Routing Protocols in Delay Tolerant Networks – A Survey

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***Abstract*— Delay Tolerant Networks (DTN) are a class of networks that lack continuous connectivity between nodes due to limited wireless radio coverage, widely scattered mobile nodes, constrained energy resources, high levels of interference or due to some other similar channel impairment. Examples of such networks are those operating in mobile networks or extreme terrestrial environments, or simply as planned networks in space. The term disruption-tolerant network is also occasionally used in place of DTN. Routing in DTN is challenging because of frequent and long duration periods of non-connectivity. Several routing protocols have been proposed with strategies ranging from flooding to opportunistic approaches. Due to the diversity of available strategies, there is a need to properly classify and evaluate their performance with various angles. In this paper, we study state of the art routing protocols and give a comparison between them with respect to the characteristic features and methodology involved. The pros and cons of each, their performance and open research issues are also discussed.**

Keywords- ***Routing, Delay Tolerant, Flooding, Erasure Coding, Scalability, Multipath***

I. INTRODUCTION

Delay-tolerant networking (DTN) is a method of building network architecture that seeks to address the technical issues in heterogeneous networks that may lack permanent network connectivity. Examples of such networks are those operating in mobile networks or extreme terrestrial environments. Several DTN have also been deployed in the form of planned networks in the space. The term Delay tolerant networking was coined in 2002 by Kevin Fall who adopted some of the ideas in the Interplanetary Internet (IPN) design to the deployment of terrestrial networks. Recently, the term Disruption-Tolerant Networking is also being used in place of Delay Tolerant Networks.

Disruption, the main feature of DTNs, may occur because of the limits of wireless radio range, widely scattered mobile nodes, energy resources, attacks, and interference etc. DTN features some important characteristics which renders the conventional routing strategies ineffective and require routing protocols quite different from these methods. Some of the features associated with DTN include the lack of continuous connectivity and disconnection between end-to-end nodes. Also lack of instantaneous path connections results in high latency of data delivery and overall low data rates. Long queuing delays and limited longevity of individual nodes is also a problem for effective routing.

Routing itself is a method of transferring or transporting data from source to destination. The above mentioned characteristics of DTN require the adoption of techniques to counter and wisely utilize resources. In order to perform efficient routing in DTN, the nodes need to utilize any available information about future link establishments, exploit mobility, and wisely allocate buffer resources to save power. Also security and reliability of the data is an important challenging issue in DTN. These characteristics also differentiate DTN from Mobile Ad-hoc Networks (MANET).

Although a few survey papers exist in this area, but these take into consideration only a few popular protocols, while we try here to incorporate, classify and present a greater range of protocols in order to have a comprehensively comparison. We also introduce a diversity of performance measure metrics for evaluation purpose inspired by the work of Jones *et al*. [1] and Shen *at al*. [9].

II. RELATED WORK

Few survey papers exist in the area of DTN as in [1] and [9]. These take into consideration a few popular protocols and discuss them in detail. Jones *et al*. [1], classifies the routing protocols into flooding and forwarding strategies and elaborate both the challenges and evaluation criteria in detail. We lay the foundations of the previous work by incorporating all available protocols in the existing categories. The work done by Shen *et al*. [9] carry out the same classification in detail. In the work by Vahdat *et al*. [3] and Ramanathan *at al*. [4], epidemic routing schemes for partially connected opportunistic networks has been discussed. The writers of [6] and [7] give methodology for routing following a probabilistic approach. In the work done by Liao *et al*. [16] routing has been done by use of erasure-codes to cope the errors introduced from the DTN environment. In the paper of Lin *et al*. [19] detailed performance of a few popular routing protocols for DTN has been done. While we borrow here some work from these surveys and research papers, we try here to include not just all the current available protocols, but also extend our classification to coding based strategies. Also we present here extensive comparison tables for all the protocols and base them on a larger number of performance measure metrics to contrast from the previous work.

The rest of the paper is categorized as follows. In section III, the routing techniques are classified. In section IV, we perform a comparison for the categorized routing techniques. Section V provides key insights into developing future routing techniques and section VI concludes the paper.

III. ROUTING PROTOCOLS

Due to the above mentioned properties, conventional ad-hoc protocols like MANET (mobile ad-hoc network); focused on situations where nodes act as routers, fail to establish routes in DTN. This is mainly because the standard routing protocols focus mainly on selecting paths from many options whereas in DTN focus is mainly on being as efficient as possible with the few paths available. Hence routing protocols have been established for DTN according to the practical scenarios. These protocols can be classified according to the methodology used to find destinations and whether replicas of messages are transmitted or not. Consequently routing protocols can be broadly characterized by

1. Replica based (flooding) protocols
2. Knowledge based (store and forward) protocols
3. Coding based protocols

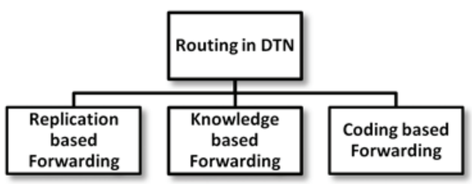

FIGURE 1 ROUTING IN DTN CLASSIFICATION

A. REPLICA BASED(FLOODING)PROTOCOLS

Replication based protocols allow for better message delivery ratios than in forwarding-based protocols. These schemes work by making several replicas of the original message or packet. Each node maintains a number of copies of each message and retransmits them upon connection establishment. These protocols are also referred to as flooding based protocols. Using several copies increases the probability of message delivery to the destination. Flooding based approach is resource hungry, unable to cope network congestions and does not scale well.

Decision making for the priority of message replication and dropping under constrained environments is a challenging task. Protocols characterized under the replica based family include the direct contact, two hop relay, relay cast, tree based flooding, epidemic routing, maxprop, probabilistic routing, spray and wait, rapid and runes.

Direct Contact scheme lets the source hold the data until it comes in contact with the destination. This simple strategy uses one message transmission. It is a degenerate case of flooding family, requiring no info about network but requires a direct path between source and destination. Hence if no contact occurs, message is not delivered.

In Two Hop Relay, the message is copied to the first n nodes with which the source comes in contact making the total copies of data in the network to n+1. The message is delivered to the destination upon the first contact with any one of the nodes holding the message [1]. Hence the transmission occurs in two hops. This strategy consumes more bandwidth and storage capacity but has a better chance of delivering message to the destination than direct contact.

Relay Cast is a routing scheme that extends the two-hop relay algorithm in the multicast scenario that was proposed as a result of the poor scalability of unicast networks [2]. The algorithm seeks to improve the throughput bound of wireless multicast in a delay tolerant setting using mobility-assist routing. Mobility-assist routing strategy involves holding the received data in storage by the nodes and waiting for opportunities to transfer packets to remote nodes. Scalability is the main exploited characteristic in the protocol.

In Tree based Flooding, the message is replicated in a tree like manner but the number of copies is controlled by indicating the number of copies to produce when copying to the relay node [1]. The set of relays form a tree of nodes rooted to the source. A strategy to decide upon the copies could be to make indefinite replicas but limiting the number of hops that could be travelled hence limiting trees depth but not width. A different approach could be to also limit the number of copies.

Epidemic Routing tries to send message over all the paths in the network and all the nodes can become the carrier [3]. However upon contact with each other nodes exchange only the data they do not have in their memory buffer. Hence it is robust to node or network failure, guaranteeing that upon sufficient number of random exchanges all nodes will eventually receive all messages in minimum amount of time. This approach does not require information about the network, however requiring large amounts of buffer space, bandwidth and power.

Prioritized Epidemic Routing made a slight change to normal epidemic routing imposes priority functions on the data transmission and deletion. Accordingly the data can be arranged in a priority order called bundle to be transmitted [4]. The priority can be decided upon the current cost to the destination or source, the expiry time and the generation time. The cost itself is derived from per link "average availability" information that is disseminated in an epidemic manner. It outperforms epidemic routing in terms of node density and storage.

MaxProp protocol puts a priority order on the queue of packets [5]. Packets that should be dropped and those that need to be transmitted are then classified in this priority queue. The basis for priority can include several methods, including the ratio of successful path establishments to peers or the number of acknowledgements etc. Such scheme increases the message delivery ratio in general. MaxProp maintains an ordered-queue where the ordering is done based on the destinations related with each message.

Probabilistic Routing approach works with the probability of a node's contact with another node [6]. The message is delivered to another node only if its probability of having contact with some other node is way above some probability threshold set. The message is forwarded along the highest probability paths.

RAPID Protocol (Resource Allocation Protocol for Intentional DTN Routing) aims at improving signal routing metrics i.e. average delay, missed deadlines and maximum delay. A utility function based upon the metric to optimize is assigned to every packet according to its contribution to that metric [8]. Only those packets that result in increase in utility function are replicated.

RUNES stand for Reconfigurable Ubiquitous Networked Embedded Systems. In this strategy, each node maintains the cost in hops from the destination and the source in the form of a vector. A message that is close to the source or destination is less likely to be dropped [9].

SaW (Spray and Wait) achieves resource efficiency by setting a limit on the upper bound on the number of copies being replicated in two distinct phases: the spray and the wait phase [10]. A bound B is attached with the original message that indicates maximum allowable copies. During the spray phase, one copy of the message is delivered to B distinct relays. The relay upon receiving the copy goes holds it and goes into wait phase until it directly comes in contact with the destination. Two versions of SaW, the vanilla and binary differentiate between the methods with which the B messages are delivered to the B distinct nodes in the spray phase. Vanilla accomplishes this with replicating to the first B nodes encountered and Binary replicates half of the copies to the very first node encountered and in term that node transmits half of the copies to the one it encounters first with the process continuing until one copy is left with the node. Binary Saw is more efficient in terms of faster distribution of messages.

B. KNOWLEDGE BASED(STORE AND FORWARD)PROTOCOLS

These routing protocol families require some form of network topology information before hand in order to transfer data from one node to the other. Hence they transfer data only in the best path instead of replicating it unknowingly. Examples of it include the location based routing, source routing, per hop routing, per contact routing, ORWAR, hierarchical routing, gradient routing, link metric routing, delay tolerant link state routing and MORA.

Location based routing works by assigning coordinates to nodes in the network [9]. A distance function is evaluated to know the cost of reaching any node in the network. This strategy does not require routing tables and also has less control overhead since only the source; destination and next hop coordinates are required. However closeness in distance does not provide guarantee of any connection establishment and in a rapidly changing environment the coordinates need to be updated rapidly.

In Source Routing only the source has to know of the whole network topology. The source determines the path that the datagram would be following [9]. Hence the source has to be intelligent enough to decide upon its closeness to the destination in hops to have a better performance.

In per hop routing, the intermediate hop or node decides upon the next hop or node to which the datagram should be forwarded according to the network topology it has gathered [11]. While in per contact routing, an updated routing table is kept. The update is done on each contact [11]. Therefore whenever a datagram is forwarded it is done upon the latest network topology information. However, the updates can create loops in the network.

Opportunistic Routing with Window-Aware Replication (ORWAR) is a distributed algorithm based approach that exploits the connectivity knowledge of mobile nodes speed, direction of movement and range to estimate the size of contact window, hence making better forwarding decisions and minimizing the probability of partially transmitted messages, thus optimizing overall bandwidth [12].

An estimate of largest transmittable message is calculated and used to relay messages that have a lower chance of transmission failure, thereby saving transmission power and bandwidth. It also differentiates between message utility, allowing more resources to high utility messages. Messages are replicated in the order of highest utility, and removed from buffers in reverse order. It provides lower overhead and higher delivery rate, as well as higher accumulated utility compared to algorithms like Maxprop and Spray and Wait.

Hierarchical routing is similar to source routing but instead of the source completely deciding the route, hop by hop decision of the datagram forwarding is done, hence making it more scalable to localized traffic [13]. This scheme provides challenge in order to keep constant track of time varying information.

Gradient Routing works by assigning a weight to each node that determines the suitability of that node to deliver message to the destination [1]. The metric can be based on many parameters such as time of between contacts, mobility, probability of delivery or remaining battery power etc. On contact with a node having better metric value, the message is delivered to that node; hence a gradient of improving utility function is followed. This scheme requires more network knowledge than location based routing because a metric of information regarding destinations has to be kept at each node and for computing it; sufficient information has to be propagated through network to all nodes.

Link metric routing works by building a topology graph, assigning weights to each link and finally running a shortest path algorithm [1]. The challenge here is to assign those link weights that provide highest bandwidth and delivery ratio while minimizing the delivery latency and resource consumption like buffer space or power. The message is forwarded along the path with minimum overall link metric weight.

DTLSR (Delay Tolerant Link State Routing) protocol works in a similar manner to the typical link state schemes. Changes in the network are characterized by information message exchanges. Each individual node evaluates its own view of the topology of the network. Shortest path computation (e.g. Dijkstra) can then be used to find routes for messages to take.

Borrowing a similar idea from CSPF (Constrained Shortest Path First), a constrained flooding algorithm is used within the DTN bundle forwarding layer [14]. A simple weighting heuristic is used to capture the path selection criteria.

Multi-Objective Robotic Assistance (MORA) protocol works by analyzing and capturing structure in movement patterns of nodes in the network and use it to enable informed message passing, hence it is based on the fact that motion of participants can solely affect capacity of DTN [15]. Autonomous agents are also included in the DTN which adapt their movements in response to variations in the network capacity and demand. Multiple objective functions and control methods based on robotics are utilized to generate motions capable of optimizing multiple network performance metrics simultaneously thus significantly improving performance in DTNs.

C. CODING BASED FAMILIES

It utilizes different kinds of coding techniques to encrypt data. Each data packet is uniquely encoded by using network coding. Hence the packets leaving the source are generally coded. A node only needs to receive enough packets to decrypt the data, improving the overall delivery rate. Examples include the Estimation based Erasure Coding (EBEC) and Hybrid Erasure coding (HEC).

EBEC uses a fixed overhead to generate a large number of message blocks instead of a few copies allowing transmission of only a portion of message to a relay [16]. This ability increases the diversity in routing and effective when combined with estimation based approach. When two nodes come in contact, a copy may or may not be generated in the other node based on its ability of being better or worse in terms of probability of delivering message. But not making a copy can be a risk in the case when time between connections is large. This is catered by erasure-coding by copying only 'part' of the message to other node. This part to be forwarded is calculated by an estimation technique. The contact frequency with the destination is used as the metric to estimate node's ability to deliver the message. For each message, the source takes a replication factor R and erasure codes R×K equal sized blocks. The message can be fully decoded at the destination if at least K generated blocks are successfully received. The overhead is therefore simply the R factor.

HEC combines erasure coding and aggressive forwarding mechanism [17]. Aggressive forwarding mechanism itself has key mechanism of sending all packets in a sequential manner during a nodes contact period. If a nodes' battery is dead or node loses mobility, it cannot deliver data to the destination creating a phenomenon normally termed and referred to as 'black hole' information loss problem. The HEC model uses the nodes' contact duration efficiently and applies erasure coding to solve the black hole problem caused by aggressive forwarding.

IV. COMPARISON

It is obvious from the protocol family that replication based protocols have a higher delivery ratio while forwarding and coding based families of protocol use the benefit of low resource utilization and fixed overheads. But for a comparison these metrics are not fair enough, hence a deep comparison is needed in terms of various performance metrics [19][20]. The most common of these metrics include hop count, number of copies, latency, resource consumption, delivery ratio, scalability and overall effectiveness. Multipath support, loop freeness, information usage and use of routing table is also included in the comparison table for the three routing protocol families to have a deep insight into the overall performance assessment.

From the three comparison tables given below, following conclusions are inferred:

- Replication based protocols have an overall higher delivery ratio
- Forwarding based families have an overall low resource utilization
- Coding based families have fixed overheads
- Direct Contact in flooding family has an overall low performance and effectiveness while RAPID seems to be a good choice by giving the largest optimized performance metrics
- Location based routing and source routing in knowledge based families give the least performance while hierarchical and link metric routing are at the top in terms of performance
- In coding based family, Hybrid Erasure Coding gives better performance than Estimation based Erasure Coding
- Precise Scheduling mechanisms are covered by the forwarding families while highly random networks are catered by epidemic and tree based strategies
- Although the performance metrics used in the three comparison tables is the same but these three cannot be directly compared to choose out the best one because these are base on different networking goals in mind
- No single routing algorithm is optimized in terms of majority of the performance metrics; hence a single routing protocol can show effective performance only in particular network environmental conditions, giving importance to particular goals while delivering messages from the source to the destination.

TABLE I. PERFORMANCE COMPARISON OF FLOODING BASED FAMILIES

	Direct Contact	Two Hop Relay	Tree Based Flooding	Epidemic Routing	RAPID	Probabilistic Routing	Relay Cast	RUNES	MaxProp	SaW
Hop Count	1	2	Many	Many	Many	Many	Many	Many	Many	Many
Number of Copies	No	N	$\sum_{i=0}^{i=n}\sum_{j=0}^{j=k} M$	Unlimited (Limited in PER)	Limited	Limited	Unlimited	Limited	Limited	Limited
Latency	Large	Large	Large	Large	Low	Low	Large	Large	Moderate	Large
Resource Consumption	Low	Low	High	Maximum	Low	Limited	High	Limited	Moderate	Low
Delivery Ratio	Min	Low	Low	Maximum	High	Moderate	High	Moderate	High	High
Scalability	No	No	Yes	Yes	Low	Low	High	Low	Moderate	Low
Information Usage	Low	Low	Moderate	Moderate	High	High	Low	High	High	Low
Loop free	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes
Multipath Support	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Routing Vector/Table	No	No	No	Yes	No	Yes	No	Yes	No	No
Effectiveness	Low	Low	Low	Moderate	Good	Good	Moderate	Good	Good	Low

n = number of nodes in network, k = number of nodes at the trees depth, M = number of copies of a message at a node ance

TABLE II. PERFORMANCE COMPARISON OF KNOWLEDGE BASED FAMILIES

	Location Based Routing	Source Routing	Per hop Routing	Per contact Routing	Hierarchical Routing	Gradient Routing	Link Metric Routing	MORA
Hop Count	Small	Small	Many	Many	Many	Many	Many	Many
Number of Copies	None	None	None	None	None	None	None	None
Latency	Moderate	Large	Large	Moderate	Moderate	Moderate	Low	Moderate
Resource Consumption	Low	Moderate	Moderate	High	High	High	Low	High
Delivery Ratio	Min	Low	Low	Moderate	Max	High	High	High
Scalability	Low	Low	Low	Low	High	Moderate	Moderate	Low
Information Usage	Low	Moderate	Moderate	High	High	High	High	High
Loop free	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Multipath Support	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Routing Vector/Table	No	No	No	Yes	Yes	No	Yes	No
Effectiveness	Low	Low	Low	Moderate	High	High	High	High

TABLE III. PERFORMANCE COMPARISON OF CODING BASED FAMILIES

	Hop Count	No. of Copies	Latency	Resource Consumption	Delivery Ratio	Info Usage	Loop free	Multipath Support	Routing vector/ table	Effectiveness
EBEC	Many	Limited	High	High	Moderate	High	Yes	Yes	No	Moderate
HEC	Many	Limited	Low	High	Low	High	Yes	Yes	No	High

V. RESEARCH ISSUES

In the three dimensional research in the area of replication, knowledge and coding based routing protocols the strategy of taking advantage of the three widely used approaches in the Delay Tolerant Networking field is of great importance. Researchers would also like to use the least amounts of overhead from the three approaches when used simultaneously, but the tradeoffs of least overhead encountered here is inevitable in real world scenario where contacts and network environment parameters are really random and unpredictable.

Since replication based protocols have a higher delivery ratio while forwarding and coding based families of protocol use the benefit of low resource utilization, fixed overheads and low latency in data delivery, researches in finding an optimum routing strategy that optimizes all these constraints at the same time would be highly appreciated. Based on real world scenarios, variants of flooding families that take advantage of some learned topology information and some accompanied with some descent coding scheme would be a great step in this direction. Again there has to be a tradeoff between the amounts of participation from the three families and this can be experimented only by actually building DTNs and their applications in order to see what real world problems confer them. At the time a number of prototypes for DTNs are being deployed and monitored to measure the connectivity properties but these would not be able to accurately predict the requirements for routing of real time DTNs, but as a first critical step, these efforts need to be enlarged.

Another important research area in the field of DTNs is the integration of multiple types of networks together requiring techniques to allow messages to be exchanged between DTNs that have different types of underlying protocols running. Another issue would be to enable the DTNs nodes to communicate with the outside world, especially the internet.

VI. CONCLUSION

Routing protocols in the field of DTNs are being constantly developed to cater for better resource consumption and latency while giving higher throughputs; hence this new field of research area has a lot of room for new experiments and results. In this survey paper, a comparison was given for the currently developed protocols for DTNs. Their performance was compared in terms of different metrics like hop count, delivery ratios, and number of copies etc to gain an insight into their overall effectiveness with respect to the network environment situations. It turns out that there is not one compact routing protocol that would cater for different environment situations and every routing protocol can only work for one set of environment conditions and would drastically fail in different network situations. Said another way, each routing protocol tries to optimize small number of performance metrics, hence it should be taken as a challenge to develop a compact scalable routing protocol that has efficient resource consumption, low latency and high delivery ratios and that runs a smart algorithm that can select best paths and manage buffers in an effective way. It should also include other network parameters mentioned in the comparison tables to have smooth functionality under challenging environments and exploit contacts in much intelligent ways.

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