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# Incremental Distributed Construction Method of Delaunay Overlay Network on Detour Overlay Paths

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**Abstract:** In wide-area disaster situations, wireless mesh networks lose data communication reachability among arbitrary pairs of base stations due to the loss of routing information propagation and synchronization. This paper uses a Delaunay overlay approach to propose a distributed networking method in which detour overlay paths are incrementally added to a wireless mesh network in wide-area disaster situations. For this purpose, the following functions are added to each base station for wireless multi-hop communication: obtaining the spatial location, exchanging spatial location messages between base stations, transferring data based on spatial locations of base stations. The proposed method always constructs a Delaunay overlay network with detour paths on the condition that a set of wireless links provides a connected graph even if it does not initially provide reachability among arbitrary base stations in the connected graph. This is different from the previous method that assumes a connected graph and reachability. This paper therefore also shows a new convergence principle and implementation guidelines that do not interfere with the existing convergence principle. A simulation is then used to evaluate the detour length and table size of the proposed method. It shows that the proposed method has scalability. This scalability provides adaptable low-link quality and increases the number of nodes in wide-area disaster situations.

**Keywords:** delaunay overlay network, structured overlays, geometric routing, ad-hoc networks, computational geometry

## 1. Introduction

In wide-area disaster situations, it is important to maintain the soundness of the access network for assisting evacuation and rescue work. Large-scale earthquakes have recently struck Japan about once every eight years (Great Hanshin Earthquake in 1995, Chuetsu Earthquake in 2004, Great East Japan Earthquake in 2011), which created a strong need for research, development, and deployment of a wide-area, disaster-proof access network. We regard wireless mesh networks as disaster-proof access networks from a network-structure standpoint [1]. In this paper, these access networks must possess the following attributes:

1. The access networks are constructed by many wireless base stations.
2. The Base stations are connected to each other by wireless communication links (e.g., Wifi links). And, some communication links are wired.
3. Terminals can connect the base stations. In some cases, the terminals carry encrypted data.
4. The access networks have mesh topology for keeping numerous redundant routes.
5. There is no central-role node.
6. The access networks are independent of central power supply by energy harvesting modules and battery cells.
7. The access networks must work in the engineers unmovable situations by wide-area disasters.

A function of wireless mesh base stations is data forwarding to linked near base stations. Base stations are permanently installed or installed during disaster situations. Mesh networks are connected with nearby mesh networks, and consequently a wide area is covered. However, prediction of wireless link quality is difficult in a wide-area disaster situation. Therefore, a general networking method using a location advertisement as in **Fig. 1** may not work since the method has all nodes sending a location advertisement message to all nodes, and the wireless link capacity may be inadequate for the quantity of messages.

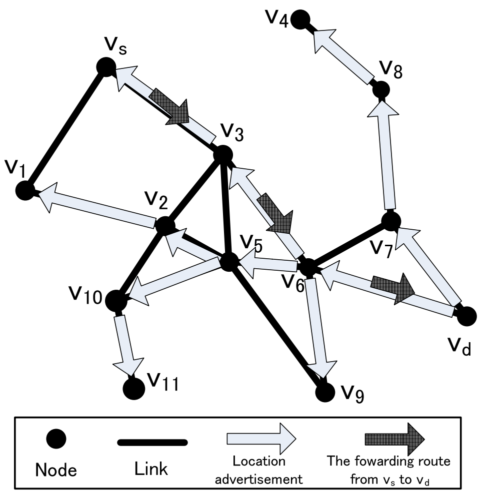


**Fig. 1** General networking method using location advertisement.

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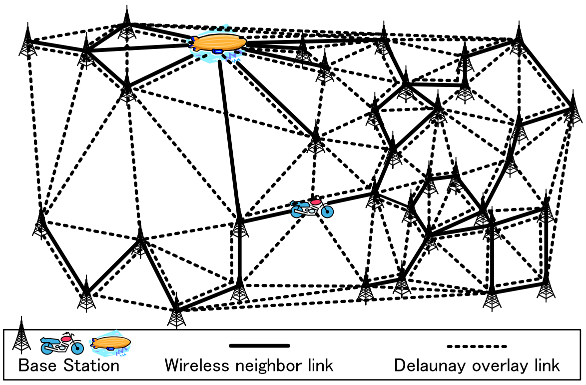


**Fig. 2** Wireless mesh BSs and Delaunay overlay network.

We studied adapting a Delaunay overlay network construction method [2] that uses spatial location information with the wireless mesh network. This method can construct a network (having reachability) by locally exchanging few control messages. A Delaunay overlay network has Delaunay graph topology with many minimum triangles with three nodes. These triangles do not include all the other nodes. The topology is a Voronoi diagram's dual graph and the Voronoi diagram is every node's territory diagram [3].

From these features, the Delaunay graph and Voronoi diagram can be calculated based on nearby node's spatial locations. Delaunay graph topology is also a necessary and sufficient condition for ensuring the success of greedy routing based on Euclidean distance. Sensor data collection methods on a Delaunay overlay network [4] are researched as well. The Delaunay overlay network is therefore adaptable for both distributed networking and distributed data management.

**Figure 2** shows a Delaunay overlay network on wireless links. A solid line represents the wireless links between nearby base stations.

But, existing method [2] assumes that a lower layer network is a complete reachable network (CRN), namely, a network in which arbitrary nodes can communicate with each other. An IP network is an example of a CRN-type low-layer network. In wide-area disaster situations, network resource is uncertain. Communication reachability may be limited in sub-networks because of loss of routing information propagation and synchronization. We call such a network a partially reachable network (PRN). Delaunay overlay construction method [2] cannot be applied to PRN.

This paper proposes a new Delaunay overlay construction method that networks wireless links by local control messages. A Delaunay overlay network is constructed on the wireless link network, which is a detour overlay network from the standpoint of the Delaunay overlay network layer.

**Figure 3** shows the concept of a detour path. In the upper left, the source node and destination node are connected by a one-hop direct overlay connection. On the other hand, detour paths include certain amounts of relay nodes between the source node and destination node. In the upper right of Fig. 3, there is one relay node between the source node and destination node. This two-hop detour path is the minimum size of a detour path. In the

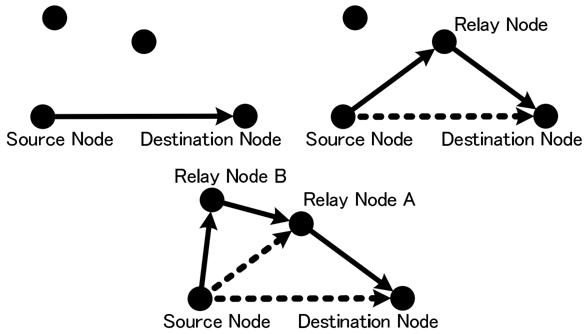


**Fig. 3** Relay nodes in detour paths.

lower part of Fig. 3, there is one relay node between the source node and destination node. This two-hop detour path is the minimum size of a detour path. In the lower part of Fig. 3, the one-hop path in the two-hop detour path is added to a relay node, so the detour path sizes are increased. As a result, a three-hop detour path is constructed. Thus, if a relay node with both edge nodes of a one-hop path is detected, the detour path can be constructed.

When a lower-layer network is a CRN, the existing method and a proposed method can construct a Delaunay overlay network by using the above-mentioned detour path. On the other hand, when a lower-layer network is a PRN, only our proposed method can construct a Delaunay overlay network.

The rest of this paper is as follows. Section 2 gives an overview of the existing Delaunay overlay construction method [2]. Section 3 describes the convergence principle and implementation guidelines. These were never described in Ref. [2]. And, the Delaunay overlay a network construction method that uses detour overlay paths. Section 4 details an evaluation of the proposed method using a simulation. Section 5 discusses related works. Section 6 concludes the paper.

## 2. Overview and Convergence Principle of Existing Overlay Network Construction Method

This section gives an overview of the existing Delaunay overlay network construction method [2] and goes into greater detail on the convergence principle of Ref. [2]. These are important areas because they are assumptions of the incremental distributed construction method of a Delaunay overlay network on detour overlay paths.

### 2.1 Overview of the Existing Method

Each node calculates the local Delaunay graph based on the neighbor node's position. Each node sends messages on connection construction to other nodes based on this diagram, and each node disconnects some connections.

Each node asynchronously executes the sequence, and as a result the entire network topology converges to a Delaunay graph topology network. The existing Delaunay overlay network construction method is composed of three main parts: local Delaunay triangulation, delegation of connections, and notification of triangulation. The method converts connected graph topology to a Delaunay graph topology, wherein each node executes these three parts. Nodes execute local Delaunay triangulation when they re-

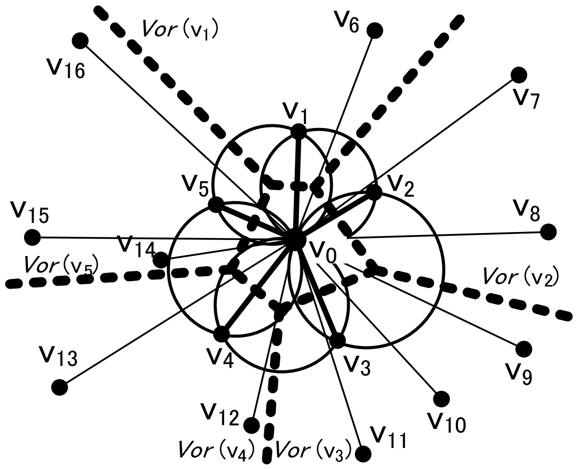


**Fig. 4** Local Delaunay triangulation.

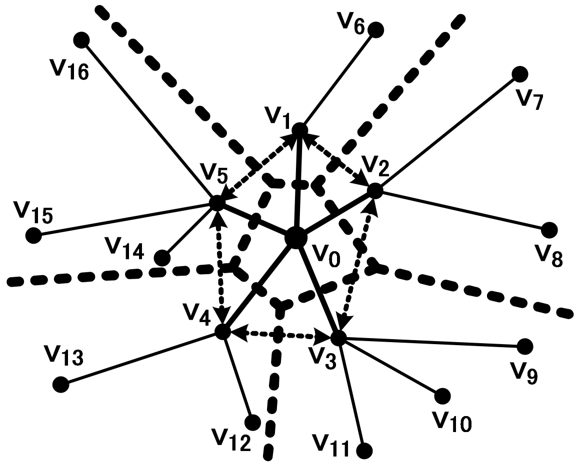


**Fig. 5** Delegation of connections and notification for triangulation.

ceive delegation of connections or notification for triangulation. They then execute delegation of connections and notification for triangulation.

Hereinafter, let S = $v_0$, $v_1$, $v_2$, $\cdots$, and $v_N$ is a set of communication nodes on the Euclidean plane. The initial state of the overlay network topology is a connected graph topology. Each node has the following assumptions.

1. It has its own position on the Euclidean plane as well as an ID.
2. It can create overlay connections using IDs with all other nodes by underlay networks.
3. It can exchange control messages with directly connected nodes in an overlay network.
4. It sends its own ID and position to one-hop neighbors when new nodes are connected.
5. It executes local Delaunay triangulation, delegation of connections, and notification for triangulation

In what follows, the three main parts of the existing method are described with a central focus on the behavior of $v_0$.

**Local Delaunay triangulation** **Figure 4** shows $v_0$'s local Delaunay triangulation, thin solid lines show its default connections to nodes, and thick solid lines show its connections to Delaunay neighbor nodes. Dotted lines show its Voronoi diagram by Delaunay neighbors. Vor$(V_i)$ is $V_i$'s Voronoi region. Delaunay triangulation is for computing the local Delaunay graph and acquiring Delaunay neighbors. In Fig. 4, the neighbors are $v_1$, $v_2$, $v_3$, $v_4$, and $v_5$. These nodes are used virtually to construct triangles with $v_0$ (e.g., $\triangle v_0$, $v_i$, $v_{i+1}$ and $\triangle v_0$, $v_5$, $v_1$ [for $1 \leq i \leq 4$]). On the other hand, $v_6$ - $v_{16}$ are non-local Delaunay neighbors. $v_0$ calculates the Voronoi regions (Vor$(v_1)$ - Vor$(v_5)$) of Delaunay neighbors.

**Delegation of connections** The thin solid lines in **Fig. 5** show delegated connections. Connections to nodes in each Delaunay neighbor node's Voronoi region are delegated to Delaunay neighbor nodes. $v_0$ basically delegates connections only to neighbor nodes. The delegation needs to exchange control messages between three nodes: a connection owner node ($v_0$), opposite side connection owner node ($v_6$ - $v_{16}$), and delegation-receiving node ($v_1$ - $v_5$). $v_0$ prompts the other two nodes to connect to each other. The network topology's processes for maintaining connectedness are also needed, so the number of nodes for exchanging control messages must be minimized. Neighbor nodes make connections to nodes in their own Voronoi region. Delegated nodes delete connections with $v_0$ (e.g., connection between $v_0$ and $v_6$ connection is replaced with connection between $v_1$ and $v_6$). $v_i$ (i.e., $1 \leq i \leq 5$) executes local Delaunay triangulation when it receives delegation of connections.

**Notification for triangulation** The small-dotted lines with two arrows in Fig. 5 show notification for triangulation. $v_0$ sends notification to Delaunay neighbor nodes $v_i$ about each $v_i$'s Delaunay neighbor nodes on the local Delaunay graph using the local Delaunay neighbor nodes of $v_0$ (in Fig. 5, nodes indicated by small-dotted lines with two arrows interact with each other). $v_i$ computes a local Delaunay graph when it receives notification of triangulation from $v_0$. If nodes in the notification are $v_i$'s local Delaunay neighbor nodes, $v_i$ connects them. However, $v_i$ does not send notification to $v_0$ in the received notification. This rule is important for avoiding unlimited repetition of notification among nodes.

### 2.2 Convergence Principle of the Existing Method

This subsection details the reason for using a connected-graph topology network converted into a Delaunay-graph-topology network with the existing Delaunay overlay construction method [2].

This existing method constructs many tree graphs, and a tree graph's root node is nearest each of all the points on a Euclid plane. Position based greedy routing is available through the combination of all tree graphs' topology. Delaunay graph topology is a necessary and sufficient condition for ensuring the success of greedy routing based on Euclidean distance. Therefore, a combination of all tree graph includes Delaunay graph topology. In the existing method, extra connections that combine the topology of all tree graphs are disconnected. Network topology also converts the Delaunay graph topology. The construction method of the tree graphs is described below. Notification of triangulation and delegation of connections provides delegation of connections and nodes. The delegated nodes and receiving nodes may become Delaunay neighbors. A node $v_0$ sends information (ID, position, lowlayer network locator) to both nodes that have potential to touch Voronoi regions, including $v_0$'s Delaunay neighbors ($v_0 : DN$), via notification of triangulation. $v_0$ delegates non Delaunay neighbor nodes ($v_0 : NDN$) to the nearest $v_0 : DN$ node via delegation of connections.

For example, in Fig. 5, the connection between $v_0$ and $v_6$ is replaced with a connection between $v_1$ and $v_6$ and they have the potential to touch other $v_0 : DN$'s Voronoi regions in $v_0 : NDN$.

This node connects $v_0 : DN$ with the potential to touch $v_0 : NDN$'s Voronoi regions by notification of triangulations. Therefore, if a $v_0 : NDN$ and $v_0 : DN$ must connect with each other, two nodes are connected by notification of triangulations and delegation of connections.

For the above mentioned reason, all nodes can acquire the potential to touch Voronoi region nodes from one-hop neighbors by notification of triangulation and delegation of connections. Incidentally, the second nearest node is touching the first nearest node's Voronoi region by the Voronoi diagram's attributes. Therefore, each node have following phenomenons as a and b.

**a.** When each node executes "Local Delaunay triangulation," "Delegation of connections," and "Notification for triangulation," each node connects any two-hop neighbors. The two-hop neighbors are closer to an arbitrary point in each node's Voronoi region than any one-hop neighbors.

**b.** When each node executes every three sequences, each node is connected by any two-hop neighbors. At that time, each node is closer to an arbitrary point exclusive of each node's Voronoi region than any two-hop neighbors.

The tree graph for greedy routing to reach the root node from an arbitrary node consist of the superposition of the line graph. Therefore, a node is inserted in the line graphs. This insertion into the line graph process is equivalent to insertion into the tree graph process.

All that is needed is to connect the new $v_j$ to the node closer to the root, when any of such line graphs receive and insert a new node $v_j$.

Then, via two repeatedly occurring phenomena, we examine whether insertion of $v_j$ into the tree structure that can reach to the root node takes place by greedy routing.

Even if these tree graph constructions are performed in parallel and distributed by the network at each location, they do not interfere with each other because reachable nodes by greedy routing are only increased by receiving notification of a triangulation message and do not interfere with processing of other nodes. Since the topology of the entire early network is a connected graph, all the nodes are inserted into one of the line graphs. Finally, the tree graph in which greedy routing is possible as a set of line graphs is constructed based on all the points on a plane. The set of the tree structure for this greedy routing is redundant to the connection that is not included in the Delaunay graph. Excess connection is reduced by connection transfer and made to converge on the Delaunay graph topology.

# 3. Distributed Construction Method of Delaunay Overlay Network Connections over PRN

Regarding the distributed construction method of Delaunay overlay network connections over PRN, first implementation guidelines of existing Delaunay overlay network construction method on CRN are described, followed by low-layer connections, high-layer connections, and detour connections management method. Then, the distributed construction method of Delaunay overlay network connections using detour tables on PRN is detailed.

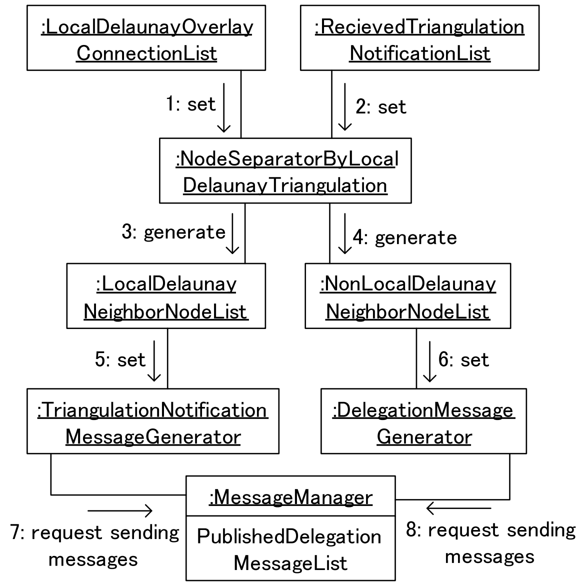


**Fig. 6** Message publication process based on local Delaunay calculation.

## 3.1 Implementation Guidelines of Existing Delaunay Overlay Network Construction Method

The message publication process based on local Delaunay graph calculation is stated in **Fig. 6** using a communication diagram. The LocalNodeSeparator of the local Delaunay graph calculation is a connection list of Delaunay overlay layers that each node currently possesses. This is carried out based on the LocalDelaunayOverlayConnectionList and ReceivedTriangulationNotificationList, which are lists of node information given by the notification of a triangulation message received from other nodes (1, 2). The LocalDelaunayNeighborNodeList and NonLocalDelaunayNeighborNodeList are generated (3, 4). The TriangulationNotificationMessage and DelegationMessage are generated and a transmitting request is removed from these two lists to the MessageManager (5, 6, 7, 8).

The above is the flow of a series of processes included in the message transmission in the conventional construction. However, in practice, construction of a connection and transfer of a connection need to have message exchange performed with other nodes, and operation from start to finish does not immediately conclude them. Even if the composition of the connection to other nodes is requested, before that connection is ultimately constructed, new notification of triangulation may reach each node, or a new connection may be established. However, even if the connection making process is established in the conventional construction, there is no process of cutting a connection by way of the connection not being established. For this reason it is necessary to merely perform a series of processes again when establishment of a connection is completed. There is also a state of being in

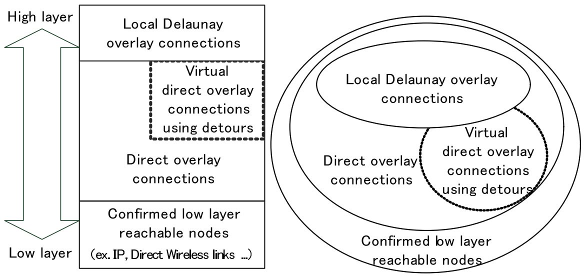


**Fig. 7** Inclusive relation between the connection types classified by layer.

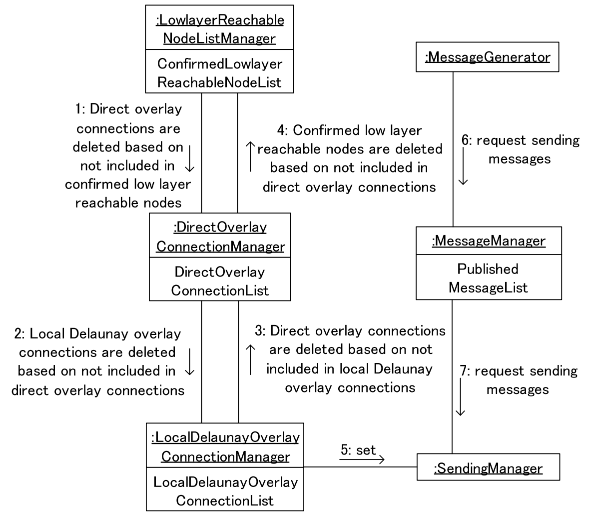


**Fig. 8** Connection management mechanism based on a connection type inclusive relation.

a one way connection, and a state of bidirectional connection in connection via an overlay network layer. Moreover, since reachability in a low layer is also a kind of connection, one of the preconditions for an overlay connection is also that it can reach the locator of a low layer.

The inclusive relation between the connection types classified by layer is shown on left of the **Fig. 7**. *Confirmed low layer reachable nodes* were established as a connection that becomes the initial foundation. This is a connection of the low layer to an overlay network, and is a list of nodes that have been checked for their ability to communicate with the locator of a low layer. For example, since the assumption of the most general low layer that works with the conventional construction is the IP layer, it will be referred to as a set of the nodes that have checked that this list can also be reached using an IP network. The existing construction method assumes that all nodes can communicate with all nodes using a low-layer network. If the assumption is not approved, the existing method is not available.

*Direct overlay connections* were also established as the connection between the nodes that can communicate by the low layer. Though this is a type of overlay connection, it is in a state in which it is not necessarily still used for the Delaunay overlay construction method. An overlay connection may be required for maintenance, and may also be used as a component of the detour path mentioned later.

The connections in which the premise used by the Delaunay overlay construction method were completely ready are local *Delaunay overlay connections*. Meanwhile, *virtual direct overlay connections using detours* are described in Section 3.3. Moreover, if the connection of each class does not have a low-layer connection, connection of a higher-layer cannot be constructed; but since it is definitely constructed, there is a dependency on the connection of the low-layer being used as a support in the connection of a higher-layer. If such dependency exists, a set of low-layer connections will have an inclusive relation that exceeds it, including a set of connections of a corresponding higher-layer. The inclusive relation is shown on the right of Fig. 7.

Each node manages the connection list of each class internally so that this inclusive relation can be maintained. **Figure 8** shows this connection control mechanism.

When the lower layer connection is cut by some failure, all connection of the higher layer depending on it are cut (1, 2). When the higher connection is cut, the lower layer connections are cut from a resource-saving standpoint (3, 4). The message in the Delaunay overlay layer is delivered after these processes using the LocalDelaunayOverlayConnection remain (5, 6, 7). Moreover, since this connection-control mechanism is always working, when adding the connection in the Delaunay overlay layer, after preparing the connection in all the layers beforehand, the connection list must be added to simultaneously.

### 3.2 Motivation for Proposed Method

The existing construction method of the Delaunay overlay network is premised on a network that can communicate with arbitrary nodes with arbitrary locators by the low-layer network. However, when using this as the networking method for a set of only radio links before becoming a radio mesh network, it cannot communicate only to the node connected directly by a radio link.

Therefore, *confirmed low-ayer reachable nodes* are part of the needed connections in the existing Delaunay overlay network construction method. Naturally, the existing method cannot construct a Delaunay overlay network.

Therefore, by the proposed method, *virtual direct overlay connections using detours* as in Fig. 7 are constructed and used as a substitute for a *direct overlay connection*.

The existing method directly changes to *direct overlay connections* of one-hop by the locator of a low-layer network. On the other hand, proposal method constructs a liner overlay connection by combine some *Direct overlay connections*, and is used as new *Direct overlay connections*.

*Virtual direct overlay connections using detours* in Fig. 7 are equivalent to this detour path. It is necessary to know the relay node in order to construct the path. The connection transfer message or notification of triangulation message from a certain node starts the new establishment process of a connection in the composition method by reaching the node of both ends of the newly and conventionally established connection. That is, the node that has sent the message has a connection with both nodes, and can be used as a relay node. Based on the above, this section proposes the basic idea and composition procedure of the Delaunay overlay network construction using the overlay of the shape of a line used as a detour path. A greedy routing procedure for when a detour path overlay network exists is also proposed.

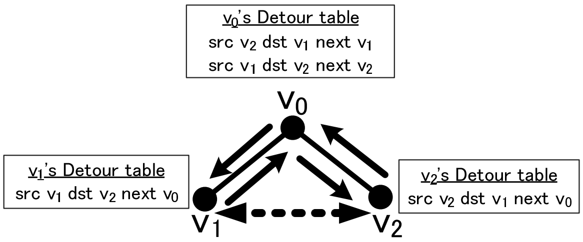


**Fig. 9** Formation of an relay node of Delegation of connection message and notification of triangulation message publication node.

### 3.3 Detour Path Construction Method that Passes along a Message Publication Node

This subsection describes the composition method of the overlay of the shape of a line used as the detour path for a Delaunay overlay network.

**Assumptions addition**

The following premises are added to premises 1 though 5 before presenting the outline in Section 2.1.

**6.** Each node $v_i$ has a detour table.

**7.** Each node holds the list of publishers of delegation of a connection message and notification of triangulation message that was received.

And, premise **2** is removed.

In **Fig. 9**, $v_0$ is the publisher of the delegation of connection messages or notification for triangulation messages. $v_1$ and $v_2$ will connect with each other via the messages. Solid lines represent direct overlay connections. The dotted arrow is a connection that failed in construction via underlay networks. Solid arrows indicate a detour route. The composition procedure of the detour path that makes an agency node the publisher of a message that transmits new node information to a lower-layer is described.

In Fig. 9 when a low-layer network $v_1$ and $v_2$ cannot connect mutually, and the detour path that sets to a relay node the node ($v_0$) that has transmitted new node information, is constructed.

Detour paths are constructed by some node's detour path routing tables as liner overlay networks for substitute the possessed DirectOverlayConnection. The detour path has a source (src) and destination (dst). Each column of the table has the next node for arriving at the destination.

An agency node candidate is selected from the received list of publishers of a connection transfer message and a notification of a triangulation message. The following list and **Fig. 10** show a detailed sequence for constructing detour tables in $v_2$. Though the detour path composition based on notification of triangulation messages is shown, the procedure when based on a connection transfer message is also the same. Each column of a detour path table is also constructed by src (source node), dst (destination node), next (the following transmission place), and detourID.

**Step 1.** $v_0$ executes local Delaunay triangulation.

**Step 2.** $v_0$ sends TriangulationNotificationMessage to $v_2$. The TriangulationNotificationMessage ($v_1$) means that the receiver construct an underlay connection with $v_1$.

**Step 3.** $v_2$ tries to construct a connection to $v_1$ by using the underlay network.

**Step 4.** If the underlay connection construction process fails, $v_2$ sends a DetourAdvertisementMessage to $v_1$ through $v_0$.

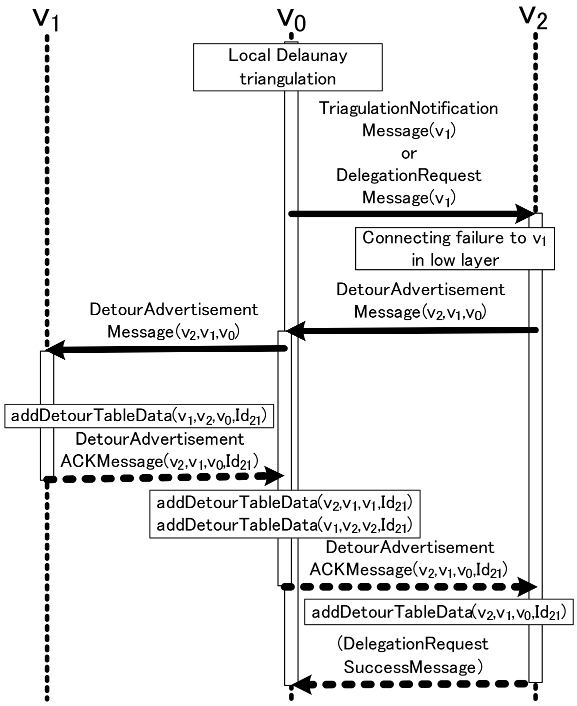


**Fig. 10** Detour table construction sequence diagram.

**Step 5.** If $v_1$ receives a DetourAdvertisementMessage from $v_2$, $v_1$ inserts new data in its detour table via addDetourTableData ($v_1$, $v_2$, $v_0$, $Id_{21}$). This method adds new detour table data (src $v_1$ dst $v_2$ next $v_0$, detourID $Id_{21}$) to the detour table. And, DetourAdvertismentACKMessage is generated based on received DetourAdvertisementMessage and $v_1$'s direct overlay connections.

**Step 6.** $v_1$ sends DetourAdvertisementACKMessage to $v_0$.

**Step 7.** If $v_0$ receives a DetourAdvertisementACKMessage from $v_1$, $v_0$ inserts new data in its detour table via addDetourTableData ($v_2$, $v_1$, $v_1$, $Id_{21}$) and addDetourTableData ($v_1$, $v_2$, $v_2$, $Id_{21}$).

**Step 8.** $v_0$ sends DetourAdvertisementACKMessage to $v_2$.

**Step 9.** If $v_2$ receives a DetourAdvertisementACKMessage from $v_0$, $v_2$ inserts new data in its detour table via addDetourTableData ($v_2$, $v_1$, $v_0$, $Id_{21}$).

The above process generates a liner overlay network between $v_1$ and $v_2$. In the existing method, when $v_0$'s connection is delegated, delegated connections are disconnected. But in the proposed method, when detour paths use a delegated connection, connections are maintained. Since the proposed method is concealed in the connection establishment process in the existing method, it does not affect the existing method's composition procedure. In Fig. 7, constructed detour paths are managed as a type of direct overlay connections. All that is needed is to add the maintenance as a detour path overlay of a standalone, and this does not affect the treatment of local Delaunay overlay connections.

### 3.4 Generating Detour Path on Other Detour Paths

Since a Delaunay overlay composition layer considers that a detour path is a direct overlay connection, a detour path may be created as in **Fig. 11** using this connection. This nested Detour

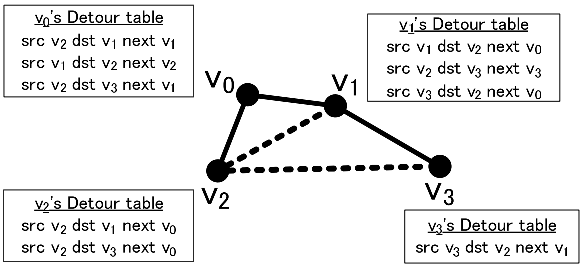


**Fig. 11** Constructing nested detour paths ($v_3$-$v_1$-$v_2$).

| Number of nodes | 200 | 400 | 600 | 800 | 1000 |
|---|---|---|---|---|---|
| Direct overlay connections | 579 | 1182 | 1779 | 2376 | 2974 |
| Detour overlay connections(r=0.1) | 54(9.3%) | 31(2.6%) | 27(1.5%) | 24(1.0%) | 25(0.8%) |
| Detour overlay connections(r=0.15) | 13(2.2%) | 13(1.0%) | 10(0.5%) | 9(0.3%) | 7(0.2%) |

**Fig. 12** Numbers of direct overlay connections and direct overlay connections using detour path by proposed method.

Table Data for detour paths is added to a course node based on the node information passed at the time of transmission of the DetourAdvertisementACKMessage.

### 3.5 Greedy Routing Using Detour Paths

Greedy routing in a Delaunay overlay network using a detour path is effective for performing routing that comes closer to the destination than in a direct overlay connection or detour path table. As long as a transmission location is chosen based on the position of dst in detour tables, even if it is not from the starting point of a detour path, the destination can be received because of the characteristics of greedy routing.

## 4. Evaluation via Simulation

This section evaluates the Delaunay overlay network construction method using a detour path. Nodes are arranged uniformly to the Euclidean plane of 1*1. The numbers of nodes in network range from 200 to 1,000. The topologies are generated by using unit disc graph [5]. The unit disc graph (UDG) topology imitates wireless mesh topology [5]. The disc radius r is 0.1 and 0.15.

Low neighborhood correlation between the Euclidean plane and discrete graph tends to generate very long detour paths. Therefore, we evaluate detour path length and detour table size on the topology that connects the arranged node serially at random (serial graph).

The above three topologies for evaluation can change to Delaunay graph by the proposal method. A simulation was implemented using Java for the instance equivalent to a message between the instances expressing each node.

The number of direct overlay connections and direct overlay connections using a detour path by the proposed method are shown in **Fig. 12**. For complete success, position based greedy routing needs all Delaunay overlay connections. Even in high density (UDG r = 0.15), adding a small number of detour path connections are needed. Thus, position-based routing successfully works with the proposed method. Incidentally, when the proposed method is executed without using a detour, the constructed overlay network topology is a subgraph of UDG.

**Figure 13** shows the average hop counts and the maximum hop counts in the combination of two arbitrary nodes in a network. Each maximum is worst case scenario in each evaluation.

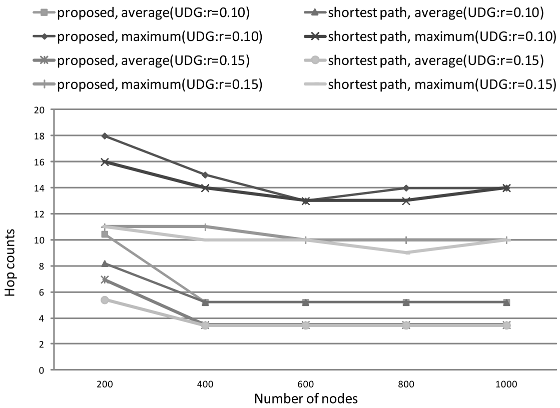


**Fig. 13** Average hop counts and maximum hop counts.

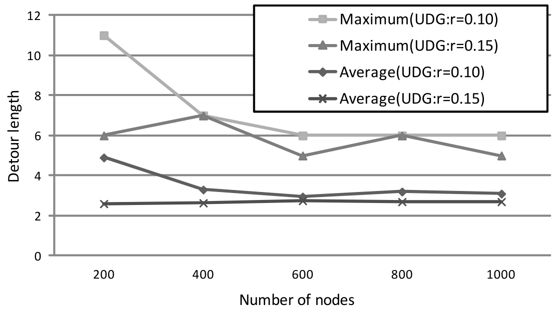


**Fig. 14** Detour path length on UDG.

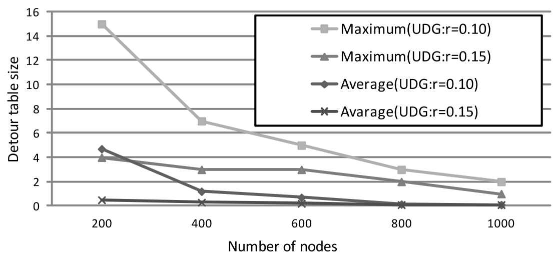


**Fig. 15** Detour table size on UDG.

The numbers of hop counts are measured with the shortest path by hop based Dijkstra search method [6] and the proposed routing method. This evaluation is for making reference value of the proposed routing's optimal degree. The proposed method is effective when there is a low difference between the proposed routing's path hop counts and shortest path hop counts. Direct overlay connections were constructed for all the nodes by unit disc. At high density (i.e., 400 nodes or more), the maximum hop count in the proposed routing method is almost the same as that in the shortest path method. Even in low density (200 nodes), the difference was seen slightly. The average hop counts are also measured and tendency is the same as the case of maximum hop counts. Therefore, the proposed method is applicable to these networks with almost optimum performance. In high-density situations, every one-hop maximum distance on the Euclidean plane is the same as for low-density situations. The distance is UDG's radius (0.1 or 0.15). Therefore, hop counts are the same in several higher-density situations.

The detour path length and table size in two types of UDG are shown in **Fig. 14** and **Fig. 15**. The detour path length is the same as advertisement message's exchange range for detour construction. Therefore, the length can be used as an indicator for

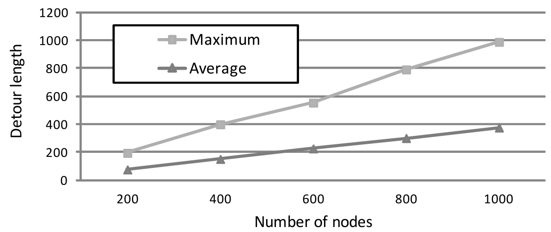


**Fig. 16** Detour path length on serial graph.

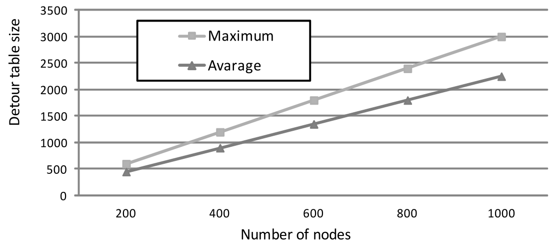


**Fig. 17** Detour table size on serial graph.

localized networking methods. The detour table size can also be used as an indicator for usage memory resources. The maximum hop counts in shortest path in Fig. 13 is the same as advertisement message's exchange range by general networking method using general location advertisement. Therefore, we compare between the detour path length and the shortest path hop counts for a proof of exchange range's locality of the proposed method. For example, when r = 0.1 and 200 nodes, the maximum detour path length is about 70% of the maximum shortest path hop counts. And, when r = 0.1 and 1,000 nodes, the maximum detour path length is about 40% of the maximum shortest path hop counts. In all the cases, the proposed method's advertisement message's exchange range is lower than the general networking methods. And, in highest density cases, the detour path length percentage is the lowest than other cases. Therefore, when neighbor nodes are connected, proposed method is more effective than general networking methods. And, detour table size is low value in 400 nodes or more. On the other hand, the general networking method's routing table size is equal to the number of nodes. Because, general location advertisements are sent from all nodes to all nodes.

From the above the detour path length size evaluation and the detour table size evaluation, the proposed method has locality and scalability in situations that enough neighbors interconnected.

The detour path length and detour table size in the serial graph are shown in **Fig. 16** and **Fig. 17**. The evaluation is for a topology that serially connects the arranged node at random (serial graph). Therefore, in the topology, nodes almost connect to non-neighborhood nodes on the Euclidean plane. In this result, the detour path length and table size are, however, extremely large. This is because there is a very low possibility of each node will being connected with neighboring nodes, unlike for UDG. Moreover, as the number of nodes becomes large, the possibility that each node has connected with a neighboring node in space decreases. For this reason, the detour path length and table size ultimately turns out to be large. But detour paths can be constructed on the topology. Therefore the proposed method is applicable to non-neighborhood graph topology too.

From above all results, the proposed method has high scalability overlay network on wireless mesh network. The proposed routing method also provide high routing performance on the proposed overlay network on wireless mesh network.

## 5. Related Work

For the sake of scalability, routings on wireless networks need to avoid flooding. Research has therefore focused on communication cost-cutting routing methods using network structuring and limited-destination communication based on an ID or node position. Karp et al. [7] proposed greedy perimeter stateless routing (GPSR), a non-flooding method using greedy routing, and the right-hand rule on Gabriel graphs generated from unit disc graphs. Our proposed method, on the other hand, uses greedy routing and detour path routing, and is not premised on the existence of unit disc graphs. Liebeherr et al. [8] proposed a Delaunay overlay construction method that has a great deal of cooperative operation between nodes. For this reason it is difficult in a distributed environment. Li et al. [9] focused on the wireless communication range, proposing a k-localized Delaunay graph generated from a unit disc graph as a possible wireless-communications graph. They also discussed greedy routing on the network. Our method, however, can construct a detour path to nodes outside the wireless communication range; thus Delaunay networks can be constructed on a connected graph network. These are independent from the wireless communication range. Wang et al. [10] proposed a clustering method that divides a plane with grid partitioning. This method chooses a leader node in each partition. Leader nodes exchange routing information via multicast and each sends a multicast to the under-nodes of the others. Caesar et al. [11] proposed a greedy routing method using a chord ring structure. When neighbors on the ID space are out of the communication range, each node uses a multi-hop path to the neighbors. However, the number of links to neighbors increases with an increase in the number of nodes. Our proposed method has a constant number of neighbors.

## 6. Conclusion

This paper shows a problem that the existing Delaunay overlay network construction method cannot apply to PRN. And, a new applicable to PRN method using detour paths is proposed. The new method does not affect the convergence principle and implementation of the existing method. Moreover, a simulation is used to verify that the method operates in a set of low-layer connections before networking. The proposed method is confirmed as having high locality in the control signal exchange range, low memory usage, high scalability for networking, and high routing performance. The method is also confirmed that the topology is usable in a low-correlation neighborhood relation between nodes on Euclidean plane.

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