Research Article

Using Mobile Robots to Establish Mobile Wireless Mesh Networks and Increase Network Throughput

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We discuss the proof of concept that gives mobile robotic units the ability to provide a mobile wireless mesh network providing wireless service to end-clients and also demonstrate the ability to increase the throughput of this mobile wireless mesh system by autonomously reducing the hop count required for network traffic to transit through. In doing so, this proof-of-concept contributes to future development of a robust system which can be deployed and utilized in different situations and industry.

1. Introduction

In the 21st century, WIFI and wireless hotspots are familiar services provided to consumers—specifically referring to the 802.11a/b/g/n IEEE standard. In many nations, consumers access data and web content using mobile devices such as tablets, phones, and laptops via WIFI. It has integrated so effectively into our lives and social fabric that we easily take it for granted. What would we do without broadband wireless?

The motivation of the paper is to demonstrate the ability of using mobile robotic units to establish a mobile mesh network. The concept of mobile networks using robotics is nothing of a novel idea as our research group already introduced in [1, 2]; however, the use of robots to form a wireless mesh broadband network is a novel idea and approach to providing broadband wireless service almost anywhere in the world and in any situation. We believe robotics autonomously forming self-healing broadband wireless networks will be the future of wireless services and data communication. Realisticly, we look to apply this technology first to search-and-rescue situations. However, we introduce this concept with the intent for it to be applicable to many different industries and situations.

The purpose of this paper is to demonstrate a proof-of-concept robotic system that utilizes wireless mesh technology to form autonomous wireless broadband networks. Furthermore, the system will also demonstrate the ability to increase the throughput of the existing system by redistributing the nodes of the existing network given that a precondition is met. Through this proof-of-concept, we hope to show the potential of future networks to be self-forming, adaptable, and self-healing whenever node failures exist in the network. We further emphasize that the use of mesh technology is a differentiating factor from other existing systems with a similar purpose.

In this paper, we will discuss related works and how our system and concept differ from other systems. We further explain and demonstrate how it is more scalable and adaptable. We reference our previous work regarding radio frequency (RF) signal sensing and the use of relative signal strength indicator (RSSI) [3] to control the actions of our robotic units. Thereafter, we apply this basic concept to multiple robotic units and test the system in an open outdoor environment. We will describe the layout and results of our simulation and experiment. Additionally, we will explain the algorithm of our system, demonstrating the proof of concept

of which we hope future research could use as a basis to build upon. Finally, we will discuss the assumptions and limitations that enable this system and concept to work and the future work that is required.

2. Background

Conventional mesh technology is known to be extensible, resilient, self-healing, and provide coverage in hard-to-wire areas [4, 5]. Conventional wireless implementations rely on a wired wireless distribution system (WDS) to communicate between APs for roaming and management; this communication link is known as the backhaul [6]. Mesh technology eliminates the need of a wired WDS. This enables mesh technology to be rapidly deployed with a lower-cost backhaul and allows more flexibility in the configuration of the network based on demand. Additionally, another benefit of wireless mesh technology is the high data rate of 54 Mbps [7]. With these benefits of wireless mesh access point (AP) compared to conventional wireless AP implementation and configuration, wireless mesh APs were used in our system to establish an autonomous wireless broadband networks [8].

We understand the importance of wireless communication; we utilize its services every time we check our email at the airport or coffee shop on our laptops, whenever we turn our phones to WIFI mode when we enter a building to check the news or the weather. Without a doubt, WIFI services are important. The degree of importance of communication and wireless communication is further elevated during instances of natural disasters. According to a World Health Organization (WHO) report after the earthquake of Haiti:

> *Information may be the most important commodity during emergencies. Information may also be the most rapid public health response ahead of the delivery of aid. In addition, the dissemination of information in a timely and transparent manner also helps generate trust and credibility in response activities and agencies providing relief [9].*

During severe natural disasters, like the earthquake of Haiti [10] or the tsunami that hit Japan in 2011 [11], communication infrastructures are either obliterated or so severely damaged that they are rendered inoperable. Hence, rescue teams and responders resort to two-way radios [12] or flying in circles broadcasting emergency messages to victims [13].

Our system or proof-of-concept's design goal is to provide broadband wireless communication. We find that if we can prove the ability to establish a mobile wireless mesh network, we can provide a basis for which this concept can be integrated onto different robotic platforms to be implemented during severe natural disasters. Because mesh network technology is known to be resilient, self-healing, and scalable, we find these qualities appropriate to address the need to fulfill a communication gap during severe natural disasters. Additionally, the ability of a mobile platform is desirable to accommodate for topographical challenges and operational movement of personnel.

There are similar systems and research ongoing with the same purpose and goal as our system; however, none have implemented mesh technology; hence, they do not benefit from the attributes of a mesh network. The US Navy uses robots to deploy network "relay bricks" to extend a single communication link to a robot from a far distance, allowing the operator to control the unit from many miles away [14]. The limitations of this approach are the ability to communicate with one end-device and the immovable nature of the "relay bricks." If the bricks were laid out in a northward direction, but later in the operation, the robot on the far end needed to move west, east, or south, the system would not be able to accommodate due to the immovable bricks.

In London, researchers use mobile robots equipped with ad hoc radios to help officials coordinate search and rescue operations. The use of ad hoc radios, however, limits the system from establishing communication with other nodes through a third-party node; all communication established must be peer to peer using ad hoc radios [15]. Another system known as Autonomous Wireless Aerial Vehicles (AWARE) uses aerial vehicles and personnel to establish a communication medium for emergency personnel. The system relies on aerial vehicles to place static wireless sensors in different locations to provide communication coverage for personnel. The system's static placement of wireless nodes does not scale well to changing environments and conditions or operational needs [16].

Our research concept began using small robotic units, iRobot Create [17], integrated with mesh AP, Proxim-4000 [18]; we successfully demonstrated the ability to have robots perform specified actions based on the RF signal received. We further demonstrated that based on simple RF sensing, our robotic unit was able to complete and optimize a communication link of which two stationary APs were initially placed at a distance and initially unreachable [1]. From this basic concept, we derived a more robust system, of which outdoor robots, P3-AT [19], were equipped with mesh APs with the goal to establish autonomously a linear wireless broadband mesh network [20].

The motivation for this paper is to demonstrate that it is possible to establish a mobile broadband wireless network using mobile robots and wireless mesh technology. The proof-of-concept is evaluated through a two-stage experiment of which the first stage, a wireless mesh network, is established in a linear topology. In the second stage of the experiment, we demonstrate the ability for a robot to redistribute autonomously the network to reduce the hop count network traffic transit, which results in an increase in throughput. The increase in throughput allows for more devices and units to exist on the network and to communicate and transmit data in a timely manner.

3. Concept of RF Signal Sensing

In our previous work, we experimented with the basic concept of RF signal sensing, and based on the RSSI the robotic unit performed a certain action. We denote the RSSI which a robotic unit responds to as the RSSI Threshold.
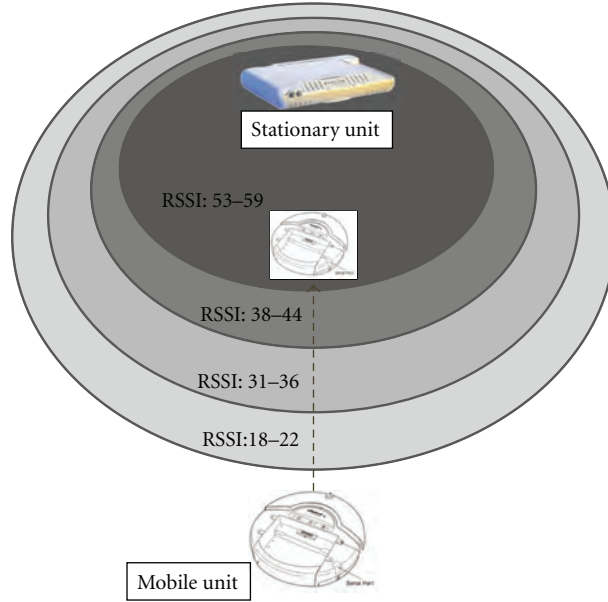
FIGURE 1: Basic RF sensing using iRobot Create and simple-reflex agent model [1].
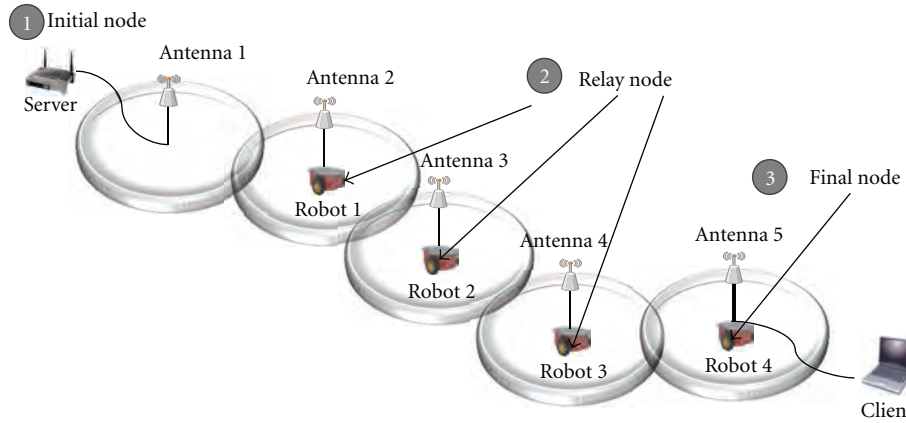

FIGURE 2: A configuration of self-configurable wireless networks using multiple mobile robots carrying antennas.

Figure 1 demonstrates the robotic unit's ability to stop when it detects an RSSI level greater than 53. This condition could have been applied to any RSSI level, but the condition **If** *RSSI Threshold* ≥53 **then** *stop* was used as an example—it is utilizing the simple-reflex agent-based model.

Based on this simple concept of RF sensing and utilizing simple-reflex agent model, we further applied it to our proof-of-concept using mesh technology with more robust robotic units.

4. Algorithm

The algorithm of this proof-of-concept consists of two stages: *linear expansion* (LE) and the *backbone infrastructure route optimization* (BIRO). Essentially, not only is it the experiment demonstrating that robotic units can autonomously create a mobile broadband mesh network but also it is

capable of increasing the throughput of the network by autonomously reducing the hop count that network traffic requires to transit through. The basic concept of using multiple robots in the proposed application is shown in Figure 2.

As depicted in Figure 2, the use of multiple mobile robots carrying APs will allow a wireless signal to be relayed from the server to the client. Each robot carries one AP with an internal antenna to form a linear network for long distance coverage. Also, additional antennas and radios can be added to create additional multipoint connections. The number of robots is determined by the requirements of the system, that is, $N_n = N_r$, where N_n is the number of nodes to form a linear link and N_r is the number of needed mobile robot. The set of robotic units in the algorithm can be then represented by $\mathbf{S} = \{L, F, T, R\}$, where L is a leader, F is a set of followers, T is a tail robotic unit, and R is a BIRO robotic unit. Then,
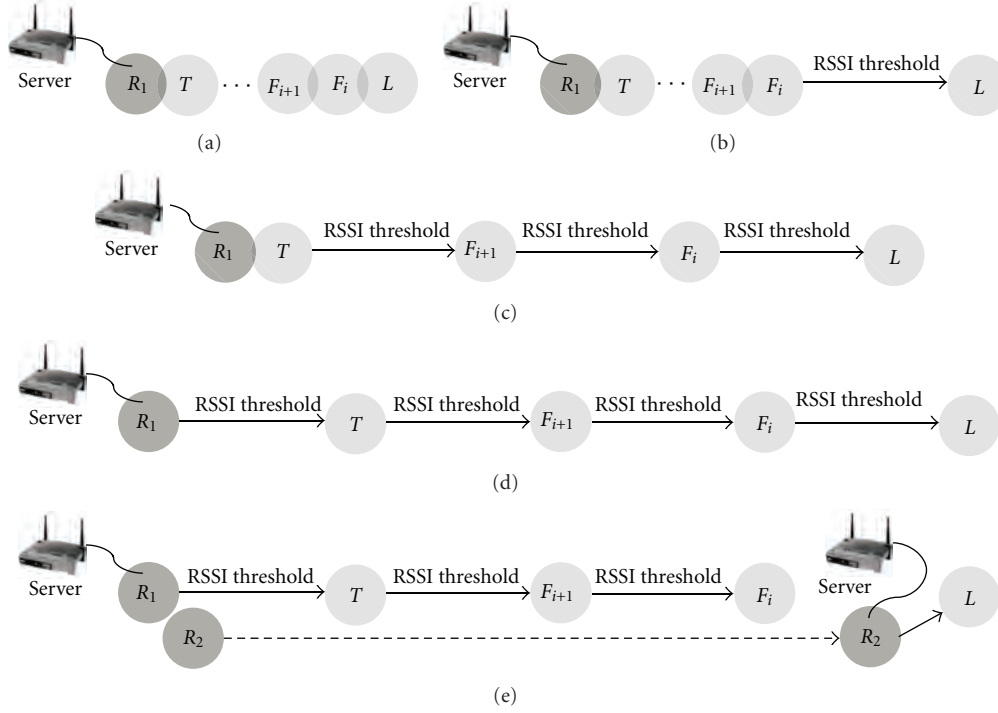
Figure 3: Visual description of LE algorithm: (a) initial state (b) for leader, L (c) for followers, F_i (d) for tail, T (e) visual description of BIRO algorithm.

the number of robotic units in the set **S** is determined by N_n. Their relations can be expressed as follows:

$$N_L = N_T = 1,$$
$$N_F = N_n - 2, \tag{1}$$

where N_L and N_T are the number of the leader and the tail, respectively, and N_F is the number of followers. Note that $N_n = N_r = (N_L + N_F + N_T)$. Thus, in order to form a linear link, N_r should be at least three (one is for the leader, second is for the follower, and last is for the tail robot).

In the first stage of the algorithm, LE, the purpose is to establish a wireless mesh link using multiple mobile mesh APs and a root AP. Additionally, the purpose of the LE stage is to stretch the coverage of the mobile network as far as possible without losing the established connection with the previous node.

LE stage begins with all multiple mobile units associated to the root node, which remains stationary and positioned in a straight convoy formation, as depicted in Figure 3(a). Each unit is assigned a role based on its position in the convoy. The first node is designated as L (leader). The nodes from the second unit to the unit preceding the last in line are designated as F_i (follower), where $i \in \{1 \ldots N_n - 2\}$. The last unit in line is designated as T (tail node).

The algorithm is set up so that the robots are always sensing RF signal to determine their action. In this algorithm, each robot is responsible for sensing the RF of the robot preceding it, and the tail node robot is responsible for sensing the RF of the stationary *root* or *gateway* meshed enabled AP.

With this algorithm, if the "*root*" AP is to move closer to the T node unit, then the entire system will move forward to account for the change in *RSSI Threshold* in effect, it would create a ripple effect that is reflected throughout the system.

Each robotic unit looks up their assigned priority and the assigned RSSI threshold limit, and sonar range limit. If robot is assigned "L," the robot will drive straight until the RSSI connection with "F_1" has reached the assigned RSSI threshold; that is, the condition **If** *RSSI Threshold* $\geq$ *certain value* **then** *stop* is activated. This role of the leader is algorithmically summarized in Algorithm 1 and is depicted in Figure 3(b) for a visual explanation.

If robot is assigned priority "F_i," object detection capabilities have been enabled, given the initial close proximity of the robotic units. The use of object detection prevents the robots from running into each other as they are sensing RF levels of their peers at different interval times. Then, the robot will drive straight until the RSSI connection with "F_{i+1}" or with "T" (if the robot is the last follower, i.e., when $i = N_n - 2$) has reached the assigned RSSI threshold. If there is an obstacle within the sonar range, the robot will stop. If obstacle is no longer in range, robot continues to drive if RSSI threshold has not been reached. This role of the follower is algorithmically summarized in Algorithm 2 and is depicted in Figure 3(c) for a visual explanation.

If robot is assigned T, object detection capabilities have been enabled as well, and the robot will drive straight until the RSSI connection with *root*1, R_1, has reached the assigned RSSI threshold. Then, most of its actions are similar with those of the follower. This role of the tail node is
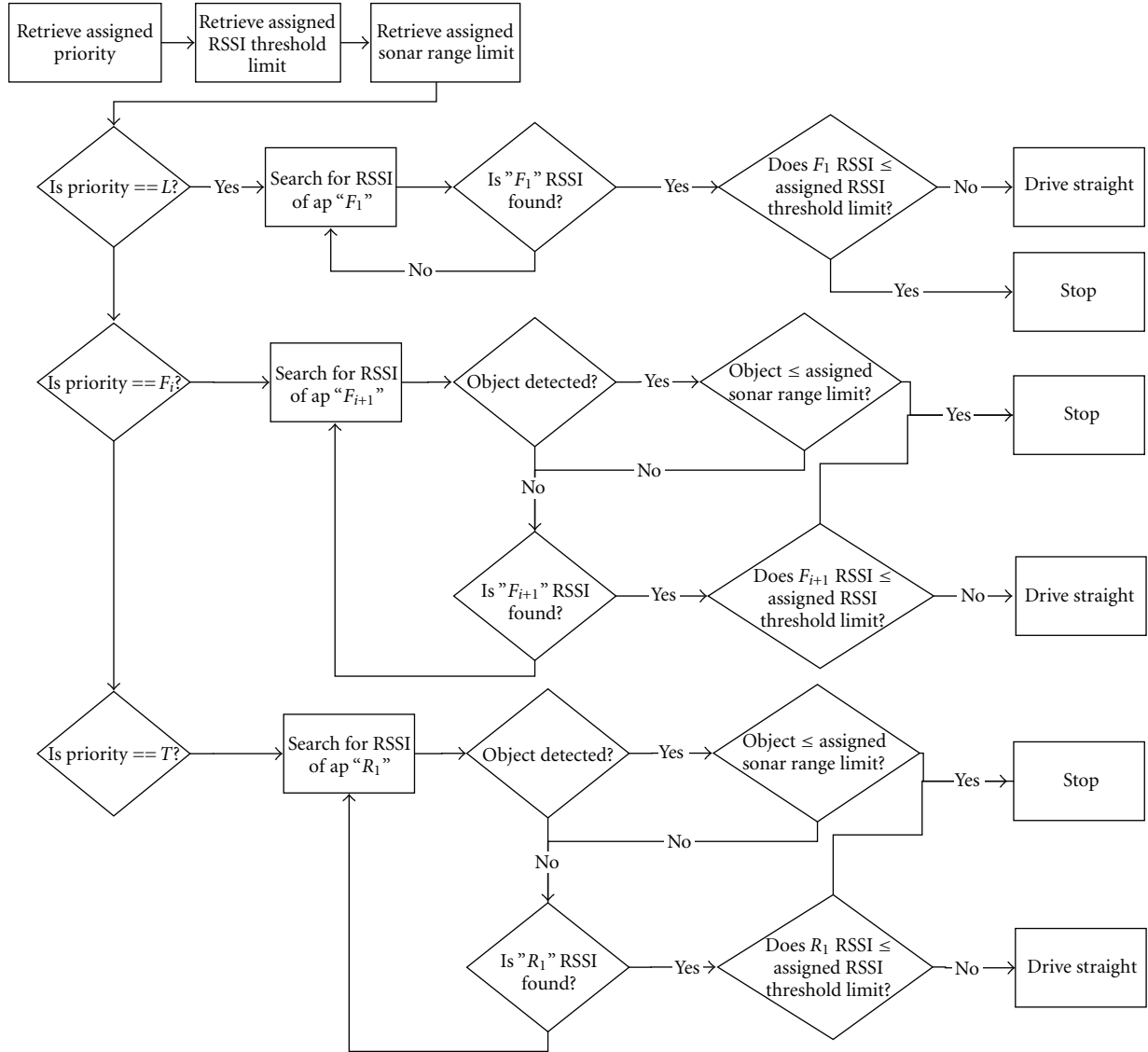
FIGURE 4: LE Algorithm formalized.

algorithmically summarized in **Algorithm 3** and is depicted in **Figure 3(d)** for a visual explanation. Then, **Figure 4** shows a formalization of the LE algorithm.

It is important to mention that the *root* or *gateway* mesh AP, denoted as R_1 in **Figure 3**, has the ability to redistribute nodes of an existing network. Using indicators such as *RSSI factor, Hop Factor*, and *Roaming Threshold* [3], the AP using its internal designed algorithm makes a decision of how to redistribute the network to reduce the hop count of network traffic. Based on *root* mesh AP ability to redistribute the network, a robotic unit is equipped with a *root* mesh AP, denoted as R_2. In the second stage of the experiment upon the completion of the first stage, the BIRO algorithm initiates.

In the BIRO algorithm, the robotic unit is designated as R_2 (*root*). This unit drives straight scanning its network topology tree until it detected "L," which is the end node of the network. Once the end node of the system is detected, then stop as shown in the algorithm in **Figure 3(e)**. The BIRO

algorithm is summarized in **Algorithm 4**. Then, this action changes the existing network topology tree and reduces the hop count that network traffic form "L" has to travel. Note that the BIRO algorithm is dependent upon the *root* mesh AP's ability to redistribute the network.

5. Simulation

To validate our approach, especially for the LE algorithm, we have built a simulation environment in Simulink of Matlab. We have then run the program in a second time scale to obtain the simulation results that would be the same as those from the real world. **Figure 5** represents the entire simulation environment, mainly composed of mobile robots motion block and main block with the LE algorithm (original simulation blocks were from [21] and slightly modified for this research). We have then established several assumptions as follows.

```
/* Stage 1. Linear Expansion Algorithm (LE)              */
/* For a leader                                          */
if Priority == "L" then
    repeat
        Search for RSSI of AP "F₁";
    until "F₁" RSSI found
    if "F₁" RSSI ≤ assigned RSSI threshold limit then
        Stop driving;
    else
        Drive straight;
```

ALGORITHM 1: The LE algorithm for a leader.

```
/* Stage 1. Linear Expansion Algorithm (LE)              */
/* For a follower                                        */
if Priority == "Fᵢ" then /*  i ∈ {1 … Nₙ − 2}            */
    if Object detected ∧ Object ≤ assigned sonar range limit then
        Stop driving;
    else
        repeat
            Search for RSSI of AP "Fᵢ₊₁" or "T" when i = Nₙ − 2;
        until "Fᵢ₊₁" or "T" RSSI found;
        if "Fᵢ₊₁" or "T" RSSI ≤ assigned RSSI threshold limit then
            Stop driving;
        else
            Drive straight;
```

ALGORITHM 2: The LE algorithm for a follower.

```
/* Stage 1. Linear Expansion Algorithm (LE)              */
/* For a tail                                            */
If Priority == "T" then /* Last robot in the line        */
    if Object detected ∧ Object ≤ assigned sonar range limit then
        Stop driving;
    else
        repeat
            Search for RSSI of AP  root 1 "R₁";
        until "R₁" RSSI found;
        if "R₁" RSSI ≤ assigned RSSI threshold limit then
            Stop driving;
        else
            Drive straight;
```

ALGORITHM 3: The LE algorithm for a tail.

```
/* Stage 2. Backbone Infrastructure Route Optimization (BIRO)   */
begin
    View topology tree;
    if "L" is in topology tree then
        Stop driving;
    else
        Drive straight;
```
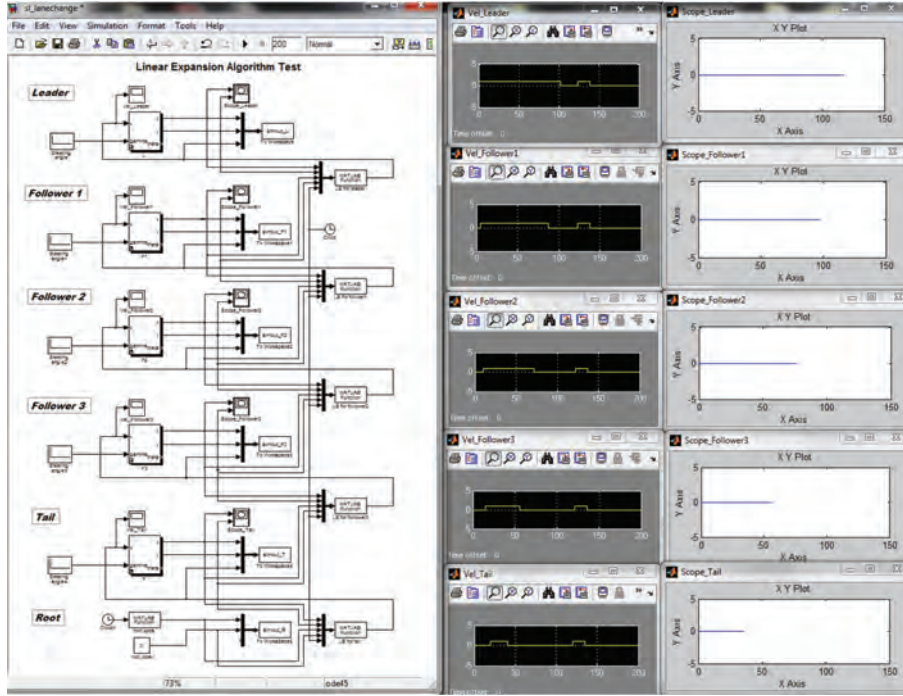
ALGORITHM 4: The BIRO algorithm.

FIGURE 5: LE Algorithm test environment built in Simulink.

(i) Slew rates of the mobile robots' velocity are instant; that is, acceleration and deceleration of the robot's motion are ignored.

(ii) RSSI values for RF signal sensing are proportional to the distance between neighboring two nodes.

(iii) All robots are located in a same point at the initial simulation run.

The second assumption may differ from the real world application, because the RSSI values are not often proportional to the distance between the two nodes due to the ever-changing RSSI patterns [2]. However, in the *Friis transmission formular* (2), if we assume antenna gains G_R and G_T are equal to 1 and the loss factor also equals 1, then the power level of received signal P_R can be approximated as a function of distance r between the two nodes as a domination factor affecting its value $P_R/P_T \approx 1/4\pi r^2$:

$$P_R = G_R \left(\frac{\lambda^2}{4\pi} \right) \frac{G_T}{4\pi r^2} P_T, \tag{2}$$

where P_R and P_T are the power level of received and transmitted signal, G_R and G_T are the gains of the receiving and transmitting antennas, r is the distance between the antennas, and $(\lambda^2/4\pi)$ is called the *free-space loss factor*.

For simulation, we have used a simple model of the mobile robot having a motion equation as [21]

$$\dot{x} = V \cos\theta,$$
$$\dot{y} = V \sin\theta, \tag{3}$$
$$\dot{\theta} = \frac{V}{L} \tan\gamma,$$

where x, y, θ, V are the robot's x position, y position, heading angle, velocity in the world frame. L is a length between two wheels, and γ is the angle of the steered wheel. Note that the position of the robot having this motion equation is controlled by the robot's velocity manipulation in general. We have used five mobile robots ($N_n = N_r = 5$) in this simulation and have denoted them as L, F_1, F_2, F_3, and T, respectively. All robots and the root node are initially located at the same origin $(0, 0)$, and the robots are set to move only to the x direction with the same velocity, $V = 1$ m/sec. The robots heading angles θ are all set to $0°$. To avoid running into each other, all robots start moving with 5-second time interval. We have set the value of the condition, **If** *RSSI Threshold* (here, distance-based) $\geq$ *certain value* **then** *stop*, as 20 meters. With all these presettings, if the LE algorithm works properly, the leader mobile robot L will move and locate at 100 meters away from the origin because there will be 5 nodes established, and each node has a capacity of 20 meters connectivity. In addition, since the robots position is controlled by its velocity manipulation, the displacement D_L can be calculated by $D_L = \int_0^t V_L dt$, where V_L is the leader robots' velocity and t is the total simulation time.

Figure 6 shows the linear formation was generated over about 110 seconds of the simulation time. In Figure 6, time transitions during the simulation are depicted on top right figures. At the beginning of simulation, all robots and the root node were located in the origin. Then, the first mobile robot, denoted as L, started moving forward. This robot kept moving until the stop condition was activated at 105 sec (look at the top graph in Figure 8). The second mobile robot then, denoted as F_1, followed the first robot until the stop condition, based on the distance between its position and
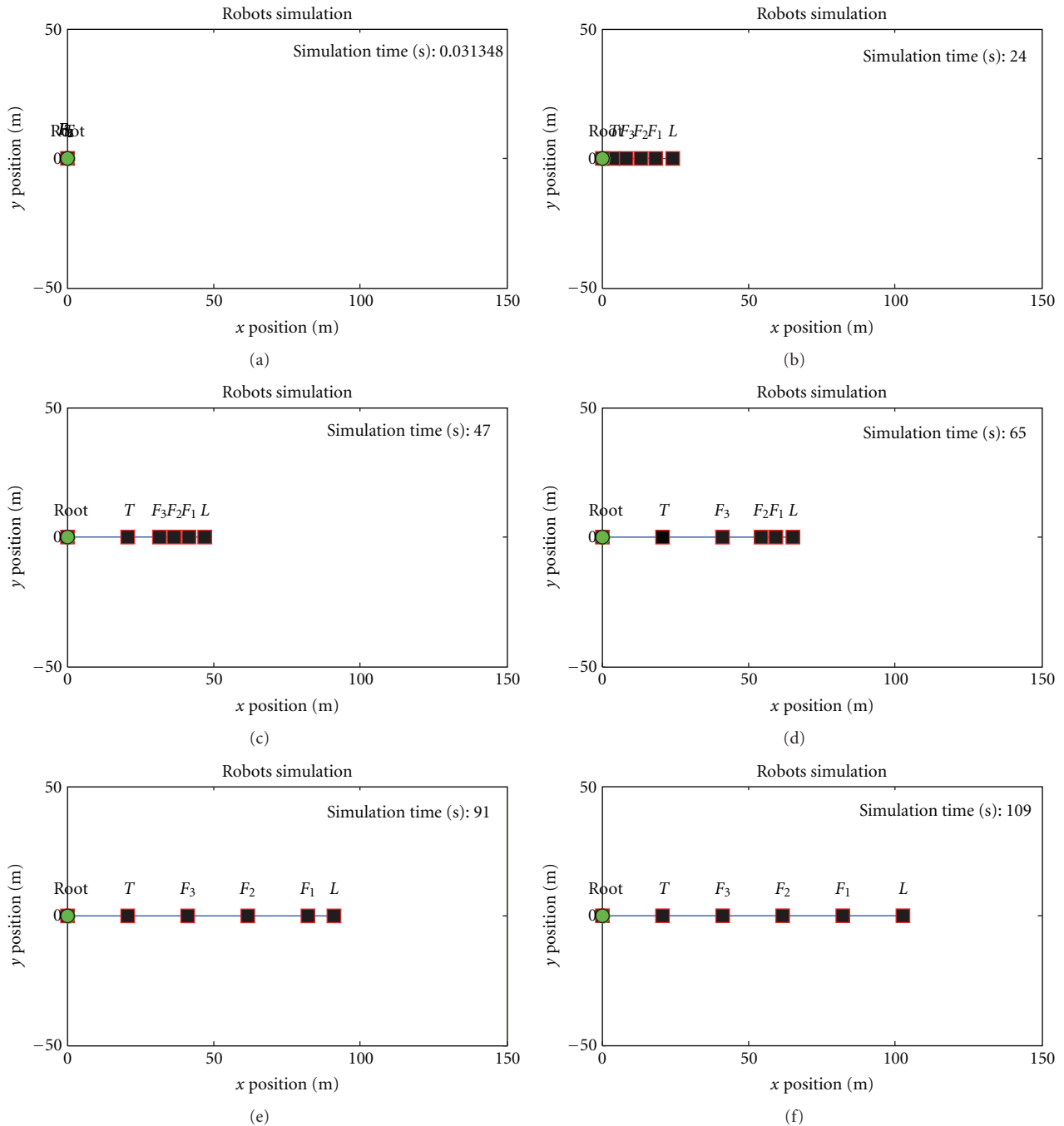
FIGURE 6: Linear formation results using LE Algorithm.

the third robots position, was activated at 90 sec. The third robot, the fourth robot, and the fifth and the last robot, denoted as F_2, F_3, and T, started moving at 10, 15, and 20 sec, respectively. And then they also kept moving until their stop conditions are activated. The all robots stopped eventually at 105 sec in the simulation, and the final formation is depicted in the bottom right figure in Figure 6. As shown in the final figure, all robots were correctly located with 20-meter distance interval each other, and the leader robot L is located at (100 m, 0 m) as expected. You can also verify this

linear formation result from graphs (from 0 sec to 110 sec) in Figure 8 showing all robots' velocity history along with time. Consequently, from these two figures (Figures 6 and 8), we could confirm that the LE algorithm successfully forms a linear formation with multiple robots satisfying the given condition.

After the complete of the first linear formation (around 110 sec), we have investigated the effect to the entire system when the *root* AP moves closer to the T node unit. In this simulation (from 120 sec to 200 sec), we have intentionally
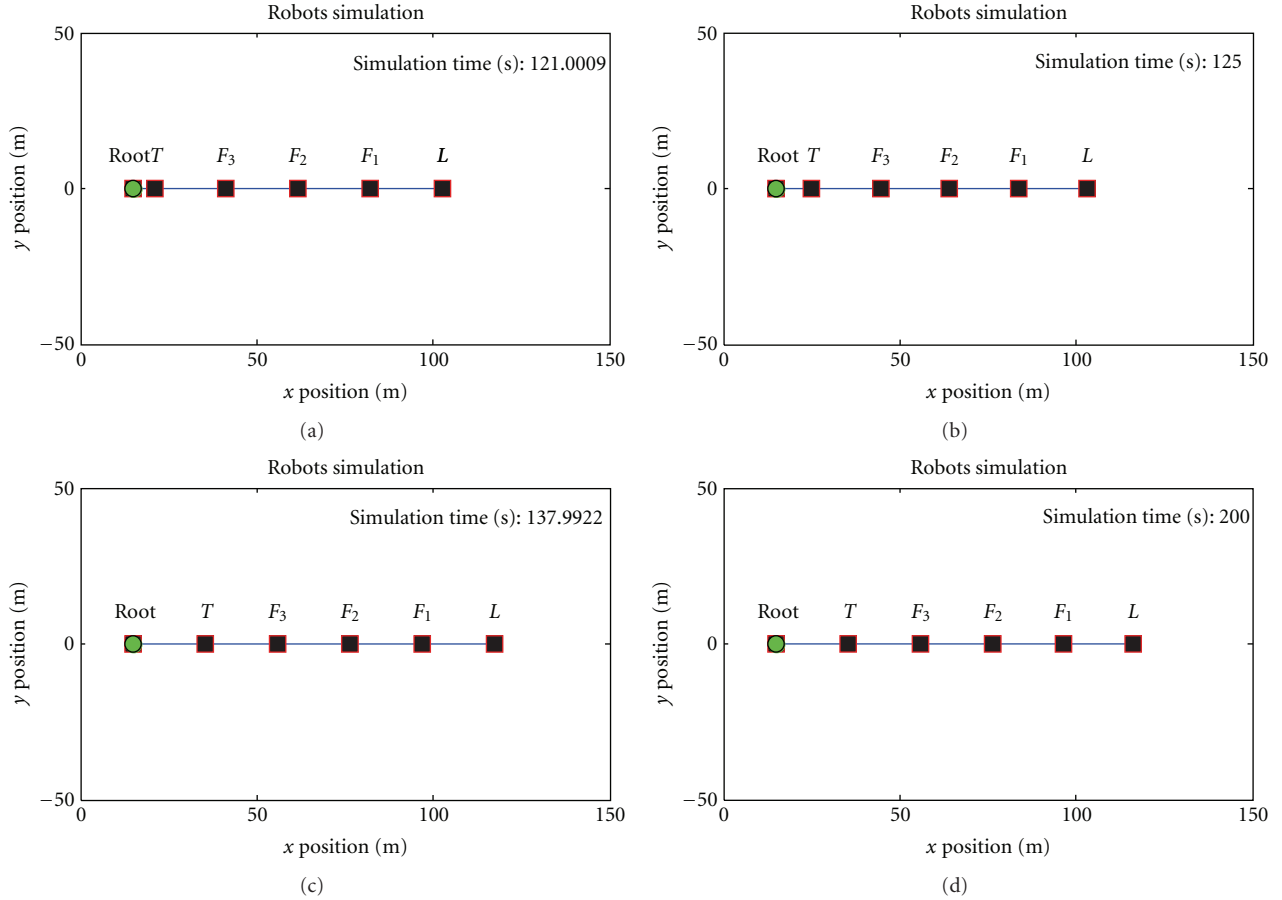
Figure 7: Effects of relocating of *root* node.

moved the *root* AP to 15 meters to the right direction from the beginning of simulation (120 sec) so that it could be closer to the tail node T. The results of this additional simulation are depicted in Figure 7. As shown in Figures 7 and 8 around at 120 sec, as soon as *root* was closer to the T, the distance-based condition of the most left node was deactivated, and then the T resumed moving forward. The movement of the T resulted in having F_3 move forward as well, and finally the shift of the root initial position moved the entire system to the right direction sequentially, from the left to the right. Eventually, the leader robot L ended up locating at $(115\,m, 0\,m)$ as expected. Consequently, from this additional simulation, we could also confirm that all nodes already established with the LE algorithm could move again in a convoy formation by means of the relocating of "*root*" position.

6. Experiment Setup

Before the experiment could be executed, 4 mobile P3-AT (three are for the LE, and one is for the BIRO, so the number of nodes and robots in the algorithm becomes $N_n = N_r = 3$ in the LE), 5 Proxim-4000, and 6 laptops were required with crossover cables. Three P3-AT each equipped with a Proxim-4000 and the LE algorithm, installed on each laptop, were positioned in a convoy formation. Each AP on each P3-AT was set to *Mobile AP* mode [3]. The R_1 mesh AP was placed stationary at the end of the convoy, and the AP was set to *Mesh Portal* mode [3].

On the left of the tail node T, a P3-AT equipped with a Proxim-4000 is set to *Mesh Portal* mode and remains until the first stage of the experiment is completed. Two laptops are equipped with Iperf [22]; one is set as the server, and the other is set as the client. Additionally, crossover Ethernet cables are used to ensure that the laptops are associated to their assigned units and do not associate wirelessly to other units; this ensures validity in the experiment.

The experiment is executed in two stages: LE and BIRO. Procedures for the first stage of the experiment, LE, are depicted in Figure 9(a) and as follows.

(1) Initiate and start all robotic units, execute LE algorithm.

(2) Wait for all units to stabilize (stop) for good.

(3) Start Iperf server connected via crossover to R_1.

(4) Connect Iperf client connected via crossover to L.

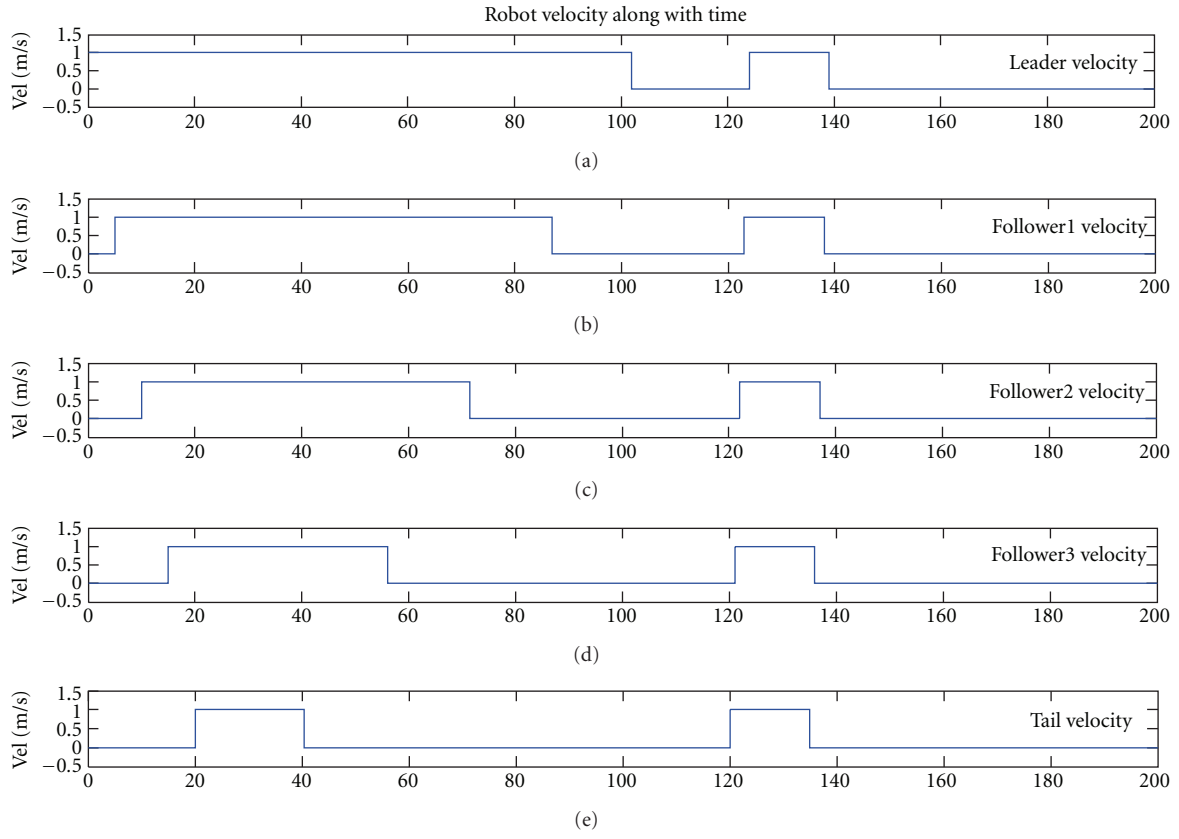(5) Collect throughput measurement three times, each measurement collected in 10 seconds interval.

Figure 8: Mobile robots' velocities from the LE simulation.

(a) Data collection of LE stage of algorithm

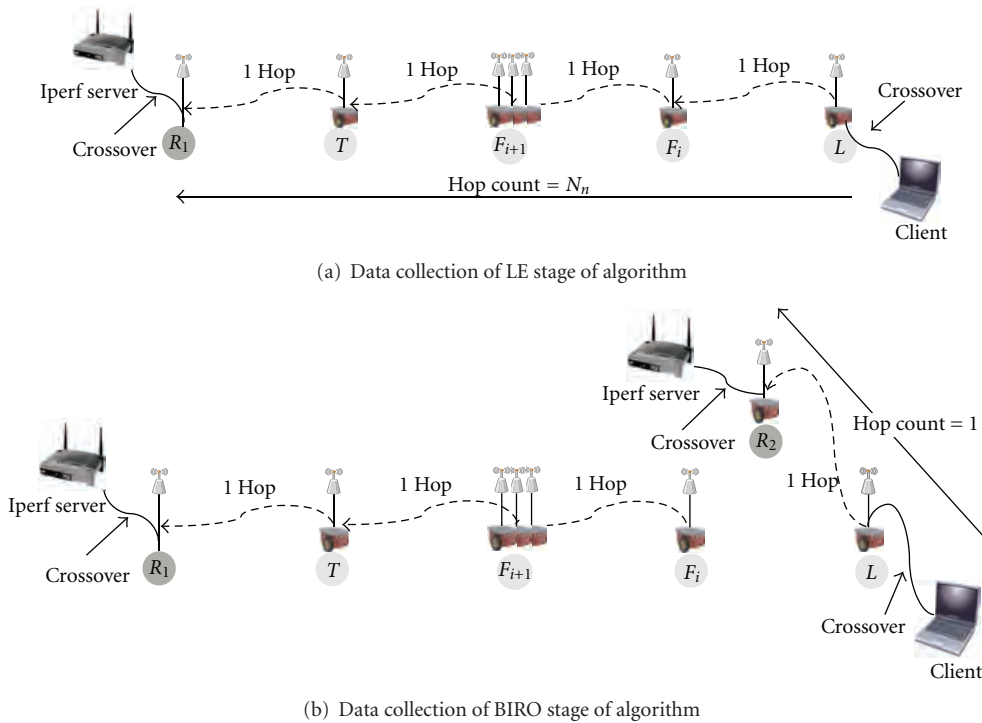(b) Data collection of BIRO stage of algorithm

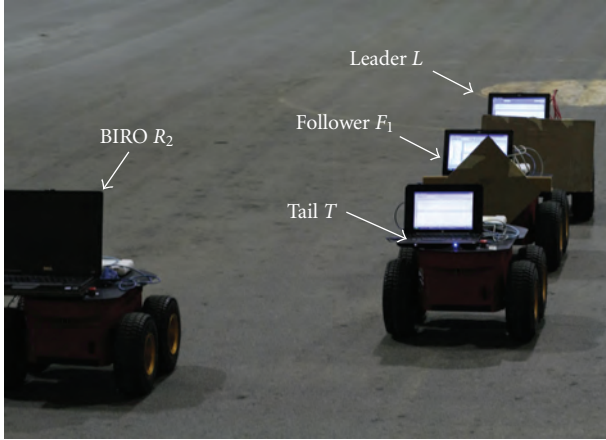Figure 9: Stage transition from LE to BIRO.

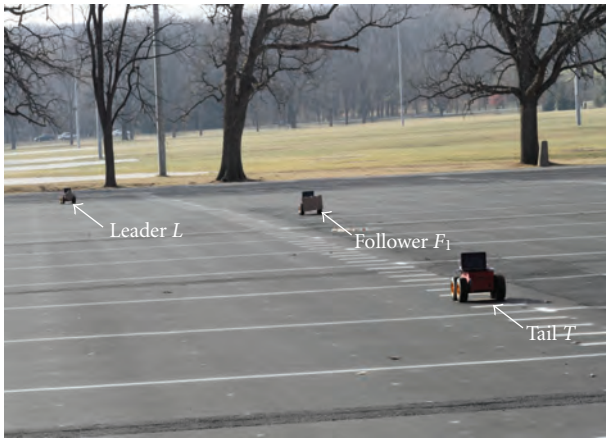FIGURE 10: Initial state of system, robots in a convoy formation.

FIGURE 11: Outdoor field experiment of LE stage of experiment.

After the completion of the LE stage, the BIRO stage executes as depicted in **Figure 9(b)** and as follows.

(1) R_2 initiates and executes BIRO algorithm.

(2) Wait for R_2 to stabilize (stop).

(3) Start Iperf server connected via crossover to R_1.

(4) Connect Iperf client connected via crossover to N_1.

(5) Collect throughput measurement three times, each measurement collected in 10 seconds interval.

The entire 2-staged experiment was repeated 10 times. Over 300 data points were collected as a result. Additionally, the *RSSI Threshold* set for this experiment was 30.

7. Results and Analysis

The results of the experiment were a linear formation of robotic units connected via wireless mesh APs using internal antennae. The backhaul was using 802.11a, and 802.11g was used to provide wireless data service to end-users and end-devices. **Figure 10** shows the robots in formation and ready for deployment, and **Figure 11** shows the three robotic units stretched over a football field.
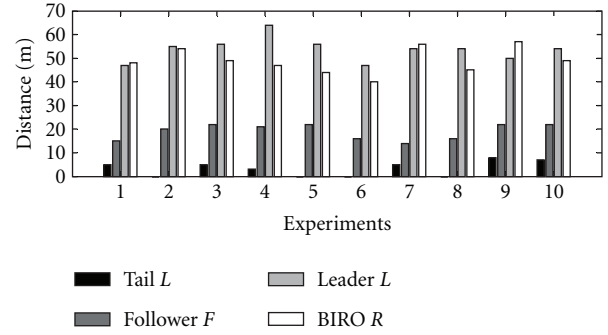

FIGURE 12: Distances from outdoor field experiment of LE stage and BIRO stage.
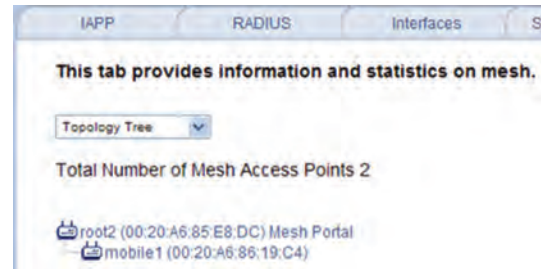

(a) LE stage of experiment

(b) BIRO stage of experiment of R_2

FIGURE 13: Network Topology.

Figure 12 shows the three nodes stretched over a distance up to 70 meters. This figure proves that a short communication link with one node could be extended to a far distance using multiple robots in a linear link. Also, it proves that the BIRO node successfully detected the end node "L" and stopped around it.

In the LE stage of the experiment, when all three mobile units were stretched out in a linear formation, the R_1 AP established the following network topology in **Figure 13(a)**. As shown in **Figure 13(a)**, mobile1 L associates with mobile2 F_1 and mobile2 associates with mobile3 T, which finally associates with the *root* AP R_1. With this topology, we could guarantee that network traffic would transit three hops before reaching the *root* AP.

Following the completion of the LE stage, the BIRO stage was executed. Upon the completion of the BIRO stage, the following network topology was established as shown in **Figure 13(b)**. As shown in **Figure 13(b)**, *root* AP R_2 was able
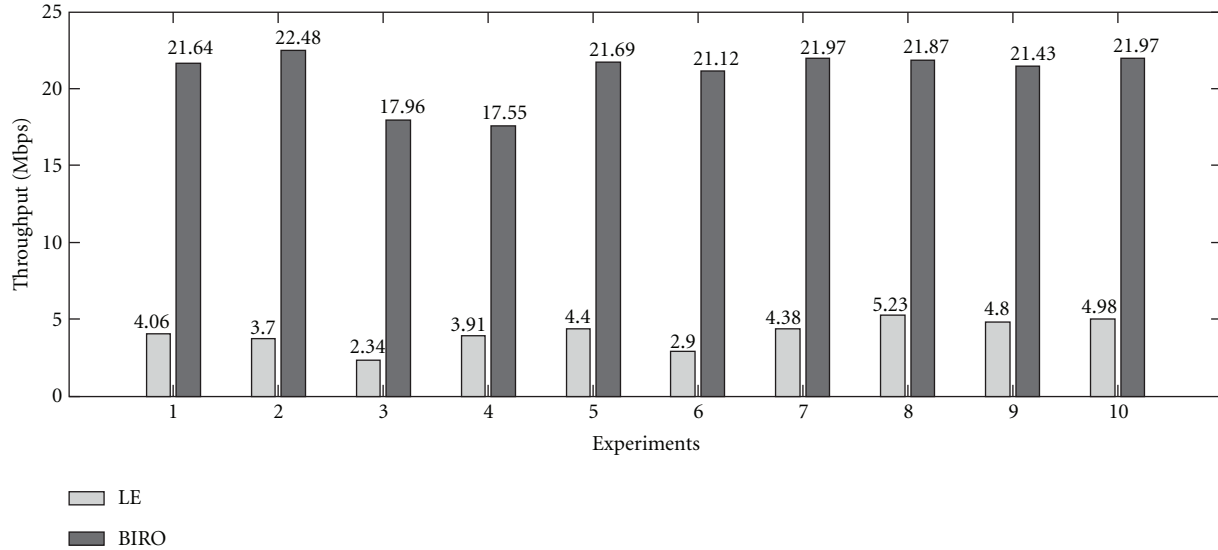
FIGURE 14: Network throughput performance over 10 experimental runs.

to redistribute the network so that mobile1 L associated to R_2 and mobile2 F_1 and mobile3 T are associated with R_1. By associating to the new *root* AP, clients connected to mobile1 L transit only one hop count to reach the *root* or *gateway* AP. It is an assumption of this experiment that once clients are able to reach the *gateway* in R_2, they have access to the same network resources and services as if they were connected through the *gateway* in R_1.

From the collection of network throughput from 10 experimental runs, Figure 14 shows the throughput performance of the experiment for the LE and BIRO stage of the experiment. From the chart in Figure 14, it is observed that by reducing the hop count during the BIRO stage of the experiment, the throughput was significantly greater than the throughput performance during the LE stage of the experiment. During the LE stage, network traffic transits through 3 hops, compared to 1 hop during the BIRO stage. The chart also shows the numerical data of the throughput collected for each experimental run. During each experiment of each stage, the collection of throughput data was measured 3 times for 10 seconds. The average was calculated from the 3 measurement instances taken from each experiment of each stage.

As a result, Figure 14 shows that robotic units have the ability to optimize a mobile wireless mesh network by reducing the amount of hop counts a network much traverses. Finally, this experiment shows that it is not only possible to establish a mobile wireless mesh network but it is also possible to improve the existing mobile wireless mesh network with additional robotic units equipped with *gateway* AP that have the ability to redistribute the wireless mesh network.

8. Assumption and Limitations

The success of the experiment and the future applicability of this research concept run under the assumption that the *root*

APs, R_1 and R_2, have a way of connecting to each other, either through the use of external omni antennae or directional antennae or have the ability to connect to a stationary point-to-multipoint WIFI system. A successful connection between R_1 and R_2 would allow clients connected to nodes associated to R_1 can connect and communicate with clients connected to nodes associated to R_2.

Additionally, the three mobile AP units were limited to the use of internal antennae, and the units were only mounted 0.5 meter above the ground. This low-level mount of the AP significantly reduces the distance covered by each mobile AP unit and the performance of the overall system. Additionally, the units were limited to a small power source lasting only 4 hours.

9. Future Work and Conclusion

Future work will include the implementation of a system that utilizes external antennae, both omnidirectional and directional. Additionally, a new mounting system will be designed to increase the height of the antennae to increase coverage and network performance for the system.

With the given experiment, we have successfully proved the proof-of-concept of establishing mobile broadband mesh networks using mobile robots. Additionally, we have shown that we can further improve network performance by reducing the hop count of the network traffic from the furthest network node, all of this operation done robotically and autonomously. If R_1 was to move closer to tail node T, the entire system would autonomously shift to accommodate the change. We further emphasize the successful redistribution of the network through topology trees of the first and second stage of the experiment.

We hope that through the use of the simple concept of RF sensing, the concept of mobile broadband mesh network can be further developed and matured to be implemented on different robotic platforms paving way to a new era of

wireless communication and services by providing wireless communication almost anywhere and at anytime in the world.

References

[1] C. Nguyen, B. Leong, E. Matson, A. Smith, and J. Wachs, "AWARE: autonomous wireless agent robotic exchange," in *Proceedings of the International Conference on Intelligent Robotics and Applications (ICIRA '10)*, Shanghai, China, Noember 2010.

[2] B.-C. Min, J. Lewis, D. K. Schrader, E. T. Matson, and A. Smith, "Self-orientation of directional antennas, assisted by mobile robots, for receiving the best wireless signal strength," in *Proceedings of the IEEE Sensors Applications Symposium (SAS '12)*, pp. 261–266, February 2012.

[3] Proxim Wireless, Orinoco AP-4000, AP-4000M and AP-4900M User Guide, Proxim wireless, 2006.

[4] "802. 11s IEEE standard," 2011, http://standards.ieee.org/findstds/standard/802.11s-2011.html.

[5] S. Conner, "IEEE 802. 11s tutorial oeriew of the amendment for wireless local area mesh networking," 2006, http://ieee802.org/802_tutorials/06-November/802.11s_Tuto-rial_r5.pdf.

[6] "Conguring wds, fast secure roaming, and radio management," 2012, http://www.cisco.com/en/US/docs/wireless/access_point/12.2_15_JA/configuration/guide/s15roamg.html.

[7] Proxim wireless mesh series, 2012, http://www.proxim.com/products/enterprise-wireless-lan-wi-mesh/orinocor-wi-mesh-series.

[8] A. Smith and E. T. Matson, "Use of antennas as sensors to discover signals to form mobile broadband networks," in *Proceedings of the IEEE Sensors Conference (SENSORS '09)*, pp. 581–584, October 2009.

[9] WHO, Initials, "Public health risk assessment and interentions: earthquake—Haiti," World health organization, 2010, http://www.who.int/diseasecontrol_emergencies/publications/who_hse_gar_dce_2010_1/en/index.html.

[10] "Rescue crews pull 2 more from haitian market," MSNBC, 2010, http://www.msnbc.msn.com/id/34829978/ns/world news-americas/?GT1=43001.

[11] "Japan earthquake: death toll passes 10, 000," 2011, http://www.telegraph.co.uk/news/worldnews/asia/japan/8405619/Japan-earthquake-death-toll-passes-10000.html.

[12] K. K. Hoon and C. Meyers, "Snow muffles rescue work in japan's deastated northeast," 2011, http://www.reuters.com/article/2011/03/16/us-japan-quake-snow-idUSTRE72F2WN-20110316.

[13] M. M. Ahlers and M. Mount, "Radio station in the sky warns haitians not to at-tempt boat oyage," 2010, http://articles.cnn.com/2010-01-19/world/haiti.broadcast.warning_1_haiti-migration-coast-guard?_s=PM:WORLD.

[14] N. Pezeshkian, H. G. Nguyen, and A. Burmeister, "Unmanned ground vehicle radio relay deployment system for non-line-of-sight operations," in *Proceedings of the 13th IASTED International Conference on Robotics and Applications (RA '07)*, pp. 501–506, August 2007.

[15] S. Timotheou and G. Loukas, "Autonomous networked robots for the establishment of wireless communication in uncertain emergency response scenarios," in *Proceedings of the 24th Annual ACM Symposium on Applied Computing (SAC '09)*, pp. 1171–1175, March 2009.

[16] A. Ollero, P. J. Marron, M. Bernard et al., "AWARE: platform for autonomous self-deploying and operation of wireless sensor-actuator networks cooperating with unmanned AeRial vehiclEs," in *Proceedings of the IEEE International Workshop on Safety, Security and Rescue Robotics (SSRR '07)*, pp. 1–6, September 2007.

[17] irobot create., 2012, http://store.irobot.com/shop/index.jsp?categoryId=3311368.

[18] Orinoco ap-4000, 2012, http://www.proxim.com/products/enterprise-wireless-lan-wi-fi-mesh/orinocor-ap-4000.

[19] Mobile robots., 2012, http://www.mobilerobots.com/Research-Robots/P3AT.aspx.

[20] C. Q. Nguyen, *Intelligent autonomous mobile wireless broadband linear expansion & route optimization [M.S. thesis]*, Purdue Uniersity, 2011.

[21] P. I. Corke, *Robotics, Ision & Control*, Springer, 2011.

[22] J. Dugan and M. Kutzko, "Iperf," 2011, http://sourceforge.net/projects/iperf/.