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# Transmission-Controlled Multi-Hop Augmented Direct Delivery Scheme for Resilient Post-Disaster Opportunistic Networks

Runhan Peng
College of Communication Engineering, Chengdu University of Information Technology, Chengdu, China

Wenzao Li*
College of Communication Engineering, Chengdu University of Information Technology, Chengdu, China

Bing Wan
School of Artificial Intelligence, Chengdu Polytechnic, Chengdu, China

Rongbin Gou
College of Communication Engineering, Chengdu University of Information Technology, Chengdu, China

Xin Feng
College of Communication Engineering, Chengdu University of Information Technology, Chengdu, China

**Abstract**--In disaster scenarios where communication infrastructure is paralyzed,such as earthquakes,enabling efficient information dissemination through short-range communication among mobile devices becomes a critical challenge.Focusing on Bluetooth-based opportunistic contact communication in post-disaster urban environments,this paper takes the Direct Delivery algorithm as the primary research object,analyzes its limitations in terms of low delivery ratio and poor dissemination efficiency,and proposes an enhanced multi-hop dissemination scheme based on probabilistic forwarding and transmission control strategies.The results show that the proposed method significantly improves the delivery ratio and reduces transmission delay while maintaining low network overhead.Moreover, the message dissemination process exhibits an S-shaped growth pattern,which is more consistent with real-world spreading behavior.The proposed approach achieves a good balance between dissemination efficiency and resource consumption,providing an efficient and low-cost solution for emergency communication in infrastructure-less environments.

**Keywords--**Crowd Sensing,Opportunistic Network,Direct Delivery,Information Dissemination,Disaster Communication

## 1.INTRODUCTION

### 1.1Motivation & Problem Statement

In recent years, natural disasters such as earthquakes, floods, and wildfires, as well as battlefields and other infrastructure-less environments, have frequently caused severe damage to communication facilities, resulting in large-scale network disruptions. Under such conditions, traditional communication systems become unavailable, making timely and reliable information dissemination a critical requirement for emergency response, disaster relief, and rescue coordination. Opportunistic networks, which exploit intermittent contacts among mobile devices without relying on fixed infrastructure, have therefore become an effective and indispensable communication paradigm in these scenarios.

However, existing opportunistic routing algorithms still face a trade-off between dissemination efficiency and resource consumption. Lightweight routing strategies achieve low communication overhead but suffer from slow message dissemination and low delivery ratio, whereas flooding-based approaches significantly improve delivery performance at the cost of excessive message redundancy. Therefore, designing an efficient information dissemination mechanism that achieves a balance between dissemination performance and network overhead remains a key challenge in opportunistic networking and constitutes the primary motivation of this work.

### 1.2Proposed Approach

With the widespread adoption of smart devices, most individuals carry mobile terminals equipped with short-range communication technologies such as Bluetooth, which provides a practical foundation for contact-based information dissemination. Opportunistic networks[1] exploit intermittent contacts among mobile nodes and employ the store-carry-forward paradigm to enable message delivery in disconnected environments.

Based on this paradigm, Direct Delivery represents the simplest routing strategy, where only the source node transmits messages directly to encountered nodes. Although this method incurs minimal communication overhead, its performance is severely limited by low delivery ratio and slow dissemination speed, especially in sparse or highly dynamic environments. In contrast, Epidemic Routing improves delivery performance by flooding messages across encountered nodes, but introduces excessive redundancy and network resource consumption.

## 1.3Challenges and Solutions

The above approaches reveal a fundamental trade-off between dissemination efficiency and resource overhead, making it difficult to simultaneously achieve high delivery ratio, low delay, andlow overhead. This challenge becomes more critical in post-disaster scenarios, where device energy is limited and communication opportunities are sparse and unstable.[2]

To address this issue, a key research problem is how to enhance the dissemination capability of Direct Delivery while preserving its low-overhead characteristics. In this work, we focuson the Direct Delivery algorithm and analyze its inherent limitations in dissemination performance. Based on this analysis, a controlled multi-hop dissemination mechanism[3] is proposed.

Without introducing uncontrolled flooding, the proposed method enables limited multi-hop message propagation through probabilistic forwarding and transmission constraints, thereby improving network reachability. In addition, link reliability and node resource constraints are incorporated to better reflect realistic post-disaster communication conditions.

## 1.4Novelty and Technical Advantages

To evaluate the effectiveness of the proposed method, extensive simulations are conducted. The results demonstrate that the enhanced scheme significantly improves the delivery ratio and reduces transmission delay while maintaining relatively low network overhead.

Furthermore, the message dissemination process exhibits a characteristic S-shaped growth pattern, reflecting the dynamic evolution from slow initial spreading to rapid expansion and eventual saturation. This indicates that the proposed approach not only improves performance but also better captures realistic dissemination behavior.

Overall, this study provides an effective and practical solution for information dissemination in infrastructure-less environments, achieving a balance between efficiency and resource consumption.

# 2.SYSTEM MODEL

## 2.1Scenario Description

We consider a post-disaster urban environment where the communication infrastructure is completely unavailable due to events such as earthquakes. A group of mobile users carrying smartphones are randomly distributed within a two-dimensional square area of size L×L.Each device is equipped with Bluetooth capability, enabling short-range peer-to-peer communication without relying on centralized network support.

Let N denote the number of mobile nodes in the system. Each node represents a user device capable of storing, carrying, and forwarding messages. Initially, only one node possesses the message (e.g.,an evacuation notification), andthe goal is to disseminate this information to as many nodes as possible within a limited time.

## 2.2Mobility Model

The movement of nodes follows a random mobility pattern. At each time step, node i updates its position according to:

$$\mathbf{x}_i(t+1)=\mathbf{x}_i(t)+v_i\begin{bmatrix}\cos\theta_i\\ \sin\theta_i\end{bmatrix} \tag{1}$$

Where $v_i \in [v_{min}, v_{max}]$, is the movement speed, and $\theta i \in [0,2\pi]$, is the moving direction. To avoid boundary congestion, a periodic boundary condition is adopted:

$$\mathbf{x}_i(t)=\mathbf{x}_i(t)\ mod\ L \tag{2}$$

In addition, node activity is modeled probabilistically to reflect realistic human behavior, where each node moves with a certain activity probability at each time step.

## 2.3Contact and Communication Model

Communication between nodes is established through Bluetooth when two nodes are within a certain transmission range R. Specifically, nodes i and j can exchange messages if:

$$d_{ij}(t)=\left\|\mathbf{x}_i(t)-\mathbf{x}_j(t)\right\|\le R \tag{3}$$

Due to environmental interference and device limitations, communication is not always successful. Therefore, a link reliability factor is introduced, and successful transmission occurs with a probability ps.

## 2.4Message Dissemination Model

In the proposed disaster scenario, emergency information dissemination is driven by opportunistic encounters among mobile users. Initially, only one mobile node receives the evacuation message and acts as the source node. As users move throughout the disaster area, message transmission occurs whenever two nodes establish a valid Bluetooth connection. Once a node successfully receives the message, it becomes an informed node and participates in the dissemination process according to the adopted routing algorithm. The dissemination continues throughout the simulation, and the evolution of informed nodes is recorded as the Message Spread, which is used to evaluate the efficiency of different routing strategies.

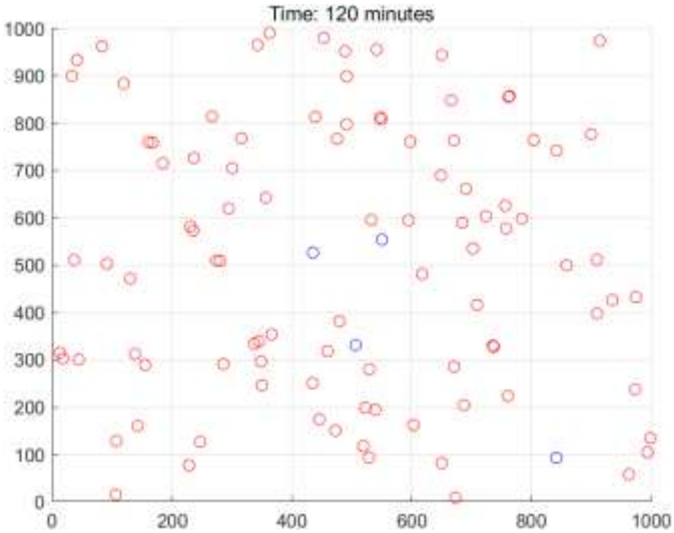


Figure 1. Spatial scatter distribution of informed nodes for emergency information dissemination in disaster scenarios at the 120-minute simulation time point (spatial unit: meter (m)).

## 3.ROUTING CHARACTERISTICS AND PROBLEM ANALYSIS

### 3.1Analysis of Direct Delivery

Direct Delivery is the most fundamental and simplest message dissemination strategy in opportunistic networks. Its core principle is that only the source node is permitted to transmit messages. In the post-earthquake scenario with completely destroyed communication infrastructure considered in this study, once a resident initially receives an emergency evacuation notification, the message can only be delivered to other encountered residents via Bluetooth by the source node. Residents who subsequently receive the message do not possess forwarding capability. Therefore, the entire dissemination process relies solely on opportunistic contacts between the source node and other nodes.

Since intermediate nodes are unable to participate in message forwarding, only a single dissemination path exists throughout the network, making it difficult for the message coverage to expand rapidly over time. Consequently, the randomness of node mobility[4] and the uncertainty of encounters between the source node and other nodes significantly reduce the message dissemination rate.

Furthermore, the performance of the Direct Delivery algorithm is highly dependent on the mobility trajectory of the source node. When the source node operates within a limited area or encounters other residents infrequently, the efficiency of message dissemination deteriorates significantly. As the network scale increases, the source node is required to undertake a greater number of dissemination tasks, resulting in increased communication burden while providing only marginal improvements in the overall dissemination efficiency. Consequently, the scalability of the Direct Delivery algorithm is inherently limited in large-scale post-disaster crowd sensing networks.

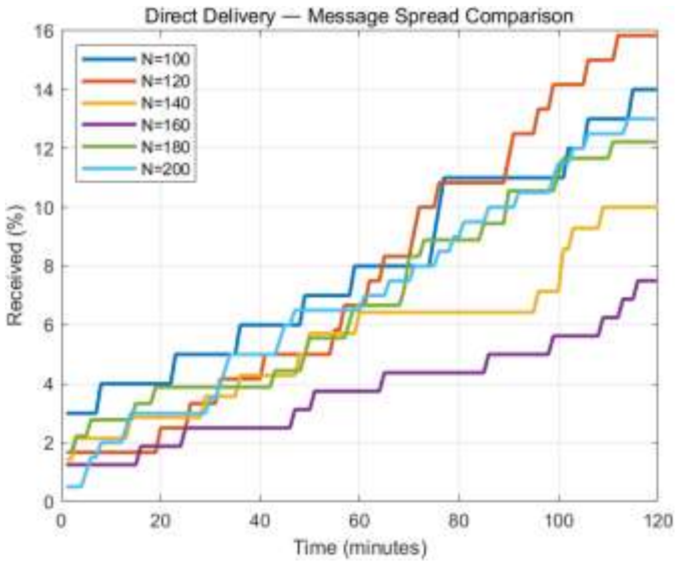


Figure 2. Message dissemination of Direct Delivery under different population sizes.

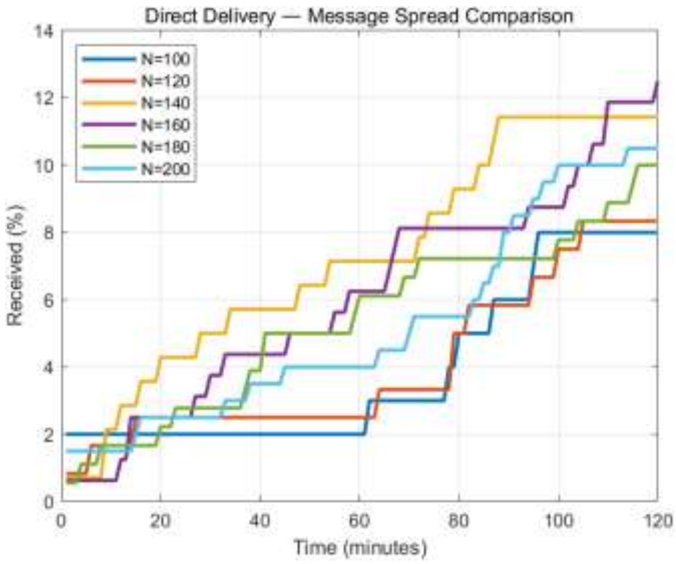


Figure 3. Message dissemination of Direct Delivery under different population sizes.

In summary, the Direct Delivery algorithm offers several advantages, including implementation simplicity and low communication overhead. However, because message dissemination relies exclusively on the source node, its performance is highly susceptible to the randomness of node mobility and the scarcity of encounter opportunities. As a result, it is unable to satisfy the requirements for rapid and large-scale dissemination of emergency information. Therefore, it is necessary to improve the message dissemination efficiency[5] while preserving its low-overhead characteristics, thereby enhancing its practicality for post-disaster emergency communication scenarios.

## 3.2Analysis of Epidemic Routing

Epidemic Routing is one of the most representative message dissemination algorithms in opportunistic networks. Its basic principle is to replicate and forward messages to nodes that have not yet received them whenever two nodes encounter each other. Through this multi-source and multi-path dissemination process, the message coverage and dissemination efficiency can be significantly improved.

However, Epidemic Routing adopts an uncontrolled message replication mechanism. Whenever two nodes establish a communication link, they attempt to exchange messages, resulting in a large number of redundant message[6] copies. Consequently, more storage space, communication bandwidth, and device energy are consumed, leading to increased network resource consumption.

Furthermore, in post-disaster emergency communication scenarios, mobile devices are generally constrained by limited battery capacity, storage resources, and wireless communication capability. Excessive redundant messages may also intensify wireless channel contention[7], thereby reducing the utilization efficiency of limited communication resources.

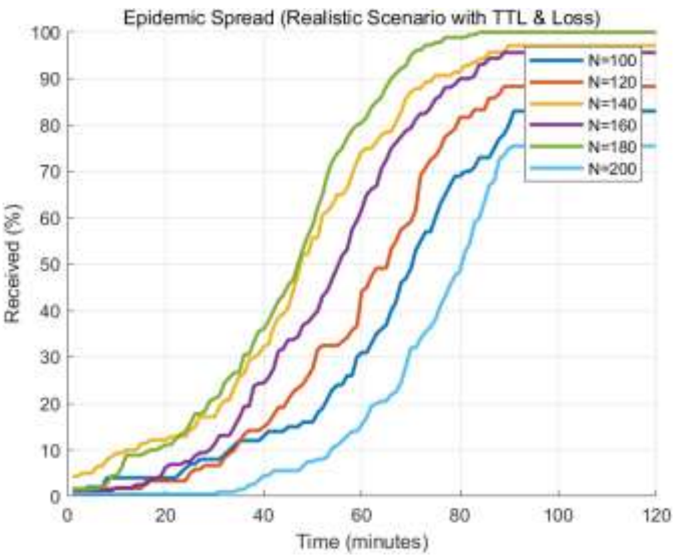


Figure 4. Message diffusion curves of Epidemic Routing with varying node quantities.

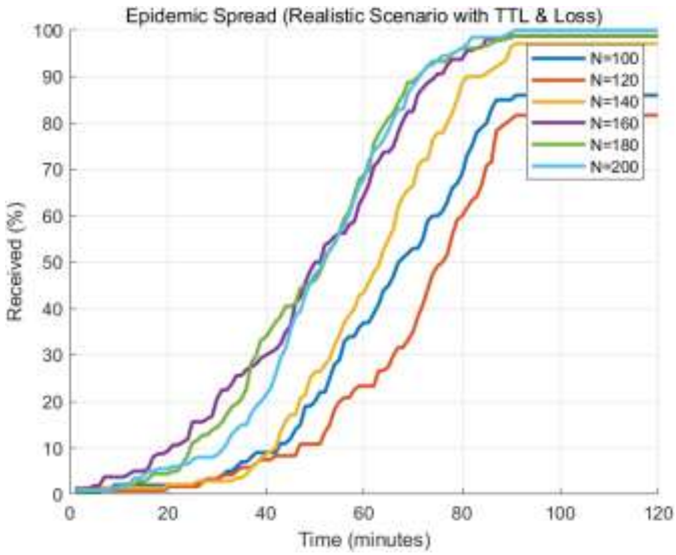


Figure 5. Message diffusion curves of Epidemic Routing with varying node quantities.

In general, Epidemic Routing can effectively utilize opportunistic encounters between nodes to improve message dissemination efficiency and coverage. However, its uncontrolled message replication mechanism results in high network resource consumption. Therefore, reducing network overhead while maintaining high dissemination efficiency remains an important issue in post-disaster opportunistic networks.

## 3.3Comparison of Existing Algorithms

Direct Delivery can effectively reduce communication resource consumption, but it is difficult to satisfy the requirements of rapid emergency information dissemination after disasters. Although Epidemic Routing provides strong message dissemination capability, its uncontrolled message replication mechanism consumes a large amount of network resources, which conflicts with the practical constraints of post-disaster scenarios, such as limited computing capability, battery capacity, and communication resources of mobile devices[8].

**TABLE 1. Qualitative Indicator Analysis of Two Routing Algorithms**

| Algorithm | Delivery | Delay | Overhead |
|---|---|---|---|
| Direct Delivery | Low | High | Low |
| Epidemic Routing | High | Low | Low |

Therefore, how to improve the message dissemination efficiency and coverage capability of Direct Delivery while maintaining its low network overhead advantage, and meanwhile avoid the resource waste caused by excessive message replication in Epidemic Routing, has become a critical problem to be addressed.

Based on this consideration, the next chapter proposes a restricted multi-hop dissemination mechanism based on the Direct Delivery algorithm. By reasonably controlling the message forwarding process, the proposed method aims to improve dissemination performance while reducing network resource consumption, thereby achieving a balance between message dissemination efficiency and network overhead.

## 4.IMPROVED DIRECT DELIVERY BASED ON CONTROLLED MULTI-HOP DISSEMINATION

### 4.1Design Motivation

As discussed in the third paragraph, both of the aforementioned algorithms have their own advantages and limitations. Therefore, based on the Direct Delivery algorithm, a Controlled Multi-hop Dissemination Mechanism[9] is proposed to improve message dissemination efficiency while maintaining its low network overhead advantage. The proposed mechanism allows selected nodes that have received the message to participate in further message dissemination. Meanwhile, probability-based forwarding and dissemination control strategies are introduced to limit the message replication range. In this way, the proposed method can effectively suppress network resource consumption[10] while improving message dissemination performance, thereby achieving a balance between dissemination efficiency and network overhead.

### 4.2Controlled Multi-hop Dissemination Mechanism

To address the problem that the Direct Delivery algorithm relies solely on the source node for message dissemination, this paper introduces a Controlled Multi-hop Dissemination Mechanism. In this mechanism, message transmission is no longer limited to single-hop delivery by the source node. Instead, selected nodes that have received the message are allowed to participate in further forwarding under certain conditions, enabling the message to gradually spread to more residents through limited multi-hop transmission and thereby improving network coverage.

Unlike Epidemic Routing, the proposed mechanism does not adopt an unrestricted message replication strategy[11]. Instead, a dissemination control mechanism is introduced during the message propagation process to regulate node forwarding behaviors[12].By limiting the number of participating forwarding nodes and the message replication range, the probability of redundant message generation can be effectively reduced, preventing excessive consumption of network resources.

Furthermore, to enhance the practical applicability of the proposed mechanism, factors such as message lifetime (Time-to-Live, TTL) and node communication opportunities are considered based on the characteristics of post-disaster emergency communication scenarios[13]. Once the message exceeds the predefined valid dissemination period, it will no longer be forwarded, while the existing message states are maintained, thereby avoiding unnecessary information dissemination.

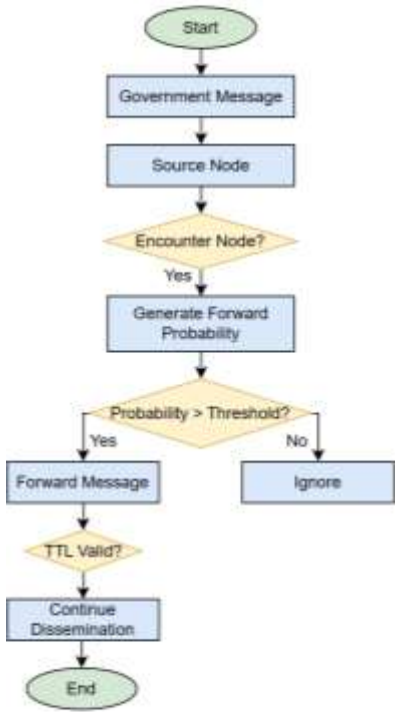


Figure 6. Controlled Multi-hop Dissemination Mechanism

### 4.3Probabilistic Forwarding Strategy

Based on the Controlled Multi-hop Dissemination Mechanism, this paper introduces a probabilistic forwarding strategy[14]. When a Bluetooth connection is established between nodes, the decision of whether to forward the message is determined according to a predefined forwarding probability, thereby effectively controlling the number of message copies in the network.

Assume that nodes i and j establish a communication connection at time t. The successful message forwarding process can be expressed as:

$$P_{ij} = P_f \tag{4}$$

$P_{ij}$:the probability that node i successfully forwards the message to node j;

$P_f$:the predefined forwarding probability configured by the system.

Meanwhile, to prevent messages from being disseminated indefinitely in the network, a message lifetime (Time-to-Live, TTL) is introduced in this paper, which is defined as:

$$T_{msg} \le T_{TTL} \tag{5}$$

$T_{msg}$:the elapsed time of message dissemination;

$T_{TTL}$:the maximum valid dissemination time of the message.

When the message dissemination time exceeds the TTL, no further message forwarding is performed. However, nodes that have already received the message retain their message states, allowing the message dissemination curve to remain stable and better reflecting the actual process of post-disaster emergency communication.

# 5.EXPERIMENTAL RESULTS AND ANALYSIS

## 5.1Experimental Setup

To comprehensively evaluate the performance of different algorithms in post-disaster communication scenarios, this paper adopts three performance metrics: Delivery Ratio, Average End-to-End Delay, and Network Overhead Ratio. Specifically, Delivery Ratio is used to measure the capability of successful message delivery, Average End-to-End Delay is used to evaluate message dissemination efficiency, and Network Overhead Ratio is used to measure the additional resource consumption incurred during the dissemination process.

## 5.2Delivery Ratio Analysis

Since Direct Delivery relies solely on the source node for message dissemination, its delivery ratio remains at a relatively low level. Epidemic Routing achieves the highest delivery ratio by allowing all nodes to participate in message dissemination. However, this high delivery ratio is achieved through extensive message replication and frequent forwarding, resulting in substantial network resource consumption.

The proposed algorithm effectively expands message coverage through limited multi-hop dissemination, significantly improving the delivery ratio without adopting a flooding-based dissemination strategy. The experimental results demonstrate that the proposed algorithm achieves a significantly higher delivery ratio than Direct Delivery while maintaining a dissemination capability close to that of Epidemic Routing, thereby achieving a balance between dissemination efficiency and resource consumption.

## 5.3Average End-to-End Delay Analysis

In Direct Delivery, destination nodes usually need to wait for a long time before establishing a communication connection with the source node, resulting in a relatively high average end-to-end delay. Epidemic Routing enables rapid message dissemination throughout the network by allowing multiple nodes to cooperatively forward messages, thereby achieving the lowest average end-to-end delay.

By introducing a limited multi-hop dissemination mechanism, the proposed algorithm effectively reduces the dependence on the source node and shortens the message dissemination path, resulting in a significantly lower average end-to-end delay than that of Direct Delivery.

## 5.4Network Overhead Ratio Analysis

In Direct Delivery, messages are transmitted only by the source node, resulting in a small number of message copies and the lowest network overhead. In contrast, Epidemic Routing allows all nodes to participate in message replication and forwarding. As the network size increases, the number of message copies grows rapidly, leading to significantly higher network overhead than the other algorithms.

The proposed algorithm limits the number of message replications through probabilistic forwarding and a dissemination control mechanism, effectively suppressing the growth of network overhead while maintaining high message dissemination efficiency.

## 5.5Comprehensive Discussion

Based on the above experimental results, it can be observed that Direct Delivery and Epidemic Routing represent two extreme message dissemination strategies.

The proposed algorithm introduces a controlled multi-hop dissemination mechanism and a probabilistic forwarding strategy based on Direct Delivery, enabling messages to gradually spread within a limited range. As a result, it significantly improves the delivery ratio and reduces the average end-to-end delay while maintaining low network overhead. The Message Spread curves show that the proposed algorithm exhibits a typical S-shaped dissemination pattern,

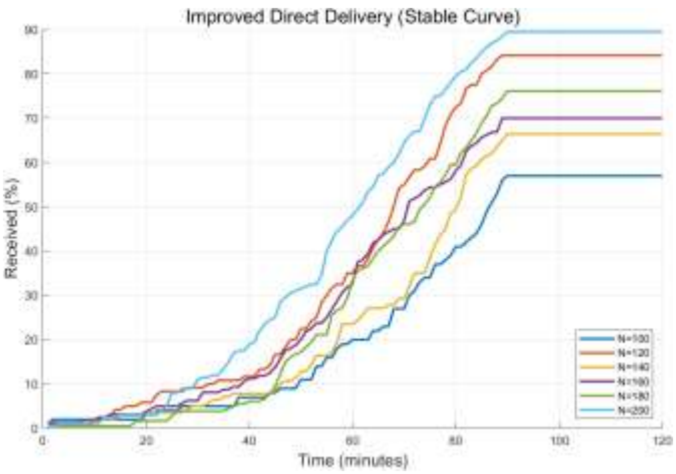


Figure 7. Message Reception Rate Curves of Improved Direct Delivery under Different Network Sizes.

providing strong dissemination capability while avoiding the excessive redundant message replication of Epidemic Routing. Therefore, the proposed method achieves a good balance between dissemination efficiency and resource consumption, making it more suitable for emergency information dissemination in post-disaster scenarios where communication infrastructure is unavailable.


Figure 8. Overall Performance Comparison of Three Routing Algorithms:Direct Delivery.

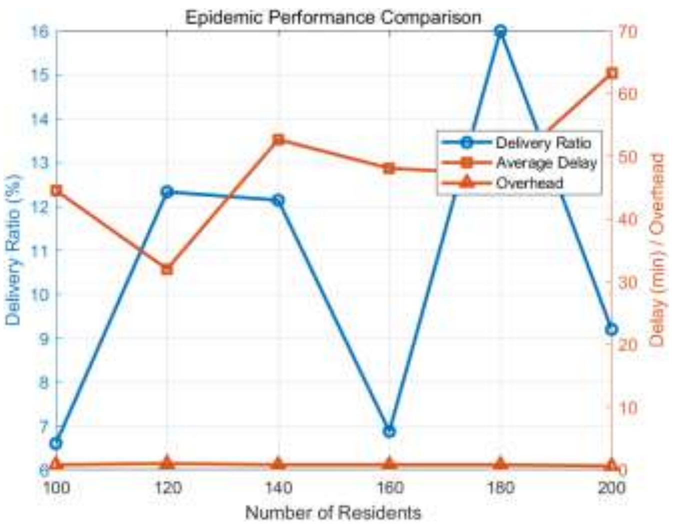


Figure 9. Overall Performance Comparison of Three Routing Algorithms:Epidemic Routing.

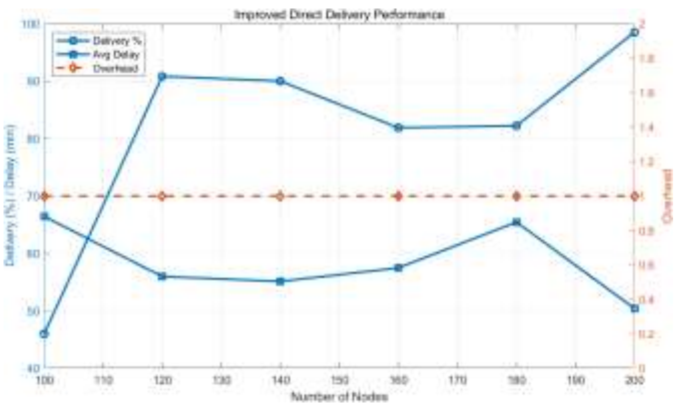

Figure 10. Multi-Metric Simulation Results of the Improved Algorithm

## 6.DISCUSSION

The proposed algorithm introduces probabilistic forwarding and dissemination control strategies based on Direct Delivery..

It should be noted that the random mobility model and fixed forwarding probability adopted in this study can reflect the basic characteristics of post-disaster communication scenarios. However, practical factors such as real urban road constraints, residual node energy, and differences in user behaviors have not been fully considered. Future work will further optimize the algorithm by incorporating more realistic mobility models and dynamic forwarding strategies, and conduct experiments on real mobile devices or embedded platforms to enhance its engineering applicability.

## 7.CONCLUSION

This paper investigates the problem of emergency information dissemination under the condition of communication infrastructure failure caused by disasters such as earthquakes. Taking the Direct Delivery algorithm as the research object, a post-disaster opportunistic network model based on Bluetooth communication among mobile devices is constructed, and a Controlled Multi-hop Dissemination Mechanism is proposed.

Simulation results demonstrate that, compared with traditional algorithms, the proposed method significantly improves the message delivery ratio, reduces the average end-to-end delay, and effectively controls network overhead. Meanwhile, the message dissemination process becomes more consistent with the actual characteristics of post-disaster information propagation, achieving a better balance between dissemination efficiency and resource utilization.

This study provides an efficient and resource-aware solution for emergency information dissemination in scenarios without communication infrastructure. It can serve as a reference for the optimization design of opportunistic network routing algorithms and the development of emergency communication systems. Furthermore, it provides new insights for future research on realistic mobility scenarios and resource-aware opportunistic routing.

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