Routing in Delay/Disruption Tolerant Networks: A Taxonomy, Survey and Challenges

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***Abstract*—The introduction of intelligent devices with short range wireless communication techniques has motivated the development of Mobile Ad hoc NETworks (MANETs) during the last few years. However, traditional end-to-end based routing algorithms designed for MANETs are not much robust in the challenged networks suffering from frequent disruption, sparse network density and limited device capability. Such challenged networks, also known as Intermittently Connected Networks (ICNs) adopt the Store-Carry-Forward (SCF) behavior arising from the mobility of mobile nodes for message relaying.**

In this article, we consider the term ICNs as Delay/Disruption Tolerant Networks (DTNs) for the purpose of generalization, since DTNs have been envisioned for different applications with a large number of proposed routing algorithms. Motivated by the great interest from the research community, we firstly review the existing unicasting issue of DTNs because of its extensive research stage. Then, we also address multicasting and anycasting issues in DTNs considering their perspectives. A detail survey based on our taxonomy over the period from 2006 to 2010 is not only provided but also a comparison is given. We further identify the remaining challenges and open issues followed by an evaluation framework proposed for routing in DTNs. Finally, we summarize our contribution with three future research topics highlighted.

***Index Terms*—Delay/Disruption Tolerant Networks, Intermittently Connected Networks, Routing, Store-Carry-Forward.**

I. Introduction

Due to the characteristic of challenged environment suffering from frequent disruption, sparse network density and limited device capability, routing algorithms designed for Mobile Ad hoc NETworks (MANETs) can not perform effectively under these constraints, since the availability of contemporaneous end-to-end connectivity is essential for conventional routing algorithms such as Ad hoc On-Demand Distance Vector (AODV) [1] or Dynamic Source Routing (DSR) [2]. However, this does not prevent bridging communication between the disconnected areas, as the concept of Intermittently Connected Networks (ICNs) is proposed to overcome these difficulties using the Store-Carry-Forward (SCF) routing behavior.

A. Concept and Applications of DTNs

In Intermittently Connected Networks (ICNs), mobile nodes are capable of communicating with each other even if the contemporaneous end-to-end connectivity is unavailable. Furthermore, the global knowledge about network is not essential for the mobile nodes in ICNs. Given the lack of contemporaneous end-to-end connectivity that prevents the conventional routing algorithms designed for MANETs from working effectively in ICNs, the Bundle Protocol [3] borrowing from the concept of Email protocol is proposed by the Internet Research Task Force (IRTF) Delay Tolerant Networking Research Group (DTNRG) [4], to behave as a convergence layer protocol on top of the Transmission Control Protocol (TCP) layer for enhancing the transmission reliability.

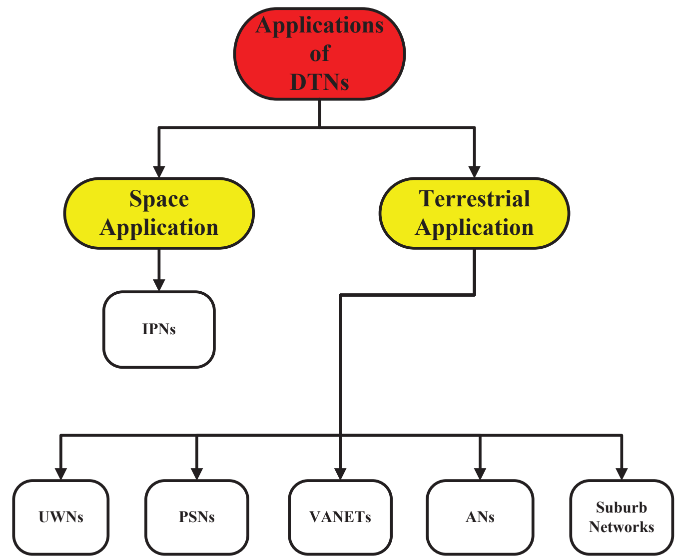

Fig. 1. Applications of DTNs

Thanks to the most recent tutorial [5], providing a rigorous definition about the difference between Delay/Disruption Networking (DTN) [6] and ICNs. Also, taking into account the understanding from the authors in [7][1], we replace the term ICNs with Delay/Disruption Tolerant Networks (DTNs) in this article for the purpose of generalization, since we focus on routing issue for this type of networks without investigating the DTN architecture.

As illustrated in Fig.1, the space application of DTNs is for InterPlanetary Networks (IPNs) [8] with a low network dynamic. In mobile wireless networks, the terrestrial applications of DTNs have been envisioned for UnderWater Networks (UWNs) [9], Pocket Switched Networks (PSNs) [10], Vehicular Ad hoc NETworks (VANETs) [11], Airborne

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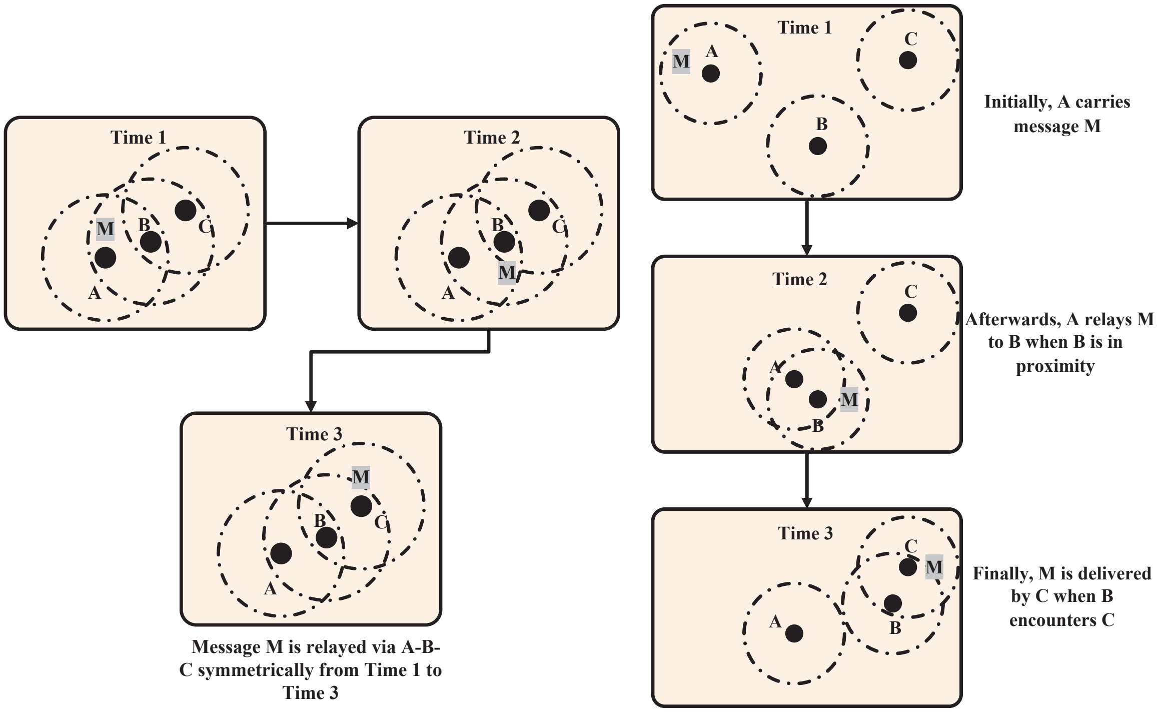
[1]In [7], the authors provide the concept of Opportunistic Networks (ONs) and interpret it is as a more flexible environment than Delay/Disruption Tolerant Networks (DTNs).



(a) Routing in MANETs (b) Routing in DTNs

Fig. 2. Illustration of Routing in MANETs and DTNs

Networks (ANs) [12] and suburb networks for developing region [13].

B. Existing Research Activities of DTNs

Up to now, the research activities in DTNs are being investigated for application layer design [14], convergence layer design [15], routing [16], congestion control [17], flow control [18] and security [19], which are briefly introduced as follows:

Application Layer Design: The design of application layer protocol is the most challenging issue since the network architecture needs to deal with system component, which is fixed and known. However, the application has to deal with user interest, which is more dynamic.

Convergence Layer Design: This research issue is separated into the proposal for space DTNs (or referred to IPNs) and terrestrial DTNs. More specifically, the long delay is more concerned for space DTNs even when the connectivity exists. In contrast, the communication in terrestrial DTNs somehow is with frequent disruption. As such, these properties have to be considered for these two types of applications.

Routing: In contrast to routing in MANETs, routing in DTNs is more difficult due to the lack of the most recent network topology information.

Congestion Control: Congestion control in DTNs is affected by the acknowledgement strategy since once the message is acknowledged, the cached message can be discarded to alleviate the buffer space exhaustion.

Flow Control: Instead of the traditional end-to-end based approach, flow control in DTNs requires a hop-by-hop behavior to provide the information on traffic and local resource availability that can also be used from upper layer.

Security: In DTNs, it would be hard for a certificate authority to exchange cryptographic message with a particular node. Apart from key management, DoS attacks, access control, privacy and anonymity are also being investigated.

C. Organization of This Article

As our focus, routing is an important research area in DTNs not only because of its unique characteristic, but also due to the extensive attention from the research community.

In section II, we provide the relevant background of routing in DTNs together with our taxonomy illustrated in III. We further provide the overview of unicasting, multicasting and anycasting issues based on our taxonomy in section IV, V, VI respectively. Given the comparison and discussion for the reviewed algorithms in section VII, we further identify the remaining challenges and open issues in section VIII, followed by a proposed evaluation framework in section IX. Finally, section X summarizes our contribution with three topics highlighted for future investigations.

II. Background of Routing in DTNs

Given the examples illustrated in Fig.2(a) and Fig.2(b) where message M is relayed from node A to node C via node B, the difference between routing in MANETs and DTNs is that the former relies more on symmetric relaying the message with a multi-hop routing behavior, thanks to the contemporaneous end-to-end connectivity. Whereas the latter relies more on the mobility of mobile nodes to create encounter opportunity for an asymmetric routing behavior, under the assumption of intermittent connectivity.

As illustrated in TABLE I, routing in DTNs suffers more from long delivery delay than that of in MANETs due to the

TABLE I
DIFFERENCE BETWEEN ROUTING IN MANETS AND DTNS

	Routing in MANETs	Routing in DTNs
End-To-End Connectivity	Contemporaneous	Frequently Connected
Delivery Delay	Short	Long
Transmission Reliability	High	Low
Routing Behavior	Symmetric	Asymmetric

asymmetrical routing behavior, and low transmission reliability while taking into account limited encounter duration due to the lack of contemporaneous end-to-end connectivity.

A. Definitions Used in This Article

Bundle: It is an arbitrary size data unit in DTNs, where the size of a bundle is defined according to the specific application requirement. It is also regarded as the message for the purpose of generalization.

Encounter Opportunity: It is an encounter between pairwise nodes. Specifically, an encounter opportunity is regarded as a tuple consisting of (d, m, b), where d is the time duration of an encounter, m is a set of messages requested for transmission and b is the bandwidth speed of DTN device. For reliable transmission, the total size of messages m being transmitted during an encounter opportunity should not exceed the maximum volume of the encounter opportunity, which is determined by $d \times b$.

Store-Carry-Forward: When a node carries a message while there is no contemporaneous end-to-end path to its destination or even a connectivity to any other node, this message would be stored in this node, and wait for the upcoming encounter opportunity with other nodes for message relaying.

Candidate Node: Based on the definition of Store-Carry-Forward, the encountered node selected as the message relay is defined as the candidate node for this message.

B. Inherent Challenges

Bandwidth: This factor determines the number of messages that can be transmitted at each encounter opportunity. For instance, if the bandwidth of a DTN device is sufficient to transmit all the requested traffic load within a given encounter duration, then this is reasonable. However, if the traffic load increases due to a large number of users or a larger size of messages being transmitted, then the unsuccessful transmissions due to insufficient encounter duration should be taken into account. Therefore, to estimate the number of messages that can be successfully transmitted is useful to reduce the number of aborted messages due to insufficient encounter duration. In addition, to transmit messages according to a corresponding priority is beneficial to utilize the bandwidth.

Buffer Space: The sufficient buffer space is essential for the carried messages, since they would be buffered for a long period time until the upcoming encounter opportunity is available. In light of this, to discard the least important message due to buffer space exhaustion is beneficial to utilize the buffer space.

Energy: A DTN device often has limited energy and can not be connected to the power supplier easily. Energy is required for transmitting, receiving, storing messages and performing routing process. Hence, the routing algorithms which transmit few messages and perform less computation are more energy efficient.

C. External Challenge

Apart from the inherent challenges, mobility factor as the external challenge describes the variation of movement and plays an important role in routing performance. Therefore, it is desirable to emulate the movement pattern of the targeted real world applications in an appropriate way. Otherwise, the conclusions and observations drawn from the results may be misleading.

In light of this, it is necessary to select the appropriate underlying mobility model while evaluating the routing performance. For example, the mobile nodes under the Random WayPoint (RWP) mobility model would behave differently from the group based mobility model. Since it is difficult to obtain the global knowledge about the distribution of encounter probability or inter-meeting time in reality, knowledge and assumption regarding mobility model are more crucial to DTNs.

D. Evaluation Metrics and Routing Objective

Delivery Ratio: It is given by the ratio between the number of delivered messages and the number of generated messages.

Overhead Ratio: It is given by the ratio between the number of message transmissions required for delivery and the total number of messages delivered.

Delivery Delay: It is given by the time duration between the messages generation and their delivery.

The routing objective provides a tradeoff between maximizing the delivery ratio and minimizing the overhead ratio. On one hand, the ideal case of delivering the message before its given lifetime with the lowest overhead ratio is to keep this message until the destination is in proximity. While on the other hand, the effective approach to maximize the message delivery ratio is to relay this message at each encounter opportunity taking into account the candidate node selection. Although it is expected that the applications of DTNs are inherently tolerant to the long delivery delay, this does not mean they would not benefit from short delivery delay, thus this should be a particular target with the given message lifetime.

III. TAXONOMY OF ROUTING IN DTNS

Based on previous works [7][16], we firstly specify and extend the corresponding branches giving our understanding of the algorithm characteristic, then classify the existing routing algorithms in DTNs into unicasting, multicasting and anycasting issues.

As the taxonomies of the previous works illustrated in Fig.3 and Fig.4, our contributions are as follows:

1: We specify the detail of Dissemination Based (we name it as "Naive Replication" family) and Context Based (we name it as "Utility Forwarding" family) branches in [7].

2: We then extend another branch named as "Hybrid" family taking the advantages of "Naive Replication" family

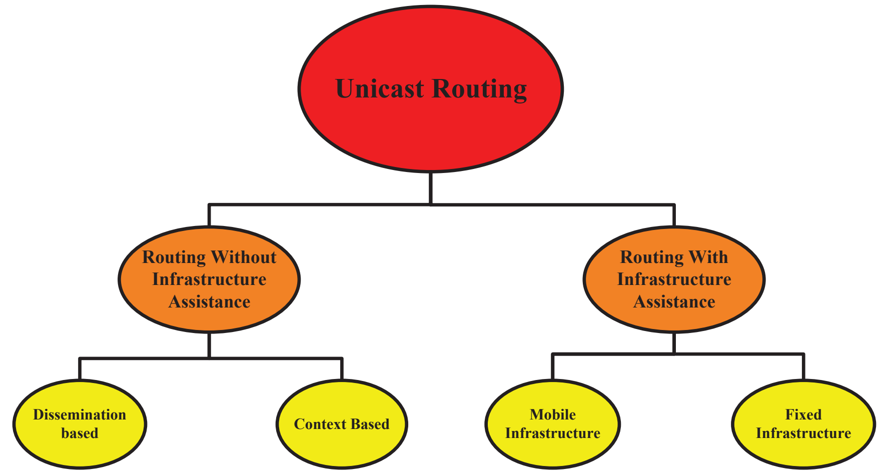


Fig. 3. Taxonomy of the Work in [7]

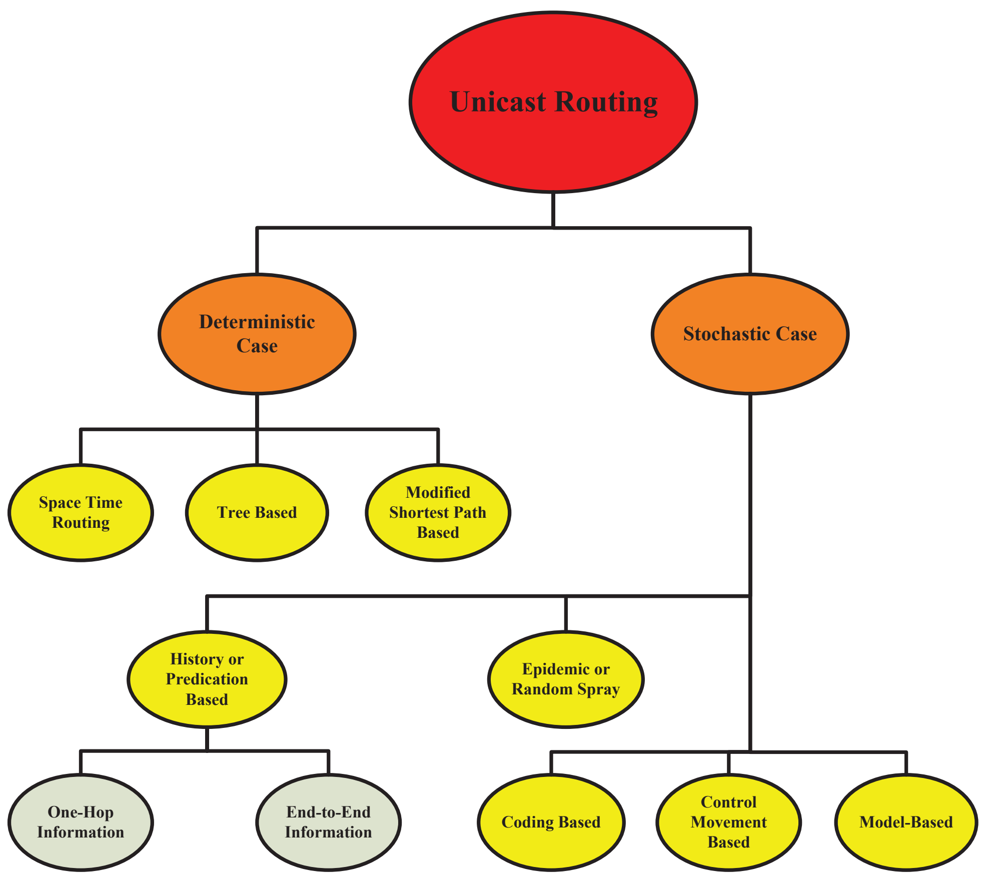


Fig. 4. Taxonomy of the Work in [16]

and "Utility Forwarding" family, as an extensively investigated branch of routing in DTNs.

3: Different from the perspective of the taxonomy proposed in [16] which classifies the routing algorithms depending on the underlying mobility model, we classify the routing algorithms according to their design characteristics, which is significantly highlighted in "Hybrid" family.

4: We also address multicasting and anycasting issues in DTNs given their current research stages.

5: We survey a large number of high quality references between 2006 and 2010, following our taxonomy illustrated in Fig.5 as our improvement.

IV. Unicasting Issue

The term unicasting means to deliver the message to its unique destination. Regarding the algorithms without infrastructure assistance, we start from two basic families named as "Naive Replication" and "Utility Forwarding", where the former relies on the replication approach to achieve a sufficient delivery using multiple message copies, while the latter is based on a utility metric to qualify encountered node to achieve an efficient forwarding by using single message copy. The "Hybrid" family as the evolution of the above two families is receiving extensive attention for routing in sparse networks.

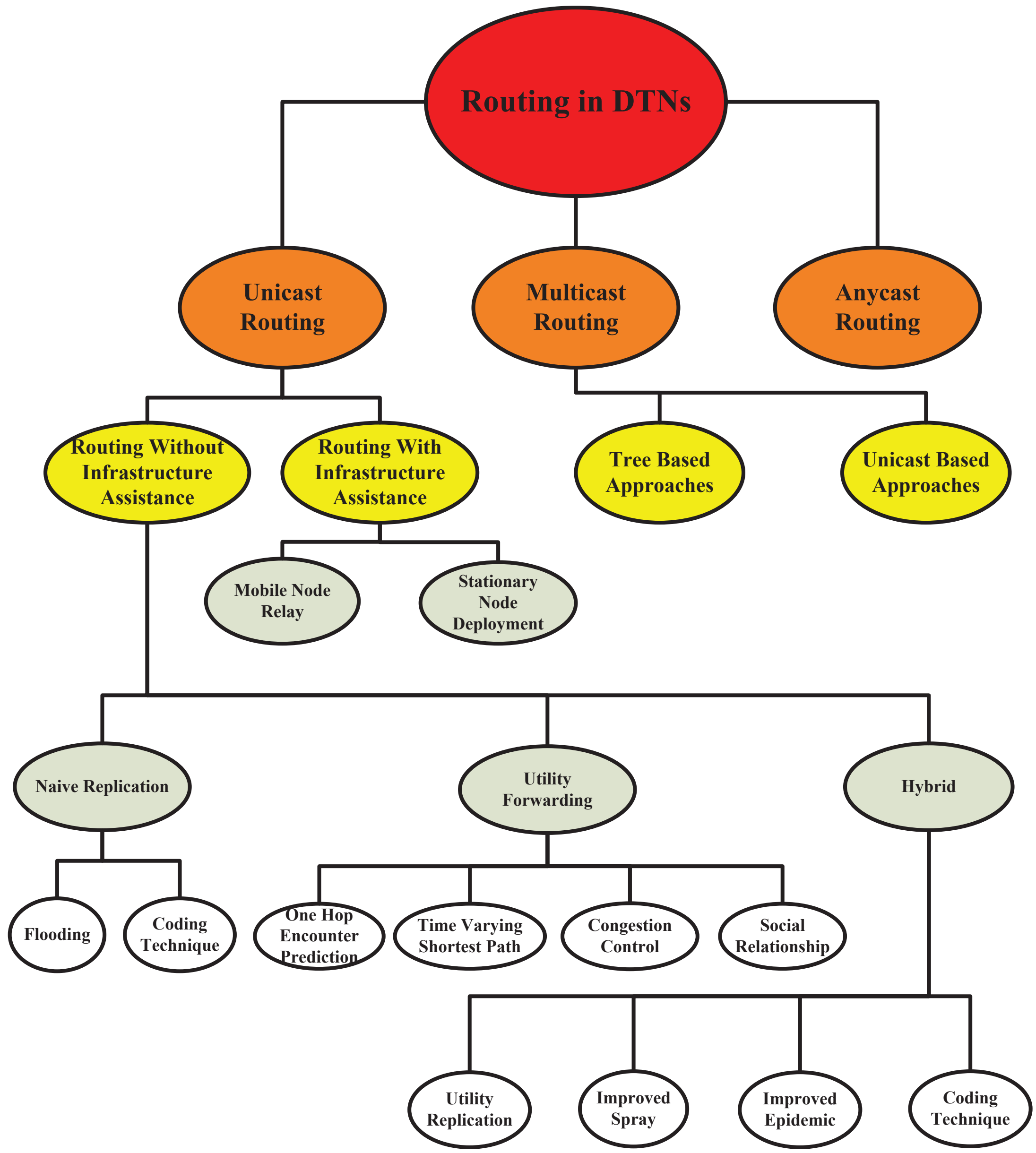


Fig. 5. Our Taxonomy of Routing in DTNs

Relatively, the algorithms with infrastructure assistance focus more on route design or location deployment for such infrastructure, where the infrastructure is not regarded as an intrinsic node in the network.

A. Routing Without Infrastructure Assistance

1) Naive Replication Family: Regarding algorithms in this family, multiple copies of each message are replicated without considering the candidate node selection .

[Flooding Based]

Starting from Direct Delivery (DD) [20], in which the source node constantly keeps the message until the destination is in proximity. Strictly speaking, DD is a degraded case of the flooding based algorithm. Firstly, DD does not require any knowledge, which means the routing behavior is naive. In addition, the message is only relayed to its destination without any additional relaying, thus the number of hops required for delivery is just one rather than multiple times using intermediate node forwarding. To this end, we consider DD as a degraded flooding based algorithm in "Naive Replication" family.

Epidemic [21] replicates the message without considering the candidate node selection. Regardless of the buffer space exhaustion, Epidemic could guarantee the maximum delivery ratio.

In Two-Hop-Relay [20], the source node only replicates each generated message to the first T encountered nodes, where the message is then delivered within two hops given the encounters between these T intermediate nodes and destination.

Particularly, Spray-and-Wait (SaW) [22] combines the diffusion speed of Epidemic [21] and the simplicity of Direct

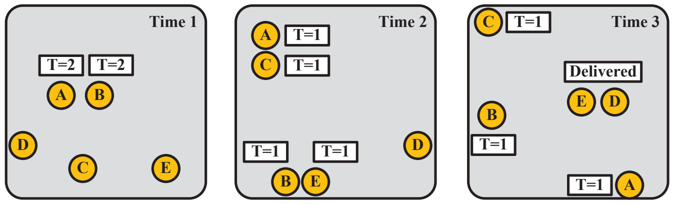


Fig. 6. Example of Binary Spray-and-Wait

Delivery [20]. Initially, the source node sprays[2] T message copies, where the message with one remaining copy ticket is then processed by Direct Delivery. Note that T is a predefined value for the copy tickets cached in each message. In detail, the source SaW is extended from Two-Hop-Relay[3] which uses one more relay. The binary SaW as an optimal approach to promote fast diffusion speed adopts a binary tree to equally spray the message copies rather than only allowing the source node to spray them. As an example of binary SaW illustrated in Fig.6, where the initial value of the copy tickets is defined as $T = 4$ for message M. If source node A encounters node B which does not have M, a copy of M with $T = (4/2) = 2$ is replicated to node B and the original M with $T = (4-2) = 2$ is kept by node A. This process continues until $T = 1$ and then followed by Direct Delivery for final delivery to node D. However in Fig.7, only node A can spray the message copies, resulting in a longer delivery delay.

[Coding Based]

The coding technique is a methodology to compensate the degraded performance due to the link failure in DTNs.

The initial work in [23] combines erasure coding with Two-Hop-Relay [20], in which the message is spit and encoded into a set of smaller size blocks. The receiver would reconstruct the original message on receiving a portion of these encoded blocks.

Furthermore, the work in [24] generates a copy of each encoded block, performing transmission for both of them at each encounter opportunity. Specifically, the original block is transmitted in a similar way as mentioned in [23], while its copy is transmitted using aggressive forwarding during the residual encounter duration once the first block is sent out. This approach is considered as an enhanced version based on the work in [23].

Although the message can be split into a number of smaller size encoded blocks using a larger coding rate to promote reliable delivery, such approach would generate more redundancy. In contrast, a smaller coding rate might be insufficient for delivery. Motivated by this consideration, the authors in [25] propose to adopt rateless code[4] instead of erasure coding for adaptivity.

Inherently, the main difference [26] between network coding and erasure coding is that the former allows the intermediate node to encode the message, whereas the latter only allows the source node to encode the message. Furthermore, as illustrated in Fig.8, erasure coding relies on the redundancy of the small size encoded blocks to guarantee delivery reliability, whereas network coding encodes the messages together for achieving the robust transmission and low overhead ratio. For instance, the work in [27] combines network coding with Epidemic [21], achieving a lower overhead ratio particularly for diffusing a large number of messages.

2) Utility Forwarding Family: In this family, each node maintains an updated utility metric to qualify the encountered node, and adopts gradient forwarding using single copy of each message. Consequently, there are no more message copies existing in the network.

[One Hop Encounter Prediction Based]

Starting from First Contact (FC) [28] which considers the routing loop, the message is prevented from forwarding to

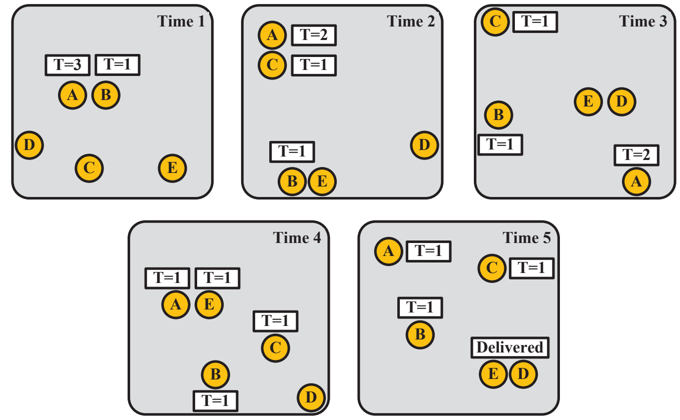


Fig. 7. Example of Source Spray-and-Wait

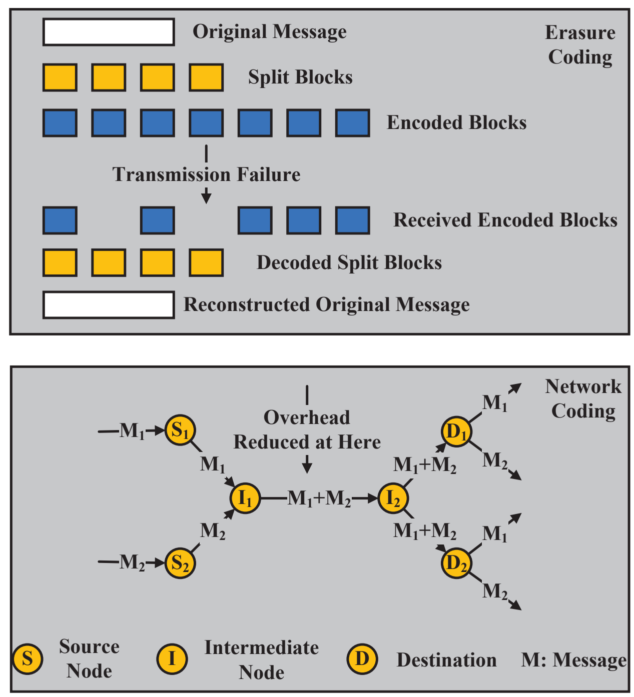


Fig. 8. Difference Between Erasure Coding and Network Coding

[2]The term “spray” means the source node replicates $T-1$ message copies to the first $T-1$ encountered nodes.

[3]In Two-Hop-Relay, the source node replicates T message copies to the first T encountered nodes.

[4]Rateless code as a class of erasure code, sometimes is also known as fountain code. The term fountain or rateless refers to the fact that these codes do not exhibit a fixed code rate. It is applicable at a fixed code rate, or where a fixed code rate cannot be determined a priori, and where efficient encoding and decoding of large amounts of data is required.

any encountered node already carrying this message before. In particular, the reason that FC is regarded as a one hop encounter prediction based algorithm is that the message is forwarded via a set of intermediate nodes, although these nodes are qualified with an equal encounter prediction for destination.

Seek-and-Focus [29] consists of the Seek Phase with random forwarding approach, and the Focus Phase using a utility forwarding approach based on recent encounter time. This approach starts from Seek Phase and shifts to Focus Phase if a better candidate node with a more recent encounter time for destination is in proximity. Seek-and-Focus also sets a timer to shift from Focus Phase back to Seek Phase.

MOtion VEctor (MOVE) [30] utilizes moving direction as the utility metric in VANETs based on the Global Positioning System (GPS). Since the movement of vehicles is not random, pairwise encountered vehicles would calculate the prediction for destination by geometry, enabling the encountered node moving towards destination to carry the message. The distance factor is further considered to filter the node which does not extensively contribute to message delivery.

PrEdict and Relay (PER) [31] assumes that each node may always move to some places with an interest, and such node can partially determine its movement behavior rather than random movement, where the transition probability matrix (consisting of the probability to visit a place) and the sojourn time probability distribution matrix (consisting of the sojourn time or state holding time at a place) are required by each node to calculate the utility metric for destination.

Starting from probabilistic time space graph[5], Routing in Cyclic Mobility (RCM) [32] assumes a cyclic mobility model where pairwise nodes would encounter with a higher probability given their historical encounter at previous cycle. Since it is difficult to obtain the global knowledge about network, the probabilistic time space graph is thus converted into a probabilistic state graph by removing the time factor, enabling the routing decision to derive the Expected Minimum Delay (EMD) as the utility metric. Therefore, the single copy based RCM utilizes the cyclic mobility model to calculate the EMD and selects the candidate node with a shorter EMD for destination as the message relay.

MobiSpace [33] constructs a high dimensional Euclidean space based on the pre-known mobility model. In particular, each axis of the Euclidean space is denoted as a potential encounter opportunity, where the distance towards this axis is calculated as an encounter probability. However, this work assumes that each node has the global knowledge about the mobility patterns of other nodes in the network, thus it is unpractical under realistic scenario.

The work in [34] is based on the fixed point theory for candidate node selection, starting from the analysis of Two-Hop-Relay [20] and then extending to recursively minimize the delivery delay using inter-meeting time. Based on this extension named as 2-Multi-Hop (2-MH), MH* is proposed without the constraint of replication count, using this defined recursive utility metric to select candidate node with the consideration to achieve loop free.

[5]The probabilistic time space graph is modeled as $G = (V, E, T_c)$ where V is the set of nodes, E is the set of edges between the nodes and T_c is the common motion cycle. An encounter probability p_e between pairwise encountered nodes at time slot t_s is defined as the tuple (t_s, p_e).

In particular, a Bayesian classifier based routing framework is proposed in [35] using the historical information such as region ID and message forwarding time, where the concept of Bayesian classifier is used to estimate the posteriori probability of event by its prior probability.

Prediction Assisted Single copy Routing (PASR) [36] is particularly designed for UWNs where the mobility of mobile nodes follows the fluctuation of water. At first, the author propose the Aggressive Chronological Projected Graph (ACPG) to capture the mobility property and then utilize the historical information including trajectory, inter-meeting time, encounter duration and encounter frequency for prediction.

Context-aware Adaptive Routing (CAR) [37] utilizes the context information such as residual energy and dynamic of network topology. Furthermore, CAR adopts the traditional end-to-end based routing algorithm given the available contemporaneous end-to-end connectivity, alternatively it adopts the context information to select the candidate node for the Store-Carry-Forward (SCF) based routing behavior by Kalman filter prediction.

[Time Varying Shortest Path Based]

In IPNs, each node has a global view about the knowledge such as queue size and inter-meeting time of other nodes in the network. Using these information, the algorithms under this branch adopt the classic Dijkstra's approach considering the time varying property.

Originated from the work in [28], proposing the Minimum Expected Delay (MED), Earliest Delivery (ED), Earliest Delivery with Local Queue (EDLQ) and Earliest Delivery with All Queues (EDAQ), the routing decision of these algorithms is considered as a Linear Program (LP) problem since the complete knowledge is beneficial to make accurate routing decision. Furthermore, since these algorithms are based on the global knowledge about the network, their scalability is limited under the highly dynamic scenario with an unpredictable mobility model. While additional improvement [38][39] can enhance their scalability.

Delay Tolerant Link State Routing (DTLSR) [38] is based on the Minimum Estimated Expected Delay (MEED) [40] to construct a time varying end-to-end path. Particularly, DTLSR considers that the unencountered node also has an eligibility on the selected path.

DTN Hierarchical Routing (DHR) [39] focuses on hierarchical routing under the scenario consisting of stationary nodes and mobile nodes with repetitive movement. Inherently, the shortcoming of hierarchical routing under the highly dynamic scenario is to manage a huge number of time varying information. To this end, an aggregation level is defined to mitigate such difficulty, where the nodes above this level maintain the information about the time invariant hierarchical network, while those below this level maintain the information for the time varying based shortest path construction.

[Congestion Control Based]

The assumption of traditional congestion control approach is based on the contemporaneous end-to-end connectivity, enabling both the congestion feedback and control information

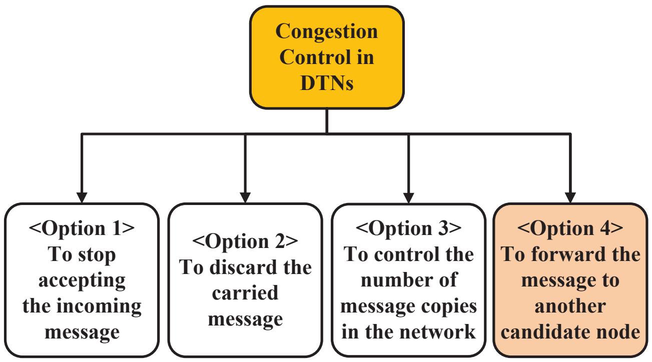


Fig. 9. Congestion Control Options in DTNs

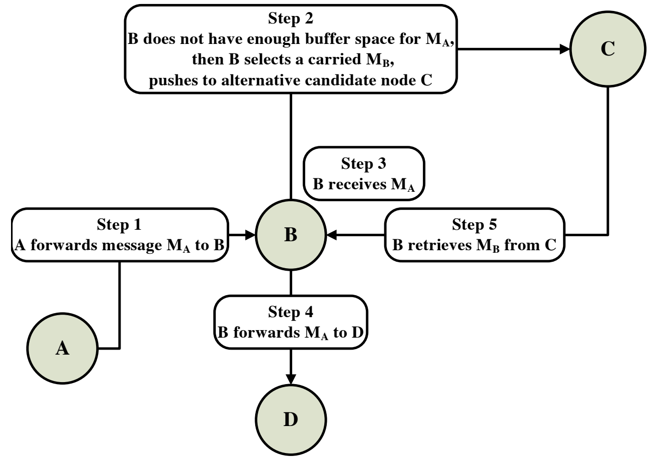


Fig. 10. Congestion Control Process of the Works in [43][44]

to be received timely and successfully. Since it is difficult to perform this end-to-end based approach due to the constraints in DTNs, the hop-by-hop approach is appropriate instead.

In general, there are four options for congestion control in DTNs, as illustrated in Fig.9:

Firstly, to reject the incoming message is feasible only if the upstream node has the capability to handle this message. Based on a financial model, the work in [41] makes decision to receive the incoming message based on a local estimation of congestion potential. The second option is based on the buffer management to discard the message from the buffer space if congestion happens. Since the algorithms under congestion control branch focus on routing using single message copy, we highlight the work in [42] as the third option but omit its discussion at here as it is replication based.

Regarding the fourth approach, the authors in [43][44] decompose the congestion problem into separate routing domains, where the loops are permitted among a subset of the nodes to make use of the distributed storage in adjacent nodes. In detail, this approach selects an alternative candidate node based on the utility metric using Expanding Ring Search (ERS) if the buffer space of the selected candidate node is insufficient for the incoming message, where the cost of the utility metric $C(M)$ is normalized as:

$$C(M) = T(M) \times \omega_T + S(M) \times \omega_S \quad (1)$$

Considering the size of message M, $T(M)$ and $S(M)$ are the transmission cost and storage cost for this message, while ω_T and ω_S are their weighted values respectively. As an example illustrated in Fig.10, node B would retrieve its pushed message from an alternative candidate node C, once node B has released its buffer space.

Using a vector optimization built on Multi-Attribute Decision Making (MADM) with the metrics such as Bundle Buffer Occupancy (BBO), Average Bandwidth (AB) and Transmission Time (TT), the work in [45] proposes a congestion aware routing algorithm for IPNs, where each node utilizes one of the three MADM based forwarding approaches, named as Simple Additive Weighting (SAW), Minimum Distance with Utopia Point (MDUP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). An extension using Random Early Detection (RED) mechanism is further proposed in [46].

Previous works under this branch are mainly designed for IPNs with a low network dynamic, while the congestion control based routing algorithms designed for sparse and highly mobile scenario are still in infancy. Recently, BackPressure (BP) routing [47] has received attention since it is not only resilient to the network disruption but also optimizes the throughput. In particular, BP routing does not perform any explicit end-to-end path construction from the source to destination. Instead, the routing decision is made independently for each message, by computing a BP weight based on the localized queue size and the link state information.

Regarding investigating BP routing in DTNs, the work in [48] computes the BP weight based on the queue differential between pairwise encountered nodes and the local reception rate. Furthermore, the work in [49] designs a two-level BP mechanism, where the results show this two level BP mechanism reduces the queue length for most of the nodes in the network as compared to the case using one level BP mechanism.

[Social Relationship Based]

From social networks aspect, each node has two kinds of neighbors, which are friend and stranger. Moreover, each node has more common interest with its friend while has less common interest with the stranger. Since the perspective in social networks is to diffuse the message to its interested nodes fast, the results in [50] show each node should forward the message which is most similar to its common interest given an encounter between the friend, or forward the message which is most far away to its common interest given an encounter between the stranger. Rather than the one hop encounter prediction and the time varying shortest path based metrics, the social relationship based metric considers the social tie among the linked nodes.

Since it is difficult to calculate the centrality[6] in a large scale network, SimBet [51] estimates the centrality for each node in Delay/Disruption Tolerant Social Networks (DTSNs), borrowing from the concept of Ego networks [52] to define the utility metric measured by betweenness and similarity. More specifically, the betweenness of each node is defined as a capability to facilitate interaction between the nodes it links.

[6]The centrality in general is a measurement of the structural importance to identify the key node to bridge the message in the network.

Regarding the similarity, the number of common neighbors between the current node and destination is calculated as a sum of the total overlapping encounter opportunities. However, SimBet prevents its forwarding behavior if the utility metrics of pairwise encountered nodes are equal.

Motivated by this shortcoming, BUBBLE [53] combines the knowledge of community structure with the centrality of each node to make routing decision. The message carrier firstly bubbles the message up to a hierarchical ranking tree ranked by the current community, until this message reaches a node in the community of the destination. Afterwards, the message carrier in the destined community also adopts the local ranking tree to forward the message.

Although BUBBLE makes use of the distributed computation to ensure message diffusion, it requires the knowledge about the address and the social group of destination, which is unfair to the algorithms requiring only the address. Besides, the weighted values for the betweenness and similarity in SimBet are only equally allocated, requiring more consideration. Furthermore, the topology of social networks varies over time, thus the aging factor should be taken into account for the outdated information. Finally, the betweenness in SimBet is only considered as the shortest path, whereas the realistic social networks are unlimited only to the shortest path, while the betweenness of a node would become less important if the message is close to its destination. In light of this, SimBetAge [54] is proposed to overcome these addressed shortcomings.

The web service technique can also be borrowed for routing in DTSNs, where PeopleRank [55] adopts the PageRank proposed by Google to rank the importance of the encountered node. Apart from PeopleRank, the algorithm in [56] defines the social distance[7] using Jaccard index.

Interestingly, Fair Routing [57] is motivated by the unfair load distribution problem, using perceived interaction strength and assortativity. In Fair Routing, the perceived interaction strength originated from social influence is used to reflect a social relationship between pairwise nodes, depending on both the short term value and long term value. In order to reduce useless transmissions to any node with a weak social tie, the assortativity[8] takes into account the queue size of the encountered node. Thus the routing decision of Fair Routing is based on the joint consideration of these two metrics.

Taking into account the concept of friendship, the work in [58] is based on the designed Social Pressure Metric (SPM), using a time duration between the disruption of pairwise encountered nodes and their upcoming encounter. The reciprocal of SPM is then defined as the link quality, while a set of encountered nodes with a higher link quality than a predefined threshold are classified within a friendship community. Taking into account the indirectly encountered node, the conditional version of SPM borrowing from the work in [59] is further proposed to measure the link quality between the local node, directly encountered node and indirectly encountered node. Particularly, the message is prevented from forwarding to an encountered node even if it is with a higher value of the link quality taking into account the aging factor, since the message destination is not included in the friendship community of this encountered node.

In real world, people may not be willing to forward the message to other individuals who has no social tie, thus to take into account the selfish behavior is essential. Apart from a set of incentive and reputation schemes that can be borrowed into DTSNs, Social Selfish Aware Routing (SSAR) [60] addresses this problem from a different aspect, allowing each node to behave according to its unique selfishness, since SSAR considers the selfishness as an underlying service requirement. To this end, the selfishness of each node is used to define a willness for making routing decision, where the node with low message delivery probability and high willness might be a better candidate node than those with high delivery potential and low willness. The selected candidate node would recalculate a new priority for its carried message according to its willness, which implies this message might be allocated with a low priority at this hop even if it was with a high priority at previous hop.

3) Hybrid Family: Even with redundancy, it is more effective to adopt replication approach under the scenario with sparse network density and given message lifetime, since the message copies promote fast diffusion and increase the possibility that one of them would be delivered. Therefore, the algorithms in "Hybrid" family take the advantages of "Naive Replication" and "Utility Forwarding" families to control replication.

[Utility Replication Based]

The straightforward approach is to replicate the message according to the utility metric rather than gradient forwarding using single message copy. In particular, the utility metric can be defined in various ways given the historical information.

In Probabilistic ROuting Protocol using History of Encounters and Transitivity (PROPHET) [61], the utility metric is based on an encounter probability with the transitivity to achieve congestion avoidance. For example, given that node A encounters node B most likely, and in similar manner that node B encounters node C. Then node C may be a good candidate node for node A even if their encounter is least likely. Therefore, messages carried by node A would also be replicated to node C in addition to node B, alleviating the buffer space exhaustion at node B. In particular, the aging factor is also taken into account for the outdated information.

Considering the limited buffer space, PRiority EPidemc (PREP) [62] partitions the buffer space into two separate bins, where messages in the downstream bin are selected for discard since their priorities are lower than those in the upstream bin. Similar to the work in [63], PREP adopts the Dijkstra's approach to select the candidate node based on the encounter duration.

NECTAR [64] utilizes the occurrence of an opportunistic encounter to calculate a neighborhood index, and replicates the message in a controlled manner. Based on the hop count between pairwise encountered nodes and their encounter duration, the neighborhood index is updated in a weighted fashion

[7]Generally, social distance is measured either by direct observation of people interacting or more often by questionnaires in which people are asked what kind of people they would accept in particular relationships.

[8]For example, a big shot professor would allocate his time to review preliminary work from an equal peer, but he is unlikely to do the same for a graduate student. This behavior, known as assortativity or homophyly.

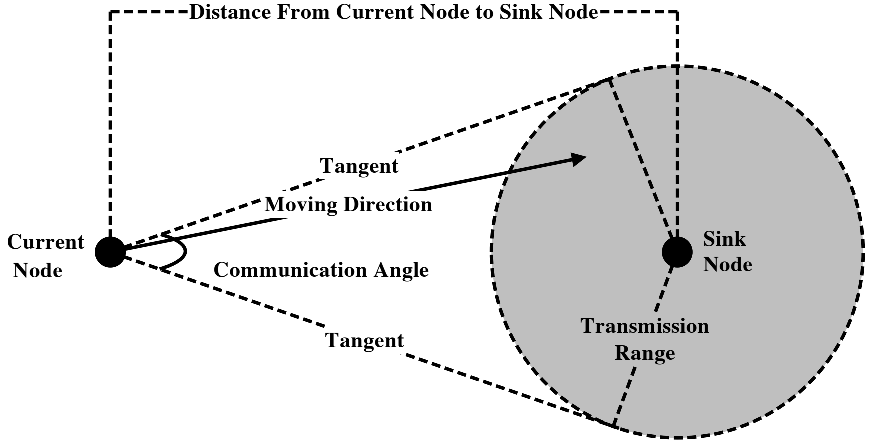


Fig. 11. Illustration of the Geometric Property in [68]

to avoid a dramatic variation. NECTAR also defines a threshold regarding message lifetime, where messages are replicated using Epidemic [21] if their lifetime are below this threshold, otherwise they are replicated using this neighborhood index.

The powerful Resource Allocation Protocol for Intentional DTN (RAPID) [65] uses a random variable to represent the encounter between pairwise encountered nodes, and replicates messages in the descending order according to a marginal utility. In detail, the marginal utility is calculated based on the ratio between the decreased delivery delay and message size. The message estimated with a positive value of the marginal utility is then replicated for bandwidth usage.

As a geographic replication approach, Distance Aware Epidemic Routing (DAER) [66] adopts current distance towards destination as the utility metric using realtime location information. Furthermore, DAER reduces the replication redundancy after message transfer only if the message carrier is moving away from destination.

Rather than taking into account each message in DAER to make routing decision, Packet Oriented Routing (POR) [67] takes into account the distance factor for all the requested messages. The idea behind is to replicate a less number of messages using a longer distance, promoting the prioritized candidate node selection and message transmission.

In Mobility Prediction based Adaptive Data (MPAD) [68], the delivery potential is estimated as an intersection between the moving direction and the transmission range of the stationary sink node, as illustrated in Fig.11. Alternatively, the communication angle is adopted if such intersection does not exist. Thus a closer distance to the stationary sink node indicates a larger communication angle, increasing the delivery potential. As an extension to alleviate the dependence on GPS, the delivery potential estimated in [69] is based on the information broadcasted by the stationary sink node.

Taking into account the concept of community, LocalCom [70] adopts the average disruption period and the fluctuation of this period to define a similarity weight. Furthermore, the degree of a node is defined as a sum of the weight values connecting to this node, while this information is used to select the node with a higher degree as the initiator to detect the community. Thus the intra-community replication is adopted if the source node and destination are within a same community, whereas the bridge node for inter-community replication is either statically or dynamically pruned for redundancy reduction.

A general disconnected network may have many small instantaneously clustered mobile nodes, while mobility allows the nodes carrying the messages to deliver them to other clusters. In Articulation Node Based Routing (ANBR) [71], the articulation node is selected to reduce the delivery delay and overhead ratio, since the communication between these subnetworks would be disconnected if without these crucial nodes.

Inherently, the performance of the above algorithms under utility replication branch rely on their defined utility metrics to control replication. While the following optimization methodologies can further enhance the routing efficiency.

Delegation Forwarding (DF) [72] enables each message to cache an updated threshold value equal to the utility metric for message destination. Rather than comparing the utility metrics between the encountered node and message carrier, DF only replicates the message if the encountered node has a better utility value than the threshold value cached in this message. This work is also extended as a probabilistic version and a threshold version in [73].

The algorithm in [74] adopts fuzzy logic to define the community membership considering multiple metrics. In particular, each node in LocalCom [70] only belongs to an independent community, whereas the node in [74] can belong to a set of communities. Based on the membership of each node in a community, the target is to replicate a message copy to each community using DF for efficiency.

The motivation of Optimal Probabilistic Forwarding (OPF) [75] is to find the optimal stopping rule at some stage to maximize the expected reward, where the routing objective is to achieve the maximum delivery ratio under the constraint of hop count. Based on a joint delivery potential[9] estimated by the message carrier and the encountered node with the replicated message, the routing decision is based on the

[9]For example, we initially denote the delivery potential of message carrier N_i for message M is p_i, where $p_i \in [0, 1]$. Given an assumption of message replication to encountered node N_j, then both N_i and N_j will carry M where their delivery potential are recalculated by OPF as p_i' and p_j. To this end, the condition $p_i < [1 - (1 - p_i')(1 - p_j)]$ would promote message replication.

assumption that this joint delivery potential is higher than the previous value of the message carrier before message replication.

[Improved Spray Based]

Since Spray-and-Wait [22] has already been analyzed and proved as an efficient algorithm relying on the limited number of replications, we classify its extensions as another branch in "Hybrid" family. In particular, some interesting investigations regarding this branch are highlighted as follows:

1: To Select the Candidate Node for Spraying

Sensor Context Aware Routing (SCAR) [76] adopts the utility metric of CAR [37] to perform based on source Spray-and-Wait, where the message is sprayed only if the utility differential between pairwise encountered nodes is higher than a predefined threshold.

As an advanced version of binary Spray-and-Wait, Selectively MAking pRogress Towards delivery (SMART) [77] defines a frequently encountered node as "companion", where the message copies are initially sprayed to the companions of the destination. After a predefined time threshold, they are then performed by binary Spray-and-Wait.

Based on source Spray-and-Wait, the work in [78] focuses on destination dependent and destination independent utility spaying. The former sprays the message if the encountered node has a higher utility metric for destination than that of current carrier, whereas the utility metric of the latter is independent of the message destination. In detail, the destination dependent based Last Seen First spraying (LSF) sprays the message copies to the encountered node which has seen the destination most recently. Regarding the destination independent approaches, Most Mobile First (MMF) spraying is based on the priority of node's ID, while Most Social First (MSF) spraying is based on an encounter ratio of the nodes identified by ID.

The publish/subscribe is a mechanism where the publisher (message carrier) publishes the message to the subscriber (candidate node) that only receives the message that is of interest. For instance, SocialCast [79] anticipates the candidate node by observing social mobility using the similar utility metric of CAR [37]. The message carrier firstly broadcasts its interest to its one hop's neighbors, then the utility metric is calculated for all the received interests by Kalman filter prediction. Finally, the published message is sprayed to the subscriber.

2: To Dynamically Control the Number of Copy Tickets

The motivation in [80] is to control the number of copy tickets using source Spray-and-Wait. This work initially sprays the message with a less number of copy tickets, while another larger number of copy tickets is then redefined for this message if it was not delivered during an initial duration. Furthermore, this work is extended as a multi-period based approach in [81].

Based on binary Spray-and-Wait, the idea behind [82] is to dynamically determine the number of copy tickets depending on the current status of network. Assuming the global knowledge about the current and future states of network would behave, the centralized Oracle-based Spray-and-Wait (O-SaW) adjusts the number of copy tickets of the message according to the desired average delivery delay. Since it is difficult to obtain such oracle information in reality, the distributed Density Aware Spray-and-Wait (DA-SaW) adjusts the necessary copy tickets of the message according to the current average degree[10] maintained by each node.

Since either a less or exceeded value of the copy tickets would result in extra delivery delay considering the limited bandwidth, the work in [83] aims to define an optimal number of copy tickets to achieve the minimum delivery delay. To this end, an adaptive approach to dynamically adjust the number of copy tickets is proposed based on a differential, between the expect delivery delay estimated using the current number of copy tickets and the historically shortest delivery delay of the message.

3: To Proportionally Spray the Copy Tickets

Regional Token Based Routing (RTBR) [84] is based on binary Spray-and-Wait by taking into account the region concept. For each message destined to inter-region, the message carrier hands over the total number of copy tickets of this message to an inter-regional node, rather than binary spraying them to an intra-regional node.

The work in [85] extends the previous idea for DTSNs, where the message with T copy tickets is sprayed with T_{in} copy tickets to an encountered node in the same community. Alternatively, this message is sprayed with $T_{out} = T - T_{in}$ copy tickets to an encountered node in the community of the message destination.

Encounter Based Routing (EBR) [86] takes advantage of the observed mobility property of certain network, assuming the future rate of node encounters can be roughly predicted by historical information. This is useful since nodes experience a large number of encounters would have a higher potential to relay the message to final destination. For example, given an encounter between node A and node B, for each message M with T copy tickets carried by node A, it sprays $\frac{(T \times EV_B)}{(EV_A+EV_B)}$ copy tickets to node B, where EV is the number of encounters calculated within a time window. Note that the value of the distributed copy tickets is indiscrete. Although the number of replications in EBR is unlimited, EBR is still considered as a spray based algorithm since the initial value of the copy tickets affects routing performance.

Up to now, the proportion of copy tickets distribution is still an open issue, while the authors in [87] analyze that optimal solution relies on the initial defined value of the copy tickets.

4: To Spray According to the Target Delivery Delay

The novelty of Adaptive Multi-copy Routing (AMR) [88] is to control the spray process according to the target delivery delay. Given that the estimated residual delivery delay is longer than a differential between the target delivery delay and the elapsed time since from message generation, AMR would promote message replication via binary Spray-and-Wait.

5: To Adopt the Forwarding Approach for Assistance

Borrowing from the utility metric adopted by Seek-and-Focus [29], Spray-and-Focus (SaF) [22] adopts the Focus Phase instead of Wait Phase, decreasing the delivery delay via a utility forwarding approach. This is different from binary Spray-and-Wait in which the message with one remaining copy ticket is only relayed to its destination.

[10] The average node degree is given by the number of encounter opportunities a node has during a given time interval.

Efficient Adaptive Routing (EAR) [89] considers the bandwidth consumption, where the two defined routing phases are allocated with different bandwidths for transmission. A logic cloud is designed to limit the number of neighbor nodes under the constraint of hop count, while the node within the range of this hop count based cloud would perform Destination Sequenced Distance Vector (DSDV) routing algorithm. Another modified version of binary Spray-and-Wait is activated only if the destination is outside the range of this logic cloud. Note that the number of replications using this modified Spray-and-Wait is unlimited, since the initial value of the copy tickets for each message is set with 1 but equally distributed based on the residual bandwidth.

The difference of using the context information between CAR/SCAR [37][76] and HiBOp [90] is that the former only calculates the delivery potential for the nodes which have been encountered before, whereas HiBOp can also exploit the delivery potential for the nodes which have not been encountered. In HiBOp, the source node sprays the message using source Spray-and-Wait, together with a utility forwarding approach using the context information. In comparison, CAR/SCAR focuses more on combining the context information with routing decision, whereas HiBOp aims to define, exploit and manage the context information, which are not taken into account by CAR/SCAR.

[Improved Epidemic Based]

The improved versions of Epidemic [21] still replicate the message regardless of the candidate node selection. However, rather than using the utility metric for destination or the limited number of replications, the algorithms under this branch are able to control replication via other heuristic schemes.

Taking into account the limited bandwidth and buffer space, MaxProp [91] unifies the problem of scheduling message transmission and discard. The core of MaxProp is a cost of virtual end-to-end path assigned to destination, where the cost is based on an estimation of the route failure likelihood. Initially, the failure likelihood of pairwise nodes is uniformly distributed and then updated according to an incremental averaging manner. Besides, a threshold value related to the average transferred size is designed to classify the message freshness, where messages are prioritized according to the hop count if their hop counts are below this threshold value, alternatively they are sorted by the cost mentioned above. Furthermore, MaxProp informs the encountered nodes to clear out the existing copies of the delivered messages via a broadcasted acknowledgement information.

The contribution of FuzzySpray [92] is the Forwarding Transmission Count (FTC)[11] estimated for message replication count in a global view. Furthermore, the message size and FTC are selected as the input of a fuzzy logic function, enabling the output to qualify the priority for message transmission. Similar to MaxProp, the acknowledgement function is integrated for redundancy reduction.

The novelty of Vector Routing [93] is to replicate the message according to an encounter angle $\omega \in [0, \pi]$ between pairwise encountered nodes. Taking into account the factor of velocity, this approach replicates a less number of messages given a small value of ω, since a similar moving direction between pairwise encountered nodes would result in redundant replication. Although a different moving direction could contribute to message diffusion, it is also undesirable to replicate a large number of messages given $\omega = \pi$, since the encountered node is currently moving with the previous trajectory of the message carrier. This work is further integrated with a utility replication based algorithm in [94].

The algorithm in [95] proposes to adaptively replicate the message using Gossip routing. Different from Gossip(p_r, k) [96], here the replication probability p_r is exponentially decreased if the message is replicated beyond k hops. In particular, this work also refers the update process of the hop count as mentioned in [92].

Another work in [97] adopts a differentiated based Gossiping routing, determining the respective replication probability for messages according to their different lifetimes. The message replication probability would be decreased if this message is delivered before its expiration time, otherwise the replication probability is increased for performance compensation.

Furthermore, the summary information in [98] contains the number of nodes n_d that have already held the message, while n_c is denoted as those have not held such message. In addition, the replication threshold RT and discard threshold DT are defined for each message. Since it is unnecessary to promote replication given a large enough number of existing message copies, the message is discarded given $n_d \geq DT$ with $n_d = 0$ reset or replicated given $n_c \leq RT$. Particularly, the work in [99] proposes a heuristic to guide this counting process.

[Coding Based]

It is highlighted that to combine the coding technique with the algorithms in "Hybrid" family can further improve the routing performance than those in "Naive Replication" family.

The work in [100] aims to maximize the delivery ratio taking into account the transmission failure probability. Motivated by the purpose to optimally allocate the number of encoded blocks for each potential path, the authors analyze this problem under the assumptions of Bernoulli (0-1) and Gaussian distribution with the proposed heuristic approaches.

Different from the work [23] in "Naive Replication“ family achieving the high delivery ratio via redundancy, the work in [101] concentrates on achieving the low overhead ratio using the concept of source Spray-and-Wait rather than binary Spray-and-Wait [22]. The motivation behind is that binary Spray-and-Wait is less efficient than source Spray-and-Wait, since the latter only allows the source node to spray the encoded blocks, reducing the number of replications even with a longer delivery delay. This work is also enhanced considering the multi-period based approach mentioned in [80][81].

The hybrid algorithm in [102] integrates erasure coding with the encounter prediction, where the size of the encoded block is adaptively calculated to achieve the maximum delivery ratio based on a utility metric for destination. While the algorithm in [103] integrates the concept of content with erasure coding.

[11] The FTC is considered as an updated hop count value cached in each message, where FTC is updated to the value of the message including its copies which has been replicated with the largest hop.

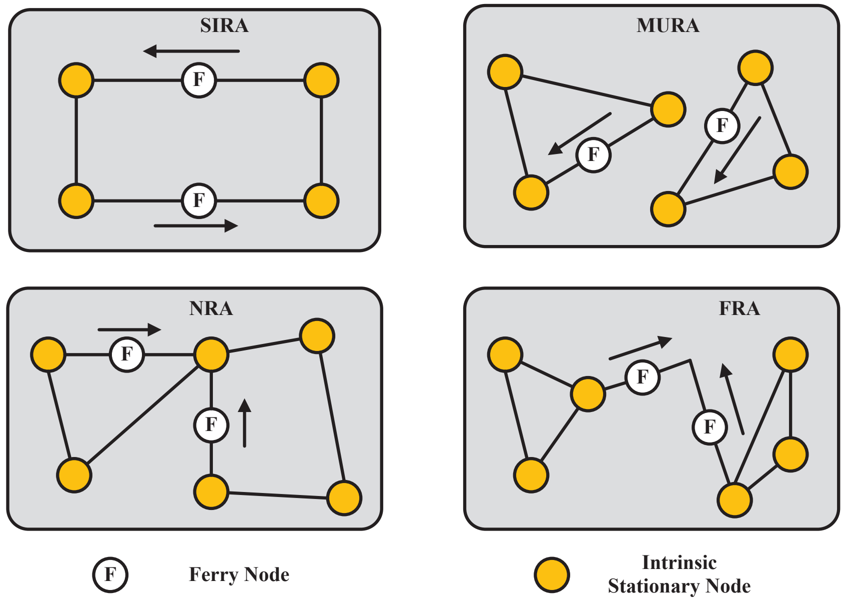


Fig. 12. Example of the Algorithms in [112]

Recall that fountain coding (or referred to rateless coding [25]) achieves the effective delivery via redundancy, while OPF [75] achieves the efficient delivery via hop constraint. To this end, the work in [104] is regarded as a tradeoff between these two approaches.

Combining with network coding, the work in [105] replicates the encoded blocks to the candidate node with a lower end-to-end cost towards destination, using the inter-meeting time as the link cost. A coefficient called forwarding count is adopted to further enhance the candidate node selection.

The work in [106] is regarded as a hybrid of Gossip routing [96] and Epidemic routing [21]. Here, based on a predefined parameter called forwarding factor f normalized as $f \in [0, 1]$, the encoded block is performed by probabilistic replication given that $f < 1$, otherwise this block is replicated using Epidemic.

Borrowing from the concept of articulation node [71], HubCode [107] replicates the message only to the hub (or referred to articulation node) using network coding. Given a message handover between pairwise hubs, the message carrier only encodes the messages with the same destination together, where the decision that whether to hand over the encoded block is determined by its linear independence recorded by pairwise hubs. However, this specific checking process of linear independence requires an exchange of coefficient matrix, resulting in extra exchange overhead. Motivated by this shortcoming, the improved approach adopts message ID instead during the checking process.

B. Routing With Infrastructure Assistance

1) Mobile Node Relay: Using mobile agent as an additional participant is effective to increase the encounter opportunity if the limited mobility of intrinsic nodes is unable to bridge the communication.

Date Mule [108] is capable of exchanging the message between the nearby sensor access point with random movement.

Besides, the work in [109] assumes the mobile nodes would move according to their habit. To this end, the concept of Virtual Data Mule (VDM) is proposed to leverage the encounter opportunity, where the role of VDM is handed over and determined by the output of a fuzzy logic function, using the fitness of VDM based on location, moving speed and trajectory.

The authors in [110] propose to adopt Message Ferrying (MF) under the sparse scenario where additional ferries are within the dedicated region to relay the message. The main contribution is to exploit the non-randomness to assist the message delivery with two approaches proposed. In Node Initiated MF (NIMF), the ferries move around the dedicated region according to the predefined route, while the intrinsic nodes with the oracle of ferries' movement would pro-actively move towards them for communication. In contrast, Ferry Initiated MF (FIMF) allows the ferries to pro-actively move towards intrinsic nodes. On receiving this request, the corresponding ferry will adjust its trajectory to meet the requested node.

As a hybrid approach, Meeting and Visit (MV) [111] utilizes the encounter prediction between pairwise encountered nodes and the probability to visit a dedicated place, together with the assistance of additional mobile nodes.

As an extension based on MF [110], the work in [112] focuses on using multiple ferries and designing their appropriate routes to maximize the throughput and minimize the delivery delay with four approaches proposed, which are SIngle Route Algorithm (SIRA), MUlti Route Algorithm (MURA), Node Relaying Algorithm (NRA) and Ferry Relaying Algorithm (FRA). Given an example in Fig.12, all ferries follow the same route in SIRA, whereas the ferries follow different routes in MURA. In particular, the ferries are not intersected in SIRA and MURA. Furthermore, NRA utilizes node relaying and ferry relaying to bridge the message between ferries.

In contrast, FRA minimizes the waiting delay through direct interaction between ferries unlike NRA which minimizes the carrying delay in each ferry using stationary nodes as the relay.

Based on the region concept, the work in [113] classifies two types of ferries. Specifically, the regional ferry belongs to source region and bridges the message towards destination region. In contrast, the independent ferry does not belong to any region but can be managed with a temporal ownership.

Another work in [114] is motivated by the Traveling Salesman Problem (TSP), focusing on designing the ferry route to balance the delivery delay and the required buffer space.

Furthermore, the authors in [115] investigate the concept of MF from another aspect, by voting the role of MF given the mobility of intrinsic nodes, without modifying their mobility patterns or utilizing any assistance of additional node. Based on the definition of Message Ferry Dominating Set (MFDS) - a space time dominating set constituting the nodes that behave as intrinsic message ferries, the Connected Message Ferry Dominating Set (CMFDS) is used to classify the nodes providing the connectivity. Here, the ferry capacity is considered as an ability to provide service for a number of nodes, thus a larger value of the ferry capacity implies a higher capability to provide connectivity.

2) Stationary Node Deployment: Apart from the mobile infrastructure, the stationary infrastructure can also bridge the communication. Contrary to Data Mule [108] and MF [110] of which the main idea is to control the mobility pattern, the deployment of stationary node is for increasing the encounter opportunity via the appropriately deployed location.

Throwbox [116] is inexpensive, battery powered with short radio and storage. When two nodes pass by a same location at different time, Throwbox can behave as a router to relay the message.

Given the network graph and the requested traffic rate, the relay node deployment problem can be described as a Linear Program formulation. In [117], Minimizing Relay node and Hop count (MRH) searches the optimal path constrained by the traffic requirement and hop count, followed by a compensation approach that only adopts the hop count if no such path exists in the initial step. As an improved version, Minimizing Relay node and Delivery time (MRD) selects the relay node providing the shortest delay to destination instead of the least hop count as the compensation approach.

Furthermore, the quadratic-complexity algorithm proposed in [118] takes into account the delivery delay and the number of replicas. In detail, the greedy solution is proposed to select the potential location by sequential selecting the location with the highest utility value of conditional efficiency[12], without any change to existing selection. Another solution called back greedy solution gradually clears out the existing selection with the lowest influence on the utility value.

V. Multicasting Issue

The term multicasting means to deliver the message to a group of its interested destinations. Inherently, the multicast receivers are well predefined in MANETs with a relatively small network topology variation. However, this is no longer feasible for multicasting in DTNs due to the large variation of network topology.

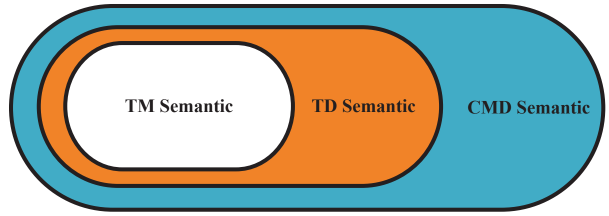


Fig. 13. Semantic Model of Multicasting in DTNs

In [119], Temporal Membership (TM), Temporal Delivery (TD) and Current Member Delivery (CMD) are proposed as the three semantics for multicasting in DTNs. Regarding TM, the message receivers are temporally regarded as the group members within a defined interval. Relatively, TD is defined based on TM with an additional interval for message delivery, thus TM enables each node to clear out the message which is invalid within this delivery interval. As illustrated in Fig.13, the term CMD includes the considerations of TM and TD, specifying that the message receivers are required to be group members at the time of message delivery.

Furthermore, five multicasting algorithms are designed in [119], which are Unicast Based routing (UBR), Static Tree Based Routing (STBR), Dynamic Tree Based Routing (DTBR), Broadcast Based Routing (BBR) and Group Based Routing (GBR).

In UBR, the source node multicasts the message via the existing unicasting algorithms in DTNs. Based on Epidemic [21], the message in BBR is flooded to all the nodes in the network. With respect to GBR, the group members are limited within a set of nodes, borrowing from the concept of Forwarding Group Multicast Protocol (FGMP) [120]. Regarding the tree based approaches including DTBR and STBR, the message is forwarded along a time varying based end-to-end path from the source node to destination, replicated at the branch nodes which have more than one subbranches. The authors also report that the network topology information is more important than the group membership information for multicasting in DTNs.

Given the current research stage of multicasting in DTNs, mainly the tree based and unicast based (or referred to UBR) approaches have been investigated.

A. Tree Based Approaches

Starting from STBR, it is based on the shortest path between the source node and destination, using the link state information adopted in [28].

However, STBR can not be dynamically adaptive to the large variation of network topology in DTNs, since the message would be constantly kept by its carrier until the connectivity is available, even if the message carrier is within the group membership of destinations. Motivated by this shortcoming, DTBR updates the path towards destination on receiving the message from previous hop.

[12]The conditional efficiency means given a set of instrumented locations L, to deploy another location l with c as the cost per location is measured by $\frac{U(l/L)}{c}$, where U is denoted as the utility.

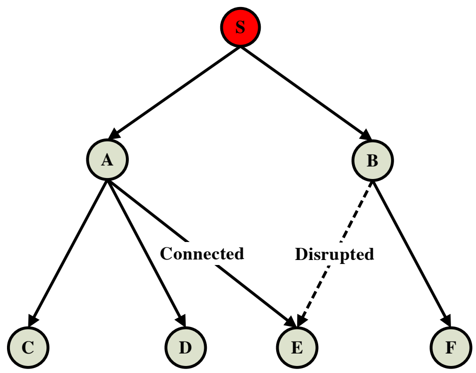


Fig. 14. An Example About the Shortcoming of DTBR

Although DTBR overcomes the limitation of STBR, to some extent, DTBR still does not make use of the available connectivity. As an example in Fig.14, where a multicast tree for source node S is illustrated. Regarding its branches, node A is only responsible for multicasting to node C and node D, while node B is only responsible for multicasting to node E and node F. If the connectivity between node B and node E is disrupted at any time, the message destined to node E would not be delivered even if there is a connectivity between node A and node E, since node E is not within the membership of node A. Accordingly, OS-Multicast [121] is proposed to overcome this shortcoming by periodical deleting the disrupted paths and adding the current available paths. In addition, the authors in [122] compare the performance among STBR, DTBR and OS-multicast, where the results show DTBR can achieve a higher message delivery ratio than other strategies. Also, the results show OS-Multicast is more bandwidth efficient.

In Scalable Hierarchical Inter-domain Multicast (SHIM) [123], the determined group leaders construct the upper layer network, while the other nodes in different groups form the respective lower layer network. Comparing with DTBR and OS-Multicast, SHIM hierarchically organizes the multicast structure and efficiently manages the network topology information.

Context Aware Multicast Routing (CAMR) [124] is particularly designed with the capability to work under the highly dynamic scenario. Based on the two hops information for prediction, CAMR shifts to route discovery model given the connectivity disruption. Particularly, CAMR adopts a high power transmission given an estimated sparse network density, otherwise it adopts a regular power transmission instead. Furthermore, CAMR would shift to route recovery model if the topology of multicast tree varies over time.

B. Unicast Based Approaches

As it is difficult to maintain the multicast tree in DTNs due to the large variation of network topology, UBR is extensively investigated because of its scalability. Note that the destinations of the multicast message are a set of nodes using UBR. In contrast, there is only a unique destination for unicast message performed by the unicast algorithms reviewed in section IV.

Encountered Based Multicast Routing (EBMR) [125] is proposed based on PROPHET [61], where each node broadcasts and updates the information containing an encounter probability for destination. The current carrier would keep the message until an encountered node with a higher encounter probability for multicast destination than a predefined threshold is in proximity.

Borrowing from Two-Hop-Relay [20], RelayCast [126] multicasts the message via the intrinsic mobility of mobile nodes, using a multi-queue transmission .

Besides, the work in [127] provides a more efficient and resource friendly replication system based on the concept of publish/subscribe mechanism, in which the intermediate node individually applies a priority to control the message processing based on a local resource situation.

The work proposed in DTSNs [128] focuses on multicasting using the centrality and community. This work starts from the analysis of Single Data Multicast (SDM) which forwards a single message to a set of destinations, followed by Multiple Data Multicast (MDM) as an extension. Specifically, the cumulative encounter probability estimated according to the centrality is adopted for candidate node selection in SDM. In contrast, since it is difficult to obtain a global view of the information required for candidate node selection in MDM, a community based approach is proposed to alleviate this difficulty, where MDM only requires each node to maintain the information about its neighbor nodes in the same social community to construct a social forwarding path towards destination.

Borrowing from the additional infrastructure, Ferry Based Inter-domain Multicast Routing (FBIMR) [129] combines the characteristic of EBMR [125] with the assistance of message ferry [110] for multicasting between inter-domains. Within each domain, the leader node and ferries construct the upper layer network, while other intrinsic nodes are classified into the lower layer network. During multicast process, the message generated from the source node is forwarded to the leader node, using EBMR for intra-domain multicasting. In addition, the ferries in proximity relay the message for inter-domain multicasting.

Interestingly, the work in [130] distributes the multicast destinations to the encountered node with a higher value of the proposed active level. Furthermore, a ratio based distribution methodology is adopted to determine the number of destinations h and the order for distribution. Therefore, only the first h destinations are kept by the message carrier, while the rest $s - h$ destinations are distributed to the encountered node, where s is the total number of destinations of a multicast message.

Furthermore, the following two methodologies [131][132] can improve the multicasting performance, borrowing from the research activities of existing unicasting algorithms in DTNs.

The authors in [131] utilize Delegation Forwarding [72] for multicasting in DTNs. Besides, the results in [132] show that using network coding offers a significant benefit for multicasting in DTNs, particularly given the limited buffer space.

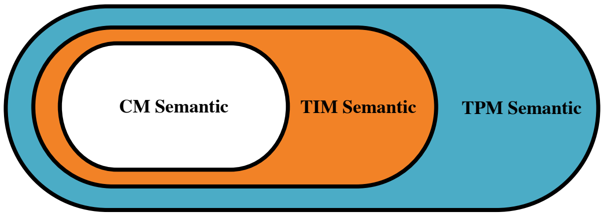


Fig. 15. Semantic Model of Anycasting in DTNs

VI. Anycasting Issue

Anycasting in DTNs is a unique and challenging problem. Particularly, the anycast destination can not be initialized since it can be any one of the nodes within the membership group. Furthermore, traditional anycast routing algorithms are relatively straightforward since the message can be unicasted to the candidate node with the lowest cost to destination. In contrast, it is difficult to determine both the path towards group member and the anycast destination due to the large variation of network topology in DTNs.

Similar to the semantics of multicasting in DTNs, Current Membership (CM), Temporal Interval Membership (TIM) and Temporal Point Membership (TPM) are defined in [133], as the semantics of anycasting in DTNs.

In detail, CM defines the receiver should be a member node within the destination group. Moreover, TIM defines the temporal period during which the intended receiver must be a member of destination group. As illustrated in Fig.15, taking into account CM and TIM, TPM defines the intended receiver at least should be a member of destination group within the temporal period.

Based on CM, Expected Multi-Destination Delay for Anycast (EMDDA) [133] assumes all the DTN nodes are stationary, and selects the group member with the shortest path towards anycast destination based on Practical Expected Delay (PED), which is borrowed from the definition of Minimum Expected Delay (MED) [28].

The work in [134] focuses on anycasting under mobile scenario, where the message forwarding is based on the path length and the number of receivers reachable, named as Receiver Base Forwarding (RBF). However, this algorithm assumes the future mobility is deterministic and known in advance, thus it is unrealistic for most of the application scenarios in DTNs.

In particular, Genetic Algorithm (GA) is appropriate if multiple objectives are needed to be achieved. For instance, the work in [135] adopts GA to incorporate the storage constraint and combine the searched routes with a shorter delay towards destination.

As proposed in probabilistic connected DTNs, Maximum Delivery Rate for Anycast (MDRA) [136] adopts an encounter probability instead of the MED adopted in EMDDA.

Furthermore, the authors in [137] design an independent interface and integrate it with the existing unicasting algorithms in DTNs.

VII. Comparison and Discussion

In this section, we provide a comparison for our reviewed unicasting, multicasting and anycasting routing algorithms in DTNs.

In detail, we define the term "Limited" for the bandwidth metric if the corresponding algorithm either defines the message priority for transmission or evaluates the performance with the varied traffic load. Similarly, the algorithm either with the consideration of buffer management or with the varied buffer space for performance evaluation is defined as "Limited" for the buffer space metric. The limited energy is also taken into account if the algorithm is either with this consideration for design or evaluation.

Particularly, the routing performance qualified according to the evaluation metrics defined in section II can not be compared, since various algorithms are designed with different characteristics and implemented under different scenarios. Also, the algorithm complexity is out of discussion due to its subjectivity.

In addition, we provide the knowledge[13] for routing decision and the number of copies required for message delivery, particularly for the unicasting algorithms without infrastructure assistance. The comparison among the algorithms with such assistance focuses on the infrastructure movement and assistance behavior controlling. The comparison among multicasting algorithms focuses on the replication behavior rather than number of copies required for message delivery, since they are either tree based or unicast based approaches. The comparison among anycasting algorithms is only based on the knowledge for routing decision because of its early research stage.

Regarding the unicasting algorithms without infrastructure assistance illustrated in TABLE II, TABLE III and TABLE IV, the "Hybrid" family inherits the effectiveness from "Naive Replication" family and the efficiency from "Utility Forwarding" family. Where various definitions of the utility metrics borrowing from "Utility Forwarding" family contribute to the development of the utility replication based branch. Based on Spray-and-Wait [22], the improved spray based branch further integrates the concept of "Utility Forwarding" for performance enhancement. Besides, the improved epidemic based branch does not take into account the candidate node selection and the initialization of the copy tickets, has the highest scalability. The coding technique can further enhances the routing performance together with those under the utility replication, improved spray and improved epidemic based branches.

Meanwhile, the NP-hard problem of using mobile relay based infrastructure is how to achieve the target delivery delay requirement by controlling the movement. Furthermore, to hand over the role of mobile relay [109], to shift the ownership of mobile relay [113] and vote the role of mobile relay among the intrinsic nodes [115] are worthwhile investigating. Similarly, to appropriately deploy the stationary node is also a NP-hard problem.

With respect to multicasting in DTNs, the large variation of network topology limits the scalability of the tree based approaches, since it is difficult to maintain and update the multicast tree using partially historical information. Instead, UBR attracts more research attention by borrowing from the

[13]We suggest the readers refer the corresponding paper for detailed information, since the naming of these information are defined based on the different views of their authors.

TABLE II
COMPARISON AMONG UNICASTING ALGORITHMS IN NAIVE REPLICATION FAMILY

Unicasting Issue					
Routing Algorithm	Knowledge for Routing Decision	Number of Copies	Bandwidth	Buffer Space	Energy
★Routing Without Infrastructure Assistance★					
◊Naive Replication Family–Flooding Based◊					
Direct Delivery [20]	None	1	Not Mentioned	Not Mentioned	Not Mentioned
Epidemic [21]	None	Unlimited	Not Mentioned	Limited	Not Mentioned
Two-Hop-Relay [20]	None	Limited	Not Mentioned	Not Mentioned	Not Mentioned
Spray-and-Wait [22]	None	Limited	Limited	Limited	Not Mentioned
◊Naive Replication Family–Coding Technique Based◊					
Algorithm in [23]	None	Limited by Coding Rate	Not Mentioned	Not Mentioned	Not Mentioned
Algorithm in [24]	None	Limited by Coding Rate	Not Mentioned	Not Mentioned	Not Mentioned
Algorithm in [25]	None	Unlimited	Limited	Not Mentioned	Not Mentioned
Algorithm in [27]	None	Unlimited	Limited	Limited	Not Mentioned

TABLE III
COMPARISON AMONG UNICASTING ALGORITHMS IN UTILITY FORWARDING FAMILY

Unicasting Issue					
Routing Algorithm	Knowledge for Routing Decision	Number of Copies	Bandwidth	Buffer Space	Energy
★Routing Without Infrastructure Assistance★					
◊Utility Forwarding Family–One Hop Encounter Prediction Based◊					
First Contact [28]	None	1	Limited	Limited	Not Mentioned
Seek-and-Focus [29]	Recent Encounter Time	1	Not Mentioned	Not Mentioned	Not Mentioned
MOVE [30]	Moving Direction, Distance	1	Not Mentioned	Limited	Not Mentioned
PER [31]	Encounter Count, Sojourn Time	1	Not Mentioned	Not Mentioned	Not Mentioned
RCM [32]	Expected Minimum Delay Based on Cyclic Mobility	1	Not Mentioned	Not Mentioned	Not Mentioned
MobiSpace [33]	Encounter Potential Estimated Using Euclidean Distance	1	Not Mentioned	Not Mentioned	Not Mentioned
MH* [34]	Inter-Meeting Time	1	Not Mentioned	Not Mentioned	Not Mentioned
Algorithm in [35]	Region ID, Message Forwarding Time, Message Class	1	Not Mentioned	Not Mentioned	Not Mentioned
PASR [36]	Location, Encounter Duration, Inter-Meeting Time, Encounter Probability	1	Not Mentioned	Not Mentioned	Limited
CAR [37]	Change Degree of Connectivity, Historical Colocation	1	Not Mentioned	Limited	Limited
◊Utility Forwarding Family–Time Varying Shortest Path Based]◊					
MED [28]	Time Invariant Edge Waiting Delay	1	Limited	Limited	Not Mentioned
ED [28]	Time Varying Edge Waiting Delay	1	Limited	Limited	Not Mentioned
EDLQ [28]	Time Varying Edge Waiting Delay, Queue Size	1	Limited	Limited	Not Mentioned
EDAQ [28]	Time Varying Edge Waiting Delay, Queue Size	1	Limited	Limited	Not Mentioned
DTLSR [38]	Minimum Expected Estimated Delay	1	Not Mentioned	Not Mentioned	Not Mentioned
DHR [39]	Weighted Average Delay	1	Not Mentioned	Not Mentioned	Not Mentioned
◊Utility Forwarding Family–Congestion Control Based◊					
Algorithms in [43][44]	Link Delay, Bandwidth, Bundle Buffer Occupancy	1	Not Mentioned	Limited	Not Mentioned
Algorithms in [45][46]	Bundle Buffer Occupancy, Average Bandwidth, Transmission Time	1	Not Mentioned	Limited	Not Mentioned
Algorithm in [48]	Queue Differential	1	Limited	Limited	Limited
Algorithm in [49]	Queue Differential	1	Not Mentioned	Limited	Not Mentioned
◊Utility Forwarding Family–Social Relationship Based◊					
SimBet [51]	Betweenness, Similarity	1	Not Mentioned	Not Mentioned	Not Mentioned
Bubble [53]	Community, Centrality	1	Not Mentioned	Not Mentioned	Not Mentioned
SimBetAge [54]	Aged Betweenness, Aged Similarity	1	Not Mentioned	Not Mentioned	Not Mentioned
PeopleRank [55]	Equation of PageRank	1	Not Mentioned	Not Mentioned	Not Mentioned
Algorithm in [56]	Nationality, Graduate School, Languages, Affiliation, City of Residence, Country of Residence, Topics of Interests	1	Not Mentioned	Not Mentioned	Not Mentioned
Fair Routing [57]	Interaction Strength, Assortativity	1	Not Mentioned	Limited	Not Mentioned
Friendship Routing [58]	Social Pressure Metric	1	Not Mentioned	Not Mentioned	Not Mentioned
SSAR [60]	Delivery Probability, Willingness	1	Limited	Limited	Not Mentioned

research activities of existing unicast algorithms in DTNs, of which to distribute the multicast destinations [130] is interesting.

Anycasting in DTNs is still in infancy although the work in [137] develops a new research orientation, by adding an additional layer to support anycasting without any change to the existing unicast algorithm.

TABLE IV
COMPARISON AMONG UNICASTING ALGORITHMS IN HYBRID FAMILY

Unicasting Issue					
Routing Algorithm	Knowledge for Routing Decision	Number of Copies	Bandwidth	Buffer Space	Energy
★Routing Without Infrastructure Assistance★					
◊Hybrid Family–Utility Replication Based◊					
PROPHET [61]	Encounter Probability	Controlled	Not Mentioned	Limited	Not Mentioned
PREP [62]	Encounter Duration	Controlled	Limited	Limited	Not Mentioned
NECTAR [64]	Encounter Duration, Hop Count	Controlled	Limited	Limited	Not Mentioned
RAPID [65]	Inter-Meeting Time	Controlled	Limited	Limited	Not Mentioned
DAER [66]	Distance, Moving Direction	Controlled	Limited	Limited	Not Mentioned
POR [67]	Distance, Message Size	Controlled	Limited	Not Mentioned	Not Mentioned
MPAD [68]	Communication Angle, Moving Direction	Controlled	Limited	Limited	Not Mentioned
LocalCom [70]	Disruption Period, Encounter Count	Controlled	Not Mentioned	Not Mentioned	Not Mentioned
ANBR [71]	Connectivity Estimated Based on Network Graph	Controlled	Not Mentioned	Limited	Not Mentioned
◊Hybrid Family–Improved Spray Based◊					
SCAR [76]	Change Degree of Connectivity, Historical Colocation	Limited	Not Mentioned	Limited	Limited
SMART [77]	Encounter Count, Recent Encounter Time, Inter-Meeting Time	Limited	Limited	Not Mentioned	Not Mentioned
LSF [78]	Recent Encounter Time	Limited	Not Mentioned	Not Mentioned	Not Mentioned
MMF [78]	Priority Based on Node ID	Limited	Not Mentioned	Not Mentioned	Not Mentioned
MSF [78]	Number of Encountered Nodes Identified by ID	Limited	Not Mentioned	Not Mentioned	Not Mentioned
SocialCast [79]	Interest, Change Degree of Connectivity, Historical Colocation	Limited	Not Mentioned	Limited	Limited
Algorithms in [80] [81]	Estimated Delivery Ratio	Limited (Dynamically Adjusted)	Not Mentioned	Not Mentioned	Not Mentioned
O-SaW [82]	Desired Average Delivery Delay	Limited (Dynamically Adjusted)	Not Mentioned	Not Mentioned	Not Mentioned
DA-SaW [82]	Average Node Degree	Limited (Dynamically Adjusted)	Not Mentioned	Not Mentioned	Not Mentioned
Algorithm in [83]	Expected Delivery Delay, Historically Shortest Delivery Delay	Limited (Dynamically Adjusted)	Limited	Not Mentioned	Not Mentioned
RTBR [84]	Region ID	Limited (Proportionally Sprayed)	Not Mentioned	Not Mentioned	Not Mentioned
Algorithm in [85]	Community	Limited (Proportionally Sprayed)	Not Mentioned	Not Mentioned	Not Mentioned
EBR [86]	Average Node Degree	Unlimited (Proportionally Sprayed)	Limited	Limited	Not Mentioned
AMR [88]	Estimated Residual Delivery Delay	Limited	Not Mentioned	Not Mentioned	Not Mentioned
SaF [22]	Recent Encounter Time for Focus Phase	Limited for Spray Phase	Limited	Limited	Not Mentioned
EAR [89]	Hop Count, Residual Bandwidth	Unlimited	Limited	Limited	Not Mentioned
HiBOp [90]	Context Information of User	Limited for Spray Phase	Not Mentioned	Limited	Not Mentioned
◊Hybrid Family–Improved Epidemic Based◊					
MaxProp [91]	None	Controlled	Limited	Limited	Not Mentioned
FuzzySpray [92]	None	Controlled	Limited	Not Mentioned	Not Mentioned
Vector Routing [93]	Encounter Angle, Moving Speed	Controlled	Limited	Not Mentioned	Not Mentioned
Algorithm in [95]	Hop Count	Controlled	Not Mentioned	Not Mentioned	Not Mentioned
Algorithm in [97]	Message Lifetime	Controlled	Not Mentioned	Not Mentioned	Not Mentioned
Algorithm in [98]	Carrier Count	Controlled	Not Mentioned	Limited	Not Mentioned
◊Hybrid Family–Coding Technique Based◊					
Algorithm in [100]	Path Failure Probability, Replication Factor, Splitting Factor	Limited by Coding Rate	Not Mentioned	Not Mentioned	Not Mentioned
Algorithm in [101]	Replication Factor, Splitting Factor, Estimated Delivery Ratio	Limited by Coding Rate (Dynamically Adjusted)	Not Mentioned	Not Mentioned	Not Mentioned
RED [102]	Delivery Probability, Replication Factor, Splitting Factor	Limited by Coding Rate	Not Mentioned	Limited	Not Mentioned
Algorithm in [103]	Content	Limited by Coding Rate	Limited	Limited	Not Mentioned
vCF [105]	Inter-Meeting Time	Controlled	Limited	Limited	Not Mentioned
Algorithm in [106]	Forwarding Factor	Controlled	Not Mentioned	Not Mentioned	Not Mentioned
HubCode [107]	Determination of Hub Node, Linear Dependence of the Message	Controlled	Not Mentioned	Not Mentioned	Not Mentioned

VIII. REMAINING CHALLENGES AND OPEN ISSUES

Routing is a major challenge in DTNs since it requires to appropriately select the candidate node using the time varying information while considering the usage of bandwidth and buffer space as well as energy. However, there are still some remaining challenges and open issues that need to be investigated:

1: The comprehensive theory regarding routing in DTNs has not been adequately investigated, although some initial

TABLE V
COMPARISON AMONG UNICASTING ALGORITHMS WITH INFRASTRUCTURE ASSISTANCE

Unicasting Issue					
Routing Algorithm	Infrastructure Movement	Assistance Behavior Controlling	Bandwidth	Buffer Space	Energy
★Routing With Infrastructure Assistance★					
◊Moile Node Relay Based◊					
Data Mule [108]	Random Movement	None	Not Mentioned	Limited	Not Mentioned
VDM [109]	Deterministic Movement	Handing Over the Role of VDM Using Fuzzy Logic	Not Mentioned	Not Mentioned	Not Mentioned
NIMF [110]	Deterministic Movement	None	Not Mentioned	Limited	Not Mentioned
FIMF [110]	Deterministic Movement	Controlling the Movement Based on Request	Not Mentioned	Limited	Not Mentioned
MV [111]	Deterministic Movement	Controlling the Movement Based on Bandwidth, Unique Bandwidth, Message Delay, Peer Delay	Limited	Limited	Not Mentioned
SIRA [112]	Deterministic Movement	Controlling the Movement Based on Estimated Weighted Delay	Limited	Limited	Not Mentioned
MURA [112]	Deterministic Movement	Controlling the Movement Based on Estimated Weighted Delay	Limited	Limited	Not Mentioned
FRA [112]	Deterministic Movement	Controlling the Movement Based on Estimated Weighted Delay, Controlling the Synchronization Between Ferry Routes Based on Connectivity	Limited	Limited	Not Mentioned
Algorithm in [113]	Deterministic Movement	Controlling the Movement and Scheduling the Ownership of MF Based on Periodic, Request and Storage	Limited	Limited	Not Mentioned
Algorithm in [114]	Deterministic Movement	Controlling the Movement Based on Network Graph	Not Mentioned	Limited	Not Mentioned
Algorithm in [115]	Deterministic/Random Movement	Voting the Relay Role Based on Minimum Encounter Duration, Minimum Accumulated Contact Duration Within a Ferry Cycle, Maximum Allowed Unusable Network Time	Not Mentioned	Not Mentioned	Not Mentioned
◊Stationary Node Deployment Based◊					
NRA [112]	Stationary	Provision Connectivity Between Ferry Routes	Limited	Limited	Not Mentioned
Throwbox [116]	Stationary	Deployment Based on Probability of Entering the Radio Range	Limited	Not Mentioned	Limited
Algorithm in [117]	Stationary	Deployment Based on Traffic Information, Storage, Hop Count, Average Message Delivery Time	Not Mentioned	Limited	Not Mentioned
Algorithm in [118]	Stationary	Deployment Based on Number of Replicas and Delay Time	Not Mentioned	Not Mentioned	Not Mentioned

analysis have been investigated for Epidemic [21], Spray-and-Wait [22] and MF [110].

2: It is difficult to compare the performance of various routing algorithms, since they are designed for different optimization objectives under different scenarios. To this end, these different objectives affect the scalability under different scenarios.

3: Numerous existing routing algorithms in DTNs are based on the historical information to predict future encounter opportunity. As addressed in [138], the problem is how to select the useful information for prediction.

4: Although the routing behavior in DTNs relies on the mobility of mobile nodes to create encounter opportunity, the inherent problem such as achieving the loop free should be taken into account.

5: Regardless of the selfish behavior, the candidate node has to passively allocate the buffer space for the incoming message given the buffer space exhaustion. However, the messages cleared out from the buffer space would require additional transmissions at subsequent encounter opportunity, resulting in redundancy. To this end, the consideration of congestion control is essential.

6: It is necessary to keep on studying other types of coding techniques. This motivation is particularly arisen by our survey reviewed for the algorithms in "Hybrid" family, regarding the works combining the coding technique with those under the utility replication [105], improved spray [101] and improved epidemic [106] based branches.

7: Inherently, it is difficult to capture the mobility characteristic, and even to obtain the most recent network topology information in DTNs due to the large variation of network topology. In light of this, the realistic scenario with the more complicated mobility affects the accuracy of such information, as such topology control in DTNs [139] is a challenging issue. Although geographic routing only requires realtime geographic information to relay the message without considering the underlying network topology and the requirement of contemporaneous end-to-end connectivity, the sparse network density and high mobility result in challenge to obtain the realtime location of destination due to long delay for information request or frequent location variation. Therefore, using realtime geographic information [66][67] would be unreasonable, particularly taking into account the mobility of destination.

8: Artificial Intelligence (AI) algorithms should be adequately investigated to optimize the routing decision, although the Bayesian [35] and Reinforcement [140] learning algorithms as well as GA [135] have been initially investigated. In addition, an intelligent router could be configured with several routing algorithms, which are switched according to a fuzzy control technique. In detail, the improved epidemic based approach could be adopted given the lack of knowledge about destination. Following the elapsed time, the router could switch to the utility replication based approach given the obtained knowledge about destination. The improved spray based approach could be adopted only if the knowledge is

TABLE VI
COMPARISON AMONG MULTICASTING ALGORITHMS

Multicasting Issue					
Routing Algorithm	Knowledge for Routing Decision	Replication Behavior	Bandwidth	Buffer Space	Energy
★Tree Based Approaches★					
STBR [119]	Information Adopted in [28]	Replication at Branch Node	Limited	Limited	Not Mentioned
DTBR [119]	Information Adopted in [28]	Replication at Branch Node	Limited	Limited	Not Mentioned
OS-Multicast [121][122]	Currently Available Outgoing Links, Possible Paths to Destinations	Replication at Branch Node	Limited	Limited	Not Mentioned
SHIM [123]	Determination of Leader Node for Inter-Domain Multicasting, Information Adopted in DTBR or OS-Multicast for Intra-Domain Multicasting	Replication at Leader Node for Inter-Domain Multicasting, Replication at Branch Node for Intra-Domain Multicasting	Limited	Limited	Not Mentioned
CAMR [124]	Encounter Probability	Replication at Branch Node	Limited	Not Mentioned	Not Mentioned
★Unicast Based Approaches★					
EMBR [125]	Encounter Probability	Utility Replication	Limited	Limited	Not Mentioned
RelayCast [126]	None	Replication Using Two-Hop-Relay [20]	Limited	Limited	Not Mentioned
Algorithm in [127]	Interest	Utility Replication	Limited	Limited	Not Mentioned
SDM [128]	Accumulative Encounter Probability	Utility Replication	Not Mentioned	Limited	Not Mentioned
MDM [128]	Path Weight	Utility Replication	Not Mentioned	Limited	Not Mentioned
FBIMR [129]	Information Adopted in EMBR [125] for Intra-Domain Multicasting, Ferry Relaying for Inter-Domain Multicasting	Utility Replication With Infrastructure Assistance	Limited	Limited	Not Mentioned
Algorithm in [130]	Active Level	Improved Spray	Not Mentioned	Not Mentioned	Not Mentioned

TABLE VII
COMPARISON AMONG ANYCASTING ALGORITHMS

Anycasting Issue				
Routing Algorithm	Knowledge for Routing Decision	Bandwidth	Buffer Space	Energy
EMDDA [133]	Practical Expected Delay	Limited	Limited	Not Mentioned
Algorithm in [134]	Path Length, Number of Reachable Receivers	Not Mentioned	Limited	Not Mentioned
Algorithm in [135]	Storage, Moving Delay, Leaving Time	Limited	Limited	Not Mentioned
MDRA [136]	Encounter Probability	Not Mentioned	Not Mentioned	Not Mentioned

sufficient to estimate a limited number of copy tickets for efficient delivery. Such decision could be made by a fuzzy logic function using the partially historical knowledge.

9: It is observed that both the multicasting and anycasting issues have not been extensively investigated so far. Meanwhile, to borrow from the research activities of existing unicasting algorithms in DTNs has more research potential than the tree based approaches for multicasting and the initial works regarding anycasting, as highlighted in [130] and [137]. Given the research motivation of geographic routing discussed previously, geocasting [141] in DTNs is also worthwhile investigating.

10: Energy issue should be adequately taken into account for routing decision, given the research vacancy highlighted in Table II, Table III, Table IV, Table V, Table VI and Table VII. Apart from the energy consumed for communication, to control the sleeping functionality and the movement speed are also worthwhile investigating for saving the device maintenance energy.

11: Finally, Quality of Service (QoS) and security issues are rarely comprehensively taken into account, even with the initial works about QoS aware routing [142] and security aware routing [143].

IX. EVALUATION FRAMEWORK OF ROUTING IN DTNS

In this section, an evaluation framework is illustrated in Fig.16.

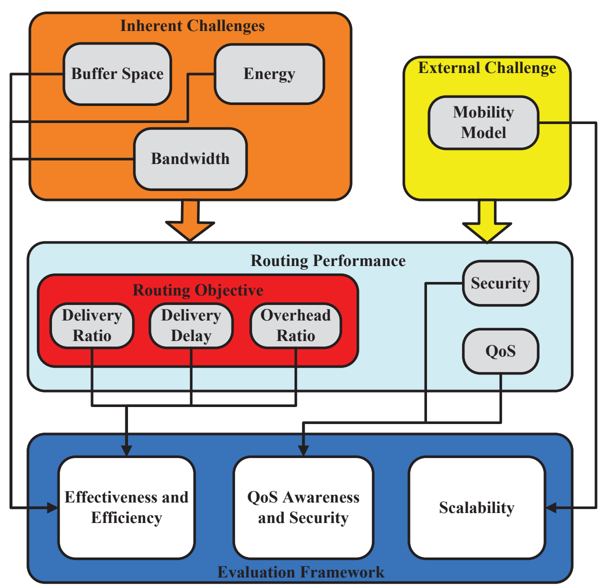


Fig. 16. Evaluation Framework of Routing in DTNs

Effectiveness and Efficiency: Given the limited bandwidth, buffer space and energy of the DTN device, the effectiveness of a routing algorithm is to achieve the sufficient delivery ratio within the target delivery delay, while taking into account the lowest overhead ratio for efficiency.

QoS Awareness and Security: For various based application services with different QoS requirements, a routing algorithm should perform prioritized transmission. The security issue of a routing algorithm requires the defense of attack such as DoS attack and spoofing attack.

Scalability: A routing algorithm has to overcome with sparse and dense scenarios, which is subject to a rapid change over time due to the mobility of mobile nodes for scalability.

X. Conclusion

In this article, we surveyed a large number of recent publications, and accomplished a comparison given the characteristics of the reviewed algorithms based on our taxonomy. We further identified the remaining challenges and open issues of routing in DTNs, together with a proposed evaluation framework.

During the last few years, the research activities of routing in DTNs have attracted tremendous attention with a large number of academic publications, even with the lack of large scale and long term applications. We hope this article would further motivate the research interest in DTNs, and accordingly highlight the following three topics for future investigations because of their perspectives:

1: Message dissemination in Delay/Disruption Tolerant Social Networks: This is because the characteristic of DTNs is robust to selfish behavior, reducing the overhead ratio [144].

2: Hybrid network application system such as cellular networks and Wireless Local Area Networks (WLANs): In [145], the authors have proposed an opportunistic based web service via wireless hotspots.

3: Combining the routing algorithms reviewed in this article with those designed for MANETs: The initial work in [146] proposes that it makes sense to adopt the routing algorithms designed for MANETs to achieve the short delivery delay given high network density. Relatively, it is more appropriate to adopt those designed for DTNs in sparse networks, where the mobile nodes are with fast moving speed or large size message being transmitted.

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