Initial Path Injection-based Opportunistic Routing for Digital Twin-enabled Smart Cities

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***Abstract*—Future smart cities are expected to provide intelligent services through their digital twins. However, an enormous network traffic will be locally produced by devices of users and sensing devices for local consumption at the city scale. While wireless device-to-device communication and multi-hop networks are expected to offload the traffic from network infrastructures in beyond 5G era, routing protocols must deal with frequent topological changes owing to the mobility of nodes and unpredictable radio interference. A digital twin may allow to handle such environments by simulating and providing routing information based on city-scale spatial information. However, this may incur high computational costs owing to frequent updates of routing information. In this paper, we propose an opportunistic routing using an initial path injection based on digital twin and self-adaptation of forwarding paths without relying on network infrastructures. Finally, we revealed its self-adaptability and resilience of forwarding paths. Moreover, the proposed method reduced the traffic and transmission delay compared to the existing protocols.**

***Index Terms*—ad hoc network, opportunistic routing, backoff, digital twin, location information, destination discovery**

I. Introduction

Smart cities are expected to provide intelligent services to support our daily living by using information and communication technologies towards the future smart society. In the beyond 5G era, digital twins (DTs) play a key role in smart services such as predictions, detections, and automation using sensing data collected from smart cities [1]. However, an enormous network traffic is expected from users through applications in their devices and from city services through sensing devices to create DT-enabled smart cities. In particular, traffic related to internet of things (IoT), such as that from sensing, monitoring, and control, will be locally produced for local consumption at the city scale via mobile networks. Hence, traffic offloading becomes important to alleviate the communication burden from mobile networks.

Wireless device-to-device communication and multi-hop networks can offload network traffic from mobile networks to local networks by exploiting direct wireless communication among local nodes independent of the network infrastructure [2]. While these solutions are expected to alleviate the communication traffic burden on beyond 5G network infrastructures [3], routing protocols must deal with frequent topological changes owing to the mobility of persons, vehicles, and robots and unpredictable radio interference in urban city environments. DTs may allow to handle such environments by simulating and providing routing information based on city-scale spatial information. However, this may incur high computational costs owing to frequent recalculation and update of routing information of nodes in real time.

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In this paper, we propose an efficient opportunistic routing using an initial path injection based on DT and self-adaptation of forwarding paths independent of network infrastructures.

II. Related Work

In urban areas where many nodes (e.g., personal devices, vehicles, and robots) coexist, adaptability to frequent topological changes caused by node mobility and flexible forwarding path selection should be achieved in real time. In an urban environment, backoff-based opportunistic routing (OR) protocols can flexibly make a forwarding decision using the backoff time by receivers of packets using the broadcast nature of wireless communication [4], [5]. First, backoff-based OR performs destination discovery by exchanging request and reply packets between the source and destination to distribute cost information (e.g., hop count) to intermediate nodes that serve as potential forwarders. After destination discovery process, potential forwarders autonomously become forwarders to relay packets based on the backoff time calculated using the cost information. However, this OR protocol discovers the destination based on request packet flooding like in general reactive routing protocols. Therefore, it leads to substantial network load owing to network construction and maintenance.

Regarding network traffic, a cellular-assisted mobile ad hoc networking architecture aims to reduce the burden of the destination discovery [6]. This method assumes that a server manages users' locations and provides a virtual area for local ad hoc networking, suppressing excessive control messages. However, it cannot suitably handle frequent topological changes because it adopts a unicast routing protocol, which requires reinitiating request packet flooding when a link in a route is broken. Therefore, this method increases the computational and network loads of the management server owing to the virtual area construction and its requests.

III. Proposed Method

To achieve both resilience to topological changes and suppress the traffic load of the destination discovery, we propose a backoff-based OR using DT-assisted initial path injection.

A. Destination Discovery with Initial Path Injection

Routing protocols cannot omit destination discovery. Therefore, we adopted initial path injection using DTs via mobile networks. For initial path injection, each node should connect to a mobile network and periodically send a message including its address and location to the management server via the network. The server keeps the received information for a specific period for initial path injection based on requests from nodes.

Fig. 1 illustrates the procedure of initial path injection. Upon initiating a communication with other nodes, a source node sends a message including its address and the destination address to the management server. The server determines an initial path from the source to the destination based on a path-finding algorithm using the links between nodes based on a DT. We use Dijkstra's algorithm with neighbor relations based on virtual communication range $C_{\max}$ assuming that the DT simulates the rough communication range of nodes. We adopt two link metrics based on (1) Euclidian distance of traversed links and (2) hop count.

If the initial path construction succeeds, the management server sends cost information, including the destination address, and hop count, to each node to inject the initial path information. Then, the source can send data packets, and nodes with the injected cost information forward them toward the destination. If the initial path construction fails, the management server sends a message to notify the source about the failure. In this case, the source performs destination discovery according to the routing protocol through a process such as request packet flooding.

B. Data Forwarding with Self-Adaptation

The proposed method performs data forwarding based on PRIOR [5]. The proposed method adaptively selects a forwarder among packet receivers as potential forwarders with random backoff times. First, each receiver of a packet calculates a random backoff time using the hop count to the destination and starts waiting as a potential forwarder. When it detects packet forwarding by others, it cancels its forwarding. Otherwise, it forwards the kept packet. After forwarding, if it detects forwarding of the same packet, it broadcasts an explicit ACK packet to cancel forwarding of neighbors.

During data forwarding, each node updates the cost information using the traversed hop count from the source of a packet. In addition, nodes without cost information record it to participate in subsequent data forwarding. This method can converge to appropriate paths to spread cost information by repeating data transmission as illustrated in Fig. 2. Thus, forwarding paths eventually adapt to the real communication environment even if these paths differ from the initially injected paths.

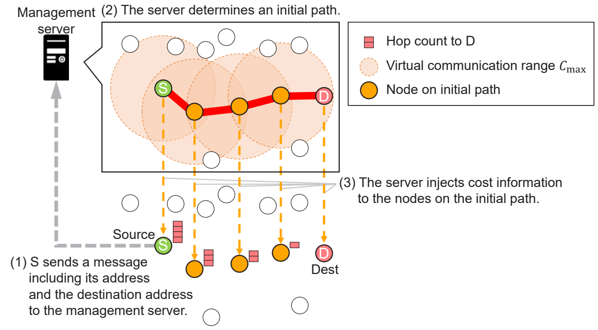


Fig. 1. Example of initial path injection.

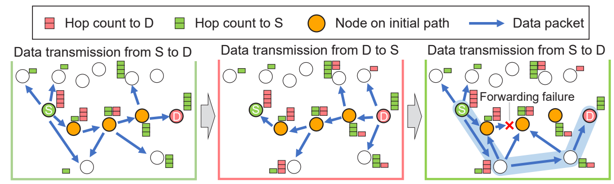


Fig. 2. Example of self-adaptation of forwarding paths.

IV. Performance Evaluation

A. Simulation Setup

We evaluated a typical unicast routing protocol called AODV [7], conventional PRIOR [5], and the proposed method using QualNet. Each node used the IEEE 802.11b under a data rate of $11\,\mathrm{Mbps}$ and communication range of approximately $150\,\mathrm{m}$. The lifetime of cost information was set to $10\,\mathrm{s}$, and the maximum backoff time was set to $60\,\mathrm{ms}$.

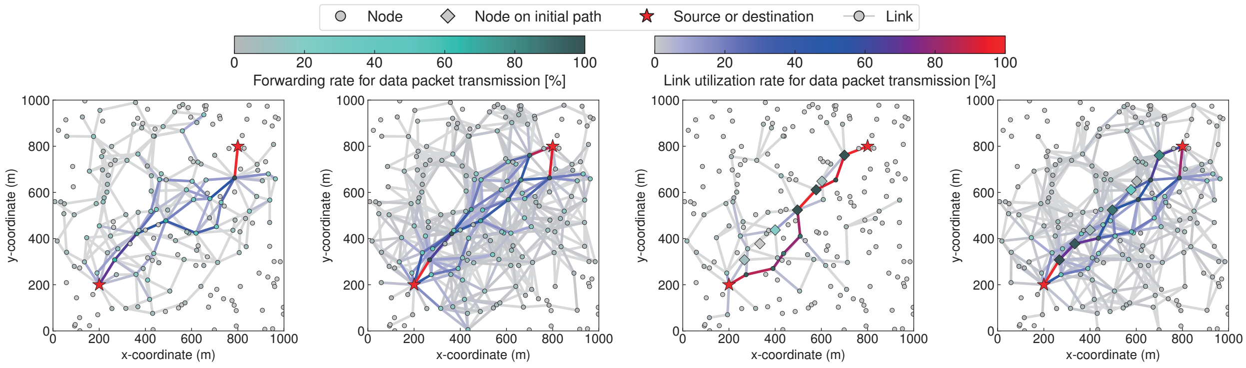
Scenario 1: We evaluated the time transition of forwarding paths to analyze its impact. In this scenario, 200 nodes on a $1000\,\mathrm{m}$ square area. The source and destination bidirectionally transmitted 1000 UDP packets of $1\,\mathrm{kB}$. For the proposed method, $C_{\max}$ was set to $150\,\mathrm{m}$.

Scenario 2: We evaluated the performance in a random scenario containing 200 nodes in a $1000\,\mathrm{m}$ square area. We generated short bidirectional communication flows between random pairs with average occurrence intervals from $40\,\mathrm{s}$ to $200\,\mathrm{s}$ over $1200\,\mathrm{s}$. Each flow was composed of 10 UDP packets of $1\,\mathrm{kB}$. All the methods enabled retransmission control [5], and the maximum retransmission count was set to 3. For the proposed method, $C_{\max}$ was varied from $130\,\mathrm{m}$ to $170\,\mathrm{m}$.

B. Results for Scenario 1

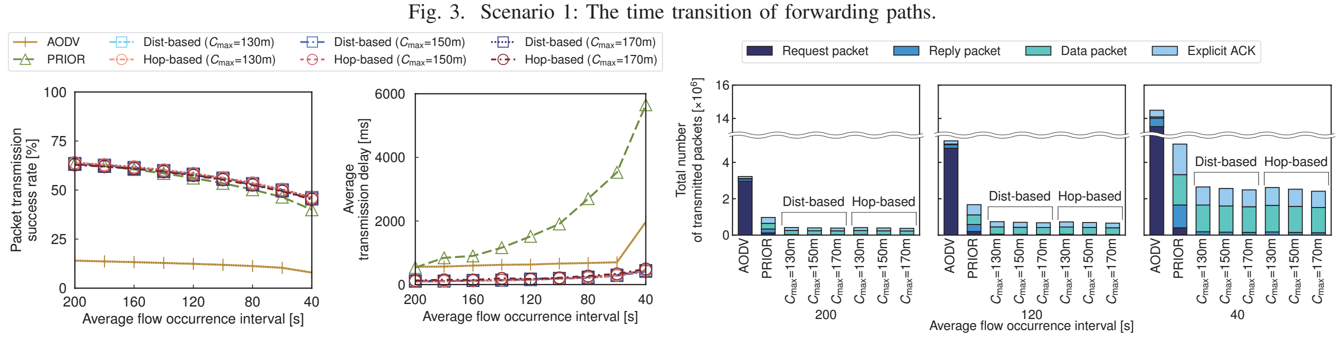
Fig. 3(a) and (c) show that nodes over a broader area participated in packet forwarding in PRIOR compared to the proposed distance-based method from $0\,\mathrm{s}$ to $60\,\mathrm{s}$. As PRIOR employed request flooding to discover a destination, it broadly spreads the cost information in any direction. In contrast, as the proposed method only spreads cost information close to the initial path, fewer nodes participated in packet forwarding.

Fig. 3(b) and (d) show that several nodes participated in packet forwarding in both methods from $0\,\mathrm{s}$ to $600\,\mathrm{s}$. Like PRIOR, the proposed method spreads cost information over a wide area by repeating data transmission, thereby allowing a flexible selection of forwarding paths.



(a) PRIOR: 0 s to 60 s. (b) PRIOR: 0 s to 600 s. (c) Dist-based: 0 s to 60 s. (d) Dist-based: 0 s to 600 s.

Fig. 3. Scenario 1: The time transition of forwarding paths.



(a) Packet transmission success rate. (b) Average transmission delay. (c) Total number of transmitted packets.

Fig. 4. Scenario 2: Simulation results.

C. Results for Scenario 2

Fig. 4 shows similar trends even under a gap between $C_{\max}$ and the actual range. Thus, although $C_{\max}$ is an essential parameter to obtain an initial path from the DT, the proposed method is robust to an inaccurate $C_{\max}$ value and can adapt the forwarding path to the actual environment via data forwarding.

Fig. 4(a) shows degradation in packet transmission success rate for all methods with increasing network load. AODV was a substantially lower success rate than the other methods due to the complex route maintenance. While the proposed method had the same or higher success rate compared with PRIOR because it skipped the destination discovery phase via a local network, thereby reducing the corresponding network load.

Fig. 4(b) shows that the proposed method considerably reduced the average transmission delay compared with PRIOR even if considering the communication delay of the proposed discovery in mobile networks. The proposed destination discovery directly reduced the waiting and congestion delays to skip flooding-based discovery before data transmission.

Fig. 4(c) shows that the proposed method achieved the smallest total number of transmissions among the evaluated methods. PRIOR sent a larger number of reply packets compared with the proposed method. In general, intermediate nodes can reply to request packets for known nodes on behalf of the destination. Therefore, many intermediate nodes send many reply packets in dense environments, thereby increasing the communication burden. In contrast, the proposed method avoids the flooding-based destination discovery, thereby reducing the transmission of request and reply packets.

V. Conclusion

We proposed an efficient OR using initial path injection based on DT and self-adaptation of forwarding paths based on the nature of OR. The simulation results revealed that the proposed method can spread cost information and adapts forwarding paths through packet transmissions even if only the nodes on the initial path hold cost information at the communication onset. In addition, the proposed method mitigated unnecessary transmission packets and suppressed transmission delay while maintaining the same success rate as the conventional methods in environments with numerous flows. For future work, we plan to revisit the path determination algorithm and evaluate including communication with the network infrastructures.

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