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A hybrid multiple copy routing algorithm in space delay-tolerant networks

Peng WAN[1*], Shi CHEN[2], Tao YU[1] & Zhongjie HUA[1]

[1]*Beijing Institute of Tracking and Telecommunications Technology, Beijing* 100094*, China;*
[2]*National Space Science Center, Chinese Academy of Sciences, Beijing* 100190*, China*

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Abstract With the development of technology and applications in space delay-tolerant networks (SDTNs), increasing attention has been paid on the routing technologies between different DTN nodes. This paper proposes a novel hybrid multiple copy routing (HMCR) algorithm that can be applied not only to deterministic space scenarios but also to opportunistic space scenarios. HMCR combines contact graph and delivery probability metrics to make forwarding decisions. In order to verify the new HMCR algorithm's performance, research work has been carried out to prove its availability in SDTNs. The analysis and simulation results show that, compared with other algorithms such as contact graph routing (CGR), Epidemic, and PRoPHET, the new HMCR algorithm performs well in the areas of message delivery ratios, average end-to-end delays, and transmission overhead, which proves to be suitable for highly dynamic SDTNs.

Keywords space delay-tolerant networks, routing algorithms, contact graph routing, hybrid single copy routing, hybrid multiple copy routing

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1 Introduction

As technology rapidly progresses, more and more space devices such as satellites, space probes, and aircraft will be temporally connected to each other to relay data. In this type of delay-tolerant network (DTN) [1], a key challenge is to design an efficient routing algorithm since it is occasionally connected and a complete path from a source to a destination does not always exist. With the development of technology and applications in DTN, increasing attention has been paid to the routing technologies between different DTN nodes. The existing mobile sd hoc network (MANET) routing protocols (such as ad hoc on-demand distance vector (AODV) [2] and Profile-based routing [3]) and wireless sensor network (WSN) routing protocols (such as ICACR [4] and MEWR [5]) can not work effectively in this type of DTN because they make the assumption that the network is fully connected.

Most of the existing space network routing algorithms are based on the requirements of satellite telecommunications, which consist of inner routers and edge routers based on inter-satellite wireless links and space-ground wireless links, and the essential part of such research is the routing technologies between

* Corresponding author (email: wanpeng@bittt.cn)

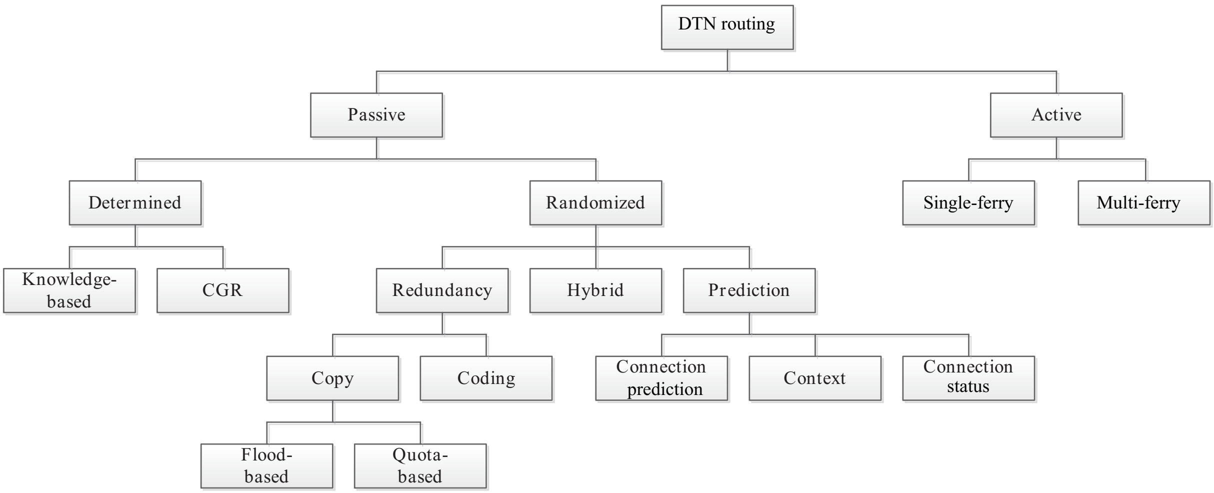

Figure 1 Classification of routing algorithms in DTNs.

different space nodes. Based on the characteristics of Space DTNs, in this paper we first study the existing DTN routing algorithms, and then we propose a new hybrid multiple copy routing (HMCR) algorithm. The proposed algorithm utilizes both the knowledge of the space movement rules to provide forwarding paths for delivering messages and the prediction metrics (e.g., delivery probability) to choose the next hop node without the apriori information of the space movement. Our hybrid routing algorithm combines prediction-based routing with the knowledge of node contact graph to make forwarding decisions, in order to make use of the best of both worlds. It can reduce reliance on oracle knowledge of the CGR and eliminate the pitfalls in using prediction-based routing while still taking advantage of their higher efficiency. The main innovation of this work is the introduction of a new prediction metric based on cumulative contact procedures and the combination of two kinds of algorithms to make forwarding decisions. The proposed hybrid routing algorithm can achieve high delivery ratios, low average delivery delays, and limited overhead in data transmission of SDTNs.

In order to verify the new HMCR algorithm's performance, we have done much research to prove its availability in SDTNs and utilized a simulation test bed to evaluate its performance under the deep space communication environment. Extensive simulations are carried out to evaluate the efficiency of our HMCR routing. The theoretical analysis and the simulation results confirm the improvement in forwarding efficiency over the previous routing protocols, such as CGR, Epidemic, and PRoPHET.

2 Existing routing algorithms in DTNs

Space Networks can be divided into two parts: the space segments, including aircraft, satellites, and deep space explorers with different orbits, and the ground segments, including stations, mission control centers, and customers with application access terminals. With inter-satellite wireless links and space-ground wireless links, we can construct a huge space-ground integrated networks based on the basic communication units in such networks, in order to share the resources and services more conveniently. In 2003, Fall [1] first advanced the concept of DTNs, attempting to solve the communication problems in Challenged Network circumstances. A Challenged Network generally refers to a wireless network that might be faced with communication problems such as link interrupts, and long-time disconnection due to the sparse distribution of nodes, fast mobility, capacity limitations, etc. Space Networks [2] share such characteristics of long-distance wireless links as long end-to-end time delays, periodic disconnection, and high data error rates, which are typical of Challenged Network. Therefore, we attempt to solve the communication problems of Space Networks based on DTN technologies.

The key technology of Space Networks is its communication routing. There are many different DTN routing algorithms, and as shown in Figure 1, the existing routing algorithms can be classified into

Table 1 Summary of DTN routing algorithms

Routing algorithms	Characteristics	Requirements
Active (DataMULEs [6])	Message delivery determined by the control of special node movement	Existence of special nodes whose movement can be controlled.
Determined (CGR [2,7])	Message delivery determined by the networks' future status	The network topology are all-known or partially known.
Flood-based (Epidemic [3,8])	Delivery of message copy when contacting each other	Large storage and band-width requirements, which brings in large network overhead.
Quota-based (Spray and focus [9], Spray and wait [10])	Fixed number of message copies before routing; delivery of each copy independently	Choose proper number of message copies and distribute the copies according to certain criteria.
Coding-based (Network coding [11])	Source encodes the message; destination receives and decodes the coded message blocks to get the original messages	Relative nodes are capable of encoding and decoding, which brings in the calculation payload for such nodes.
Prediction-based (Seek and focus [12])	Message delivery determined by node movement or contact prediction with the history or other network status	Prediction accuracy of the movement or contact plan.
Hybrid (PRoPHET [13])	Combination of parallel transmission and prediction-based routing	Similar requirements as Flood-based and prediction-based routing algorithms.

different types according to their forwarding schemes. Routing algorithms' performance should not be determined solely by special test results because the algorithms are always designed to solve special problems or to suit certain circumstances and usually perform well in some scenarios but poorly in others. Therefore, when we need to choose or design a suitable routing algorithm, we should thoroughly research the application environments and quality of service requirements.

Table 1 summarizes the characteristics and requirements of existing routing algorithms in DTNs. Recently, there have emerged other routing algorithms for terrestrial DTNs. Nishiyama et al. [14] focused on cooperative DTNs, consisting of smart phones and tablet computers, and proposed a novel routing algorithm, ring distribution routing (RDR), which controls the replication and forwarding based on the source node surroundings. Eshghi et al. [15] investigated the use of epidemic routing in energy-constrained DTNs and proved that in the mean-field regime, the optimal dynamic forwarding decisions follow simple threshold-based structures in which the forwarding threshold for each node depends on its current remaining energy. Other researchers [16,17] presented a new routing protocol for DTNs based on a distributed swarm intelligence approach, called Cultural Greedy Ant (CGrAnt), which uses a greedy version of the Ant Colony Optimization (ACO) meta-heuristics and incorporates a Cultural Algorithm (CA). All of the routing algorithms above work well in terrestrial DTNs, but cannot be applied directly in SDTNs.

Currently, the most widely studied SDTNs routing algorithm is the CGR algorithm [18] and its enhanced versions such as the ECGR [19] and MD-CGR [20] algorithms. The CGR algorithm was mainly developed based on the predictability characteristics of the contact plans in SDTNs. Each node then utilizes these contact plans to construct a contact graph of the whole network for the routing calculation. ECGR replaces the retrospective algorithm in the CGR with Dijkstra's algorithm when computing forwarding routes. This enhancement remarkably reduces the complexity of the routing calculation in CGR. MD-CGR introduces a new multi-destination scheme into CGR, which can fulfill the service requirements of the different transactions.

The effectiveness of CGR routing algorithms has been validated by several types of space experiments [21], such as the Deep Impact Network experiment (employing the EPOXI space cruise), the JAXA jointly performed space link demonstrations with NASA (where the JAXA's GEO relay satellite called Data Relay Test Satellite has been used), the Space Data Routers European Project, and the pilot operation of a DTN implementation on the International Space Station (ISS). Furthermore, Fraire et al. [22] suggestdc a Contact Plan Computation Element (CPCE) that can assist or even automate the design of contact plans for future SDTNs. CPCE can support operations of future SDTNs by periodically delivering contact plans that can optimize the performance of these networks. Other research [23] performed similar work. Such technologies can be utilized to enhance the CGR. All these works are orthogonal to ours and can be extended into our algorithm. Meanwhile, Song et al. [24] proposed the snapshot integration routing (SIR) algorithm, which firstly builds the directed graph of the SIR model, then minimizes the maximum link utilization to acquire the final transmission routes. However, this algorithm requests for periodic, symmetrical, and predictable links, thereby restricting its application to a certain extent.

In conclusion, CGR algorithms have been regarded as the classical routing algorithms in SDTNs and have been accepted by many international organizations, such as the Internet Engineering Task Force (IETF) and Consultative Committee for Space Data Systems (CCSDS). Space experiments have shown that, with an accurate predetermination of the whole SDTN contact information, CGR performs well in the areas of message delivery ratios, end-to-end time delays, and network overhead, proving to be suitable for such scenarios. However, inaccurate or partial contact information in some nodes would result in degradation of the CGR algorithm's performance, which should be improved in future research.

3 Hybrid multiple copy routing algorithm

3.1 General design of the HMCR

According to the analysis in Section 2, we conclude that CGR can be enhanced with a randomized routing method designed for dynamic networks. The enhanced routing algorithm can be applied not only to deterministic space scenarios but also to opportunistic space scenarios. We first analyze the advantages of the CGR and random routing algorithms and suggest a new Hybrid Single Copy Routing (HSCR) algorithm based on CGR. If the wireless link information used in the first mode of the standard CGR algorithm requires any changes or contains errors, our new algorithm will immediately change to the second mode of random routing algorithm, delivering the messages from one DTN node to the other based on the delivery probability. Once the wireless link information recovers and can be used again, our new algorithm will change to the first mode, delivering the messages from the current DTN node to the destination based on the standard CGR algorithm. An example of the routing procedure is shown in Figure 2. Such a hybrid routing algorithm can effectively reduce the oracle knowledge requirement of the CGR routing algorithm and make full use of the advantages of both the CGR and random routing algorithms, which are more suitable to dynamic SDTNs.

The HSCR algorithm delivers all of the network messages based on a single copy, which requires only one copy for each message in the SDTNs. Although HSCR reduces network payloads, it is not reliable enough for some urgent and essential issues. Therefore, we study further and suggest a new Hybrid Multiple Copy Routing (HMCR) algorithm, based on the thought of combining quota-based routing and HSCR, that can improve service reliability and also reduce network payloads. The key points of our HMCR algorithm are as follows: in the phase of CGR, HMCR firstly calculates all of the available routes from source to destination using the criterion of the earliest arrival time, and then sorts them in ascending order by arrival time. When delivering the messages, HMCR chooses the first N routes from all of the available route sequences as the forwarding paths and delivers the copies as soon as possible. In our new HMCR routing algorithm, N is a protocol parameter, that can be set up based on the conditions or restrictions of the current network scale, the importance of the messages, etc. In order to further reduce network payloads, we introduce an important Redundancy Copy Deletion (RCD) scheme into the HMCR algorithm, which uses a timer and feedback mechanism to delete the message copies that had been already successfully received.

To summarize the description above, the HMCR routing algorithm includes three key notions: i) the definition of the delivery probability; ii) the selection of the number of copies; iii) the deletion of redundant copies. These key notions are described in detail below.

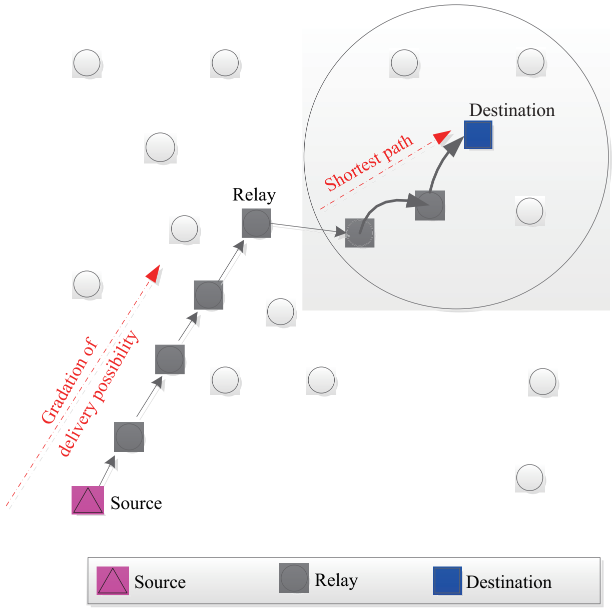

Figure 2 (Color online) Hybrid Single Copy Routing (HSCR) algorithm.

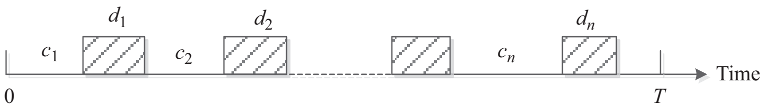

Figure 3 The contact procedure of nodes N_i and N_j.

3.2 The definition of the delivery probability

One key point of the HMCR routing algorithm is to obtain the delivery probabilities of all nodes in the network. When compared with terrestrial mobile networks and wireless sensor networks, the calculation resources and transmission bandwidth in SDTNs are more scarce, and the transmission delay are longer, making it much more difficult for routing algorithms with computational complexity or multiple interactions-such as the PRoPHET algorithm-to be applied in space networks.

In our HMCR algorithm, the calculation of the delivery probability is comparatively simple. For any two DTN nodes N_i and N_j, the contact procedures are shown in Figure 3, where the shadows on the time line indicate the contact duration of nodes N_i and N_j, and other parts indicate the inter-contact time between them.

Assuming that the continuous contact durations of nodes N_i and N_j in the $[0, T]$ time period are $d_1, d_2, \ldots, d_n$, and the inter-contact time are $c_1, c_2, \ldots, c_n, c_{n+1}$, then the contact probability P_{ij} of node N_i and N_j can be defined as (1):

$$P_{ij} = \lim_{T\to\infty} \frac{\sum_{k=1}^{n} d_k}{T} = \frac{E[d]}{E[d] + E[c]} \approx \frac{\bar{d}}{\bar{d} + \bar{c}}, \tag{1}$$

where $E[d]$ indicates the expectation of the contact durations, $E[c]$ indicates the expectation of the inter-contact times, $\bar{d}$ indicates the mean value of the contact durations, and $\bar{c}$ indicates the mean value of the inter-contact times. Assuming that the total number of nodes in the SDTNs is M, we can give the definition of the delivery probability P_i from node N_i to any DTN node as (2):

$$P_i = \frac{\sum_{j=1, j\neq i}^{M} \frac{\bar{d}_{ij}}{\bar{d}_{ij} + \bar{c}_{ij}}}{M - 1}. \tag{2}$$

After calculating the delivery probabilities of each DTN node, HMCR designs the random routing algorithm based on such values. Assuming that the delivery probabilities are P_i and P_j for any two DTN nodes N_i and N_j, they would exchange their own delivery probabilities when they contact each other. If P_i is less than P_j, then node N_i delivers all of the stored messages to node N_j until they are not in the contact range or all of the messages have been delivered. The random routing algorithm allows for message delivery based on the delivery probabilities, and the relative nodes in the SDTNs do not need to know the contact information of other DTN nodes. This can effectively overcome the problems of CGR routing.

The reason that we choose the well-connected nodes is that in SDTNs, if one node can contact more nodes, then the probability for it to contact the destination node or the node connected with the destination node is much higher, which can help to improve the probability of successful message delivery.

3.3 The selection of the number of copies

HMCR generates copies of each message on the network to improve the reliability of message delivery. However, the most important part of such process is to choose the appropriate number of copies. It is essential to strike a balance between the routing performance and network payloads, which calls for deep research on the quality of user service, prediction of network resources, and optimization of routing performance. Shah et al. [6] performed research on the selection of the number of copies. They designed complex equations to compute the expected number of message copies according to the expectation of delivery delay. Generally, with certain network bandwidth and buffer storage, the maximum number of message copies should not be too large: it should be less than half of the total number of nodes on the network. For example, if the node number in this network is six, then it is suitable to choose two as the number of copies.

3.4 The deletion of redundant copies

The messages might be copied many times in the HMCR algorithm, which would result in great consumption of network resources. HMCR has utilized quotas to limit the number of copies; however, some message copies can still survive for a very long time even if one of them has been delivered to the destination. In order to solve this problem, HMCR brings an RCD scheme into the algorithm, which sets up a timer for each message copy to record the time threshold for its expected arrival. For simplicity, the time threshold of each message copy is set to the earliest arrival time, which can be calculated by the CGR routing algorithm; when the timer expires, the RCD deletes the corresponding message copy. Alternately, the message receiver may choose to delete the redundancies even without the feedback mechanism based on the message timer count information. If one of the message copies was delivered to the destination, the destination first analyzes the message timer information to judge whether there were other copies in the SDTNs. If other copies exists, the destination starts the feedback mechanism and sends a Delete Acknowledge (DACK) to all of the relative nodes on the networks to delete the message copies that had been already successfully received. The RCD procedure is shown in Figure 4.

4 Performance of the HMCR algorithm

To evaluate the performance of the HMCR algorithm, we conducted experiments with the typical deep space DTN simulation platform as follows:

- Experiment A: analysis of the hybrid routing mechanism in HMCR;
- Experiment B: comparison of message delivery ratios;
- Experiment C: comparison of average end-to-end delays;
- Experiment D: comparison of transmission overhead.

We have measured the following metrics:

- Delivery ratio: the proportion of messages that have been delivered out of the total unique messages created;
- Average end-to-end delay: the average end-to-end time of all the delivered messages;

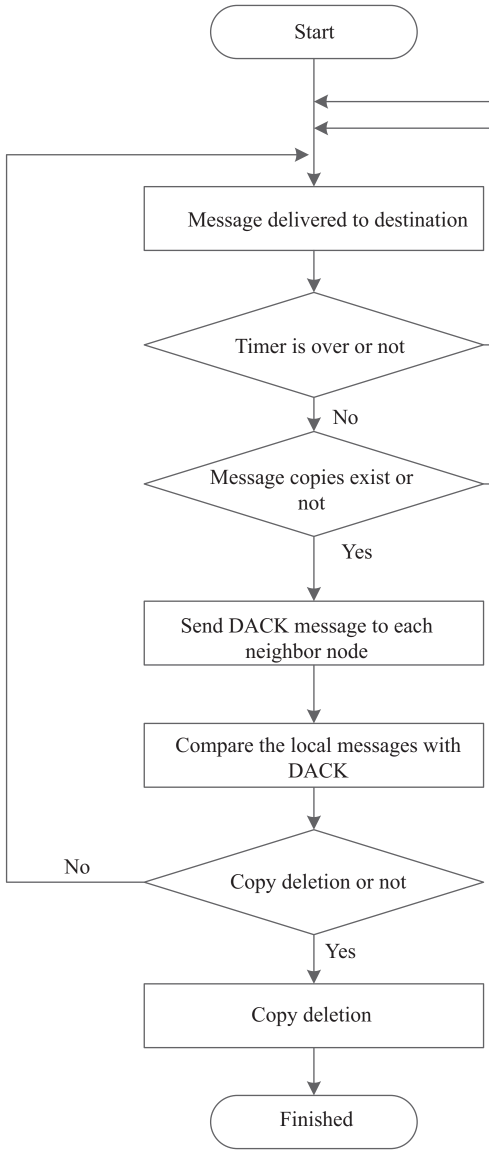

Figure 4 The procedure of RCD.

• Transmission overhead: the total size of messages (including copies and control messages) transmitted across the network.

We compare our algorithm against the following three benchmark algorithms:

• Epidemic: Messages are flooded throughout the entire network, which represents the upper bound for the delivery ratio and delay in the ideal environment.

• ProPHET: A message is forwarded to a node if it has a higher delivery predictability than the current node for that particular destination. This algorithm represents a standard non-oblivious benchmark that has been evaluated against several previous works.

• CGR: A dynamic algorithm that computes routes through a time-varying topology of scheduled communication contacts in a DTN and has been widely validated in SDTNs.

In all these experiments, shown as Figure 5, we generate a deep SDTN simulation scene by the special simulation test bed with one Mission Control Center on Earth, two ground stations, two DTN satellites, and one Lander on another planet such as Mars. Theoretically, the DTN satellites should locate at the equilibrium points in the Earth and Mars system, such as the Lagrange points, which refers to some stable points in which one relatively small object can remain stationary under the gravitational effect of two bigger objects. However, due to the rotation of the planets in the solar system, the space-ground

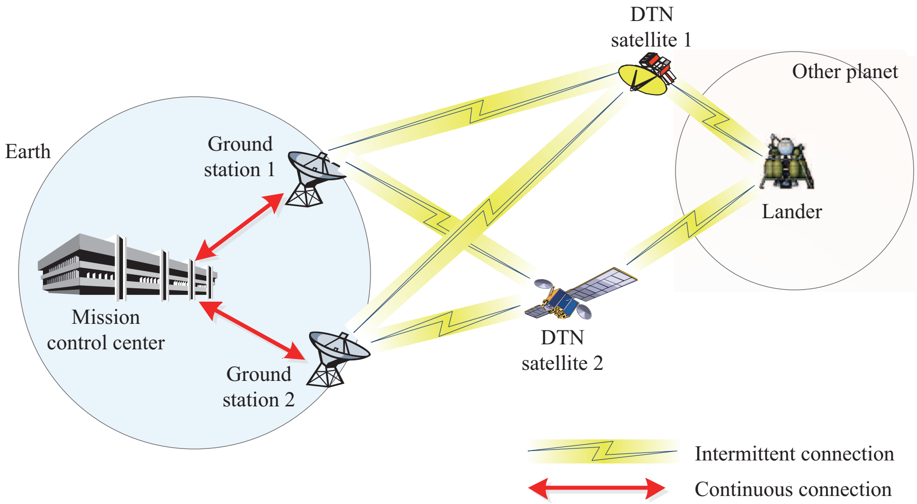

Figure 5 (Color online) Typical deep space DTN simulation scene.

links and the wireless connections between the nodes in space would always be intermittent. The wire links between the Mission Control Center and the ground stations are based on ground networks, which can be considered as the permanent links, near-zero bit error rates, and extremely little time delays.

In this paper, all of these experiments are based on the following settings:

- The simulation test-bed is based on ION software to simulate the behavior of SDTN nodes. ION is developed by the U.S. NASA Jet Propulsion Laboratory (JPL), and is usually applied for the research of interplanetary SDTNs. This software not only can simplify the structure of space links, planet surface links, and terrestrial links, but can also reduce the operation complexity of autonomic data communication networks, which can decrease the payloads and risks of communication tasks. Each computer installed with the Linux OS and the ION software can simulate one or more DTN nodes, and the space dynamic links can be simulated by the channel simulation software based on the Linux kernel.
- The protocol stacks between the nodes in the SDTNs include the application layer (tele-command and telemetry), Bundle Protocol [25], transport layer (Licklider transmission protocol, LTP [26]), network layer (IP, Encapsulation Service [27]), data link layer (CCSDS AOS [28]) and physical layer (RF links).
- The connections between the DTN satellites and ground stations are periodic; the connections between the DTN satellites and Lander are also periodic. The continuous contact duration and inter-contact time between the DTN satellites and ground stations are respectively about 120 s and 240 s; the continuous contact duration and inter-contact time between the DTN satellites and lander are respectively about 60 s and 300 s. These parameters are selected to mimic a challenged deep space scenario with a long (larger than 240 s) interruptions and short communication durations (less than 120 s) [29].
- The bit error rate and time delay on ground links are all zero, the data rate on ground links are about 100 Mbps; the bit error rate on space links are about 1×10^{-6}, the time delay on space links are about 500 ms, and the data rate on ground links are about 100 kbps. Each node in the network only stores the link information to the neighbor nodes.
- The simulation parameters of the PRoPHET algorithm are set up under the suggestion of an existing research study [13], such as $P_{\text{init}} = 0.75, \beta = 0.25, \gamma = 0.98$.

4.1 Experiment A: analysis of the hybrid routing mechanism in HMCR

Figure 6 shows a comparison of CGR, Random Routing and Hybrid Routing in message delivery ratio, where Random Routing is a simple routing algorithm that makes forwarding decision only according to the delivery probability defined in (2), and Hybrid Routing is the combination of CGR and Random Routing. We can see that the hybrid routing mechanism achieves about 7% and 20% improvements in delivery ratio compared with CGR and Random Routing, respectively, which means that it combines the advantages of these two routing algorithms.

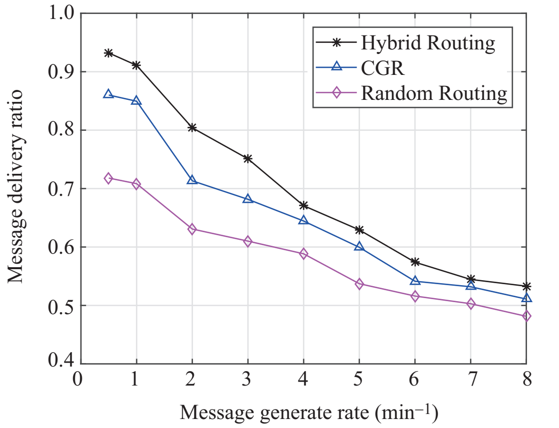

Figure 6 Comparison of CGR, Random Routing, and Hybrid Routing.

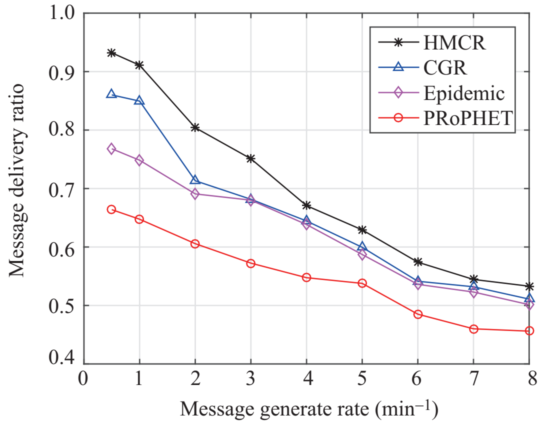

Figure 7 Comparison of message delivery ratios.

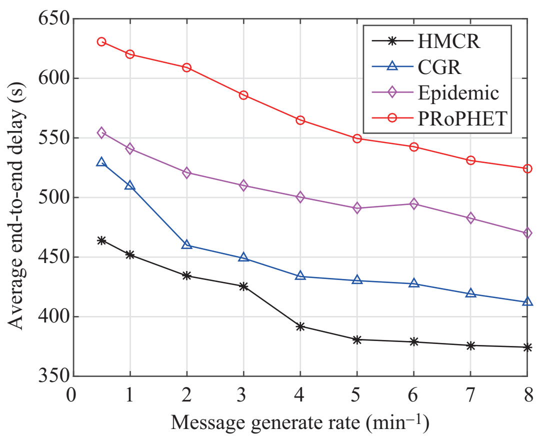

Figure 8 Comparison of average end-to-end delays.

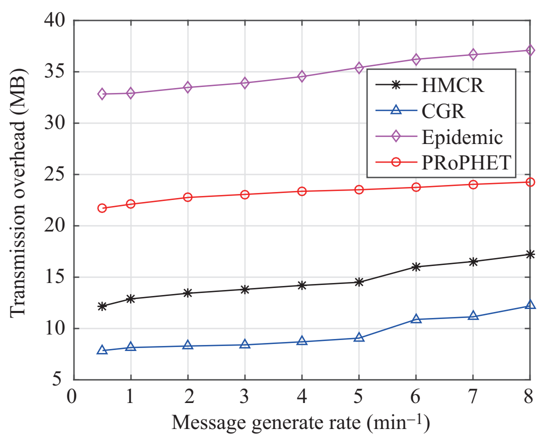

Figure 9 Comparison of transmission overhead.

4.2 Experiment B: comparison of message delivery ratios

Figure 7 shows a comparison of the message delivery ratios of four routing algorithms. We can see that when the message generation rate increases, the delivery ratios of these four routing algorithms all decrease. The reason is that as the message generation rate increases, the nodes in the network are more likely to drop the messages due to the limited buffer, which would result in the decrease in delivery ratio. We can also see that HMCR performs better than the Epidemic, PRoPHET, and CGR routing algorithms, which can be explained by the fact that HMCR combines the advantages of CGR, Random Routing, and Quota-based Routing.

4.3 Experiment C: comparison of average end-to-end delays

Figure 8 shows the comparison of average end-to-end delays of four routing algorithms. As the message generation rate increases, the average end-to-end delay decreases. The reason is that the messages with longer end-to-end delivery delays will be dropped as the total number of transmitted messages increases, which results in the decrease in average end-to-end delays. In this figure, it is also clear that HMCR performs better than the Epidemic, PRoPHET, and CGR algorithms, which means that HMCR can deliver many more messages in a shorter time period and provide better quality of service for the SDTNs. Specially, the actual delay of HMCR averages over 9%, 19%, 28% shorter than that of CGR, Epidemic, and PRoPHET, respectively.

4.4 Experiment D: comparison of transmission overhead

Figure 9 shows a comparison of transmission overhead of four routing algorithms. In this figure, it is clear that HMCR performs better than Epidemic and PRoPHET, but slightly worse than CGR, which can be explained by network resources consuming efficiencies of the different routing algorithms based on the different forwarding schemes, such as flooding, multiple copy, and single copy.

Based on the simulation results, we can conclude that HMCR performs better than CGR, Epidemic, and PRoPHET in terms of delivery ratios and end-to-end delays. Meanwhile, HMCR achieves slightly more transmission overhead than CGR, which is due to the multi-copy mechanism. This disadvantage is acceptable when considering its performance enhancement.

5 Conclusion

This paper studies existing DTN routing algorithms in SDTNs and suggests the Hybrid Multiple Copy Routing (HMCR) algorithm based on space movement rules and predictions. In order to verify the new HMCR algorithm's performance, we performed research to prove its availability in SDTNs by using a simulation test bed. The analysis and simulation results show that, compared with other algorithms such as CGR, Epidemic, and PRoPHET, our new HMCR algorithm performs well in the areas of message delivery ratios, average end-to-end delays, and transmission overhead, which proves it to be suitable for the highly dynamic SDTN environment.

Conflict of interest The authors declare that they have no conflict of interest.

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