Postprint: Improved Design and Testing of AODV Routing Protocol for Multi-Robot Communication in Orchards

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Abstract

To address the communication requirements of multi-robots operating in orchards, this study proposes an improved Ad hoc On-Demand Distance Vector Routing Protocol (AODV-SP) that introduces priority nodes and a path signal strength threshold, based on a prediction model for Wi-Fi signal received strength in peach orchards. The AODV-SP packets were designed, and NS2 simulation software was utilized to compare the performance of the Ad hoc On-Demand Distance Vector Routing Protocol (AODV) and AODV-SP across four aspects: initiation frequency, routing overhead, average end-to-end delay, and packet delivery rate. The simulation results demonstrate that the AODV-SP routing protocol proposed in this study outperforms the AODV protocol in all four performance metrics. Specifically, when the node mobility speed is 5 m/s, the route initiation frequency and routing overhead of AODV-SP are reduced by 3.65% and 7.09% respectively compared to AODV; when the node mobility speed is 8 m/s, the packet delivery rate of AODV-SP is improved by 0.59%, and the average end-to-end delay is reduced by 13.09%. To further validate the performance of the AODV-SP protocol, a small-scale multi-robot wireless communication physical platform based on the leader-follower method was constructed in a laboratory environment, and AODV-SP was implemented on this platform for static packet loss rate and dynamic testing. The test results indicate that the static packet loss rate is 0 when nodes are 25 m apart, and 21.01% at a distance of 100 m; during dynamic movement, the robots can maintain a chain topology structure. This study can provide a reference for the deployment of communication systems for multi-robots in actual orchard environments.

Improved AODV Routing Protocol for Multi-Robot Communication in Orchard

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Abstract

To address the communication requirements of multiple robots operating in orchards, this study proposes an improved Ad Hoc On-Demand Distance Vector routing protocol based on signal strength threshold and priority nodes (AODV-SP), built upon a prediction model for Wi-Fi signal reception strength in peach orchards. Unlike the traditional AODV protocol, AODV-SP incorporates the concepts of priority nodes and signal strength thresholds to construct a discovery routing algorithm and a selection routing algorithm by seeking priority nodes and calculating the maximum strength threshold between nodes, respectively. The discovery routing message and selection routing message of the AODV-SP protocol were designed according to these algorithms. To verify the performance of AODV-SP, the protocol's performance under different maximum node movement speeds was analyzed using NS2 simulation software and compared with the traditional AODV protocol. Simulation results demonstrated that the average end-to-end delay, route initiation frequency, and route overhead of AODV-SP were smaller than those of the traditional AODV protocol, while the packet delivery rate improved significantly. Specifically, when the maximum node movement speed was 5 m/s, the route initiation frequency and route overhead of AODV-SP were reduced by 3.65% and 7.09%, respectively, compared with AODV. When the maximum node movement speed was 8 m/s, the packet delivery rate of AODV-SP improved by 0.59% and the average end-to-end delay decreased by 13.09%. To further validate the simulation results and ensure AODV-SP' s applicability to multi-robot wireless communication systems, a physical platform for multi-robot wireless communication was built in a laboratory environment, with software designed to enable proper communication under the AODV-SP protocol. The physical platform was tested under both static and dynamic conditions. Experimental results showed that under static conditions, the packet loss rate was 0% when the distance between nodes was $ $25 m, and 21.01% at 100 m. Under dynamic conditions, the following robots could maintain a chain topology with the leader robot. Both simulation and physical platform experiments demonstrated that AODV-SP can be used for constructing multi-robot communication systems in orchards.

Keywords: orchard; AODV-SP protocol; wireless communication; multi-robot; physical platform; simulation

1 Introduction

Orchard production operations are characterized by high labor intensity and seasonal labor shortages. Employing robots to replace manual labor can effectively alleviate seasonal labor shortages while significantly improving operational efficiency [1]. Multi-robot collaborative systems can accomplish tasks that are difficult for single robots to complete, with communication serving as the fundamental basis for information exchange and cooperation among robots [2].

Compared with other communication technologies, Wi-Fi offers advantages including fast transmission speed, good scalability, wide coverage, and relatively low equipment cost [3], with transmission distances that can satisfy the requirements of multi-robot communication in orchards. Wi-Fi operates in two networking modes: Infrastructure mode and Ad Hoc mode [4]. Since orchards typically lack communication infrastructure, adopting Ad Hoc networks to establish Wi-Fi communication environments represents a feasible solution for multi-robot communication, reducing costs while enabling task completion.

In Ad Hoc networks, routing protocols are critical technologies that ensure effective information exchange among nodes (i.e., robots). Based on route establishment methods, Ad Hoc network routing protocols can be classified as table-driven, on-demand, or hybrid [5]. Table-driven protocols enable immediate route acquisition when nodes have packets to send, but routing update overhead increases significantly when network topology changes as robots move through orchards [6]. The Ad Hoc On-Demand Distance Vector (AODV) protocol is an optimized version of the Destination Sequenced Distance Vector (DSDV) table-driven protocol [7,8] that reduces routing overhead and conserves network resources, making it suitable for harsh orchard environments [9]. Consequently, AODV has become a research hotspot in wireless communication in recent years [10].

Numerous improvements to AODV have been proposed. Bisen and Sharma [11] developed an energy-efficient routing method to reduce unnecessary message broadcasting. Das and Tripathi [12] proposed an intelligent energy-aware routing protocol to address mobility issues related to insufficient battery capacity. Fang et al. [13] introduced a lightweight secure routing protocol to simultaneously improve transmission performance and security. Lin et al. [14]

reduced communication overhead from flooding mechanisms by introducing a route-level optimization strategy. Wang [15] proposed an energy-optimized routing algorithm to reduce network energy consumption and extend network lifetime. Mafirabadza and Khatri [16] improved AODV to address network reconstruction issues caused by battery depletion by selecting paths with greater energy to increase network lifetime. Jabbar et al. [17] introduced an energy- and mobility-aware multipath relay selection mechanism to address unpredictable node movement and high overhead. Periyasamy and Karthikeyan [18] proposed a novel node-disjoint multipath routing protocol to address link failures and route breaks. Reddy and Satyanarayana [19] developed an efficient and stable multipath routing method based on node speed, direction, residual energy, and transmission power.

However, most existing agricultural environment routing protocol research focuses on wireless sensor networks, which are unsuitable for Ad Hoc networks lacking communication infrastructure—a common condition in orchard production environments. Furthermore, orchard environments feature low canopies, dense foliage, and overlapping branches that significantly impact node data transmission capabilities. Existing improved routing protocols are not well-suited for these conditions. Particularly in "one-to-all" broadcast communication modes, environmental factors can cause redundant propagation among robots, leading to data packet congestion, loss, route interruption, increased delay, and reduced stability of wireless communication systems.

To improve multi-robot communication performance in orchards, this study selected peach orchards as the environmental context. Based on a Wi-Fi signal propagation model obtained in peach orchard environments [21], we propose an improved Ad Hoc On-Demand Distance Vector routing protocol incorporating priority nodes and path signal strength thresholds (AODV-SP). The protocol was designed with modified control packets and evaluated using NS2 simulation software, comparing performance across four metrics: route initiation frequency, routing overhead, average end-to-end delay, and packet delivery rate.

2.1.1 Introduction of Priority Nodes in AODV-SP

AODV consists of two phases: route discovery and route maintenance [22], with route discovery forming the foundation. When a source node (the robot sending information) needs to communicate with a destination node (the final receiving robot), multiple paths can be generated through different intermediate nodes. Considering the strong mobility of nodes and resulting route instability, selecting nodes within the effective communication range of the source and intermediate nodes can improve signal strength and reduce the possibility of bandwidth saturation by useless information in "one-to-all" communication modes.

The parameter variable "priority node" is introduced during the route discovery phase of AODV-SP. Within the effective communication range $\pi \mathrm{R}^2$ of a source or intermediate node (Figure 1 [Figure 1: see original paper]), where

R represents the effective communication distance for receiving and transmitting information. The effective communication distance is determined through actual testing. When nodes transmit and receive information using 2.4 GHz Wi-Fi, the optimal reconnection distance after link breakage is 5 m; therefore, R is set to 5 m in this study.

When node S needs to transmit data to destination node D but lacks a valid route, it can broadcast RREQ messages network-wide to find a route. By evaluating the relationship between inter-node distance L and the source node' s effective communication distance R, nodes A and P within distance $L < R$ from source node S are selected as priority nodes. Node S generates and broadcasts RREQ packets to adjacent nodes A and P. Upon receiving the RREQ packets, nodes A and P determine whether they are destination node D or have route information to D. If they are the destination, they establish a reverse route and send RREP packets; otherwise, they update and forward the RREQ packets.

2.1.2 Addition of Signal Strength Threshold in AODV-SP

In the preliminary research stage, our team conducted experiments at the National Peach Industry Technology System Xi' an Comprehensive Experimental Station in Yangling, Shaanxi Province. The basic orchard environment featured: row spacing of approximately 4 m, plant spacing of about 2 m, tree height of about 3 m, canopy thickness of about 2.5 m, and trees over 10 years old. The main branches were relatively low, with dense foliage covering the rows and overlapping branches reaching a maximum height of only 1.2 m from the ground, allowing passage for only a single small robot. Mobile communication equipment mounted on small robots experienced signal refraction, reflection, and scattering due to surrounding tree canopies, trunks, and weeds, increasing signal loss probability.

Through Wi-Fi signal propagation experiments in peach orchards and SPSS regression analysis, prediction models for Wi-Fi signal reception strength were obtained for different transmission-reception node azimuth angles (0°, 30°, 60°, and 90°) and heights (25, 50, 75, and 100 cm) at various distances d (in meters) [21]:

For $0^\circ \leq \quad \leq 15^\circ$:

$$P_r = -24.53 \lg d$$

For $15^\circ < \quad < 45^\circ$:

$$P_r = -25.12 \lg d$$

For $45^\circ \leq \quad \leq 75^\circ$:

$$P_r = -23.55 \lg d$$

For $75^\circ < \quad \leq 90^\circ$:

$$P_r = -19.15 \lg d$$

where P_r is signal reception strength (dBm) and d is propagation distance (m).

The signal strength threshold between nodes is calculated as:

$$\eta_{ij} = P_{rij}$$

where P_{rij} is the signal reception strength at node j when node i is the transmitting node (dBm), and η_{ij} is the signal strength threshold between nodes i and j (dBm). The path signal strength threshold η is obtained through the Wi-Fi signal reception strength prediction model and added to the RREP packet.

The distance L between nodes is calculated as:

$$L = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}$$

where $\theta = \arctan\left|\frac{y_j - y_i}{x_j - x_i}\right|$ is calculated from the coordinates of node j and its previous hop node i; x_i, y_i are the coordinates of the previous hop node; and x_j, y_j are the coordinates of the current node.

The effective communication range threshold between nodes can be adjusted based on node density in the network. When node density is high, the effective communication range value should be appropriately reduced, and vice versa. After RREP is forwarded to the source node, the final path signal strength threshold η is calculated based on the received pairwise node thresholds, and the path with the strongest signal from source to destination is selected for communication.

2.2 AODV-SP Packet Design

To adapt AODV-SP, modifications were made to AODV-SP control packets: AODV-SP RREQ (Route Request) and AODV-SP RREP (Route Reply).

The AODV-SP RREQ packet seeks destination nodes in the network (Figure 2(a) [Figure 2: see original paper]). Fields include: Type (packet type), J (flag), R (repair flag), G (indicates whether intermediate nodes have routes to destination), D (acknowledgment flag), U (flag for unknown sequence numbers), Reserved, Hop Count, Destination IP Address, Destination Sequence Number, Originator IP Address, and Originator Sequence Number. Additionally, compared with traditional AODV, the AODV-SP RREQ packet includes Source X-coordinate, Source Y-coordinate, Previous X-coordinate, Previous Y-coordinate, and Effective Communication Range.

The AODV-SP RREP packet acknowledges information receipt at destination nodes (Figure 2(b) [Figure 2: see original paper]). Fields Type, R, Reserved, Hop Count, Destination IP Address, Destination Sequence Number, Originator IP Address, Previous X-coordinate, and Previous Y-coordinate are identical to those in RREQ. Unlike traditional AODV, field A indicates reply flag, Prefix Sz indicates prefix length, Lifetime indicates RREP packet duration, Destination X-coordinate and Destination Y-coordinate indicate destination node coordinates, and Path Signal Strength Threshold indicates the path signal strength threshold.

3 AODV-SP Routing Algorithm Construction

Drawing on the working principle of AODV' s route discovery phase and corresponding to AODV-SP' s "priority nodes" and signal strength threshold, the AODV-SP routing algorithm implementation consists of two main components: a discovery routing algorithm (corresponding to "priority nodes") and a selection routing algorithm (corresponding to "signal strength").

3.1 Discovery Routing Algorithm

The AODV-SP discovery routing algorithm flow is shown in Figure 3 [Figure 3: see original paper]. When source node S sends data packets to destination node D, it first checks its routing table for a direct route to D. If a route exists, data communication proceeds along this path. Otherwise, source node S initiates a route request and broadcasts RREQ packets to adjacent nodes A and P. Upon receiving RREQ, nodes A and P determine whether they are destination node D or have a route to D. If so, a reverse route is established. Otherwise, the inter-node distance L is calculated using formula (1), and the relationship between L and effective communication distance R is evaluated to determine whether the node is a priority node of the previous node. If it is a priority node, the RREQ packet is forwarded; otherwise, it is discarded.

Inter-node distance L is obtained from node coordinates using the Universal Transverse Mercator (UTM) coordinate system to convert Global Navigation Satellite System (GNSS) latitude and longitude information. By introducing priority nodes, only two routing paths are used to broadcast RREQ packets (as shown in Figure 1), reducing flooding from two non-priority node routes and effectively suppressing AODV broadcast storms.

3.2 Selection Routing Algorithm

Route selection is crucial for providing reliable communication services in multi-robot systems [23]. The AODV-SP route selection algorithm flow is shown in Figure 4 [Figure 4: see original paper]. When an intermediate node receives an RREP packet, it first calculates the signal strength threshold η_{ij} for that node using formula (4). If $\eta_{ij} < 1$, the packet is forwarded and the path signal strength threshold is calculated using formula (5); otherwise, the packet is discarded.

When the destination node receives RREP packets, it evaluates the signal node strength thresholds of all possible routes and selects the path with the smallest signal node strength threshold as the optimal route from source to destination. As shown in Figure 4, after introducing node signal strength threshold and path signal strength threshold, the data transmission capability of each node is fully considered. Paths with signal node strength threshold η are first discarded. The path signal strength thresholds of remaining routes are calculated, and the route with the smallest value (e.g., path D with threshold 2.35) is selected as the data communication path between source node S and destination node D.

By introducing priority nodes and signal node strength thresholds, the number of routing paths for multi-robot "one-to-all" communication in orchards is reduced from four to one, ensuring effective information transmission while reducing bandwidth saturation by useless information.

4 AODV-SP Performance Simulation Testing

To verify the improved AODV-SP performance, NS2 simulation software was used to analyze protocol performance under different node movement speeds and compare it with traditional AODV.

4.1 Simulation Environment Setup and Parameter Configuration

NS2 is an object-oriented, discrete-event-driven, open-source network simulator. The simulation environment referenced the orchard environment of the National Peach Industry Technology System Xi' an Comprehensive Experimental Station, configured as a 500 m × 500 m area with 300 s simulation time. The system randomly generated 50 nodes distributed randomly, with each node moving at different speeds within the 500 m × 500 m area according to the Random Waypoint mobility model configured in Table 1 .

Agricultural robots have different operating speeds depending on their tasks. Weeding robots typically travel at 0.45-1 m/s [24], while spraying and fertilizing robots operate at higher speeds [25,26]. For example, field autonomous sprayers travel at 3-8 m/s, and aerial UAV sprayers operate at 1-10 m/s [27]. To ensure the improved protocol is suitable for high-speed agricultural robots, node movement speeds were set to 1-10 m/s, referencing agricultural spraying robots. Simulation results are shown in Figure 5 [Figure 5: see original paper]. Specific parameters are listed in Table 1.

Table 1 AODV-SP Simulation Parameters

Parameter	Value
Simulation time (s)	300
Simulation area (m^2)	500 × 500
Traffic type	CBR
MAC layer model	IEEE 802.11b
Mobility model	Random Waypoint
Movement speed (m/s)	1, 2, ···, 10
Transmission distance (m)	105

4.2 Simulation Test Results and Analysis

Performance differences between AODV and AODV-SP were compared across four metrics—route initiation frequency, routing overhead, average end-to-end delay, and packet delivery rate—to verify improvement effectiveness. To ensure accuracy, each result represents the average of 10 trials.

(1) Route Initiation Frequency: The ratio of route requests initiated by source nodes to simulation time, indicating network stability (formula (6)):

$$\text{Route Initiation Frequency} = \frac{\text{Source node route requests}}{\text{Simulation time}}$$

(2) Routing Overhead: The ratio of control packets for route discovery and maintenance to data packets received by destination nodes, indicating network overhead (formula (7)):

$$\text{Routing Overhead} = \frac{\text{Total control packets}}{\text{Received data packets}}$$

(3) Average End-to-End Delay: The average time required for packets to travel from source to destination, indicating network real-time performance (formula (8)):

$$\text{Average End-to-End Delay} = \frac{\text{Packet reception time} - \text{Packet sending time}}{\text{Number of received packets}}$$

(4) Packet Delivery Rate: The ratio of data packets received by destination nodes to those sent by source nodes, indicating network reliability (formula (9)):

$$\text{Packet Delivery Rate} = \frac{\text{Packets received by destination}}{\text{Packets sent by source}}$$

Test results are shown in Figure 6 [Figure 6: see original paper]. AODV-SP demonstrated lower average end-to-end delay, route initiation frequency, and routing overhead compared to original AODV, with significantly improved packet delivery rate. Specifically, at 5 m/s node speed, AODV-SP reduced route initiation frequency and routing overhead by 3.65% and 7.09%, respectively. At 8 m/s node speed, packet delivery rate improved by 0.59% and average end-to-end delay decreased by 13.09%.

The introduction of priority nodes and path signal strength thresholds makes selected paths more stable and less prone to breakage. Consequently, AODV-SP exhibits lower route initiation frequency than AODV at different node speeds (Figure 6(a)). At 5 m/s, AODV-SP reduced route initiation frequency by 4.73% compared to original AODV.

Routing overhead increases with node mobility (Figure 6(b)). However, AODV-SP' s more stable routing reduces route breakage probability, decreasing route discovery and maintenance packets. At 5 m/s, AODV-SP reduced routing overhead by 8.38% compared to original AODV.

Both protocols show small average end-to-end delay at low speeds, with delay increasing as network node speed increases (Figure 6(c)). AODV-SP' s higher route reliability saves significant route discovery time, resulting in lower delay than AODV at the same speed. At 8 m/s, AODV-SP reduced average end-to-end delay by 13.09%.

Packet delivery rate decreases as node mobility increases (Figure 6(d)). AODV-SP's improved route stability reduces route breakage probability, yielding higher packet delivery rates than AODV at the same speed. At 8 m/s, AODV-SP improved packet delivery rate by 0.59%.

Simulation results indicate that while traditional AODV and node mobility cause increased route initiation frequency, routing overhead, and average end-to-end delay—impacting communication stability and real-time performance, with correspondingly lower packet delivery rates and poorer reliability—AODV-SP provides improvements in communication delay, energy consumption, and route breakage.

5 AODV-SP Physical Platform Testing

To further verify AODV-SP simulation results and ensure applicability to multi-robot wireless communication systems, a physical platform for multi-robot wireless communication was built using the commonly employed leader-follower formation control method. The platform' s communication performance was tested.

5.1 Multi-Robot Wireless Communication Physical Platform Construction

To ensure proper operation, the platform' s system hardware and software were designed based on leader-follower multi-robot motion patterns. The leader robot is controlled by a remote controller, while follower robots maintain consistent motion states with the leader through wireless communication system information exchange.

5.1.1 System Hardware Selection The multi-robot system hardware employs an ARM11-based S3C6410 processor (Forlinx OK6410-A development board) equipped with an SDIO Wi-Fi module (FIT-WIFI-II_{RTL8189ES}), GNSS module (ATGM332D-5N), ultrasonic sensor (HC-SR04), infrared sensor (5 mm IR pair), and 4.3-inch LCD screen (Figure 7 [Figure 7: see original paper]). The Wi-Fi module handles data packet communication, the GNSS module obtains robot latitude and longitude information (converted to coordinates via UTM), ultrasonic sensors detect following distance in peach orchards, infrared sensors maintain following distance, and the LCD displays robot operation and command information.

5.1.2 Communication System Software Design The communication system software primarily includes modified AODV-SP packet programming and a data packet visualization interface. Data transmission format is shown in Table 2 . Except for start and stop bits, D0, D1, D3, and COM represent the machine identifier (leader robot set as "0" , follower robots incrementing from "1"), IP address, operational status, and control commands (forward, left turn, right turn, stop), respectively. Qt Creator was used to design a real-time visualization interface displaying robot IP address, operational status, latitude/longitude information, following distance, and other robots' status. The wireless communication system updates information every 100 ms. After initialization, the system continuously monitors for data packets. When the leader robot receives packets from followers, it extracts data to check for abnormal stop commands, stopping if abnormalities occur; otherwise, it sends control commands and continues monitoring.

Table 2 Communication System Data Packet Format

Field	Size (bits)
Start bit	8
D0	8
D1	8
D3	8
COM	8
Stop bit	8

5.2 AODV-SP Testing

Packet loss rate and communication link interruption are critical metrics for orchard multi-robot communication systems. Network packet loss rate and physical platform tests were conducted to verify data packet loss and communication link interruption under static and dynamic conditions in a laboratory environment.

5.2.1 Static Packet Loss Rate Testing Peach orchard plant spacing is approximately 2 m with row spacing of about 4 m. The Wi-Fi communication module' s maximum effective communication distance is 105 m. To ensure the leader robot can establish connections with followers through Wi-Fi, the communication distance corresponding to 0% packet loss rate (25 m) was used as the initial test distance, with test intervals of 5 m and maximum communication distance of 100 m. During each test, the leader robot sent 400 data groups, and packet loss rate was calculated by recording the number of packets received by followers. Test results showed 0% packet loss rate at 25 m node distance and 21.01% at 100 m, demonstrating applicability for peach orchard multi-robot collaborative operations (Table 3).

Table 3 Packet Loss Rate of Multi-Robot Data Transmission in Wi-Fi Network

Distance (m)	Packet Loss Rate (%)
25	0
100	21.01

5.2.2 Dynamic Multi-Robot Communication System Testing To test data loss and communication link interruption under dynamic conditions, IP addresses were automatically assigned to leader robot A and follower robots B and C, with ports manually set to 9000. Based on infrared sensor effective detection range, inter-robot distance was set to 40 m. The physical platform robots operated in chain topology formation, with robots sequentially traversing previous robots' positions along a straight line (Figure 8 [Figure 8: see original paper]).

The remote controller first sends commands to leader robot A. Upon receiving control signals, robot A executes commands while continuously updating data packets with latitude/longitude and control information, transmitting them to follower robots. Follower robots B and C parse and execute commands from received packets, periodically updating their latitude/longitude, operational status, and following distance information. Follower robot B sends packets to leader robot A, while follower robot C sends packets to both leader robot A and follower robot B. As shown in the visualization interface (Figure 9 [Figure 9: see original paper]), the multi-robot physical wireless communication platform achieves bidirectional communication during motion, with follower robots completing formation straight-line and turning maneuvers according to control commands. Test results demonstrate that AODV-SP is applicable to multi-robot wireless communication physical platforms.

6 Conclusion

This study addresses multi-robot communication needs in peach orchards by proposing an AODV-SP protocol based on a Wi-Fi signal reception strength prediction model. AODV-SP introduces priority nodes and path signal strength threshold parameters as route request considerations during route discovery. NS2 simulation comparisons between existing AODV and improved AODV-SP show that AODV-SP outperforms AODV in route initiation frequency, routing overhead, average end-to-end delay, and packet delivery rate. At 5 m/s node speed, AODV-SP reduced route initiation frequency and routing overhead by 3.65% and 7.09%, respectively. At 8 m/s node speed, packet delivery rate improved by 0.59% and average end-to-end delay decreased by 13.09%.

To further verify AODV-SP' s practicality, a leader-follower based multi-robot wireless communication physical platform was constructed and tested for packet loss rate and transmission performance. Results showed 0% packet loss at 25 m node distance and 21.01% at 100 m under static conditions. Dynamic testing demonstrated that robots could maintain chain topology formation. This research provides a reference for constructing multi-robot communication systems in actual orchard environments.

Future work should consider the impact of node mobility states on routing and port the communication system to orchard-operating robots for further testing in real orchard environments.

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Note: Figure translations are in progress. See original paper for figures.