemes are presented. In the first scheme, referred to as the earliest deadline (ED) scheme, the ferry maintains a list of nodes that need to be visited either because messages need to be picked up or dropped off. This list is ordered based on the deadlines of the messages (assuming that the reservation message indicates the message deadlines). After the ferry has visited the current node, it picks the node with the earliest deadline to visit next. In the second scheme which is referred to as the Elliptical Zone Forwarding (EZF) scheme, the overall average delay is minimized while attempting to maintain a high Quality of Service (QoS) satisfied ratio for urgent messages (which is defined as the fraction of delivered urgent messages that meet the deadlines). The ferry maintains a list of destinations that need to be visited and another list of reservations that it has received (i.e., nodes with messages that need to be picked up). Currently, in the EZF scheme, higher service priority is given to those messages that have been picked up over those that are waiting to be picked up. After the ferry has visited a node, it checks its destination list and decides if there is any node in the reservation list that it can visit before visiting a node in the destination list with the earliest deadline.

However, in Reference [5] the authors identify that there is a weakness in the EZF scheme that prevents it from achieving high delivery ratio. Accordingly, they design two new, lookahead ferry route scheduling schemes that provide better delivery performance than the EZF scheme. The two lookahead schemes are: (a) the fixed k-lookahead scheme (FKLAS) and (b) the dynamic lookahead scheme (DLAS). The authors evaluate the impacts of message deadlines, service priority, traffic models, and different k-lookahead values on the delivery performance of these ferry route design schemes. Numerical results indicate that (a) the delivery ratio improves when service priority is turned on, (b) higher delivery ratio is achieved with a sensor-like traffic model compared to a random traffic model, (c) higher delivery ratio is achieved with less stringent message deadlines. Simulation results also indicate that the DLAS achieves the highest delivery ratio with reasonable message delivery latency.

2.2.2. Multiple ferries case

The capacity of a single ferry to carry and forward traffic is limited. A single ferry system is vulnerable to ferry failures. Multiple ferries offer the advantages of increasing system throughput and robustness to ferry failures. On the other hand, the cost of deploying

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multiple ferries is obviously higher than the single ferry case. There is a trade off on the number ferries to be used.

In Reference [6], the authors study the problem of using multiple ferries to deliver data in networks with stationary nodes and designing ferry routes so that the average message delay can be minimized. They present a single route algorithm (SIRA) and multi-route algorithm (MURA) for networks with stationary nodes, focusing on the design of ferry routes. The objective is to develop algorithms to generate ferry routes that meet the traffic demand and minimize the average data delivery delay.

In SIRA, all ferries follow the same route but with different timing. That is, each node is assigned to all ferries which share the responsibility of transporting data between nodes. The objective is to design a single ferry route for multiple ferries so that the weighted delay is minimized. To this end, solutions for the well-studied TSP are adopted. Basically, SIRA first generates an initial route using some TSP heuristic algorithm, for example, the nearest neighbor heuristic, and then refines the initial route using local optimization techniques. The following *2-opt swap* and *2H-opt swap* operations to improve the route are used.

- *2-opt swap*. Consider the route as a cycle with edges that connect consecutive nodes in the route. A 2-opt swap removes two edges *AB* and *CD* from the route and replaces them with edges AC and BD while maintaining the route as a single cycle.
- *2H-opt swap*. A 2H-opt swap moves a node in the route from one position to another.

The algorithm tries to reduce the weighted delay of the route by applying 2-opt swaps and 2H-opt swaps until no further improvement can be found.

The algorithm (sketch) for computing the best route in the single ferry case is presented below.

```
Compute an initial route using TSP heuristic
   algorithm;
do
   Apply 2-opt swaps;
   Apply 2H-opt swaps;
while (weighted delay is reduced);
Extend ferry route to meet bandwidth requirements;
```

In contract to SIRA, MURA allows different ferries to follow different routes. The MURA uses a greedy heuristic for assigning nodes to ferries. MURA starts with n ferries and each node is assigned to a ferry. That is, each ferry route consists of one node. MURA refines the node assignment and reduces the number of ferries to m by using four types of operations. In each step, MURA estimates the weighted delay of the resulting node assignment for each operation and chooses to perform the best one until the number of ferries is m and no further improvement can be found (how to estimate the weighted delay for a node assignment is given in the paper). Then, if necessary, MURA modifies the node assignment, if necessary, to insure feasibility, that is, there is a path between each sender/receiver pair and the total traffic load on each route is lower than its capacity. Given the node assignment, one can apply the algorithms in SIRA to compute the route for each ferry. MURA is presented below, where EWD stands for estimated weighted delay.

```
EWD(op): EWD of node assignment after
operation op
Set the number of ferries to n;
Assign each node to a ferry;
while number of ferries > m or EWD is reduced do
   Identify the best overlap or merge operation op_s;
   Identify the best merge- or reduce operation op_l;
   if EWD(op_s) < EWD(op_l) and
         EWD(op_l) < current EWD then
         Perform op_s;
   else
         Perform op_l;
   Refine node assignment to maintain feasibility;
   Compute each ferry route;
```

Simulation results are obtained to evaluate the performance of route assignment algorithms, especially the impact of the number of ferries on the average message delay. Numerical results indicate that when the traffic load is low, the improvement in delay due to the increased number of ferries is modest. This is because the delay is dominated by the distance between nodes. However, when the traffic load is high, an increase in the number of ferries can significantly reduce the delay.

2.3. Integration of Buffer Management and Ferry-Based Routing

An interesting problem to investigate for an MF system is fairly allocating storage resources among

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the various active communication sessions, since the storage available at an MF is limited. If a buffer allocation scheme is not properly designed, some sessions may end up hogging the available buffers while other sessions are starving for buffers. In Reference [7], the authors consider a remote village communication scenario where there are stationary nodes that accept messages. It is assumed that message delivery between the nodes can only be performed *via* an MF. They first define a new fairness model for DTN environments. Then, they describe a buffer allocation scheme that can achieve max–min fairness among different active sessions. Several routing schemes are discussed in the paper.

Even though the messages to be delivered in an MF system do not require real-time delivery, it is still useful to provide differentiated delivery services similar to the regular and express mail features offered by the post office. Thus, in Reference [8], the authors consider the case where messages can be divided into two classes, namely urgent and regular messages. Urgent messages have smaller delay requirements and need to be delivered quickly. In the constrained scenario (CS), the MF delivers the urgent messages to the destination node immediately after picking them up from the source node. A methodology for designing the *ferry route* given such a constraint and the performance evaluation of the proposed method was presented as well. However, in Reference [8], they assume that the nodes are fixed in their locations and that messages arrive shortly before the ferry visits a node which is not quite realistic. In addition, they also assume that the buffers available at the nodes and at the ferry are unlimited. To overcome these shortcomings, the authors in Reference [4] investigate a scenario where the nodes move and messages arrive according to a certain probability distribution. They further assume the buffers available at the nodes and at the ferry are limited. They investigate how the buffer allocation scheme impacts the satisfactory ratio of urgent messages (i.e., urgent messages that are delivered on time), and the message dropping rates of both the urgent and regular messages as a result of buffer contentions at the ferry and source nodes. The authors propose three simple buffer allocation schemes that are normally implemented in routers: the drop-from-front (DFF) scheme, fixed partition (FP) scheme, and dynamically-partitioned (DP) scheme. For the DFF scheme, older messages will be dropped to accommodate new messages when the buffers are full. For the FP scheme, x% of the buffer space is reserved for the urgent messages. For the DP scheme, the regular messages are allowed to occupy at most $(1-x)\%$ of the buffer space but can be preempted by urgent messages.

2.4. Applications of Ferry-Based Routing

The concept of Message Ferrying is attractive in many scenarios such as common battlefield and disaster recovery, where network partition often occurs. It has been applied in two emerging scenarios: sensor networks for habitat monitoring [9,10] and remote village communication [11]. Message ferrying is also used in multicasting in sparse MANETs [12], in anycast in DTNs [13], and in inter-region routing [14] which will be discussed in more detail in Sections 3 and 4.

3. Inter-Region Routing

Scenarios such as disaster relief efforts, field hospitals, battlefields, and remote disconnected villages bring new challenges for wireless network design. In these scenarios, nodes form clusters such that a communication path exists between any two nodes *within* each cluster. Such a cluster is called a *region*. The communication within a region is relatively homogeneous. Region boundaries are used as interconnection points between dissimilar network protocol and addressing families. The boundaries between regions are defined by some metrics such as link delay, link connectivity, data-rate asymmetry, error rates, addressing and reliability mechanisms, quality of service provisions, and trust boundaries. Inter-region routing in the conventional Internet has been studied extensively in the past. However, in DTNs, regions are often disconnected, which makes the inter-region routing more difficult. Major issues including naming, path selection, protocol translation, reliability control must be addressed in inter-region routing. Considering the heterogeneity among different regions, when and how the name-binding takes place is an essential issue. In the following, we will review several inter-region routing approaches for: (1) stationary DTN scenario and (2) mobile DTN scenario in *ad hoc* networks.

3.1. Inter-Region Communication for Stationary DTN Scenario

In Reference [15], Fall provides a generalized overlay architecture as an attempt to achieve inter-operability

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between heterogeneous networks deployed in extreme environments. In this framework, for routing of DTN messages, *name tuples* are adopted as identifiers for objects or groups of objects in the form (Region Name, Entity Name). The first portion is a globally-unique, hierarchically structured region name. It is interpreted by DTN forwarders in order to find the path(s) to one or more DTN gateways at the edge of the specified region. The second portion identifies a name resolvable within the specified region and need not be unique outside the region. As a message transits across a potentially long and heterogeneous collection of regions, only its region identifier is used for routing. Upon reaching the edge of the destination region, the entity name information is locally-interpreted, and translated if necessary, into a protocol-standard name (or address) appropriate to the containing region. This method of resolving names results in a form of *late binding* for tuples in which only the portion of the tuple immediately needed for message forwarding (the region portion) is used by DTN forwarders.

Recall that this DTN architecture is targeted at networks where an end-to-end routing path cannot be assumed to exist. Thus, in Reference [15], routes are comprised of a cascade of time-dependent *contacts* (communication opportunities) used to move messages from their origins toward their destinations. Contacts are parameterized by their start and end times (relative to the source), capacity, latency, endpoints, and direction. In addition, a measure of a contact's predictability can help to choose next-hop forwarders for message routing as well as to select the next message to be sent. The predictability of a route exists on a continuum ranging from completely predictable (e.g., wired connection or a periodic connection whose phase and frequency are well known) to completely unpredictable (an 'opportunistic' contact in which a mobile message router has come into communication range with another DTN node). The particular details of path selection and message scheduling are expected to be heavily influenced by region-specific routing protocols and algorithms.

3.2. Inter-Region Routing in Mobile DTN Scenario

With respect to the dynamic scenario, where the group (similar in concept to region) may be split into disconnected groups due to the varying environment, Chuah *et al* [16]. propose a generalized naming convention for the enhanced DTN architecture, Enhanced Disruption and Fault Tolerant Bundle Delivery (EDIFY) system, that permits separate representations of network topology, administrative control, physical location, and other factors. This allows for bundle routing preferences or requirements to be expressed as functions of a name. Networks that are partitioned can get new names dynamically while retaining their old identities so that information can still be delivered if needed. Instead of regions, EDIFY provides the concept of groups. Each group has a group identifier (GID) and each entity within a group has its own personal identifier (PID). Any device within the group can be identified with the appropriate tuple (GID, PID). A hierarchical naming technique is adopted for groups, which allows both for scaling and for better mapping of real-life complexity, such as geographical location or an administrative hierarchy.

The naming convention adopted in EDIFY allows for role-based addressing and multiple namespaces. It provides layered resolution of address and routing information. This naming convention supports policy-based routing. DTN nodes are configured with individual and domain-wide routing policies for selecting the routing approach at any particular time. The routing policies can mandate the preferred domains for the bundles to go through and also command that certain domains should be avoided due to security or cost reasons. Such naming may provide additional routing hints (such as preferring a gateway to the longest-matching prefix). It is further generalized to permit multiple naming hierarchies. This allows incorporating information from multiple naming systems, including those based on network topology, network administration, and physical location.

Focusing on *tetherless computing*, where client applications running on small, inexpensive, and smart mobile devices maintain *opportunistic* wireless connectivity with back-end services running on centralized computers, Seth *et al*. [17] propose a DTN architecture to achieve the goals of mobility transparency, disconnection transparency, identity management, and low control overhead. Their architecture seamlessly supports mobility and disconnection even in networks where an end point may never have a direct connection to the Internet, relying instead on a proxy to ferry data to and from it.

A special type of node, *custodian*, is introduced that acts as always-available proxy for intermittently connected mobile hosts. Custodians store data on behalf of disconnected mobile hosts and deliver them whenever the hosts reconnect to the network. In this architecture, all mobile hosts are identified using an opaque globally unique identifier (GUID).

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The Internet region, which has special status in this proposed architecture, maintains a *Home Location Register* (*HLR*), which uses distributed hash table (DHT) to map from a mobile's GUID to its current region. Each region maintains at least one Visitor Location Register (VLR) that is either stored at, or accessible to, *all* of its gateways. The VLRs store a mapping from the GUIDs of all mobile hosts currently in the region to the custodian DTN router of the mobile hosts. Finally, each custodian maintains a Local Location Register (LLR) that maps from the GUID to the best last-hop fixed or mobile local DTN router for each mobile. In summary in the proposed architecture, a three-stage lookup hierarchy, that is, HLR, VLR, and LLR, is proposed.

When a mobile host moves, its location must be updated in the location registers. Therefore, the mobile device will determine its new region, custodian, and local DTN router. As stated above, in Reference [15] the notion of late binding is proposed, where the administrative ID portion of the DTN address is bound to an actual next-hop only at the destination region. The authors in Reference [17] extend this notion to allow even a node's region to be late bound. This optimization allows a disconnected node to send a bundle to a destination knowing only its GUID. Thus it does not have to query the HLR for the mobile's current region.

A more challenging scenario, where nodes in different regions cannot communicate except through long-range and high-power wireless or satellite networks, is tackled in Reference [14]. Since regions are assumed to be disconnected from each other, the authors propose using a dedicated set of messengers that relay messages between regions. Each region generates large amounts of data that can be grouped into bundles, which are then relayed to other destination regions. Multiple messengers would provide fault tolerance and faster delivery of message bundles. The regions could either be mobile, as in search-and-rescue groups or military battalions, or stationary, as in field hospitals or remote disconnected villages. In such an environment, the authors focus on designing efficient scheme for *messenger scheduling* to achieve inter-regional communication.

Two messenger ownership schemes, regional and independent, as well as three scheduling strategies for message delivery in their system, *periodic, storage-based*, and *on-demand*, are introduced in Reference [14]. The tradeoffs among the schemes are investigated under different environments and network conditions. The simulation results have demonstrated that the choice of a particular scheme ultimately depends on the environment under which it is deployed.

The novelty of their work is in two main areas. First, they consider environments where regions are mobile and dynamic in nature, as opposed to single stationary or mobile node. Second, they introduce the idea of using dedicated messengers under different scheduling strategies rather than discovering and maintaining routing paths in these types of networks.

In this section, the existing study related to inter-region routing for both stationary DTN and mobile DTN are reviewed. Most of the existing studies so far are evaluated through simulation. It is commonly recognized that simulation can only provide limited fidelity, especially for wireless related research. Thus, building a real testbed for DTNs to conduct real system performance evaluation is an important area for future study. Moreover, it is worth noting that all of the reviewed work addresses unicast delivery among different regions. How to conduct efficient multicast and anycast for inter-region communication is an interesting direction to be explored. In the next section we will review some of the recent efforts in this direction. However, more studies are needed.

4. Multicast Routing

Multicast service supports the distribution of data to a group of users. Many potential DTN applications operate in a group-based manner and require efficient network support for group communication. For example, in a disaster recovery scene, it is vital to disseminate information about victims and potential hazards among rescue workers. Although group communication can be implemented by sending a separate unicast packet to each user, this approach suffers from poor performance. Thus efficient multicast services are necessary for supporting these applications. Multicasting in the current Internet and MANETs has been studied extensively in the past. However, since the network is often disconnected in DTNs, multicasting in DTNs is a considerably different and challenging problem. The multicast semantics (group membership management) should be re-defined for DTNs. The design of multicast routing algorithms (when and where to forward) in DTNs also faces new challenges.

The semantics of multicasting in traditional networks such as the Internet are straightforward, specifying that packets sent to a multicast group be delivered to members of the group. Since data transfer delay in these networks is short (on the order of

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milliseconds), group membership changes during data transfer are rare and can be ignored. Thus the receivers of a multicast packet are well defined. This, however, is no longer valid in DTNs. Due to frequent partitions and consequently large transfer delays in a DTN, membership changes during data transfer are the norm rather than the exception. Under these situations, it is not obvious how to define the receivers of a multicast packet, relative to the group membership over time. To address this problem, new semantic models are needed for DTN multicasting.

In Reference [18], the authors first define three semantic models for multicasting in DTNs. The *first model* is called temporal membership (TM). In the TM model, a message includes a membership interval that specifies the period during which the group members are defined. Under the TM model, the receivers of a message are well defined. The *second model* is the Temporal Delivery (TD) model. In this model, messages specify additional constraints on the action of message delivery beyond the unconstrained TM model. A message specifies both a membership interval and a delivery interval. The delivery interval indicates the time period during which the message should be delivered to the intended receivers. In the *third model*, the Current-Member Delivery (CMD) model, messages explicitly specify whether the receivers of a message are required to be group members at the time of delivery. A message includes a CMD flag as well as a membership interval and a delivery interval. When the CMD flag is set, the receivers of the message should be group members at the time of message delivery. Note that in both TM and TD models, the receivers of a message are not required to be group members at the time of delivery.

Once the semantics are defined, the authors in Reference [18] present a multicast routing framework and four routing protocols which are adopted from multicasting in the Internet. These four routing protocols are

A. Unicast-Based Routing (UBR). This approach implements multicast service by using unicast transfer, that is, the source will send a copy of the message to every intended receiver.
B. Broadcast-Based Routing (BBR). In BBR, messages will be flooded throughout the network in order to reach the intended receivers.
C. Tree-Based Routing (TBR). In TBR, messages are forwarded along a tree in the DTN graph that is rooted at the source and reaches all receivers. Messages are duplicated only at nodes that have more than one outgoing path. The tree can be static (STBR) or dynamic (DTBR).
D. Group-Based Routing (GBR). GBR uses the concept of forwarding group [19] which is a set of nodes that are responsible for forwarding the message. Messages will be flooded within the forwarding group to increase the chance of delivery.

Through extensive simulations in *ns-2*, the authors compare these multicast algorithms and study how routing performance is affected by the availability of knowledge. Based on the simulations, the following results are reported. First, efficient routing for multicast can be constructed using only partial knowledge. In addition, the marginal improvement in performance with accurate contact information is generally more significant than that with up-to-date membership information. Second, GBR and BBR achieve the best delivery ratios depending on the amount of knowledge available. Third, UBR performs poorly in DTNs, indicating that multicast routing using multiple unicast messages is not efficient in DTNs, as expected.

The performance of different multicast approaches depends on the knowledge of network conditions discovered in DTN nodes. Therefore, situational awareness can be applied to help DTN nodes control the message forwarding behavior and discover different message delivery paths, based on policies and network conditions at different times. In Reference [20], the authors first identify several drawbacks in UBR and TBR studied in Reference [18] and then propose an on-demand, situation-aware, multicast (OS-multicast) scheme. Unlike the above two methods, OS-multicast is a dynamic tree-based multicast approach. A unique multicast tree is built up for each bundle and the tree varies according to the changes of the network at each intermediate DTN node. First, a source-rooted tree is constructed in a way similar to static tree-multicast. When a DTN node receives a bundle, it will dynamically rebuild the tree rooted at itself to all the destinations based on its knowledge of the current network conditions. If there is a newly available path to a destination, which was not discovered by the upstream DTN nodes, this node will immediately take advantage of that fresh information and send the bundle out. The OS-multicast consists of the following components: (a) *Membership management*, when a DTN node intends to join a multicast group, it registers with its membership period by explicitly sending a GROUP_JOIN message. This membership management method conforms to the TM semantic model proposed in Reference [18]

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with an explicit receiver list known at the source. (b) *Bundle storage*, each DTN node has a local storage with finite size. (c) *Forwarding state maintenance*, a forwarding state is associated with each bundle. (d) *Message forwarding*, when a bundle is generated, the source queries its knowledge base to retrieve all the discovered paths to the receivers. Then the source combines those paths to become a multicast mesh that covers all the valid receivers. (e) *Bundle retransmission*, a DTN node periodically checks its local storage to see if there is any opportunity to forward the buffered bundles further. Simulation results show that the OS-multicast can achieve better message delivery ratio than existing approaches with similar delay performance. When network connectivity becomes worse due to the high link unavailability, OS-multicast also has better efficiency.

The downside of DTBR and OS-multicast is that both schemes fail to provide good performance in very sparse networks and a receiver may receive multiple copies of the same bundle. To overcome this drawback, in Reference [21], the authors present a context aware multicast routing (CAMR) scheme. This CAMR scheme consists of five components: (a) *Local Node Density Estimation*, (b) *2-Hop Neighbor Contact Probability Estimate*, (c) *Route Discovery*, (d) *Route Repair, and* (e) *Data Delivery.* The local node density estimation component estimates the number of neighbors periodically (through neighborhood information exchange). If the node density is below a pre-defined threshold, it issues a flag indicating the network is sparse. Each node also maintains its contact probabilities with its 2-hop neighbors, which is handled by the neighbor contact probability estimation component (the contact probability is set to 1 if the node can communicate with the contact. The contact probability is decreased by an aging factor if the node has not been able to communicate with the contact for some time period). A source initiates a route discovery process by the Route Discovery component if it cannot reach any of the receivers to which the multicast traffic needs to be delivered. A detailed procedure of route discovery is presented in the paper. When the multicast tree is broken as a result of node mobility, the route repair component will repair the route locally. Two local repair methods are presented in the paper depending on whether user mobility information is used or not. For data delivery, an extra header is piggybacked to each data bundle by the data deliver component. The header contains information on the receivers to which a particular multicast bundle needs to be delivered. Any intermediate node that supports the CAMR scheme will duplicate the bundle if the node discovers that it is the branching point. The performance of the proposed CAMR scheme was evaluated and compared with other existing proposed multicast routing schemes for DTNs through simulation. Simulation results show that the CAMR scheme is more flexible and can provide a high delivery ratio with the highest data and overall efficiency especially when the network becomes sparser. In terms of the impact of mobility on the system performance, they observe that the data efficiency and overall efficiency is higher with ZebraNet mobility scenario [22] than with the random waypoint mobility model.

In Reference [12], the authors propose a multicast scheme that integrates both epidemic routing (ER) and MF, assuming a simple membership semantic model. Under this semantic model, if a node belongs to the group when a multicast message is generated, it is a destination for this message. Using this membership semantic model and a group management scheme, it is possible to support multicast using ER [23] and message ferrying. With these assumptions, the authors propose three multicast routing approaches using message ferrying.

The first scheme is Message Ferry with Epidemic Routing (MFER). This protocol is similar to ER [23] except that the ferry helps to disseminate messages around the network. If the source wants to send a multicast message to the group, it passes the message to the ferry. Then the ferry 'starts' the multicast session and every node can now participate in this dissemination process. In MFER, a certain level of overhead is inevitable due to the data exchange among non-members.

The second scheme is Message Ferry with Group Routing (MFGR). In MFGR, the participants are limited to be only the ferry and group members, and message exchanges can only happen among the ferry and group members. When the group member percentage, that is, the number of group members divided by total number of nodes, is small, MFGR provides both high efficiency and reasonable message delivery latency. On the other hand, when the group member percentage becomes large, the MFER provides short message delivery latency and is reasonably efficient. Based on this observation, the authors also propose an adaptive scheme. In the adaptive scheme, the ferry monitors the size of the multicast group and adjusts the routing strategy accordingly. Two-level thresholds are used to avoid oscillation between the choices of MFGR and MFER while the group size changes as the members join and leave. In this adaptive scheme, the

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scope of the 'flooding' is determined based on the group member percentage: if it is above the upper threshold, all the nodes participate in the flooding; if it is less than the lower threshold, only the ferry delivers the multicast messages. Since the ferry is the repository of group membership information, it determines the routing strategy for a particular multicast session. Once a source sends a message to the ferry, a specific routing strategy (based on the group member percentage) is encoded in the message header. Simulation results were obtained to evaluate the performance of the proposed schemes. As expected, both MFER and MFGR perform well in some circumstances and poorly in others. The hybrid protocol generally performs well due to its adaptations to membership dynamics.

Anycast is a service that allows a node to send a message to at least one, and preferably only one, of the members in a group. Anycast in DTNs is a quite unique and challenging problem. It requires both redefinition of anycast semantics and new routing algorithms. The first work dealing with anycast in DTNs is reported in Reference [13], in which the authors define three semantic models and propose a new routing protocol, based on a newly defined routing metric named expected multi-destination delay for anycast (EMDDA). They assume there are many unconnected islands which are periodically connected through uncontrolled random *MFs*. The routing metric EMDDA accurately indicates the delay from a node to the nearest member of the anycast destination group. Extensive simulation results show that the proposed EMDDA routing scheme can effectively improve the efficiency of anycast routing in DTNs.

5. Transport Layer Issues

Most of today's research related DTN is focusing on introducing different DTN architectures and solving routing and message delivery problems in extreme environments. It is worth noting that it is also important to investigate the performance of the service offered by the transport layer, such as sequencing, congestion control, and reliability. However, there are only a few efforts in this direction at this stage.

Under the most widely used transport protocol, TCP, a three-way handshake is usually required that consumes 1.5 round-trip times (RTTs). There is a generic, 2-min timeout implemented in most TCP stacks: if no data is sent or received for 2 min, the connection breaks. In the interplanetary Internet case [24], data communication between the Earth and (very) remote spacecrafts is required. In the case of Mars, for example, a worst-case RTT is approximately 40 min. Thus, normal TCP does not work at all under such scenarios. New transport protocols must be developed for DTNs. Besides long RTT, the not always-on connectivity also brings a big challenge to transport protocol design. For a source-to-destination data delivery, the intermediate nodes have to involve in the transport layer control when no end-to-end connectivity is supported in the underlying networks. With the absence of an end-to-end connectivity, the key focuses on transport protocol design are then congestion control and reliability.

In this section, we review transport layer protocols proposed in DTNs. For generic DTN, custody transfer [15,25] , Licklider Transmission Protocol (LTP) [26], LTP-T [27], and autonomous congestion control [28] are discussed. For a more challenging scenario where all nodes in the network are mobile, several reliability approaches have been studied in Reference [29].

5.1. Transport Layer Protocols for Generic DTN

In the general architecture proposed in Reference [15], one of its suggested components, called *custody transfer*, is proposed for enhancing reliability in DTN. This mechanism, which utilizes hop-by-hop transfer of reliable delivery responsibility, shares many features in common with a database transaction. It offers a way to enhance end-to-end reliability in these networks by moving the responsibility for reliable delivery of a message toward its ultimate destination. Applications may request an (optional) end-to-end acknowledgment in addition to the enhanced reliable delivery provided by custody transfer. In Reference [25], the authors further investigate the custody transfer mechanism, with particular emphasis on its implications for congestion management and the semantics of its protocol operation. The congestion management problem can lead to a form of head-of-line blocking. The relationship of custody transfer to traditional transaction commit protocols is discussed. It is observed that the problem of network partitioning can create duplicates that pose troubles if in-network message fusion is to be utilized. Thus the concept of joint custody to mark messages that may have been duplicated is proposed, which can help to ameliorate this problem.

As mentioned above, because end-to-end connectivity may not exist continuously, solutions for

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Internet congestion control do not apply readily to DTN. In DTN, end-to-end rate control is not feasible. This calls for congestion control mechanisms where the decisions can be made autonomously with local information only. Burleigh *et al*. [28] use an economic pricing model and propose a rule-based congestion control mechanism where each router can autonomously decide on whether to accept a bundle (data) based on local information such as available storage and the value and risk of accepting the bundle. Preliminary experimental results show that this congestion control mechanism can protect routers from resource depletion without loss of data.

With respect to links characterized by extremely long RTTs and/or frequent interruptions in connectivity, LTP is designed to tackle delay tolerance and disconnection in a point-to-point environment with an emphasis on operation over single links. LTP provides retransmission-based reliability over those links. Note that LTP is a point-to-point protocol, thus there are no routing or congestion issues to consider. There are three Internet drafts describing LTP, one covering the motivation for the protocol [30], one specifying the base protocol itself [26], and one on protocol extensions [31]. As illustrated above, to operate in the environments considered in DTN, a protocol can't be chatty like TCP because requiring any handshaking before application data flows is simply not an option. Consequently, LTP effectively has no negotiation, and nodes must agree on all parameters required for interoperability before a contact occurs. LTP is thus highly stateful, requiring relatively large amounts of information about previous and upcoming contacts.

Farrell *et al*. propose a generic delay tolerant transport protocol, LTP-T [27], constructed as an extension of LTP. As the transport protocol for source-to-destination data transmission, LTP-T needs to carry a destination identifier, has to consider fragmentation and also needs to consider congestion at intermediate nodes on a path. All these requirements are handled using the LTP extension mechanism, which was originally defined to handle the addition of authentication fields to LTP. Note that, in Reference [27], only a generic framework is proposed for LTP-T; important performance of the protocol in terms of throughput, latency, fairness, etc. has not been evaluated yet.

5.2. Transport Layer Protocols for Mobile DTN

With respect to a special type of DTN, delay tolerant mobile network (DTMN) [32], where all nodes in the network are mobile and that an end-to-end path may not exist between any two nodes in the network, the authors investigate and compare several reliability approaches in Reference [29]. Four different reliability approaches: *hop-by-hop*, *active receipt*, *passive receipt*, and *network-bridged receipt* are introduced. With the extreme hostility and mobility assumed in DTMN applications, each node in the network acts as a region and a gateway with respect to the DTN architecture. For hop-by-hop reliability, any exchange of messages between nodes is acknowledged, and all nodes are assumed to reliably forward the message. While the *hop-by-hop* approach ensures some level of reliability, it does not ensure end-to-end reliability. *Active receipt* is basically an end-to-end acknowledgment, which they call a receipt, created by the ultimate destination after it receives a message from the source. This receipt is actively sent back to the source. By 'actively', they mean that nodes treat this receipt as a new message that needs to be forwarded. While *active receipt* offers end-to-end reliability, its cost in many situations is high. Thus, *passive receipt* is introduced, which ensures end-to-end reliability, without the incurred cost of *active receipt*. The idea is to have an implicit/passive receipt, instead of an active one, to traverse the network back to the source. Motivated by the wide spread use of cell phones, the authors further proposed a *network-bridged receipt* to exploit the availability of the cellular network by using it as an alternative path for communication. While such a network does not have the required bandwidth for delivering large bundled messages, it could be used for transmitting lightweight control information. These approaches have been investigated and evaluated *via* simulation. Overall, it was discovered that the choice with the best reliability depends on the expected complexity of the underlying DTMN.

As mentioned in the beginning of this section, there are only a few works on the transport layer protocol at this stage. Many research directions are worth further exploring such as hop-by-hop reliability *versus* end-to-end reliability, interaction between transport layer and routing and message forwarding, and performance evaluation on real systems.

6. Conclusions

Many excellent approaches to addressing the unique problems in DTNs have been reported in the literature. In this paper, we provide an overview on the latest

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developments in DTNs after the publication of Reference [1], including MF-based approaches for unicast, inter-region routing, multicast, and work related to transport layer. It is the authors' desire that this summary provides a jump-start for new researchers in this area and motivates the research community in developing new, improved protocols.

As discussed in the previous sections, there are still many open issues that need to be resolved before the benefit of the DTNs can be fully utilized. Here we briefly list some of the open issues.

- The MF-based approach is a very powerful method to connect many isolated islands or to help data delivery when the network is partially disconnected. As pointed out earlier, there is a tradeoff on how many ferries should be used in the system. Efficient methods to determine the optimal number of ferries needed in the system should be developed.
- To evaluate the performance of proposed protocols in DTNs, simulation is used most times. It is highly recommended to develop test bed to evaluate the real system performance of different protocols.
- Currently, there are few efforts addressing issues in the transport layer. More work is needed to study the tradeoff between hop-by-hop reliability and end-to-end reliability. Interaction between transport layer and routing and message forwarding should be studied as well.
- How to conduct efficient multicast and anycast for inter-region communication is an interesting direction to be explored.

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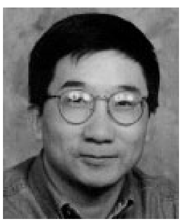
Authors' Biographies



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