IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 3, 2019, accepted May 26, 2019, date of publication June 19, 2019, date of current version July 16, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2923837

Local Flooding-Based on-Demand Routing Protocol for Mobile Ad Hoc Networks

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This work was supported in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT, and Future Planning under Grant NRF-2019R1A2C4070466, in part by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean Government Ministry of Trade, Industry, and Energy, under Grant 20174030201810, and in part by the Ministry of Science and ICT (MSIT), South Korea, under the Information Technology Research Center (ITRC) Support Program supervised by the Institute for Information and Communications Technology Planning and Evaluation (IITP) under Grant IITP-2019-2018-0-01799.

ABSTRACT This paper proposes a local flooding-based on-demand routing protocol for mobile ad hoc networks to reduce the flooding overhead and offers effective alternative paths between the source and destination nodes. The proposed protocol first uses overhearing to identify the one-hop neighbors along the shortest path between the source and destination. Then, it performs periodic local flooding initiated by the destination node, which offers the latest route information along the routing path. This technique only involves one-hop neighbors along the shortest path, with the result that the flooding overhead is significantly reduced and seamless rerouting is possible when the current routing path is either disconnected or outdated. Intensive simulations show that the proposed routing protocol improves the routing performance in terms of data delivery ratio, end-to-end delay, and jitter, and it significantly reduces the control overhead in a wide range of node mobility and density, compared to conventional routing protocols.

INDEX TERMS Routing protocol, local flooding, overhearing, on-demand routing, mobile ad hoc network.

I. INTRODUCTION

In a mobile ad hoc network (MANET), the purpose of the routing protocol is to identify the dynamic topology quickly and to provide the shortest routing path between the source and destination nodes at all times. Achieving this goal requires the routing protocol to be designed such that the unnecessary transmission of control packets within the network is minimized. This eventually makes it possible to improve the end-to-end performance in terms of throughput and delay. Routing protocols are functionally divided into three sub-protocols: route setup, route maintenance, and route recovery protocols [1]. For ideal routing, the *route setup* protocol is required to find a routing path as soon as possible while using as few control packets as possible. The *route maintenance* protocol should be able to accurately recognize changes in the network topology with minimum overhead during data transmission. The *route recovery* protocol must seamlessly re-provide a new route to re-establish the connection with low control overhead if the route being used is no longer available because of node movement.

In the MANET environment, reactive routing protocols are known to be more suitable than proactive routing protocols because of frequent changes in the network topology due to node mobility [2]. Numerous reactive routing protocols for MANETs are based on dynamic source routing (DSR) [3] and the ad hoc on-demand distance vector (AODV) [4], [5]. These routing protocols identify a new routing path in an on-demand manner only when new data traffic arrives at the source or the current routing path no longer exists. In order to find the shortest path to the destination, the source node initiates *flooding* of a *route request* (RREQ) packet across the entire network. When the destination node receives the RREQ packet, it responds by transmitting a *route reply* (RREP) packet to the source via unicast. Finally, when the RREP arrives at the source, a new bidirectional shortest path between the source and destination is established.

The flooding operation propagates the RREQ to the entire network; thus, the amount of overhead for control packet transmission is proportional to the number of nodes in

The associate editor coordinating the review of this manuscript and approving it for publication was Peng-Yong Kong.

the network. This implies that the problem caused by flooding overhead becomes severe in a high-density environment. Moreover, the flooding overhead becomes extremely large in a high-mobility environment because the process of network flooding is repeated whenever the routing path no longer exists [6].

Early routing protocols in MANETs considered single-path routing and did not maintain multiple routing paths after initial route setup. This can reduce the routing overhead in low- or medium-mobility situations. However, in high-mobility environments the single-path routing protocol causes more frequent route disconnection, resulting in an even greater increase in overhead when searching for a new route. Therefore, some routing protocols have been extended to manage multiple routing paths between the source and destination [7]–[9]. These multipath routing protocols generally reduce the underlying flooding overhead by reducing path disruption, but can introduce additional overhead associated with managing multiple paths. In particular, this overhead increases significantly as the number of nodes increases because all nodes in a MANET can be connected dynamically in an arbitrary manner. Therefore, there is a need for an efficient multipath management protocol with the ability of finding an effective alternative path while minimizing the overhead especially in a high-density MANET environment.

Considering the various mobility levels and network densities in MANETs, in this paper we propose a new on-demand routing protocol to reduce the typical flooding overhead and to offer effective alternative paths between the source and destination with low control overhead. To reduce the flooding overhead, the proposed protocol identifies one-hop neighbors along the current routing path by overhearing and then performing *local flooding*, the propagation of which is limited to the predetermined one-hop neighbors. Moreover, to offer effective multiple alternative paths, the proposed protocol performs periodic local flooding initiated by the destination node, which offers a plurality of routing information along the current routing path. In this way, the proposed routing protocol maintains the use of the shortest path with high probability in a high-mobility environment, while minimizing the control overhead in a high-density environment.

The remainder of this paper is organized as follows: Section II explains the basic flooding operation and related routing protocols. Section III describes the motivation of the proposed protocol and presents preliminary results to validate our hypotheses. Section IV explains the operation of the proposed routing protocol in detail. Section V presents the performance of the proposed protocol considering the node mobility and density. Finally, Section VI concludes this paper.

II. RELATED ROUTING PROTOCOLS

We first explain the general flooding operation based on AODV [4] and introduce its enhanced routing protocols. Figure 1 shows an example of the flooding process of RREQ, which is generated by the source and is broadcasted to the neighboring nodes. If one node receives the RREQ, it updates the routing table by using the information in the RREQ and then rebroadcasts it. If the node receives another RREQ with the same sequence number as before, it discards the RREQ without processing it. In this way, the RREQ spreads throughout the entire network, providing the routing information to the source (i.e., a reverse distance vector (DV)), and eventually arriving at the destination. The destination responds by transmitting an RREP in response to the first arriving RREQ. This RREP is transmitted in unicast mode from the destination to the source using the reverse DV information generated via the RREQ flooding process. The nodes receiving the RREP store the DV information toward the destination (i.e., the forward DV) in their routing tables. Therefore, when the RREP arrives at the source, the forward DVs are created along the shortest path from the source to the destination. That is, a bidirectional DV is formed along the shortest path between the source and the destination.

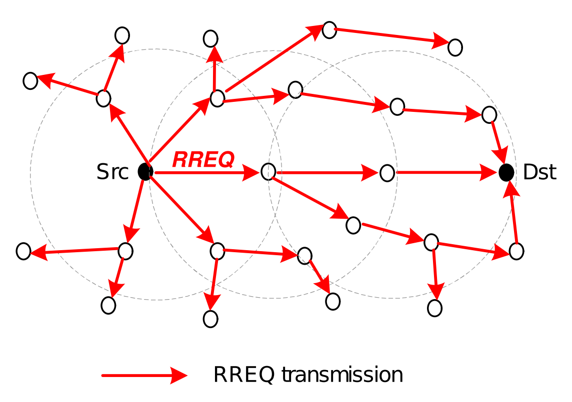

FIGURE 1. **Flooding of RREQ.**

In the AODV protocol, the number of RREQ transmissions is proportional to the number of nodes in the network. Moreover, the flooding process is required after every link failure. Thus, the flooding overhead is significantly increased as the node density and the node mobility increases. In addition, AODV basically manages only a single routing path protocol such that the first established path is used until it is disconnected. This does not provide the shortest path all the time and causes frequent flooding in the event of a link failure. To overcome these drawbacks, many on-demand multipath routing protocols have been proposed, including split multipath routing (SMR), multipath dynamic source routing (multipath DSR), temporally ordered routing algorithm (TORA), routing on-demand acyclic multipath (ROAM), ad hoc on-demand multipath distance vector (AOMDV), AODV backup routing (AODV-BR), multipath AODV (AODVM), and multipath on-demand routing (MORT), multipath AODV (MP-AODV) [7]–[9]. Here, SMR and multipath DSR are based on source routing, TORA and ROAM are distance-vector based, and AOMDV, AODV-BR, AODVM, MORT, and MP-AODV are based on AODV [10]–[14].

Among these protocols, AOMDV uses the basic AODV route setup process, but was extended to create multiple loop-free and link-disjoint paths during route discovery. Loop-freedom was guaranteed by using the notion of "advertised hopcount," whereas link-disjointness of multiple paths was achieved by using a particular property of flooding [10]. AODV-BR uses the same route setup process as AODV. An alternative route is created during the RREP response phase. When a node that is not part of the selected route overhears RREP, it records the sending neighbor as the next hop to the destination in its alternative route table. In this way, some backup paths with a fish bone structure are formed around the primary path [11]. AODVM ensures that the destination node selects paths that pass through more reliable nodes. In contrast to the AODV, an intermediate node does not discard a duplicate RREQ. Instead, these nodes use the RREQ to construct a table that includes a list of neighboring nodes for alternative path construction. Moreover, the destination node replies to all RREQ packets it receives from its neighbors. This ensures the formation of a reliable alternative path between the source and destination [12]. MORT provides multiple routes via the intermediate nodes on the primary path between the source and destination. These alternative paths are created by the combination of the node-disjoint path and fail-safe paths during the route discovery and route maintenance phases [13]. MP-AODV finds a backup route provided by node-disjoint from the main route by preventing additional nodes along the main route from participating in the backup route. Data transmission starts immediately after the main route is established. The process of searching for the backup route takes place while data is being transmitted to reduce the transmission delay [14].

Multipath on-demand routing algorithms such as these reduce the frequency of path disruption, thereby reducing the flooding overhead for route discovery. However, additional overhead is still required to find multiple paths and the use of the shortest path cannot be guaranteed as the network topology changes. Therefore, a routing protocol capable of enhancing the routing performance while reducing the control overhead in dynamic MANET environments continues to be in demand.

III. MOTIVATION AND PRE-VERIFICATION

To explain our motive, we first introduce the concepts of one-hop neighbor and one-hop region, as illustrated in Figure 2. *One-hop neighbors* are defined as the nodes that are located in the vicinity of a certain routing path between the source and destination and can overhear bidirectional packets transferred back and forth along that path.[1] A *one-hop region* is defined as the network area in which the one-hop neighbors exist. To apply these two concepts to the considered routing protocol, we state two hypotheses:

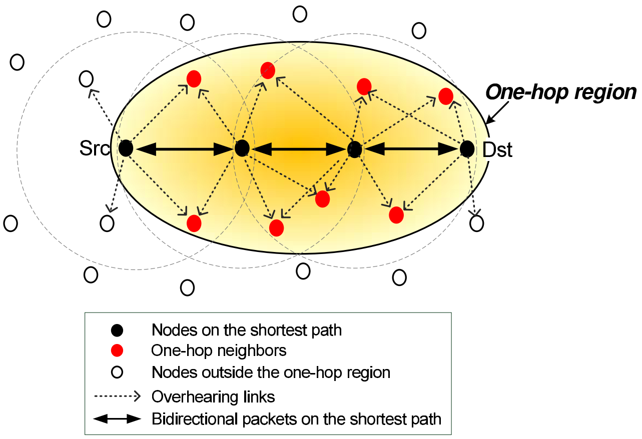

FIGURE 2. Concepts of one-hop neighbor and one-hop region.

- There are one-hop sufficient neighbors to provide alternative paths around the shortest path between the source and destination in MANETs.
- If the current shortest path in use is disconnected, a high probability exists that the next shortest path is found in the one-hop region within the MANET.

To verify the above two hypotheses, we perform a preliminary experiment in a general MANET environment by considering random network topology with uniform node distribution [15]. We simply consider one communication session and select a source and a destination randomly. The communication range of the nodes is set to $\delta W/\sqrt{N}$ where δ is a weighting factor to adjust the communication range with a value from 2 to 3 [16], W is the length of one side of the square network area, and N is the number of nodes in the network [17]. We investigate how many one-hop neighbors exist along the shortest path and how possibly the next shortest path can be found within the one-hop region when the current shortest path is broken, by varying the node density (i.e., the number of nodes in the network).

Figure 3(a) shows the average number of one-hop neighbors versus the number of nodes in the network (N) for various communication ranges. The results show that, as the number of nodes increases from 50 to 300, the number of one-hop neighbors increases accordingly. Moreover, as the communication range increases with the increase in δ, the number of one-hop neighbors increases as well. In terms of the ratio of the number of one-hop neighbors to the total number of network nodes, it is shown that the one-hop neighbors constitute at least 10 percent of the total nodes. To validate this result, we also analyzed the one-hop region numerically–these results are provided in the Appendix B. The level and tendency of the results of the analysis are similar to those of the simulation. Therefore, this result shows that almost all routing paths have one-hop neighbors irrespective of the node density and the communication range.

Figure 3(b) shows the probability of the new shortest path being found within the one-hop region when the shortest path being used is broken. For this experiment, we consider a

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[1] Details on how to determine the one-hop neighbors are provided in Subsection IV-A.

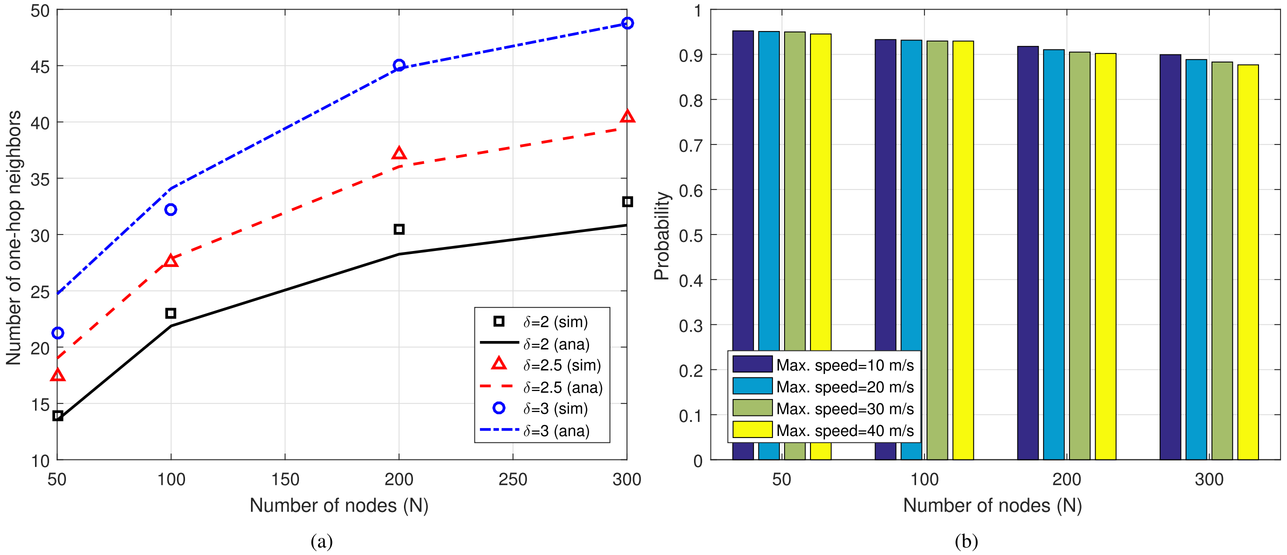

FIGURE 3. Verification of two hypotheses in MANETs: (a) average number of one-hop neighbors and (b) probability of the new shortest path being found within the one-hop region versus number of nodes in the network.

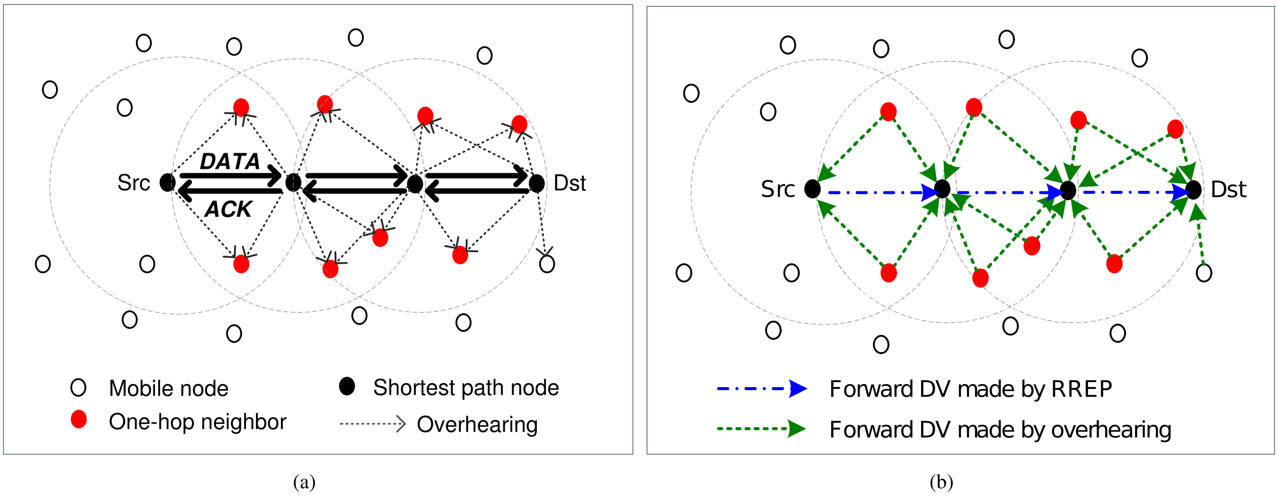

FIGURE 4. Operations of overhearing and one-hop neighbor decision. (a) Overhearing of one-hop neighbors. (b) Forward DV formed by overhearing.

random waypoint (RWP) mobility model and vary the maximum speed of nodes in the RWP model to control the level of mobility [18]. The results show that, as the node density and the mobility level increase, the probability decreases slightly but maintains a high level, running from 0.88 to 0.95. This implies that the new shortest path can be found in the vicinity of the previous shortest path (i.e., within the one-hop region) with high probability. On the basis of these two results, our two hypotheses are verified and confirm that our local flooding-based approach can be effectively applied to the MANET environment.

IV. PROPOSED ROUTING PROTOCOL

The proposed routing protocol consists of three operations: 1) overhearing and one-hop neighbor decision, 2) local flooding and route maintenance, and 3) rerouting. Each of these operations is described in detail in the following subsections.

A. OVERHEARING AND ONE-HOP NEIGHBOR DECISION

The purpose of this operation is to identify the one-hop neighbors along the current routing path for a given source and destination. Figure 4(a) shows the overhearing of the nodes along the given routing path in an example topology. After the initial route is set up, the nodes on the shortest path exchange data and an acknowledgment (ACK) between the source and destination.[2] This enables the neighboring nodes in the vicinity of the routing path to overhear the transmitted data and ACK packets, and check the header information of

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[2] In practice, this ACK packet can either be a transmission control protocol (TCP)-ACK or a link layer-ACK, or both.

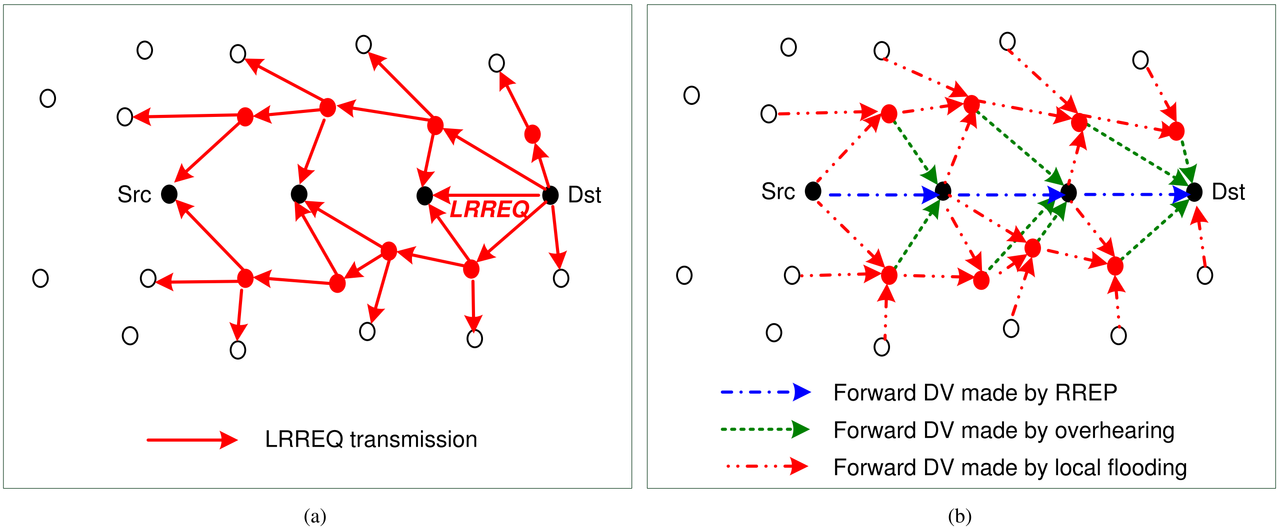

FIGURE 5. Operations of local flooding and route maintenance. (a) Local flooding initiated by destination. (b) Forward DV formed by local flooding.

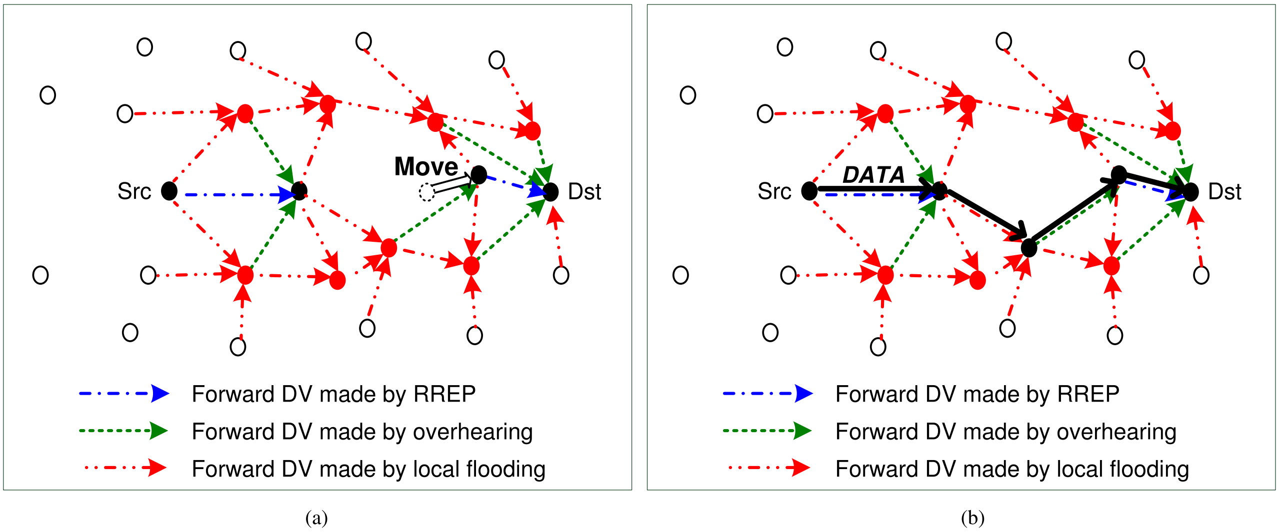

FIGURE 6. Operations of link failure and rerouting. (a) Link failure by node movement. (b) Rerouting to alternative path.

the received packets. Those nodes that receive both data and ACK that include the same source and destination addresses in their headers within a certain period of time (T_{oh1}), are defined as being one-hop neighbors of the corresponding source-destination pair. In other words, nodes capable of receiving both of these bidirectional packets on a routing path are considered as one-hop neighbors of that path. Each node maintains the qualification of a one-hop neighbor for a predetermined period of time (T_{oh2}) and no longer acts as a one-hop neighbor unless it is updated until the expiration of this time. Note that this process of identifying one-hop neighbors does not require an additional control packet to be transmitted and the node itself determines whether it is a one-hop neighbor of a corresponding path.

Figure 4(b) shows the forward DV formed by the overhearing process. The one-hop neighbors can create this forward DV to the destination by analyzing the IP header information, such as the source and destination addresses and time-to-live (TTL), of the received data and ACK packets. The forward DVs created by overhearing are added to the previous forward DVs along the shortest path, which was created by the RREP response.

B. LOCAL FLOODING AND ROUTE MAINTENANCE

Figure 5(a) shows the operation of local flooding. The operation is periodically initiated by the *destination* for route maintenance, unlike the original AODV in which the RREQ flooding is initiated by the source. To this end, we define a local RREQ (LRREQ) packet, which has the same format as RREQ, but has an indication that it is a local RREQ originated at the destination. This indication can be represented by using the reserved field of an RREQ without additional information bits. All nodes in the network receiving LRREQ during this local flooding process update their routing table information in the same way as in the RREQ flooding of AODV. However, unlike AODV, the nodes that participate in the LRREQ flooding are limited to the one-hop neighbors along the shortest routing path. That is, only the one-hop neighbors of the given routing path re-transmit the first received LRREQ, whereas the other nodes do not re-transmit it. Moreover, during this local flooding process, one-hop neighbors that receive the LRREQ with the same sequence number later additionally update the routing table information (i.e., multiple routing information is recorded for one destination) although they discard the corresponding LRREQ without rebroadcasting it. That is, an LRREQ received at a later stage with the same sequence number is used only for recoding multiple DVs in the routing table and is no longer flooded. This approach ensures that the proposed local flooding is performed only in a limited area around the source-destination path (i.e., one-hop region), thereby reducing the control packet transmission overhead remarkably while enabling the latest routing information along the current source-destination path to be rapidly obtained.

Figure 5(b) shows the forward DV, which is formed by the local flooding, and which is added to the previous forward DVs created by the RREP response and the overhearing process. As shown, various forward DVs to the destination are formed along the routing path and this provides multiple alternative paths between the source and the destination naturally. Therefore, the data packets generated from the source are delivered to the destination along the shortest route discovered.

C. REROUTING

Figure 6 shows an example operation of link failure and rerouting. As shown in Figure 6(a), a certain link can be disconnected as a result of any node repositioning itself. This link failure can be recognized as the non-reception of hello messages broadcasted periodically or by the repetitive failure of link layer transmission. The node recognizing the link failure deletes the corresponding DV information from its routing table. Nevertheless, data packets are automatically rerouted along the best alternative path based on the multiple DV information along the previous routing path, as shown in Figure 6(b). In this way, the proposed protocol provides a new alternative route seamlessly without the need for a new flooding process when link failure occurs.

D. FLOW CHART

Figure 7 shows the flow diagram for the overall operation of the proposed routing protocol. If data arrives at the source and there is no routing path to the destination, the source initiates the initial route setup process by flooding an RREQ across the network. Thereafter, if the shortest path is found and the first data arrive at the destination, the destination sets the timer for local flooding (T). Then, the source transmits the data to the destination and the destination responds with an ACK to the source. Those nodes that overhear these bidirectional packets being transmitted back and forth along the routing path determine themselves as one-hop neighbors for that path and update their routing tables. When the timer T expires, the local flooding process is initiated at the destination by broadcasting an LRREQ within the one-hop region; consequently, alternative paths are discovered around the routing path between the source and destination.

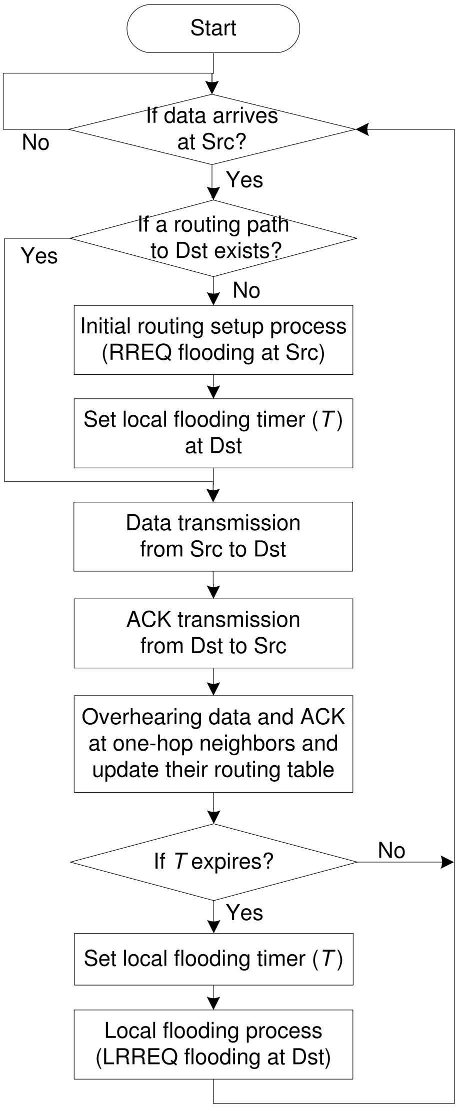

FIGURE 7. Flow chart of proposed routing protocol.

V. RESULTS AND DISCUSSIONS

We explain the simulation environments and then present the simulation results according to node mobility and density.

A. SIMULATION SETUP

We evaluated the performance by using the OPNET simulator [19] and the simulation parameters are summarized in Table 1. We considered a square network area with a

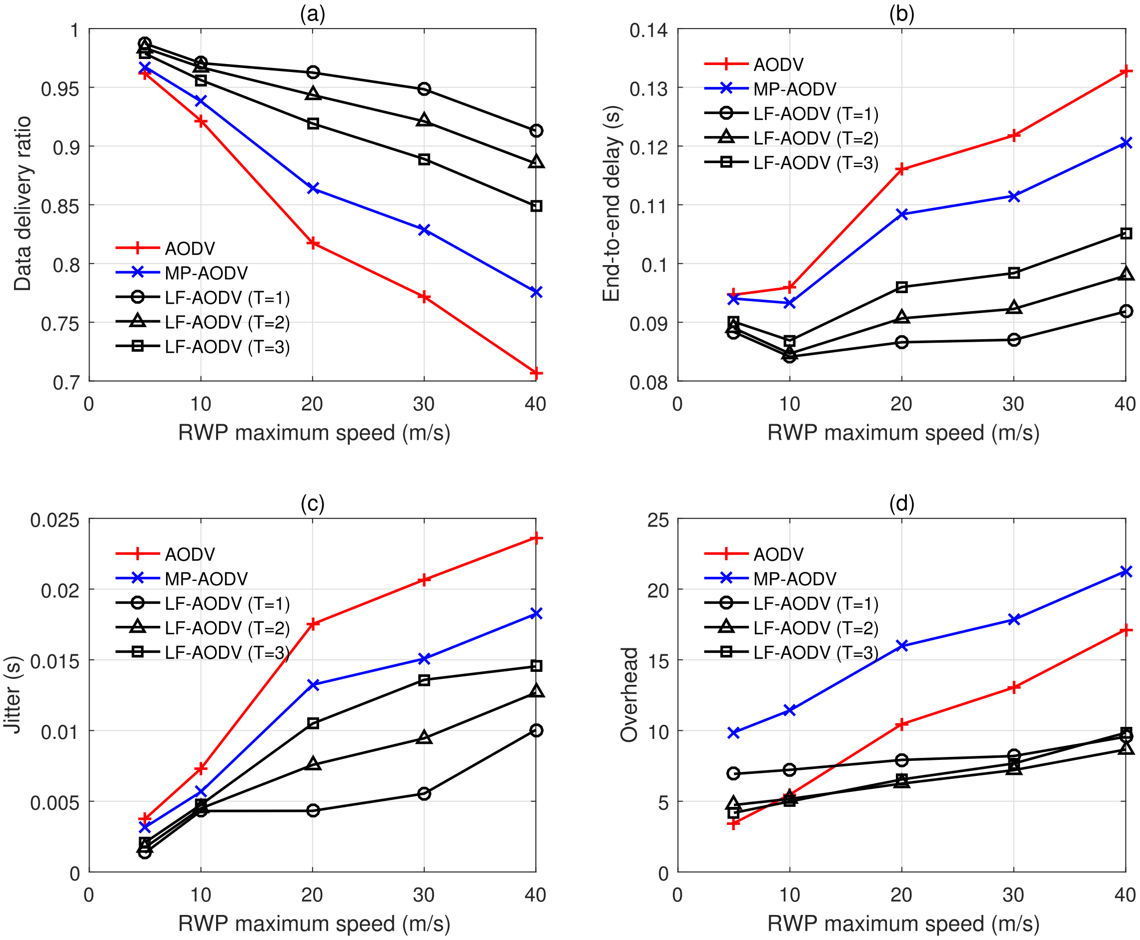

FIGURE 8. Performance of routing protocols as a function of the maximum speed in the RWP mobility model when the network contains 100 nodes: (a) data delivery ratio, (b) end-to-end delay, (c) jitter, (d) overhead.

width of 1000 m. The simulation considered various node densities by varying the number of nodes from 50 to 300. The communication range of the nodes is set to $2W/\sqrt{N}$ where W is the width of the network area and N is the number of nodes in this network [16], [17]. The nodes position themselves according to the RWP mobility model [18], in which the starting position of each node in the network area is randomly chosen. The velocity of each node is randomly chosen between a given minimum and maximum value. We used a minimum speed of 0 m/s and varied the maximum speed from 5 to 40 m/s to reflect various levels of mobility from low to high. The time during which the node is not moving is chosen randomly between 0 and 30 s [20]. The duration of each experiment is 600 s and this is repeated 100 times for averaging purpose [21]. Data traffic is delivered by using unidirectional TCP that requires an ACK response. In each session, the source generates four data packets of 64 bytes per second. The size of an LRREQ is 24 bytes similar to that of RREQ and the timer for local flooding (T) is set to a value between 1 s and 3 s. Considering the data generation cycle, we set the timers for one-hop neighbor decision and release to 0.25 s and 0.5 s, respectively.

TABLE 1. Simulation parameters.

Name	Value
Width = Height	W = 1000 m
Number of nodes	N = 50∼300
Communication range	$\delta W/\sqrt{N}$ m ($\delta = 2$)
Mobility model	Random waypoint
RWP minimum speed	0 m/s
RWP maximum speed	5∼40 m/s
Pause interval	Random[0,30] s
Simulation time	600 s
Number of simulations	100
Period of data packet generation	0.25 s
Size of data packet	64 bytes
Size of LRREQ packet	24 bytes
Timer for local flooding	T = 1∼3 s
Timer for one-hop neighbor decision	T_{oh1} = 0.25 s
Timer for one-hop neighbor release	T_{oh2} = 0.5 s

The effect of the proposed protocol on the routing performance was studied by considering only cases in which the initial number of hops between the source and destination exceeded three hops [22]. For comparison, we adopt the standard AODV protocol using the default functions and parameters and its representative multipath extension

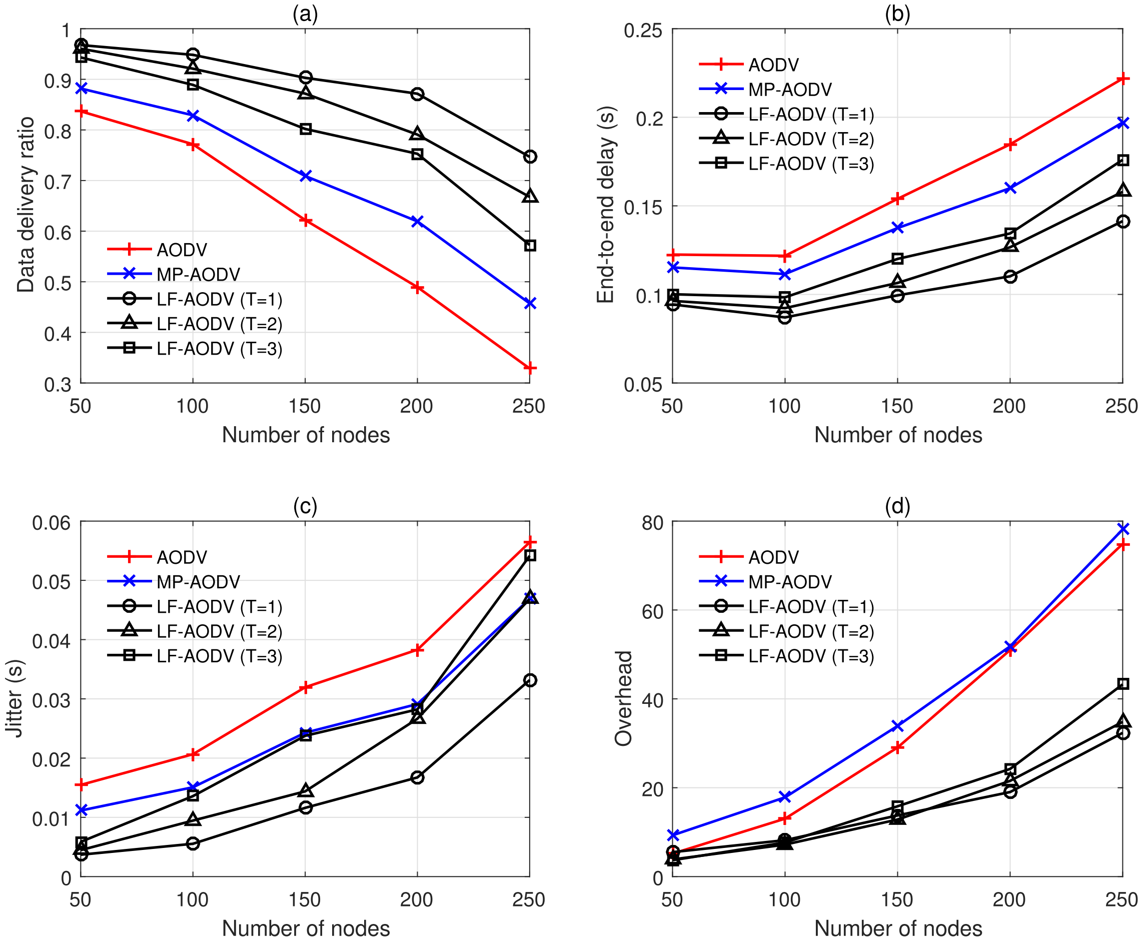

FIGURE 9. Performance of routing protocols as a function of the number of nodes in the network when the maximum speed in the RWP mobility is 30 m/s: (a) data delivery ratio, (b) end-to-end delay, (c) jitter, (d) overhead.

protocol, MP-AODV [14]. In the MP-AODV protocol, nodes construct their routing table by including multiple next-hop information for the destination.

We consider the following four different performance metrics [23]:

1) *Data delivery ratio*: It is defined as the ratio of the number of data packets received at the destination to the number of data packets sent from the source. Data packets can be lost when the routing table contains no next-hop information for the destination of the data packet because of link failure during communication. Here, we assume that retransmission of the lost data packet is not allowed.
2) *End-to-end packet delay*: It indicates the average time taken by successfully delivered data packets traveling from their source to their destination. This metric only counts the delay of successful packets; thus, end-to-end packet delay directly indicates the length of the routing path between the source and the destination.
3) *Jitter*: It indicates the variation in the time interval between the arrival of subsequent packets, and is defined as

$$\text{jitter} = \frac{\sum_{i=2}^{n} |(t_i - t_{i-1}) - (t_{i-1} - t_{i-2})|}{n-2} \tag{1}$$

where t_i is the time of arrival of the i-th packet, and n is the total number of packets received at the destination during the communication. Jitter indicates the ability of the protocol to respond to network disruption smoothly as an important measure for QoS applications.
4) *Control overhead*: It is defined as the ratio of the total number of control packets transmitted by all the nodes in the network to the total number of data packets generated at the source. This overhead metric is important for measuring the efficiency of the routing protocol because it affects the network capacity and the energy consumption of nodes.

B. SIMULATION RESULTS

We verified the adaptivity and the efficiency of the routing protocol by evaluating the performance of the proposed protocol with varying mobility levels. Figure 8 compares the performance of the routing protocols as a function of

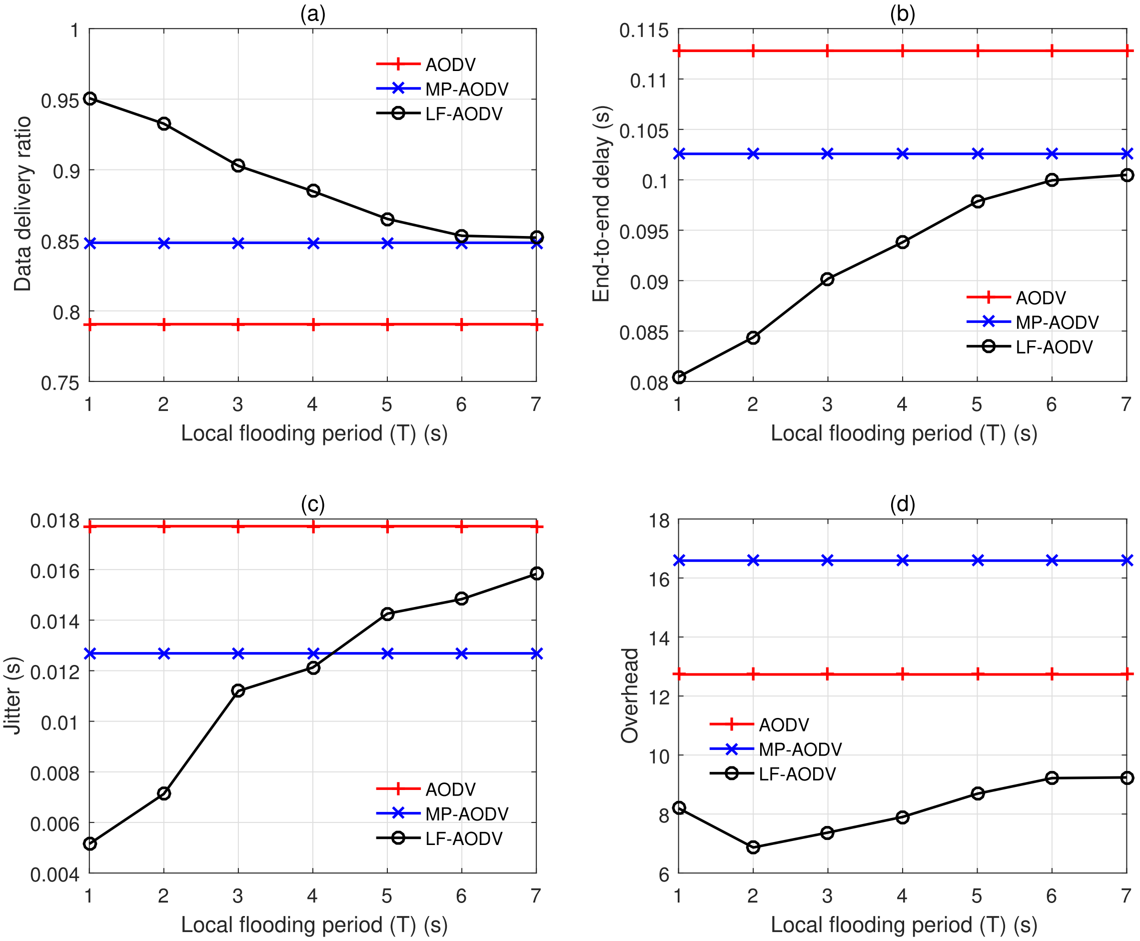

FIGURE 10. Performance of routing protocols as a function of the local flooding period T when the network contains 100 nodes and the maximum speed in the RWP mobility is 30 m/s: (a) data delivery ratio, (b) end-to-end delay, (c) jitter, and (d) overhead.

the maximum speed in the RWP mobility model when the network contains 100 nodes. As the mobility increases, path disruptions[3] occur more often and thus the data delivery ratio decreases for all routing protocols. However, the data delivery ratio of the proposed local flooding-based AODV (LF-AODV) is superior to that of AODV or MP-AODV owing to its periodic local flooding process. LF-AODV increases the data delivery ratio as the local flooding period (T) decreases because the smaller the value of T is, the more frequently route maintenance is performed. In terms of end-to-end delay, the proposed LF-AODV is more effective than the other two protocols. In addition, LF-AODV also achieves a smaller delay as T decreases for the same reason. The jitter depends on both the end-to-end delay and the data delivery ratio. Thus, the jitter of the proposed LF-AODV is lower than that of the other protocols because the proposed protocol has a low end-to-end delay and a high data delivery ratio. In terms of the overhead, MP-AODV gives rise to the highest overhead because not only does it cause flooding overhead, it also generates many control packets for managing multiple paths. When the mobility level is very low, AODV has the lowest overhead because it does not perform the route maintenance process, but as the mobility increases, its overhead increases dramatically because of frequent RREQ flooding. Compared to the rapid rate of overhead increase in the case of AODV and MP-AODV, the overhead of the proposed LF-AODV increases gradually and remains low overall. This is because LF-AODV performs periodic local flooding with less overhead and rarely causes RREQ flooding. Moreover, as the mobility increases, a smaller value of T results in less overhead because it further reduces path disruption and reduces the occurrence of RREQ flooding.

To verify the scalability of the routing protocol, we evaluated the performance of the proposed protocol by varying the node density. Figure 9 shows the performance of the routing protocols as a function of the number of nodes in the networks when the maximum RWP mobility is 30 m/s. As the number of nodes increases, the average number of hops between the source and destination increases such that the data delivery ratio decreases and the end-to-end delay increases. The proposed LF-AODV outperforms AODV and

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[3] Path disruption occurs when the node that received the data packet does not have information on the next hop to the destination of the data packet.

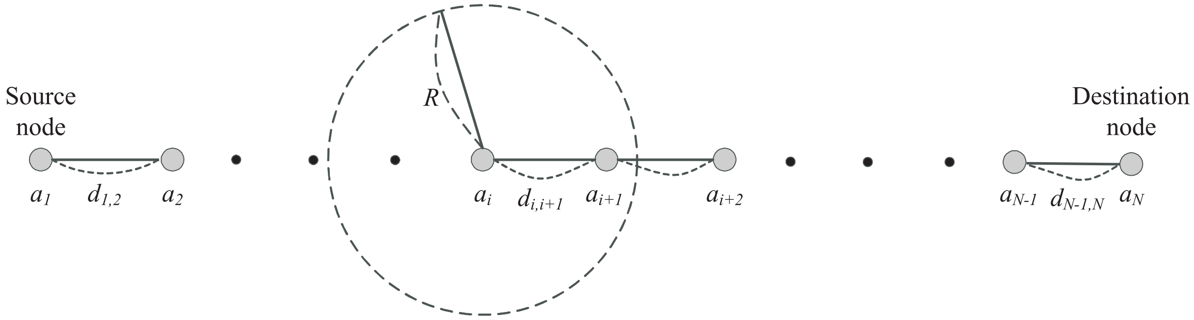

FIGURE 11. **Routing path with *N* nodes.**

MP-AODV in terms of the data delivery ratio, end-to-end delay, and jitter. In addition, the performance of LF-AODV improves as the local flooding period T becomes smaller. In terms of overhead, both AODV and MP-AODV generate quite a larger amount of overhead than the proposed LF-AODV because their RREQ flooding overhead increases in proportion to the number of nodes in the network. On the other hand, the ratio of the increase in overhead of LF-AODV is low because it performs local flooding, which considerably reduces control packet transmission.

We investigated the effect of the local flooding period T on the routing performance and determined the appropriate range of the T value to be used for the proposed protocol. Figure 10 shows the performance of the routing protocols as a function of the local flooding period T when the number of nodes in the network is 100 and the maximum RWP mobility is 30 m/s. As the local flooding period T increases, the performance of the data delivery ratio, end-to-end delay, and jitter deteriorate because a longer T results in the routing information being updated more slowly. When $T \leq 4$, the performance of LF-AODV is better than that of the other protocols. The amount of overhead generated by LF-AODV, which is significantly lower than that of AODV and MP-AODV, initially decreases as T increases, then increases gradually. This is because when T is overly small, the overhead due to frequent local flooding is more dominant than the overhead caused by RREQ flooding, but the latter overhead becomes more dominant than that caused by local flooding as T increases. That is, there exists an appropriate value of T in terms of overhead.

VI. CONCLUSION

In this paper, we proposed a local flooding-based on-demand routing protocol for MANETs. The proposed protocol first identifies the one-hop neighbors along the routing path by using the overhearing technique. Then, flooding messages are only propagated its one-hop neighbors, such that the conventional flooding overhead is significantly reduced and multiple alternative paths around the shortest path are provided. The simulation results showed that the proposed protocol outperforms the conventional AODV and MP-AODV protocols in terms of the data delivery ratio, end-to-end delay, and jitter, while effectively reducing the control overhead across a wide range of node mobility and density values. The study also revealed that the proposed protocol is quite effective when the mobility and density are high although it does not provide exhaustive search for finding paths throughout the entire network. Therefore, we expect the proposed local flooding-based routing protocol to be effectively applied to highly dynamic and large-scale networks in the future. In addition, we plan to optimize the operating parameters of the proposed protocol and to compare it with various modern routing protocols.

APPENDIX A
DEMONSTRATION VIDEO

For the sake of clarity, we provide a demo video for an example operation of the proposed routing protocol, which can be viewed by visiting the following link: https://youtu.be/JjpRpMufS9M

APPENDIX B
ANALYSIS OF ONE-HOP REGION

We analyze the one-hop region to obtain the number of one-hop neighbors numerically and validate the simulation result in Section III. Suppose that there are N nodes along a given routing path with the index from the source to the destination increasing in the order $\{a_1, a_2, \ldots, a_N\}$, as shown in Figure 11. Here, R denotes the transmission range of the nodes and $d_{i,j}$ denotes the distance between the i-th and j-th nodes.

Let $A_{i,j}$ be the size of the overlapped transmission area of nodes i and j, and let α_i be the angle between the extended line of $\overline{a_i \cdot a_{i+1}}$ and the line $\overline{a_{i+1} \cdot a_{i+2}}$, as shown in Figure 12. Then we have

$$d_{i,i+2} = \sqrt{d_{i,i+1}^2 + 2d_{i,i+1}d_{i+1,i+2}\cos\alpha_i + d_{i+1,i+2}^2} \tag{2}$$

First, we calculate $A_{i,i+1}$. Without loss of generality, we assume that the node a_i is located at the origin and the node a_{i+1} is located at the point $(d_i, 0)$, as shown in Figure 12.

Let the shadowed area in Figure 13 be Γ_i, which is exactly half of $A_{i,i+1}$. Thus, Γ_i is calculated by

$$\begin{aligned}\Gamma_i &= \pi R^2 - \left(\frac{2\pi - 2\theta}{2\pi}\pi R^2 + \frac{1}{2}R^2\sin(2\theta)\right)\\ &= \theta R^2 - \frac{1}{2}R^2\sin(2\theta)\end{aligned} \tag{3}$$

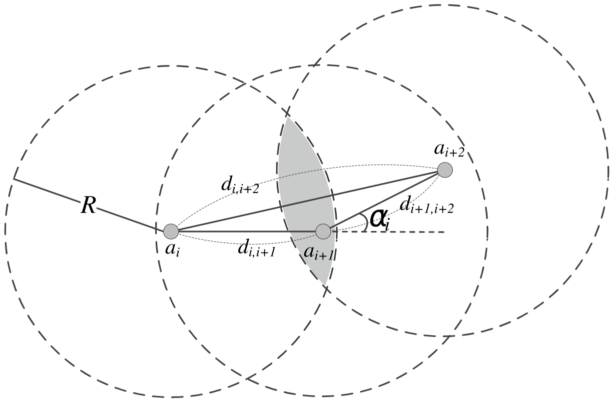

FIGURE 12. Definitions of $A_{i,j}$ and α_i.

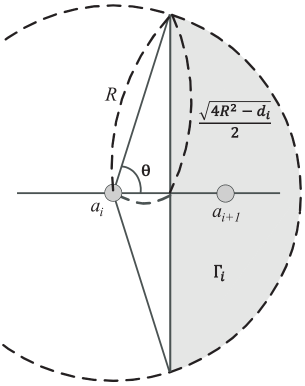

FIGURE 13. Definition of Γ_i.

where θ is the angle between the x-axis and the line passing through the origin and the upper (lower) intersection point between the transmission boundaries of the i-th and $(i+1)$-th nodes. From $\sin 2\theta = 2\sin\theta\cos\theta = \frac{d_{i,i+1}}{4R^2}\sqrt{4R^2 - d_{i,i+1}^2}$ and $\theta = \cos^{-1}\frac{d_{i,i+1}}{2R}$, we have

$$\begin{aligned} A_{i,i+1} &= 2\Gamma_i \\ &= 2R^2\cos^{-1}\frac{d_{i,i+1}}{2R} - \frac{d_{i,i+1}}{2}\sqrt{4R^2 - d_{i,i+1}^2}. \end{aligned} \tag{4}$$

Furthermore, we can obtain $A_{i,i+2}$ by substituting $d_{i,i+2}$ for $d_{i,i+1}$ in (4), which is given by

$$A_{i,i+2} = 2R^2\cos^{-1}\frac{d_{i,i+2}}{2R} - \frac{d_{i,i+2}}{2}\sqrt{4R^2 - d_{i,i+2}^2}. \tag{5}$$

From Figure 12, the one-hop region of the routing path with N nodes is calculated as

$$\begin{aligned} S &= A_{1,2} + (A_{2,3} - A_{1,3}) + (A_{3,4} - A_{2,4}) + \cdots \\ &\quad + (A_{N-1,N} - A_{N-2,N}) \\ &= \sum_{i=1}^{N-1} A_{i,i+1} - \sum_{i=1}^{N-2} A_{i,i+2} \\ &= \sum_{i=1}^{N-1} 2R^2\cos^{-1}\frac{d_{i,i+1}}{2R} - \frac{d_{i,i+1}}{2}\sqrt{4R^2 - d_{i,i+1}^2} \\ &\quad - \sum_{i=1}^{N-2} 2R^2\cos^{-1}\frac{d_{i,i+2}}{2R} - \frac{d_{i,i+2}}{2}\sqrt{4R^2 - d_{i,i+2}^2}. \end{aligned} \tag{6}$$

where $d_{i,i+2}$ is calculated by (2).

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