Design of a Networked Robotic System Capable of Enhancing Wireless Communication Capabilities

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***Abstract*—In this paper, we present the design of a networked robotic system capable of enhancing wireless communication capabilities. The core of the system is active antenna tracking with directional antennas. The proposed system is decentralized and consists mainly of a mobile robot system and a command center system. Each system is equipped with off-the-shelf network devices such as antennas, access points (AP), and network switches. For directional antennas to be beneficial to our system, we propose a weighted centroid algorithm (WCA), which is a method for active antenna tracking and direction of arrival (DOA) estimation. Through extensive field experiments in different environments and with different antenna selections, such as omni-to-omni, omni-to-directional, directional-to-directional antennas, we demonstrate the feasibility of our proposed system. We expect that our system can be applied in a variety of rescue, surveillance, and emergency scenarios where high bandwidth and long distance communications are needed.**

I. INTRODUCTION

As robots gradually replace manpower in the fields of safety, security and rescue, communication quality between robots is becoming a big issue in the advanced technological world.

In many cases, rescue robots need to be deployed distantly from a command center to carry out their missions, like the recent deployment of our firefighting robot. On June 20, 2013, our firefighting robot was deployed in a working fire inside the JR Used Tire Service building, in Illinois, USA (See Fig. 1) [1]. As the interior of the building was too dangerous, hot and full of noxious fumes for human firefighters, the Purdue University Fire Department, called by fire department officials in Champaign to help with the Hooperston tire fire, decided to deploy the robot inside the building. For about four hours, the robot helped fight the fire from inside of the ruined building. It was the first test in the real world and a successful deployment; however, through this test, we could also discover some areas for improvement, specifically in its communication range and bandwidth. That is, if the robot can maintain connectivity with the distant command center and transport high-bandwidth data, it could be much more useful, because it would allow the operator to stay in a safe zone and control the robot remotely while watching high definition images transmitted from the robot.

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Fig. 1. A firefighting robot fights a working tire fire, in Illinois , USA. (Photo by Purdue University)

In this paper, we directly focus on such improvements identified from our first test and develop a robotic system capable of enhancing wireless communication capabilities with off-the-shelf network devices. First, in order to achieve distant range communications, we use directional antennas. For directional antennas to be beneficial in our system, we propose a weighted centroid algorithm (WCA), which is a method for active antenna tracking and direction of arrival (DOA) estimation. These methods are designed to maintain the best network quality between a mobile robot and a command center by a precision tracking capability. In addition, we use network devices such as access points (AP), and network switches to create broadband networks between the robot and the command center. As our system is fully decentralized, and only requires the single robot and the command center, it can minimize the complexity and cost, which will be shown in the section on related studies that required the use of multiple robots. We believe that our proposed system can be applied in a variety of rescue, surveillance, and emergency scenarios where high bandwidth and distant range wireless communication are needed.

The remainder of this paper is organized as follows. In Section II, we present an overview of related studies. In Section III, we introduce methods for active antenna tracking and DOA estimation for directional antennas to be beneficial in robotic communications. Then, we detail components of the complete system in Section IV. In Section V, we describe the setup and results of field experiments to verify the performance of the proposed system. Finally, Section VI summarizes the conclusions and future scope of this work.

II. RELATED STUDIES

There have been a number of previous attempts to improve the network performance of robotics in applications such as disasters and emergencies where long range communications are needed. Most of those attempts employ multiple robots having wireless networking capabilities to achieve the improvement.

For human existence detection in case of disasters, Tuan et al. [2] proposed an autonomous wireless sensor network deployment system. As the authors were concerned about the connectivity issue, they introduced a role based exploration approach for cooperative exploration, composed of explorer and relay robot units. Tekdas et al. [3] studied the problem of building a commutation bridge between a signal source and a destination with mobile robots. From this research, they showed that multiple mobile robotic hubs could provide connectivity service in applications such as disaster response. Hsieh et al. [4] presented an experimental study to maintain end-to-end communication links for tasks such as surveillance and reconnaissance, where team connectivity is required for situational awareness. In order to establish mobile wireless mesh networks and increase network throughput, Nguyen et al. [5] employed multiple mobile robots. By placing one robot at the end node, i.e., by reducing the hop count required for network traffic to transit through, they could increase network throughput. Pezeshkian et al. [6] proposed an unmanned ground vehicle radio relay deployment system that employs mobile robots that carry multiple relay radio to maintain robust communications. Specifically, the system was designed to have long-range and non-line of sight (NLOS) operational capabilities.

All of the research mentioned above has demonstrated the possibility on improving network performance in the robotics domain, but all of these have to employ multiple robots, not a single robot, to fulfill their objectives. For that reason, it is unavoidable that the entire system becomes more complex and expensive.

III. ANTENNA TRACKING

A. Active Antenna Tracking

For wireless robot communications, omnidirectional antennas have been typically used. The main advantage of those antennas lies in that they are very easy to install. Due to their spherical radiation pattern, they can be easily mounted anywhere on the robot's body. Also, due to this pattern, they provide a wide coverage area from their center. This efficacy allows multiple clients diffused around the antennas to access wireless communications. Therefore, omnidirectional antennas are often considered to be suitable for communications in a multi robot system.

Whereas omnidirectional antennas provide a wide coverage area, they cannot deliver long communications distances. Also, it is known that omnidirectional antennas often experience interference from other signals, since they are operated in the unlicensed bands that any 802.11 devices can use. Recently, the use of directional antennas has received increased attention to overcome such problems. First, long communications distances can be achieved by diverting the RF energy in a particular direction with directional antennas. Second, with a narrower radiation pattern than that of the omnidirectional antenna, the directional antenna can avoid the region where wireless signal congestion occurs. However, because of the narrower radiation pattern, fine tuning is necessary in order for the antenna to be oriented in a specific angle and direction. Moreover, when the directional antenna is mounted on a moving robot, the orientation of the two directional antennas - i.e., the one installed on the robot and the other at the command center - should be continuously adjusted so as to maintain the communication link and provide high quality communications.

If two directional antennas in a point-to-point network are operated in a completely open and perfectly known location, it would not be difficult to determine the necessary orientations for the best connection with the aid of GPS (Global Positioning System) and a compass sensor [7]. In such a situation, having the two antennas point at each other would usually provide the best quality of wireless communications. However, this approach is only feasible when both communication sides are equipped with very accurate GPS and a compass sensor [8]. Furthermore, as it is almost impossible to obtain GPS signals in indoor environments, the location functionality cannot be utilized in environments where directional antennas have the potential to increase wireless capacity [7]. In addition, in a situation where the effects of multipath and the presence of other wireless interference exist, pointing at each other may not be the best orientation nor guarantee the best quality. Therefore, optimizing the function of the two antennas only by sharing information on their current orientations and positions might be the wrong approach.

In addition, in a situation where the effects of multipath and the presence of other wireless interference exist , it is hard to predict or calculate the best orientation for a directional antenna without adequate data regarding their effects.

For that reason, this paper proposes an active antenna tracking system and DOA estimation for the self-orientation of directional antennas. First, the proposed system requires two directional antennas mounted on a pan-tilt servo device on each side; i.e., a total of four antennas are used for building a point-to-point network. One antenna is responsible for data transmission, and the other antenna is responsible for DOA estimation with the opposite side. Assuming the two communication sides are far enough apart, and the two antennas are installed on the same vertical axis very close to each other, fields of view from the antennas can be projected to almost the same area. Therefore, this configuration is feasible in our study.

Figure 2 illustrates the configuration of this system, with the robot on the left side and the command center on the right side. The top antenna on both sides is the actual one for data transmission, so these antennas are paired together. The bottom antenna is for DOA estimation. By rotating the bottom antenna, taking RSSI (Radio Signal Strength Indication) measurements and finding the direction with the strongest RSSI from the top antenna on the opposite side, it can compute the best orientation of the top antenna. Therefore, the orientation

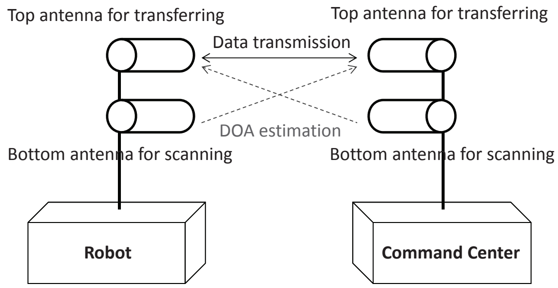


Fig. 2. A configuration of the proposed system. The system composed of two directional antennas on each side, so a total of four antennas are installed.

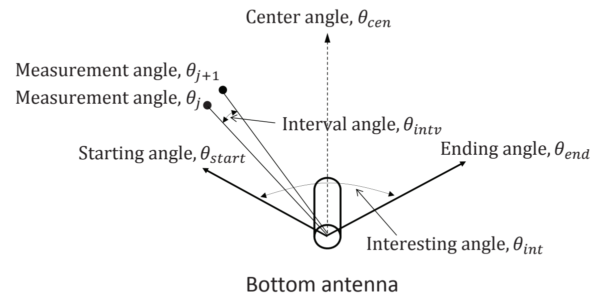


Fig. 3. Defined parameters for the self-orientation of directional antennas, when scanning clockwise.

of each of the top antennas is adjusted periodically by the bottom antennas in each rotation. This active antenna tracking system runs independently on each side, so it might take some time to adjust the top antenna orientation and to reach the best orientation. Nonetheless, with this approach, realized through the measurement of radio signal strengths, the orientations of the two top antennas can be optimized without the aid of GPS and a compass sensor.

B. Direction of Arrival (DOA) Estimation

It is known that the measurement of radio signal strengths often contains measurement noise as well as fading caused by the effects of multipath or interference from other electronics devices. Because of this unreliable measurement, estimating the right DOA is difficult. To cope with this, we develop a DOA estimation technique using directional antennas that is called the Weighted Centroid Algorithm (WCA), a type of weighted centroid approach. Weighted centroid approaches have been adopted by several research groups [9]−[12]. The previous studies used the distance as the weighting factor through power measured from multiple anchor nodes. In this paper, we examine the directionality of the radiation pattern with a stand-alone directional antenna for DOA estimation. As the basic concept of using weights to obtain the centroid of a data set is similar to the previous studies, we recommend referring to the papers referenced above for a more detailed explanation of the concept of weighted centroid approaches.

Before introducing the WCA, we first define several parameters needed in WCA, as shown in Fig. 3, where

θ_{int} = interesting range where a scanning task performs
θ_{start} = starting angle where to start the interesting range
θ_{end} = ending angle where to end the interesting range
θ_{cen} = center angle between the staring angle and the ending angle
θ_{intv} = interval angle of measurement
θ_j = measurement angle.

From the center of the antenna's body, we define an interesting range θ_{int} where a scanning task is performed. Then, the starting angle θ_{start} where the range starts, the ending angle θ_{end} where the range ends, going either clockwise or counter-clockwise from the starting angle in turn, the center angle θ_{cen} between the staring angle and the ending angle, and the interval angle of measurement θ_{intv}, are defined. At the beginning of scanning, the center angle is in front of the device. While scanning from the starting angle to the ending angle, N_t times of the measurement task are performed at a measurement angle θ_j, where j is the index of the measurement such that $j \in \{1, 2, \ldots, N_t\}$, producing $RSSI_j$, the measured RSSI at the jth measurement. For the interval angle θ_{intv}, it is assumed that this angle can be computed by dividing the interesting range by the total number of measurements N_t.

Figure 4 shows an example of a measured RSSI from an experiment that was conducted indoors, with a rotary directional antenna, showing the parameters above. In this figure, it is shown that θ_{int} = 180°, $\theta_{start} = -90°$, θ_{end} = 90°, N_t = 19, and therefore θ_{intv} = 10°.

In the first step of the WCA, a single rotary directional antenna measures the signal strength by rotating from θ_{start} to θ_{end} and produces a set of $RSSI_j$. In the second step, a weight is computed by the measured signal strengths at θ_j using the following expression

$$w_j = 10^{\left(\frac{RSSI_j}{\gamma}\right)}, \quad (1)$$

where γ is a positive gain that should be appropriately determined in every application scenario so that stronger signal strengths are more weighted than weaker signal strengths. Then, the DOA can be estimated by means of weighted

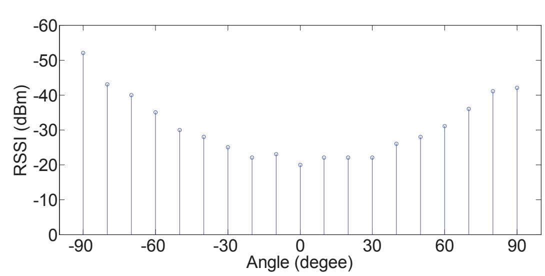


Fig. 4. An example of measured signal strength with a rotating directional antenna. The horizontal axis is the measurement angle and the vertical is the measured signal strength, RSSI.

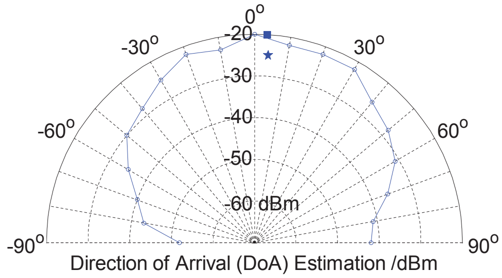


Fig. 5. Weighted Centroid Algorithm (WCA) in a polar coordinate frame.

centroid approaches as follows,

$$\widetilde{\Theta} = \frac{\sum_{j=1}^{N_t} w_j \theta_j}{\sum_{j=1}^{N_t} w_j}. \quad (2)$$

If we use the measured RSSI shown in Fig. 4 again and depict all variables used in Eq. (2) in polar coordinates, it should look like Fig. 5. Here, γ was set to 10, the estimated DOA $\widetilde{\Theta}$ using the WCA was depicted with a symbol "★" (See nearby 0° on the angle axis between -20 dBm and -30 dBm) in a polar coordinate, and the actual angle $\widehat{\Theta}$ was depicted with a symbol "■". Note that one can read the estimated DOA and the actual angle in Fig. 5 by observing a coordinate of the symbols on the angle axis. Since we do not deal with a distance-related estimation in this paper, we do not need to observe a coordinate of the symbols on the dBm-axis.

With Eqs. (1) and (2), the measured data with strong signal strengths are depicted further from the center in Fig. 5, and their angle values become more important to determine the weighted centroid. Conversely, weaker signal strengths are rarely weighted because of the log scale. Therefore, the measured data with weak signal strengths are depicted closer to the center, and their angle values become less important. As a result, it can be said that Eq. (2) calculates a reasonable DOA by averaging the measured data with appropriate weighting.

In fact, as stated in [9], weighted centroid approaches have entailed poor estimation when the actual DOAs approached both ends. Considering cases where an actual DOA is near an extreme, the other sample data will necessarily pull the average toward the side opposite the DOA. Thus, even if all sample data are averaged with appropriately assigned weights, an estimated DOA is always pulled toward the side where the most samples reside. In other words, all sample data on the side opposite the side with more data prevent the estimation from approaching the end where an actual DOA dwells.

We have partially modified the WCA to cope with this unavoidable problem. First, this modification is activated after obtaining an an estimated DOA $\widetilde{\Theta}$ using the procedure stated earlier. The key modification is that of changing the interesting range θ_{int} with the previously calculated DOA so that the center angle θ_{cen} of the range can be placed exactly on the previous DOA. By doing so, this modification can place an actual DOA away from an extreme end in the next scanning, therefore preventing the issues shown earlier.

Also, a moving average is used to smooth and thus minimize variations of estimated DOA. This may cause delayed antenna tracking, but it can be minimized by appropriately determining the window size in the moving average. In addition, as the beamwidth of the antennas we use for this research is wide enough to maintain the connection with the opposite antenna, a short delay is acceptable.

IV. DESIGN OF ROBOTIC COMMUNICATION SYSTEM

A. Robot System Design

To test the proposed methods, we have developed a prototype of the robotic system as shown in Fig. 6. The complete system mainly consists of a mobile robot system and a command center system. The mobile robot system is made up of a P3AT mobile robot, a laptop, two access points (AP) running with an omnidirectional antenna and a directional antenna respectively, a yagi antenna, a network switch , a Wi-Fi USB adapter, an IP camera, and three pan-tilt servo devices. The command center system is equipped with almost the same components as the robot, but it does not have the P3AT or the IP camera.

1) Networking Devices: Our system is designed to enhance wireless network capabilities by means of antenna tracking with directional antennas that build a point-to-point broadband network. Actually, it is possible to establish the point-to-point network with one of the following three antenna selections: 1) omni-to-omni antennas, 2) omni-to-directional antennas, and 3) directional-to-directional antennas. Hence, we test all of the three antenna selections in this paper, and analyze their performance to validate our proposed system.

For the first selection, requiring an omnidirectional antenna on each side, we use a state of the art, low-cost, high-performance, and small wireless AP, *PicoStation M2-HP*, manufactured by Ubiquiti Networks Inc. This AP is equipped with a 5dBi omnidirectional antenna, and supports passive Power over Ethernet (PoE), so it does not require an additional power code. Also, it runs with IEEE 802.11g protocol

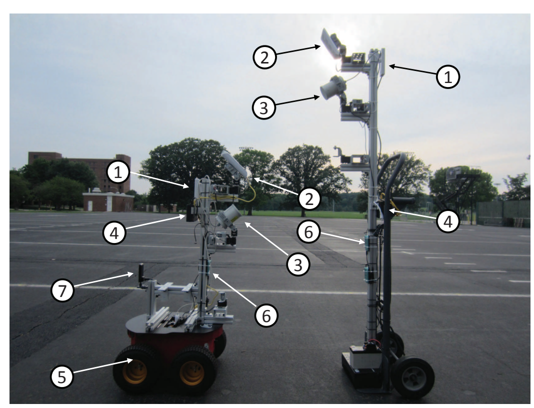


Fig. 6. Robotic communication system, composed of the robot system (left) and the command center system (right) - 1) *PicoStation* wireless AP, 2) *NanoStation* wireless AP, 3) PCTEL yagi antenna, 4) network switch, 5) P3AT, 6) Wi-Fi USB adapter, 7) IP camera.

having an operating frequency of 2.4GHz, and produces up to 28dBm output power. As this device was designed to be deployed in either indoor or outdoor environments, it is ideal for applications requiring medium-range performance and a minimal installation footprint.

For the third selection, requiring two directional antennas on each side, we installed another wireless AP, *NanoStation loco M*, manufactured by Ubiquiti Networks Inc. This AP is equipped with an 8 dBi directional antenna, which can be seen on the top of the system. Hence, this antenna is used for data transmission. This system also runs with 2.4 GHz, and produces up to 23 dBm output power. The beamwidth of this antenna is $60°$ at $\frac{1}{2}$ power for horizontal and vertical planes. This device was specifically designed for outdoor point-to-point bridging applications. In addition to this *NanoStation* AP, we installed a small and light yagi antenna, manufactured by PCTEL for DOA estimation. This device can be seen on the bottom of the system. This device has 10 dBi of gain, uses 2.4 GHz frequency range, and has $55°$ horizontal and vertical beamwidth at $\frac{1}{2}$ power.

For the second selection, requiring an omnidirectional antenna on the robot side and two directional antennas on the command center side, we utilize a *PicoStation* AP introduced in the first selection as the omnidirectional antenna. For directional antennas, we utilize the *NanoStation* AP and PCTEL yagi antennas introduced in the third selection.

We use a passive PoE managed network switch, *TOUGHSwitch*, manufactured by Ubiquiti Networks Inc., in order to power the devices that can be powered through PoE, such as two of Ubiquiti's APs and a camera. Also, by using a network switch in the communication system, we can easily add additional network devices or laptops to the established communication link between the robot and the command center. Furthermore, we can utilize this switch when we want to extend wireless signals on the robot side by turning on the *PicoStation* AP and setting it in a repeater mode. That is, Wi-Fi signals transported through the top directional antenna can be propagated with the omnidirectional antenna.

2) Robot Platform: The P3AT is a four-wheel driven autonomous ground vehicle, developed by Adept MobileRobots. This robot has been widely adopted for research purposes, as it is sturdy and durable and provides open source codes. We also adopted this robot as our mobile robot platform for this research.

3) Additional Devices: We use an Asus *Eee* laptop, running Linux, to manage high level motion planning for the P3AT, to receive radio signal from the Alfa Wi-Fi USB adaptor connected with the bottom directional antenna, and to process DOA estimation.

We have developed a pan-tilt device with off-the-shelf dc servos, manufactured by Robotis Co. Three pan-tilt devices, controlled by an ATMEL128 microprocessor, are installed at each communication side - the first is for the *NanoStation* AP, the second is for the yagi antenna, and the third is for a digital camera. The motion of the third pan-tilt device is synchronized with the top one so that we can see the current field of view

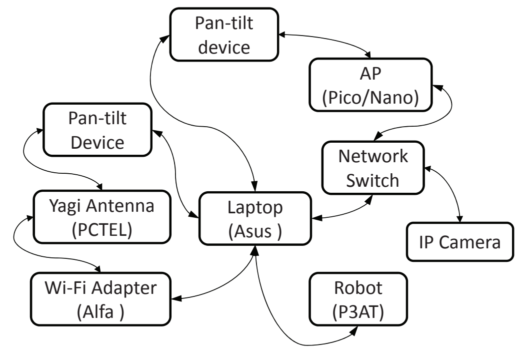


Fig. 7. An overview of the communication system architecture: robot system side.

from the top antenna for test purposes. If images from the camera contain a physical body on the opposite side at the center, we could say that our proposed methods work well.

The mobile robot system is also equipped with an internet protocol (IP) camera, *aircamMini*, manufactured by Ubiquiti Networks Inc. This camera is powered through PoE, includes a microphone and has a 1MP/HDTV 720p resolution and 30FPS maximum frame rate, so it is suitable for surveillance purposes by being installed on the mobile robot. For this paper, we utilize this camera for analyzing robot motion in the field tests.

B. System Architecture

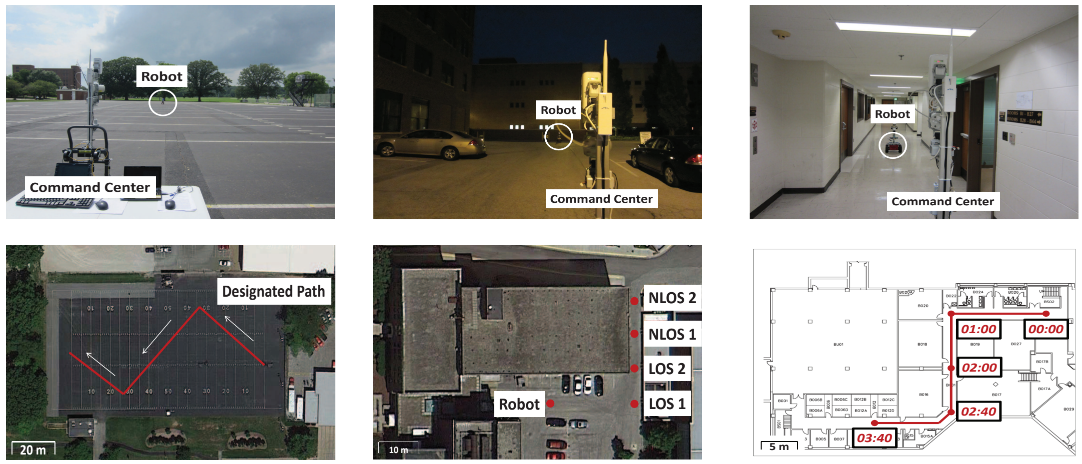
Figure 7 shows an overview of the robot system architecture.

The laptop is connected by an RJ-45 cable to the PoE network switch, by a serial connection to the P3AT, three pan-tilt devices, and the Alfa USB adapter. A pan-tilt device allows the directional antenna to be oriented in a specific angle autonomously. In this paper, we employ a pan angle only since the directional antenna we chose for this project has about $55°$ beamwidth vertically, and therefore there are few cases where our robot is deployed out of the range. However, it should be noted that vertical beamwidth would also affect wireless communication in some cases.

The PoE network switch, powered by the battery and transformer, provides the power to the APs and IP camera, and enables all of the network devices to be connected on the same network.

V. EXPERIMENTS

In order to test the proposed system, we conducted extensive field experiments in three different environments and with the three different antenna selections stated in section IV. For a comparison of the performance of each antenna selection, we implemented a data throughput test. This was done to reinforce the assumption that the strongest wireless signal has a direct correlation to the best signal for a data link connection. To perform this test, the Linux "iperf" command was used to measure a small data transfer over the established link between the robot and the command center. A laptop on the robot side running iperf was set to a server mode, and a laptop on the command center side was set to a client mode. A small



(a) Purdue Marching Band Practice Field (b) ENAD parking lot (c) Knoy hallway

Fig. 8. Experiments in three different environments at Purdue main campus - two outdoor tests and one indoor test. Videos demonstrating the field experiments can be found at `http://web.ics.purdue.edu/%7Eminb/ssrr2013.html`

amount of data was transferred through the autonomously created link and a measurement of the time to transfer rate was performed by iperf. The resulting measurement gives an accurate available throughput for the established link. Since our tracking system only takes into account RSSI, or received signal power, and not packet quality, we can use this test to verify received data integrity, which is especially important for a multipath link.

For experiments with a fair evaluation, each setting was run through at least three different trials. Also, the powers of the two antennas for data transmission, *PicoStation* and *NanoStation* APs, were set to 13 dBm and 10 dBm so that the total radio signal power can be the same setting of 18 dBm.

A. Outdoor Test in Open Environments

For the different environments, we first chose the Purdue Marching Band practice field whose size is almost the same as a typical football field. This environment was chosen to test cases where the moving robot has to be deployed in an open and outdoor environment and where a long distance and a high quality of communication are required. The environment is shown in Fig. 8 (a). During this test, the robot was set to move along a designated path with an almost constant speed of 0.5 meter/sec. The designated path is shown with a red line on the bottom of Fig. 8 (a). The total traveling distance of this path is approximately 130 meters and the longest distance between the command center and the robot is approximately 100 meters. For WCA, γ was set to 10, and θ_{int} was set to $100°$, resulting in the initial scan performed at $\theta_{start} = -50°$, $\theta_{end} = 50°$. N_t was approximately 25 for most of the tests. These settings were applied to all of the environments.

Figure 9 shows the average throughput for all tests with each antenna selection. As expected, the third selection, directional-to-directional antennas, outperformed the other two selections by showing far higher throughput by as much as one and a half times. Specifically, the third selection shows very stable data throughput over distance and time. This result indicates

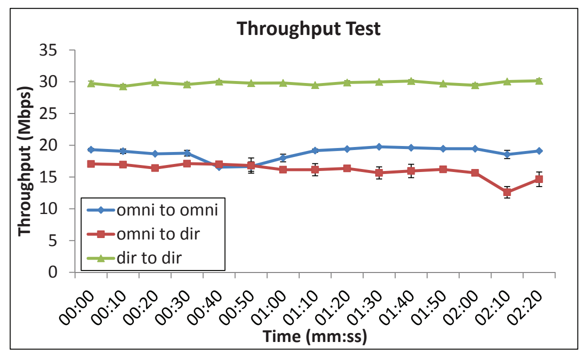


Fig. 9. Throuput measured while the robot was moving in an outdoor and open environment.

that the pair of directional antennas were adjusted and aligned well while the robot was moving. In other words, it validates that our antenna tracking system worked successfully.

To support this conclusion, we show the results of the estimated DOA by the bottom antennas on each side in Fig. 10. In this figure, the estimated DOA by the robot's antenna is depicted with a red arrow, and the estimated DOA by the command center's antenna is depicted with a blue dotted arrow. They are all averaged over three trials and projected on the designated paths by considering positions and poses of the robot. Consequently, the arrows by the robot's estimation and the arrows by the center's estimation formed almost a straight line on most of the locations except when the robot turned a corner. This indicates that our proposed system can enable proper antenna tracking, and therefore optimize the orientations of the two top antennas without acquiring the physical orientation and location of the antenna.

According to [13], the second selection would have less path loss than the first selection, therefore resulting in better throughput performance. However, from Fig. 9, the second selection showed slightly poorer performance as the robot moved further away from the command center. Conversely, the first selection showed stable performance over all the distances and times. Overall, the second selection showed poorer performance than the first selection in this test. Actually, this result was quite different from what we have expected. We are not sure yet, but this unexpected result could come from the effect on the second selection, caused by the low height of the installed antennas or different radiation patterns of the antennas. This result indicates that the second selection would be the worst choice if the robot needs to be deployed far away from the command center and in open space with the current system.

B. Outdoor Test in Complex Environments

Next, we chose the ENAD parking lot at Purdue University as shown in Fig. 8 (b), to see a level of differences in throughput when the robot is located in a LOS region and a NLOS region. For this test, we manually placed the robot at four different locations where the first two provide LOS, and the other two do not provide LOS, as shown on the bottom of Fig 8 (b). The initial distance between the robot and the command center was approximately 25 meters and the interval between the two locations was approximately 10 meters.

As Fig. 11 shows, the third selection dominantly outperforms the other two in this environment as well. Specifically, when the robot was located at the end of the test area, in NLOS 2, the third selection could reach higher than 10 Mbps throughput. On the other hand, the first two selections showed lower than 5 Mbps throughput. The results at NLOS 1 and NLOS 2 show that the first two selections fail to compromise in situations where LOS is unavailable. Conversely, throughput with the third selection had a small decrease from the third to the fourth location. Considering the final configuration, where one antenna attached on the robot points toward the same direction as the other antenna attached on the command center, this result could be expected. From this result, we conclude that the third selection is applicable to NLOS regions as well.

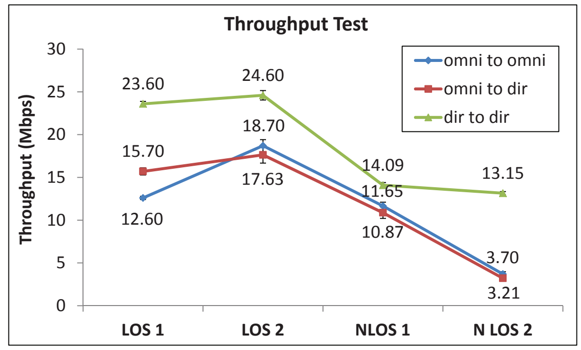


Fig. 11. Throuput measured when the robot is placed at four different locations - two provide LOS and the other two provide NLOS.

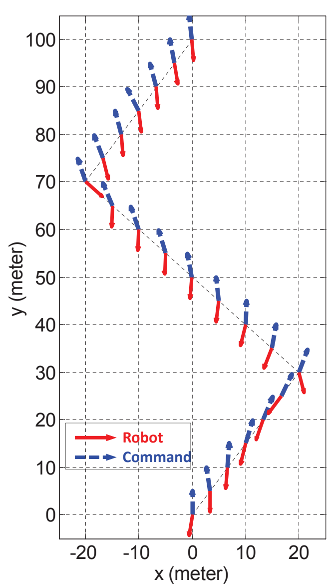


Fig. 10. Estimated DOA with the bottom antennas on the robot side and the command center side.

C. Indoor Test

It is known that the use of directional antennas is inappropriate in indoor environments. However, this type of antenna would be helpful in near LOS coverage such as long hallways or corridors. For this reason, we chose a hallway of Knoy hall at Purdue University for the third environment and tested our proposed system. This test was specifically designed to test cases where the robot needs to be deployed inside buildings.

During this test, the robot was set to move along a designated path with an almost constant speed of 0.2 meter/sec. The designated path is shown on the bottom of Fig. 8 (c). The total traveling distance of this path is approximately 50 meters, so it takes about 4 minutes to reach the final location. As shown in the floor map on the bottom of Fig. 8 (c), the robot was supposed to experience various situations including LOS and NLOS. Hence, this environment was good to check our antenna tracking system in more detail.

Figure 12 shows the estimated DOA by the bottom antenna on the robot side over the total travel. First, estimated DOA remained around $0°$ until the robot approached the first corner (See time from 00:00 to 01:00). As soon as the robot started turning counter-clockwise, estimated DOA increased to positive values until the robot's pose crossed at right angles to the command center. Then, as the robot started moving forward again, estimated DOA went to around $0°$, and decreased to negative values, reaching to a $-30°$ angle. In fact, these negative values result from the geometry of the environment. That is, because the directional antenna on the command center faced toward the front view for most of the time, its radio signal was reflected by the left wall and the upper wall around the first corner as if the original signal source was from that spot. To receive this reflected radio, the antenna on the robot side had to face in the left direction, resulting in negative values in DOA estimation. This result persisted until the robot entered the middle of the path. Then, when the robot turned clockwise at the second corner, the directional antenna oriented to the left direction, resulting in negative

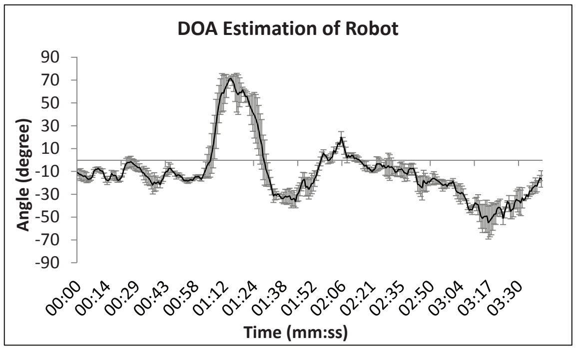


Fig. 12. Estimated DOA with the bottom antenna on the robot side.

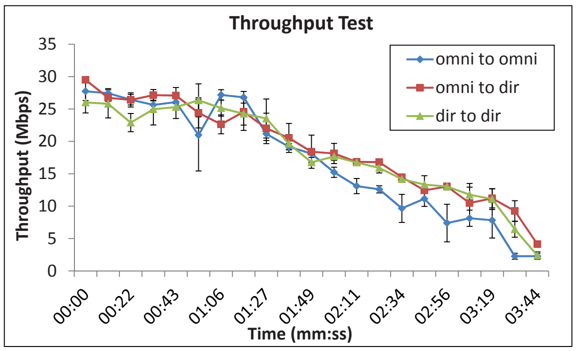


Fig. 13. Throuput measured while the robot was moving in an indoor and complex environment.

values in DOA estimation. This estimation persisted until the robot reached the final location. From this analysis on the history of estimated DOA, we could validate that our proposed antenna tracking system works properly.

Figure 13 shows throughput measured while the robot was moving from the initial location to the final location. Unlike the previous two experiments, all three antenna selections showed almost the same performance until the robot reached the middle of the designated path. Even, the third selection showed the lowest throughput until the robot entered NLOS regions (See around time of 01:00). As omnidirectional antennas are known to perform well in indoor environments, this result could be expected. However, as the robot moved further from the command center, specifically after 02:00, there was a noticeable gap in throughput between the first selection and the other two selections. That is, the second and third selections employing directional antennas showed slightly better performance than the first selection even in an indoor environment. It is undeniable that this environment would be unique and advantageous to directional antennas, but from this test, we could verify that directional antennas could be utilized and show satisfactory performance in indoor environments as well.

VI. CONCLUSIONS

This paper directly focused on problems where high quality and distant range wireless communication technology is required in rescue robotics, specifically for our firefighting robot. For these problems, we introduced a networked robotic system capable of enhancing wireless capabilities with off-the-shelf network devices. With the given field tests, we have showed satisfactory networking performance in various situations. We believe that these improved robotics communication systems can be used for a broad variety of different robotics applications, including military, rescue, and security.

In future work, we will verify our system in much longer and larger spaces to make it more robust and to cope with Fresnel zone issues that were not taken into account in this paper. Also, we will devise a new pan-tilt device allowing directional antennas to turn around in order to further maximize the performance of our system.

REFERENCES

[1] T. Moss, “Firefighting robot helps extinguish blaze from inside of ruined building | News-Gazette.com,” in *The News-Gazette.* [Online]. Available: http://www.news-gazette.com/news/local/2013-06-22/firefighting-robot-helps-extinguish-blaze-inside-ruined-building.html. [Accessed: 19-Jul-2013].

[2] G. Tuna, V. C. Gungor, and K. Gulez, “An autonomous wireless sensor network deployment system using mobile robots for human existence detection in case of disasters,” in *Ad Hoc Networks*, 2012.

[3] O. Tekdas, Y. Kumar, V. Isler, and R. Janardan, “Building a Communication Bridge With Mobile Hubs,” in *IEEE Transactions on Automation Science and Engineering*, vol. 9, no. 1, pp. 171-176, Jan. 2012.

[4] M. A. Hsieh, A. Cowley, V. Kumar, and C. J. Taylor, “Maintaining network connectivity and performance in robot teams,” *Journal of Field Robotics*, vol. 25, no. 1-2, pp. 111-131, 2008.

[5] C. Q. Nguyen, B.-C. Min, E. T. Matson, A. H. Smith, J. E. Dietz, and D. Kim, “Using Mobile Robots to Establish Mobile Wireless Mesh Networks and Increase Network Throughput,” *International Journal of Distributed Sensor Networks*, vol. 2012, pp. 1-13, 2012.

[6] 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*, Anaheim, CA, USA, 2007, pp. 501-506.

[7] B.-C. Min, J. Lewis, E. T. Matson, and A. H. Smith, “Heuristic optimization techniques for self-orientation of directional antennas in long-distance point-to-point broadband networks,” in *Ad Hoc Networks*, 2013.

[8] D. Bapna, E. Rollins, A. Foessel, and R. Whittaker, “Antenna pointing for high bandwidth communications from mobile robots,” *1998 IEEE International Conference on Robotics and Automation, 1998. Proceedings*, 1998, vol. 4, pp. 3468-3473 vol.4.

[9] R. Behnke and D. Timmermann, “AWCL: Adaptive Weighted Centroid Localization as an efficient improvement of coarse grained localization,” *5th Workshop on Positioning, Navigation and Communication, 2008. WPNC 2008*, 2008, pp. 243-250.

[10] J. Blumenthal, R. Grossmann, F. Golatowski, and D. Timmermann, “Weighted Centroid Localization in Zigbee-based Sensor Networks,” *IEEE International Symposium on Intelligent Signal Processing, 2007. WISP 2007*, 2007, pp. 16.

[11] P. Pivato, L. Palopoli, and D. Petri, “Accuracy of RSS-Based Centroid Localization Algorithms in an Indoor Environment,” *IEEE Transactions on Instrumentation and Measurement,*, vol. 60, no. 10, pp. 3451-3460, 2011.

[12] J. Wang, P. Urriza, Y. Han, and D. Cabric, “Weighted Centroid Localization Algorithm: Theoretical Analysis and Distributed Implementation,” *IEEE Transactions on Wireless Communications,*, vol. 10, no. 10, pp. 3403-3413, Oct. 2011.

[13] J. A. Dabin, A. M. Haimovich, and H. Grebel. “A statistical ultra-wideband indoor channel model and the effects of antenna directivity on path loss and multipath propagation.” *IEEE Journal on Selected Areas in Communications,*, vol. 24, no. 4, pp. 752-758, April 2006.