Performance Evaluation of Wi-Fi for Underground Robots

Lixiao Zhu, Xuejin Wen, Qi Han
Department of Computer Science
Colorado School of Mines
Golden, Colorado, USA
lizhu,wenxuejin@mymail.mines.edu,qhan@mines.edu

Alex Fryer, Neil Suttora, Andrew J. Petruska
Department of Mechanical Engineering
Colorado School of Mines
Golden, Colorado, USA
arfryer,nsuttora@mymail.mines.edu,apetruska@mines.edu

ABSTRACT

Underground environments present their unique challenges for wireless communication. This paper presents an empirical study of WiFi performance where aerial-ground robots are used to map, navigate, and search in an unknown underground environment. While wireless signal attenuates significantly around corners, WiFi's overall performance is encouraging.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

WiFi, performance evaluation, underground robots

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1 INTRODUCTION

To address population growth and resource constraints on earth, underground environments (e.g., natural caves, man-made tunnels, subway systems, or urban underground) are becoming increasingly important to cope with these societal issues. However, underground environments need to be thoroughly explored and inspected for human safety, being able to effectively perform search and rescue during/after underground catastrophes is also essential. In the past decade alone, over 40,000 miners worldwide have been killed in fatal mining accidents [1]. According to a report from the Mine Safety and Health Administration (MSHA) [1], 26 mine fatalities occurred and over 6,900 miners were injured in mine accidents in the U.S. in 2016, costing the mining industry and the U.S. government 50.2 million dollars for accident response and recovery.

Using robots to map, navigate, and search underground environments can prevent risking additional human lives. In this paper, we assume robots use wireless radio frequency for communication. Radio signal propagation in underground environments is inherently different from free space propagation for several reasons: (a) the guiding of electromagnetic waves in tunnels causes less path loss than in free space; (b) diffraction losses at branches and bends cause larger path losses than free space; (c) lots of electromagnetic noise from various equipments significantly disturbs radio propagation, so in many cases the distance between wireless nodes is shorter than that in normal environments. As a consequence of these differences, the individual links in a wireless network of randomly placed nodes in such an environment varies widely, leading to unreliable network performance. Further, underground mines pose additional challenges. This is because underground mines differ from each other in the materials being excavated, which include hard minerals such as ore containing gold, silver, iron, copper, zinc, nickel, tin, lead and also softer minerals such as salt, coal, or oil sands. The materials not only directly impact wireless signal propagation, but also indirectly impact it because of the unique requirements they impose on the excavation equipment needed. Also, due to the dynamic nature of mining operations, including exploration and excavation, the structures and equipment being used in the underground mines change over time. Various wireless devices including wearable devices such as smart helmets and wrist phones are getting increasingly popular even with miners. All of these devices affect the communication range of wireless devices and network coverage, leading to network uncertainty.

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2 RELATED WORK

Because of poor illumination in underground environments, different types of sensors are needed either on robots or on the tunnel walls to capture situational information. These sensors acquire large amounts of data to be transmitted to the control center [5, 6]. Further, computer vision and image processing techniques have been widely adopted for hazard identification, real-time reports, and victim search and rescue in underground mines [3, 10]. For instance, 3D-mapping will require cameras, LIDARS, and laser sensors [6]. All of these demand real-time and high bandwidth communication. Due to the inherent mobility of these robots and rough tunnel ground, communication with an underground robot is often done via wireless radio rather than tethering.

Existing studies [2] show that protocols such as Zigbee cannot support high bandwidth transmission. In contrast, protocols such as Wi-Fi support higher bandwidth at the cost of more energy consumption. There is no widely accepted communication method or protocol for underground environments yet. Existing robotic systems have used different communication protocols and radio frequencies, resulting in so-called "islands of automation" [6].

Wireless signal propagation is affected by many factors, including rock and soil composition, the presence of debris, and tunnel dimensions and layout [7]. Therefore, a wireless network has to be specifically designed for each underground environment. If there is a pre-existing wireless network available, robots will need to co-exist with the network. This implies that the deployment of the robots and their movement will need to take into account the existing network and ensure compatibility with existing communication protocols. In the CSIR project [3], exploration strategies for robots as well as the global and local motion planning of robots are designed to work with sensors previously hung on the tunnel walls.

Signal fading is significant in the tunnels. For instance, several experiments were performed using Rajant ME2 BredCrumb Wi-Fi nodes to quantify the distance versus signal strength for a few tunnels in the Edgar experimental mine [8, 11]. The transmitter power of these nodes were set at 34 dBm using omni-directional TX and RX antennas. The results show that signal strength is attenuated very quickly when a turn around a corner is taken within a mine. In the straight sections of the Miami tunnel about 50 dB of signal strength was lost in 1000 ft, whereas the attenuation is nearly 1.3 dB/ft around a 90 degree bend. In order to maintain communication, one approach is to use an optical cable when a robot moves away from a base station so that the robot can communicate with the remote control center in real-time [4]. Another approach is to use robot relays that apply a specific planning strategy to overcome severe signal fading and maintain constant connectivity and high signal quality in the communication network [9]. Yet another approach is to form a robot team that not only builds a real-time multi-hop communication protocol to support both communication and control, but also recognizes natural landmarks from the environment using LIDAR sensors for navigation, path planning, and coordinated deployment [10]. Depending on the mission, the robot team can also use motion planning and obstacle avoidance techniques for each robot.

3 COMMUNICATION NODE SELECTION

We are currently designing a swarm of unmanned air-ground vehicles (UAGVs) that will be used to map, navigate, and search underground environments. There are several requirements for communication nodes.

- In order to support map generation and object recognition, large amount of information needs to be shared among the platforms and also with the server, hence we require a high bandwidth wireless network.
- As the swarm of robots move around in the underground environment, they need to communicate with each other for distributed map generation and object recognition, they also need to send updated map and object information to the server outside the environment. However, robots may not always been within the communication range of each other, we hence need to drop some relay nodes to maintain communication connectivity. These relay nodes will be carried by the UAGV platform. To reduce the energy consumption and payload of the platform, the communication nodes must be light-weight.
- The power consumption of communication nodes needs to be low for the system to function for a long time.
- The communication nodes need to be placed on unmanned aerial vehicles, hence they need to be light in weight.

Further, it is desirable if communication nodes are low cost.

After comparing several options, we have decided to use Google Wi-Fi system (Figure 1). Each node uses a Quad-core ARM CPU and is powered by a 15W power adapter. It supports 2.4 GHz and 5 GHz radio frequencies and 802.11a/b/g/n/ac. Its diameter is 4.1 inches and its height is 2.7 inches. It weighs 340 grams and 215 grams after an internal metal piece is removed.

Figure 1: Google WiFi Home Node

4 PERFORMANCE EVALUATION IN EDGAR MINE

The Edgar mine (Figure 2), the Colorado School of Mines experimental mine, is located in the mountains above Idaho Springs, Colorado. The ribs (walls of the tunnels) are rough and uneven, causing significant multi-path signal degradation during radio communication. Thus the Edgar Mine testbed can serve as a highly realistic underground environment on which to evaluate the performance of Google Wi-Fi nodes.

Figure 2: Entrance of Edgar Mine

Our experiments were performed between the Miami tunnel and the work shop within Edgar Mine (the orange circle in Figure 3). The starting point is highlighted as a star in Figure 3.

One laptop (Lenovo) is used as a base station and the other (Hp Zbook) is used to mimic a robot. Both have Intel® Dual Band Wireless-AC 8265 network interface card built-in. For bandwidth measurement, we let the laptop and Google WiFi node choose the best communication band (either 2.4 or 5 GHz) that provides the best performance. For all of our experiments, we measured Radio Signal Strength (RSS) and bandwidth.

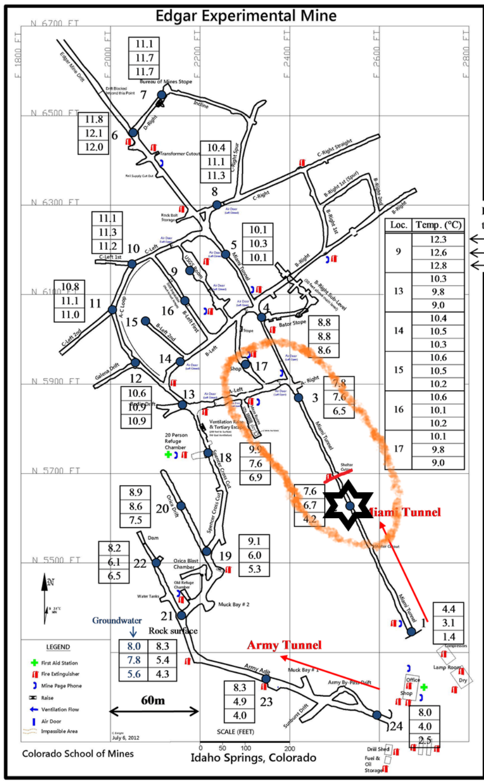
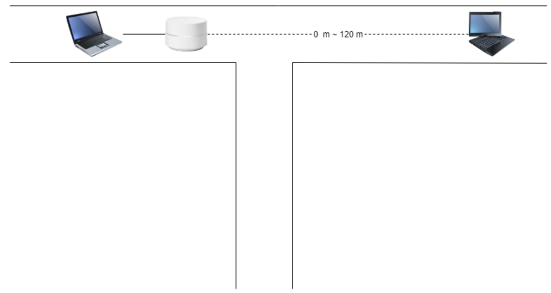


Figure 3: Experimental Area in Edgar Mine

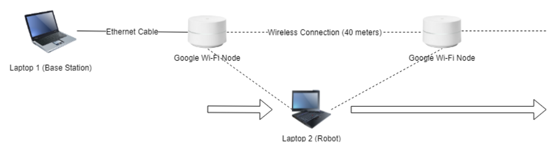
We evaluated the performance in both single-node scenario and multi-node scenario when nodes are placed in a straight line in the mine tunnel. Figure 4 shows the setup. The laptop on the left is used as a stationary server, the Google nodes are used as stationary relay, and the laptop on the right is used to mimic a mobile robot that moves away from the Google node. The left laptop is connected to a Google node via an Ethernet cable.

Figure 5 shows the results. We measured the bandwidth supported and radio signal strength between the mobile robot and the server. As the distance increases, bandwidth decreases for the single-node scenario. However, we noticed that the bandwidth decreases first and then increases again in the multi-node scenario. This shows Google WiFi node can automatically selects the best node to connect to the server, i.e., when the robot moves far away from the server, the Google nodes in between have been used as communication relays. The radio signal strength for the multi-node scenario is better than single-node scenario. By analyzing both bandwidth and RSS results, 40 meters is a reasonable distance to support needed bandwidth.

Figure 6 shows the setup for the corner tests in the mine tunnel. We let the second robot move around a corner. Figure 7 shows the multi-node scenario clearly outperforms the single-node scenario. When there is only one relay node, the robot soon lost connection around the corner. However, when another node is placed at the center of the corner, both bandwidth and radio signal strength significantly improve.



(a) Single-node scenario



(b) Multi-node scenario

Figure 4: Experimental setup of single- and multi-node scenarios for straight-line tests in Edgar Mine

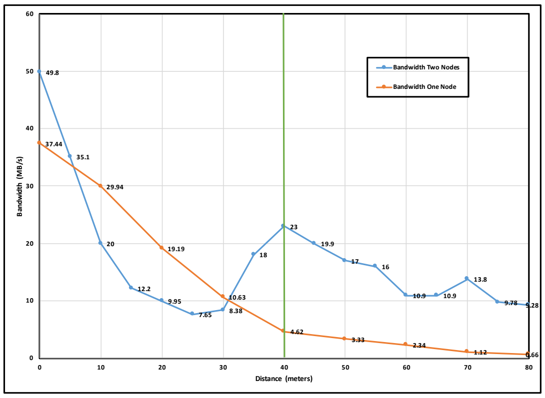
Performance Evaluation in an Office Building. In order to have a quantitative comparison of Google WiFi node's performance when used in Edgar Mine vs. being used in a lab, we performed similar straight-line tests in the hallway on the third floor of Brown Building, an office/lab building on campus. Figure 8 shows the results comparison. Surprisingly, we did not observe significant performance drop in Edgar Mine.

5 PERFORMANCE EVALUATION IN EDGAR MINE WITH A MOBILE ROBOT

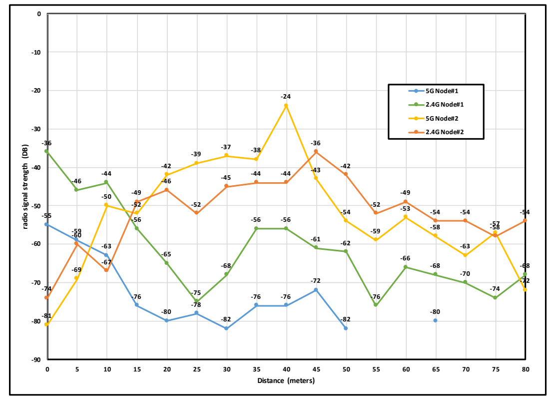
In addition to testing scenarios where all nodes are stationary, we also evaluated the WiFi performance when a robot is mobile. Specifically, we evaluated two scenarios where a Geobot moved at 0.5 m/s and 1.0 m/s. For each speed, we ran the test three times. All tests were conducted out to 80 meters. The robot lost network connectivity for the bandwidth test at about 40 meters while the RSS test reported values all the way out to 80 meters, for the most part. Comparing the results shown in Fig. 9 and Fig 5, it is clear that mobility has a significant impact on bandwidth and radio signal strength. When a node is mobile, even at the same distance as a stationary node, its bandwidth and radio signal strength are reduced significantly. results in Fig. 9 and Fig 10 show that a robot increases its speed, the bandwidth and radio signal strength decrease.

6 POWER CONSUMPTION

The original node requires a wall outlet for power, which is impractical for underground mobile robots. We made a case to replace the bottom component of the original node that fits a battery for power. We use two 21700 lithium-ion batteries to power the node. Figure 11 shows the power system design for Google WiFi nodes. We let the node send packets at maximum throughput and observed that the node can run for at least 10 hours without overheating.

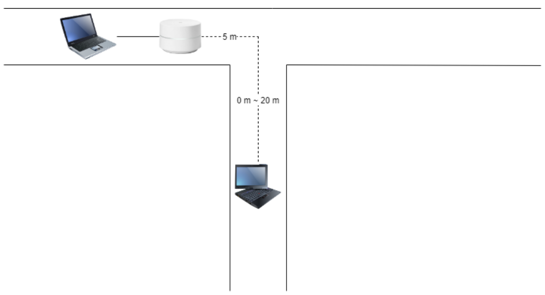


(a) Bandwidth

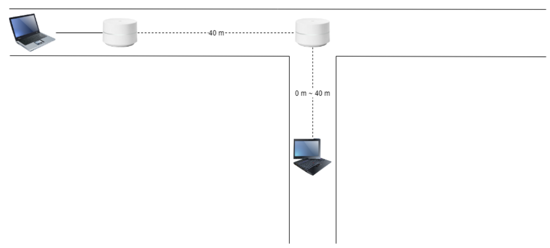


(b) RSSI

Figure 5: Performance of single- and multi-node scenarios for straight-line tests in Edgar Mine

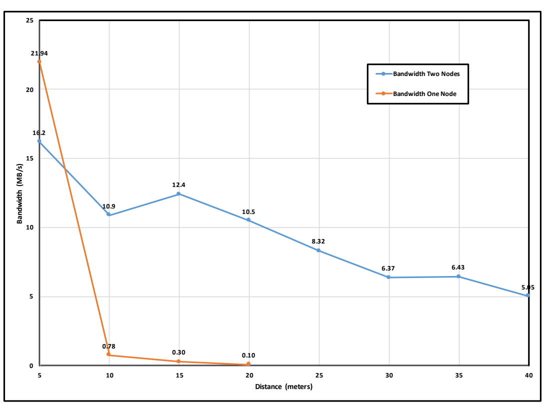


(a) Single-node scenario

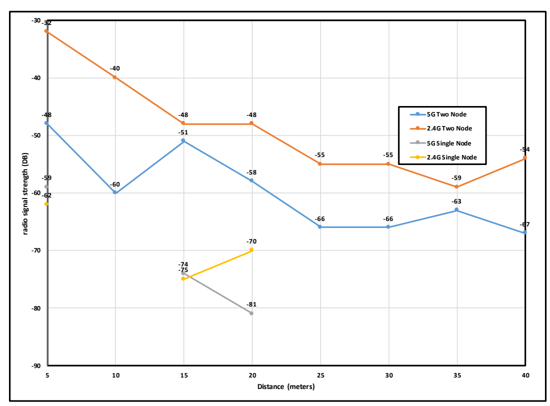


(b) Multi-node scenario

Figure 6: Experimental setup of single- and multi-node scenarios for corner tests in Edgar Mine



(a) Bandwidth

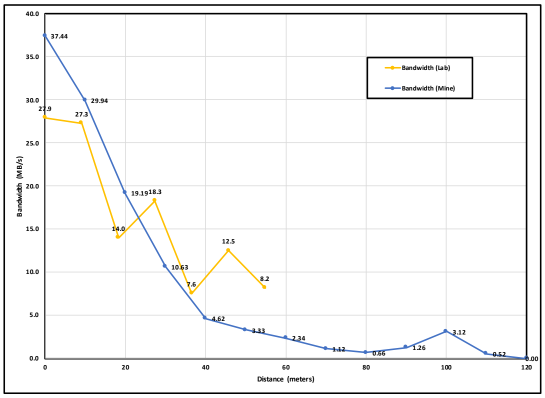


(b) RSSI

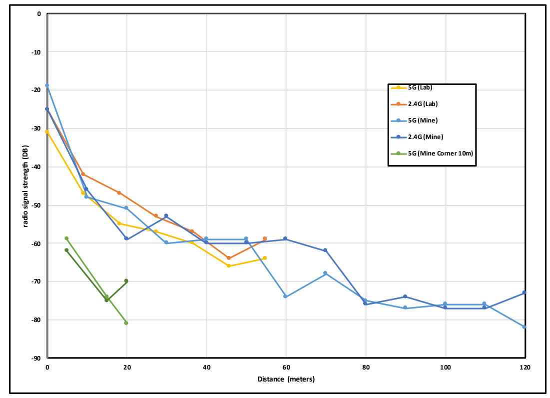
Figure 7: Performance of single- and multi-node scenarios for corner tests in Edgar Mine

7 CONCLUSION

In this work, we have selected a low-cost COTS WiFi platform (i.e., Google WiFi home nodes) to be used on underground aerial-ground vehicles and evaluated its wireless communication performance in an underground mine. As expected, we observe through multiple testings, the robot's speed has a negative impact on WiFi performance, wireless signal attenuates quickly at a bend. We also are surprised that when nodes are placed in a straight line, in an office

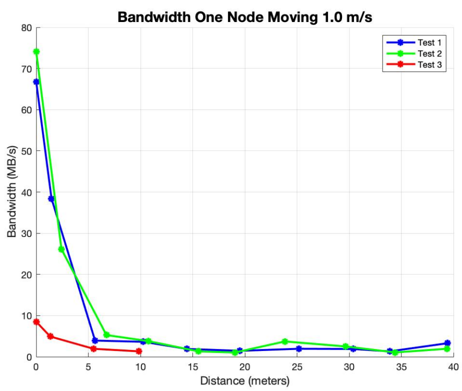


(a) Bandwidth

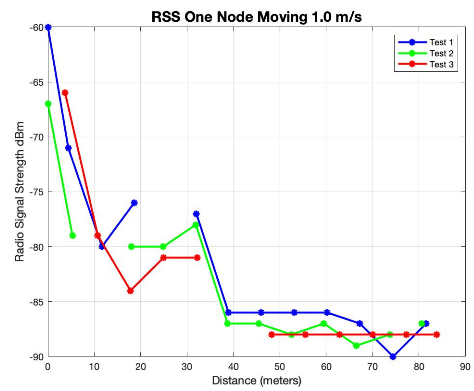


(b) RSSI

Figure 8: Performance Comparison of Google WiFi node in Edgar Mine and in an office building

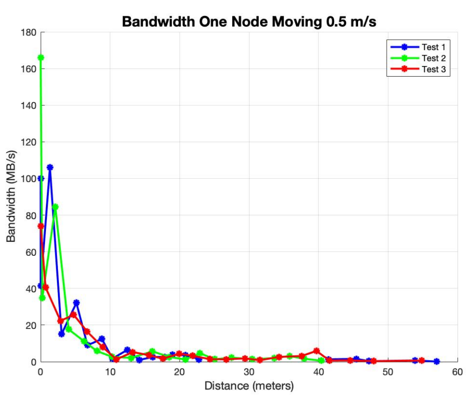


(a) Bandwidth

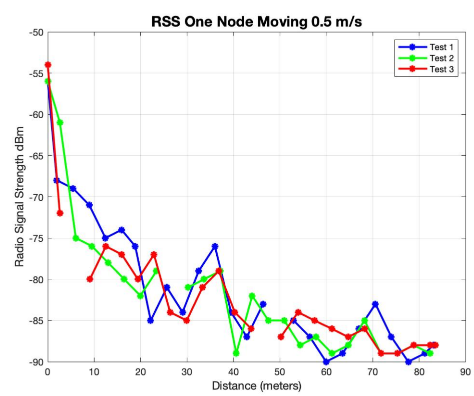


(b) RSSI

Figure 9: WiFi Performance of a moving robot in Edgar Mine (speed = 1.0m/s)

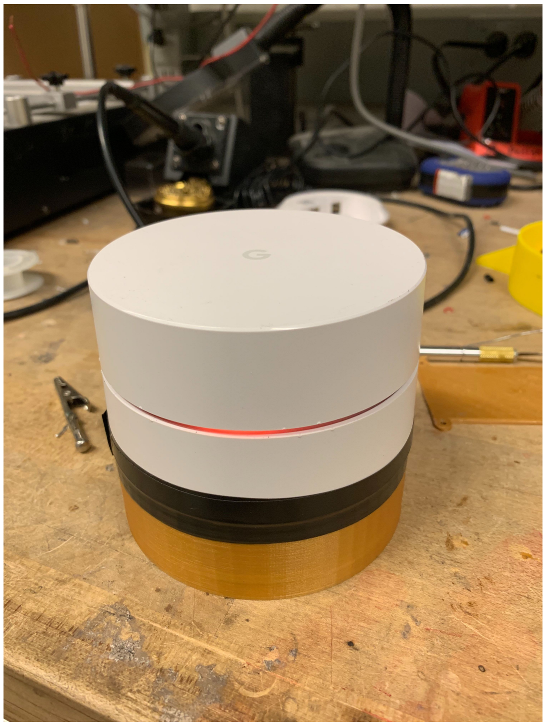


(a) Bandwidth



(b) RSSI

Figure 10: WiFi Performance of a moving robot in Edgar Mine (speed = 0.5m/s)



(a) Google WiFi Home Node with Battery

(b) Battery

Figure 11: Google WiFi node powered by batteries

building WiFi performs similarly to an underground environment. To fully support mobile robots in underground environments using WiFi, additional algorithms will be needed to place communication relays strategically and manage packet loss effectively.

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