Data Delivery in Delay Tolerant Networks: A Survey

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1. Introduction

Delay-Tolerant Networks (Fall (2003)), also called disruption tolerant networks (DTNs), represent a fairly new networking paradigm that allows inter-connection between devices that current networking technology cannot provide. There are a wide variety of networks where an end-to-end connection between a given source and destination may never be present. Consequently, traditional routing protocols cannot be directly applied in these scenarios for delivering data. However, if one were to take the graph formed by the nodes based on their connectivity dictated by their radio range and consider the overlap not only over space but also time then there is a high likelihood that the network will appear as a single connected component. So while at any given instant, the network may not be connected, it may still be possible to route data from a source to a destination. DTNs are sometimes also called Intermittently-Connected Mobile Networks (ICMNs). The primary goal in such networks is to *get* the information from a source to the destination; these networks can tolerate a relatively higher delay.

A wide variety of ”challenged” networks fall under this category ranging from outer-space networks, under-water networks, wireless sensor networks, vehicular networks, sparse mobile ad-hoc networks etc. Students moving about in a college campus (Hsu & Helmy (2006)), or buses moving about in a small metropolitan area (Burgess et al. (2006)), or a wireless sensor network with some mobile nodes (Shah et al. (2003); Juang et al. (2002)) acting as relays to assist in the data-collection phase provide representative examples of DTNs.

This chapter strives to provide a survey of some of the most relevant studies that have appeared in the domain of data delivery in delay tolerant networks. First, we introduce some fundamental challenges that are unique to DTNs. Then we present the major parameters of interest that various proposed routing solutions have considered, examples include end-to-end delay, throughput, mobility model of the nodes, energy efficiency, storage etc. Subsequently, we provide a classification of various approaches to routing in DTNs and pigeon-hole the major studies that have appeared in the last few years into the classified categories.

2. Challenges

In Delay-tolerant networks, at any given time instant, the network may not be connected. Data is delivered in a DTN using a store-carry-forward model. Nodes in the network relay data from source to the destination, where existing nodes in the network relay the data from the source to the destination, in one or more hops, such that each node along the path receives the data from the previous node and stores it locally. This node then carries the data for a while, and upon contact with other nodes, forwards the data. In this way, the data is finally delivered to the destination.
Whenever two nodes are in the vicinity of one another, they may exchange data, such an opportunity is termed as a *contact* or *encounter*. In other words, a link is established between these pair of nodes. This link is time-sensitive in that it is only valid for the duration when the nodes are in range of one another. If one or both nodes move away, then this link is broken. Moreover, at a time, there can be multiple links between a pair of nodes. For example, in case of 2 cell phones in vicinity, there can be a high-bandwidth peer-to-peer link (WiFi, IEEE 802.11 a/b/g) as well as a low bandwidth (EDGE/GPRS) link present simultaneously. In that sense, the connectivity of a DTN can be modeled as a time-varying multigraph. In the following, we enlist some of the unique challenges present in DTNs as compared to traditional networks.

2.1 Encounter schedule

In order to deliver data from a given source to a destination, the source node can wait till it encounters the destination node and then deliver the data directly to it. However, depending on the particular setting, this may take a long time and may not even happen. If the source node was an oracle and *a priori* it had information about the encounters between every pair of nodes, then it can pre-calculate and determine the best path or best set of nodes to forward its information in order to reach the destination node (Jain et al. (2004); Ghandeharizadeh et al. (2006)). In most practical scenarios, the schedules of encounters may not be known *a priori*. Even if the schedules are known to some extent, there may be errors and consequently, routing should be able to adapt and still deliver data to the destination. In the extreme case, where the mobility pattern of the nodes is random leading to memoryless encounter schedules, no assumptions can be made about the node contact pattern. Hence, the mobility model of the nodes is an important parameter that determines how the nodes will encounter one another. While a random walk based mobility model has been considered in a number of DTN studies due to its amenability to analysis, DTNs comprising vehicles or students have been shown to follow a community-based mobility model (Hsu & Helmy (2006)).

2.2 Network capacity

In general, the duration of an encounter as well as the link bandwidth dictate the amount of data that can be exchanged between a pair of nodes. Another factor is contention in the presence of multiple nodes trying to send data during a given encounter. This may also determine whether a message from a source to a destination needs to be fragmented.

2.3 Storage

During an encounter, nodes may decide to exchange all their information. However, if the nodes are storage-constrained, eventually, the node buffer will be exceeded resulting in data loss. Consequently, the naive approach of exchanging all data on an encounter may not scale or be applicable in all application settings. Intelligent schemes that restrict the number of copies of a given data item in the DTN, as well as schemes that trigger deletion of stale data (data already delivered to the destination of interest) are needed to efficiently utilize node storage. If the network is formed of nodes that have heterogenous capacities where some nodes are more powerful and less resource-constrained compared to others then this can be leveraged to design a better data delivery strategy for such a DTN.

2.4 Energy

DTNs span a wide spectrum of application settings. Transmission and reception of data as well as computation incurs power. In some settings, such as battery operated wireless sensor networks, the resources may be highly constrained where it is important to take into account the residual energy of a node while determining whether to exchange data during an encounter. However, in other settings, such as vehicular networks, the constraints on power may not be as severe. Data delivery techniques for DTNs should be able to adapt to such a wide range of scenarios.

3. Metrics of interest

The vast majority of the routing schemes for delay tolerant networks aim at optimizing a few metrics that affect their system performance. These are summarized below.

3.1 Message delivery ratio

This metric captures the number of successful deliveries in a DTN. In other words, how many packets (or messages) generated by various sources were delivered to their intended destinations in the network setting under consideration. Note that a message may be associated with a delivery deadline. If this message is not delivered within an acceptable amount of time specified by this deadline then it is considered a failed delivery. A modified definition of the delivery ratio is the fraction of the messages correctly delivered to their destinations within a specified period.

3.2 Delay

While the applications are able to tolerate larger delays in a DTN, as long as packets are delivered to their intended destinations, this is a metric of interest which should be optimized. Most DTN routing approaches aim to optimize both the delivery ratio as well as the delay. Consider an example scenario in a college campus where a professor wishes to broadcast a change in the timing of a lecture to all students or an executive trying to communicate the change in the time of an upcoming meeting. In both cases, the message is only valid if communicated before the start of the event (lecture or meeting). Consequently, while the delay in DTNs does not need to be instantaneous, the goal should be to keep it as short as possible subject to resource constraints.

3.3 Number of replicas

The efficiency of a data delivery mechanism generally improves as additional copies of a packet are generated and transported by various relays. However, the increase in the probability of data delivery comes at the cost of increase in the storage requirement at the individual nodes of a DTN. Hence, the number of replicas is an auxiliary metric that accompanies the delay and packet delivery ratio to provide an all-round indication of the performance of a given data delivery mechanism in a DTN.

3.4 Energy/Power

Usually the energy expended to achieve a given data delivery ratio and average delay is a function of the total number of transmissions and receptions incurred by all the participating nodes. This should include the energy expended due to idle receptions as well as computation (for example, aggregation etc.). Most studies employ the number of packet transmissions as an indicator of this metric. This metric is sometimes difficult to quantify especially in cases where nodes have heterogenous resources. Also, energy may not be a big concern in some application scenarios such as in the case of vehicular networks.

4. Data delivery mechanisms

In this section, we have classified routing schemes for DTNs into a small number of categories based on their characteristics.

4.1 Epidemic routing schemes

One of the earliest and probably the simplest protocols proposed for data delivery in DTNs is epidemic routing (Vahdat & Becker (2000)). The idea is whenever two nodes encounter one another they will exchange all the messages they currently carry with each other. At the end of the encounter, both will possess the same set of messages. As this process continues, eventually, every node will be able to send information to every other node. So the packets are basically flooded through the network much like the spread of a viral epidemic. This represents the fastest possible way in which information can be disseminated in a network with unlimited storage and unlimited bandwidth constraints. This scheme requires no knowledge about the network or the nodes. However, in most practical scenarios, such a scheme will result in inefficient use of the network resources such as power, bandwidth, and buffer at each node. Moreover, messages may continue to exist in the network even after they have been delivered to the destination. Epidemic routing serves as the baseline for comparison for most of the DTN routing schemes.
Davis et al. (2001) improved the basic epidemic scheme with the introduction of adaptive dropping policies. They restrict the size of the buffer at each node so that it can only store the top K packets that are sorted in accordance with a dropping policy. They explore four types of drop strategies, including Drop-Random (DRA), Drop-Least-Recently-Received (DLR), Drop-Oldest (DOA) and Drop-Least-Encountered (DLE). Their simulation results show that DLE and DOA yield the best performance. DLE seeks to drop packets based on information about node location and movement while DOA drops packets that have been in the network the longest relying on the premise that the globally oldest packets are the ones that are likely to have already been delivered to their intended destinations.
Harras et al. (2005) propose a set of strategies for controlled flooding in DTNs. These include schemes that have a Time-To-Live (TTL) as well as an expiry time associated with every message. In addition, once a message is delivered to the destination, a healing process is started to 'cure' the network of the stale copies of this message. This is similar to the concept of "death certificates" proposed earlier in the context of replicated database maintenance

(Demers et al. (1987)). All these improvements reduce the resource consumption of epidemic routing while having little impact on the average delivery delay. An aggressive death certification scheme has been shown to reduce the storage required at each node (Small & Haas (2005)) but the tradeoff is that such a scheme will consume more transmissions (Harras & Almeroth (2006)) although it can be used to provide a notion of reliable message delivery in DTNs.

4.2 Direct-contact schemes

This data delivery scheme is one of the simplest possible where a source delivers a packet to a destination when it comes in direct-contact. In other words, the source waits till it comes in radio range of the destination and then directly delivers the packet to the same. This scheme does not consume any additional resources and makes no additional copies of the data. However, the major limitation is that the delivery delay can be extremely large and in many cases the source and the destination may never come in direct-contact of each other.

Perhaps the earliest incarnation of direct-contact based delivery schemes for DTNs is the well-known infostation model (Frenkiel et al. (2000)). The idea is that infostations are deployed at certain locations providing smaller "islands" of coverage which service the needs of data-intensive mobile nodes as they pass by. This approach serves to maximize the capacity of wireless data systems while reducing the cost of the services provided. The authors present a capacity-delay-cost trade-off for the infostation model for both one-dimensional and two-dimensional systems. In wireless sensor networks, a wide variety of application scenarios involve mobile sink nodes collecting sensed data from sensors deployed in a field. The sensors themselves may be static or mobile and are independent sensing entities. In ZebraNet (Juang et al. (2002)), data sensed by sensors attached to zebras is collected by humans as they drive by in a vehicle. In the context of vehicular networks, Kapadia et al. (2009) have also employed direct-contact based data delivery. They present comparative performance of a family of replication strategies that determine the number of replicas for a given data item based on its popularity.

Shared Wireless Infostation Model (SWIM Small & Haas (2003)), represents a hybrid scheme that extends the concept of an infostation through information sharing between nodes. The idea is that the nodes, in this case sensors attached to whales, collect data that is shared among themselves via replication and diffusion employing an epidemic routing like scheme when two sensors are in the vicinity of one another. Subsequently, when the whales come to the surface, the collected data is relayed to a small number of static on-shore base-stations. By allowing the sensor nodes to share data, the capacity requirements at the individual nodes goes up; however, the delay until one of the replicas reaches an infostation reduces. The authors examine this fundamental capacity delay tradeoff in the context of a real-world application.

4.3 One-hop relay schemes

In this scheme, the source delivers a packet to an intermediate node, aka relay, which in turn delivers the same to the destination. Compared to direct-contact, this scheme only incurs an overhead of one additional copy of a packet. A large number of application scenarios have employed this scheme for successful data delivery. The mobility of the relay node may be controlled or random. With Data Mules (Shah et al. (2003)), intermediate carriers that follow a random walk mobility model are used to carry data from static sensors to base-stations.

The individual sensor nodes transfer their data to the mule when it comes in radio range and the collected data is in turn delivered to the sinks. The study shows that by increasing the buffer capacity of the mules, fewer mules can service a sensor network albeit at the cost of a higher data delivery delay.

In DakNet (Pentland et al. (2004)), vehicles loaded with Mobile Access Points (MAPs) are used to transport data between village kiosks and centralized internet hubs. This represents one of the earliest practical applications of deploying wireless technology, specifically IEEE 802.11, also documented as the first national e-governance initiative in India related to computerizing land records in rural areas. Message Ferries (Zhao & Ammar (2003)) capture a more generalized scenario where the movement of the ferries can be controlled to carry data from a source node to a destination node. The initial proposal for ferries assumed that the nodes had limited resources, were stationary, and consequently were not burdened with the routing functionality. However, in follow-up works, the authors (Zhao et al. (2004; 2005)) extend the scheme to networks with mobile nodes and multiple ferries. This scheme requires online collaboration between the ferries and mobile nodes. The nodes need to proactively move so as to intersect with the path chosen by the ferries to transfer data to the latter. This assumption in turn was relaxed in a recent study (Bin Tariq et al. (2006)) where the message ferry routes were designed based on the mobility model of the nodes and probabilistic node locations.

4.4 Routing based on knowledge oracles

Jain et al. (2004) present a family of algorithms for routing in delay tolerant networks based on the presence of knowledge oracles. They model the DTN as a directed multigraph with time-varying edge costs, based on propagation delay and edge capacity. The various knowledge oracles considered provide information about the following (a) all future contacts of nodes such as time of contact, duration of contact, bandwidth available for information exchange during contact, (b) the future traffic-demand of the nodes, (c) the instantaneous queue sizes at each node. Using information from one or more oracles, various algorithms have been designed to send data from a source to a destination along a single path using either source-routing or local-per-hop routing. The authors have extended Dijkstra's shortest path algorithm to use time-varying edge costs. The performance of algorithms has been evaluated via simulations using a discrete-event simulator. The authors also present a linear programming formulation that uses all the oracles to determine the optimal routing for minimizing average delay in the network. The solution to this optimization serves a base-line optimum. The results indicate that as algorithms are fed more knowledge from the oracles, they provide better performance. However, in most practical settings, where the future traffic demand and global instantaneous queue knowledge may not be easily available, algorithms making per-hop decisions based on local knowledge can route around congestions and provide a good performance.

In reality, complete knowledge of contact schedules may not always be available. Additionally, the schedules may be imprecise and unpredictable. Jones et al. (2005) extend some of the algorithms presented above to compute the edge costs based on a sliding window of observed connectivity. They argue that an approach that defers the routing decision as late as possible thereby allowing forwarding based on the most recent information is better suited for DTNs. They introduce the concept of per-contact routing where nodes frequently recompute their routing table, similar to a traditional link-state routing protocol, whenever contact is made with another node. This routing information is then redistributed through the network using an epidemic routing like protocol thereby allowing nodes to take advantage of opportunistic connectivity and recompute routing for each message stored in the message buffer. The authors show that this scheme shows superior performance compared to epidemic routing as well as other schemes employing wireless LAN traces of a student population collected from a college campus.

A variant of the earliest-delivery algorithm proposed above, has been employed in the context of data delivery in vehicular networks by the Zebroids (Ghandeharizadeh et al. (2006)) study. The idea is that the source has knowledge of the contacts between the vehicles for a certain limited duration in the near future and based on this schedule, it determines the delivery path of the packet via one or more carrier vehicles. The vehicles themselves have storage constraints. Consequently while accepting a packet from its predecessor, if the vehicle's buffer is full, it employs a replacement policy to determine which packet must be evicted to accommodate the new one. The authors evaluate a wide variety of replacement policies and conclude that a policy that decides eviction candidates randomly provides competent performance. This study also validates the performance of the proposed scheme based on real-world encounter traces gathered from a small bus network in and around a college campus (Burgess et al. (2006)).

Approximate knowledge of the trajectory of the nodes has also been employed to deliver data in dynamic disconnected ad-hoc networks (Li & Rus (2000)). Given this information, the authors present an algorithm to pro-actively change the trajectory of intermediate nodes in order to deliver data between hosts. The goal is to minimize trajectory modifications while getting the message across as fast as possible. The authors present an analytical framework to prove the optimality of their proposed optimal relay path calculation algorithm.

4.5 Location-based schemes

In certain scenarios, the nodes may be aware of their location which can be used for opportunistic forwarding in DTNs. The location information may be known in either a physical (for example, from GPS devices attached to nodes or through a location service) or a virtual coordinate space (designed to represent network topology taking obstacles into account). On an encounter, a node forwards data to another node only if it is closer to the destination. Hence, location-based routing is a form of greedy, geographical-based routing (Takagi & Kleinrock (1984)). This minimal information is enough to perform routing and deliver data to the destinations. Hence, location-based schemes are fairly efficient in that they avoid the need to maintain any routing tables or exchange any additional control information between the nodes. These schemes have a well-known limitation where they suffer from a local minima phenomenon. Approaches such as perimeter forwarding (Karp & Kung (2000)) have been suggested to address this limitation.

The MoVe scheme (LeBrun et al. (2005)) employs information about the motion vectors of the mobile nodes in addition to the location information to perform routing in DTNs. Given the location and relative node velocity information, the scheme calculates the closest distance a mobile node is predicted to get to the destination when following its current trajectory. So a node only forwards to a neighbor if the neighbor is predicted to be moving toward the destination and getting closer to the destination than itself. The location-based routing algorithms are shown to outperform others based on realistic mobility traces obtained from GPS data collected from buses in the San Francisco MUNI system.

Leguay et al. (2006; 2005) propose a framework for routing in DTNs, called MobySpace, where each node is represented by a point in a multi-dimensional Euclidean virtual space.

Routing is done by forwarding messages toward nodes that have mobility patterns that are more and more similar to the mobility pattern of the destination. The authors demonstrate the feasibility of this framework through an example in which each dimension represents the probability for a node to be found in a particular location. Real world mobility traces (Henderson et al. (2004); Balazinska & Castro (2003)) of users show that the distribution of the probabilities of visit to locations as well as session durations generally follow a power law distribution. This property can be efficiently utilized by such a routing scheme. The results show that this scheme can bring benefits in terms of enhanced message delivery and reduced communication costs when compared with epidemic routing.

4.6 Gradient-based schemes

In gradient-based routing, the message follows a gradient of improving utility functions toward the destination thereby delivering the packet with a low delay and using minimal system resources. One of the early proposals, PROPHET (Lindgren et al. (2003)), employed probabilistic routing using history of encounters of the node and transitivity. This strategy was designed to take advantage of the non-random mobility behavior of the nodes as is the case in typical real-world scenarios. The idea is that each node is associated with a metric that represents its delivery predictability for a given destination. When a node carrying a message encounters another node with a better metric to the destination, it passes the message to it. The metrics are positively updated based on recent node encounters and metrics for sparsely encountered nodes are appropriately aged. The connectivity information is exchanged periodically among the nodes thereby allowing nodes to maintain meaningful metrics. As nodes run out of memory, the eviction candidate is selected based on a FIFO strategy although more intelligent eviction strategies have also been studied. The PROPHET strategy has been shown to have superior performance as compared to epidemic routing in case of a community mobility model.

Other researchers have proposed similar strategies in the case of ad-hoc networks using other kinds of information to calculate the gradient metric such as age of last encounter (Grossglauser & Vetterli (2003)), history of past encounters and the encounter rate (Nelson et al. (2009)), etc. Gradient based routing is also sometimes called adaptive routing (Musolesi et al. (2005)) since the metrics used for routing decisions essentially capture the context information of the nodes such as the rate of change of connectivity of a host (i.e., the likelihood of it meeting other hosts) and its current energy level (i.e., the likelihood of it remaining alive to deliver the message). Context is defined as a set of attributes that describe the aspects of the system that can be used to optimize the process of message delivery. The authors have introduced a generic method that uses Kalman filters to combine and evaluate the multiple dimensions of the context of the nodes to take routing decisions.

The Shortest Expected Path Routing (SEPR) is another scheme based on the link probability calculated from the history of node encounters (Tan et al. (2003)). Each message in a nodes cache is assigned an effective path length (EPL) based on the link probabilities along the shortest path to the destination. A smaller EPL value indicates higher delivery probability. When two nodes meet, they first exchange the link probability table and employ Dijkstra algorithm to get expected path length to all other nodes in the network. This novel EPL metric is employed for message forwarding as well as replacement when node buffer is full. This algorithm is similar to a traditional link state routing protocol in that nodes update their local tables on an encounter and in this way connectivity information is maintained in the network in a distributed manner. Simulation results confirm that SEPR achieves a higher delivery rate employing fewer message copies as compared to epidemic routing.

Gradient-based routing schemes suffer from a slow-start phase. Sufficient number of encounters must happen before the nodes develop meaningful metrics for each destination. In addition, this information needs to be propagated through the network. One solution to address this shortcoming is the Seek and Focus scheme (Spyropoulos et al. (2004)). This scheme initially forwards the message picking a neighbor at random until the metric utility value reaches a certain threshold. Thereafter a gradient-based approach may be employed to deliver the message to the destination.

4.7 Controlled replication schemes

Compared to traditional epidemic routing based schemes and its variants that rely on reducing the consumption of network resources, Spray and Wait (Spyropoulos et al. (2005)) presents a novel way to achieve efficient routing in DTNs. The idea is that it reduces the number of copies of a given message, and hence the number of transmissions for a given message, to a fixed value L that can be tuned in accordance with the delivery delay requirement. The scheme 'sprays' a number of copies of a message into the network to L distinct relays and then 'waits' till one of these relays meets the destination. A number of heuristics are presented about how the L copies are sprayed, for example, the source is responsible for spraying all L copies or more optimally, each progressive node encountered by a source or relay is handed over the responsibility to distribute half of the remaining copies (called Binary Spray and Wait). This scheme requires no knowledge of the mobility of the nodes. The expected delay of this scheme is analytically computed for the case of mobile nodes performing random walks on the surface of a 2-dimensional torus and compared with the optimal delay. This delay is independent of the size of the network and only depends on the number of nodes. The scheme is shown to posses robust scalability as the node density goes up.

A variant of this scheme called Spray and Focus (Spyropoulos et al. (2007)) provides further improvements by taking advantage of the mobility information in the wait-phase. The idea is that once the spray phase is over, each relay can then forward the packet further using a single-copy utility based scheme instead of naively waiting to meet the destination. Hence, this scheme combines the advantages of controlled replication along with those of gradient-based schemes presented earlier. Simulation results with a variety of mobility models such as random walk, random way-point, community-based etc. show significant improvements in the delivery delay.

4.8 Network coding based schemes

As opposed to the traditional model of forwarding in DTNs where nodes may forward the entire copy of the message to encountered relays, an alternate approach is to employ network coding based schemes. In (Wang et al. (2005)), the authors provide an erasure-coding based approach to forward data in DTNs. The idea is that the source node encodes a message and generates a large number of code blocks guided by a replication factor r. The generated code blocks are then equally split among the first $k \cdot r$ relays, for some constant k, and those relays must deliver the coded blocks to the destination directly. The original message can be decoded once $1/r$ coded blocks have been received. In other words, the message can be decoded as soon as k relays deliver their data to the destination. Such a scheme is more robust to failures of a few relays or some bad forwarding choices. The authors demonstrate via simulation evaluation with both synthetic and real world traces that this scheme achieves better worst-case delay performance that existing approaches with a fixed overhead.

Study	Scheme	Mobility Model	Energy	Delay	Copies created	Storage
Drop Oldest (Davis et al. (2001))	Epidemic Routing	Random Waypoint		X	Many	X
Infostations (Frenkiel et al. (2000))	Direct	Highway		X	None	
Message Ferries (Zhao & Ammar (2003))	One-hop Relay	Nonrandom Pro-active	X	X	One	
Zebroids (Ghandeharizadeh et al. (2006))	Knowledge Oracles	Random with predictions		X	Many	X
MoVe (LeBrun et al. (2005))	Location	Bus movement		X	One	X
Seek and Focus (Spyropoulos et al. (2004))	Gradient	Random Walk	X	X	One	
Spray and Wait (Spyropoulos et al. (2005))	Controlled Replication	Random Walk	X	X	Many	
Erasure Coding (Wang et al. (2005))	Source Coding	Animal movement based	X	X	Many	

Table 1. Related studies on intermittently connected networks.

Compared to the scheme proposed earlier that employs source coding, Widmer & Le Boudec (2005) propose a network coding based protocol for routing in DTNs. The idea is that intermediate nodes send out packets based on some linear combination of previously received information. In this way, a receiver reconstructs the original message once it receives enough encoded messages. A packet received by a node is considered innovative if it increases the "rank" of the set of received packets at this node. A parameter controls with which probability the reception of innovative packets causes a node to send a packet. The authors incorporate a mechanism of information aging in their protocol so that efficient network coding can still be achieved with little available memory. The process of determining how many and which messages will be coded together poses significant challenges especially if this is to be done in a distributed manner.

On the basis of the classification introduced in this section, we provide a small summary of DTN routing schemes in Table 1 depicting their representative characteristics.

5. Conclusions and future work

In this chapter, we have presented a survey of some of the most promising approaches proposed for data delivery in DTNs. Our survey and classification has concluded that there is no universal scheme that will be applicable in all scenarios. Depending on the particular scenario in question, either one or more likely a combination of schemes will be applicable to satisfy the needs of the application. A couple of other surveys for routing in delay tolerant networks that compliment this study have also appeared in recent literature (Spyropoulos et al. (2010); Jones & Ward (2006)). However, with so many choices available, some form of industry-wide agreement on standardization of a subset of these techniques as well as a

DTN architecture is necessary. The Delay Tolerant Network Research Group (DTNRG) is one such effort where an architecture for messaging in DTNs has been proposed (Cerf et al. (2007)).

Delay Tolerant Networks are a reality. With a large amount of different devices such as the smart-phones, netbooks, thin-clients etc. available in the market today, DTN routing has become even more challenging since it has to adapt to a vast set of heterogeneous nodes with different capabilities and networking technologies. Additionally, it has become increasingly clear that DTNs must be able to reach the global Internet. One proposal that enables communication between DTNs and the Internet is the Tetherless Communication Architecture (Seth et al. (2005)). More and more real-world deployments of DTNs at different scales that practically demonstrate the utility of the routing schemes and show how they can be employed to either alleviate or solve practical problems will allow researchers to drive the adoption of DTNs.

Finally, an important consideration for DTNs relates to issues of security, privacy, anonymity, and trust. For DTN routing to function, intermediate nodes must cooperate and agree to carry content of other users. In addition, the content must be transported securely and possibly encrypted to protect the information as well as prevent man-in-the-middle kind of attacks. The routing schemes themselves must have in-built mechanisms that address all these issues. While there have been independent proposals to address some of these aspects (Farrell & Cahill (2006); Seth & Keshav (2005); Kate et al. (2007)), a framework that integrates all these aspects and provides a holistic solution for DTNs is still missing.

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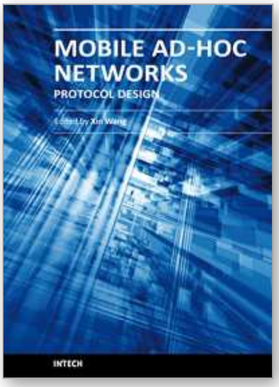
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