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Experimental Investigation into Deploying a Wi-Fi6 Mesh System for Underground Gold and Platinum Mine Stopes

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Abstract: Stopes suffer from unreliable wireless communication due to their harsh environment. There is a lack of confidence within industry regarding the effectiveness of existing solutions in providing reliable high-bandwidth performance in hard rock stopes. This work proposes that Wi-Fi6 is a good candidate for reliable high-bandwidth communications in underground hard rock stopes. Experiments in a tunnel and mine stope were conducted to evaluate the performance of Wi-Fi6 in terms of latency, jitter, and throughput. Different criteria, such as multi-hop systems, varying multipath, mesh routing protocols, and frequencies at different bandwidths, were used to evaluate performance. The results show that Wi-Fi6 performance is greater in stopes compared to tunnels. Signal quality evaluations were conducted using the Asus RT-AX53U running OpenWrt, and an additional experiment was conducted on the nrf7002dk running Zephyr OS to evaluate the power consumption of Wi-Fi6 against the industry standard for low-powered wireless communications, IEEE 802.15.4. Wi-Fi6 was found to be more power-efficient than IEEE 802.15.4 for Mbps communications. These experiments highlight the signal robustness of Wi-Fi6 in stope environments and also highlights its low-powered nature. This work also highlights the performance of the two most widely used open-source mesh routing protocols for Wi-Fi.

Keywords: B.A.T.M.A.N.; HWMP; jitter; latency; multipath; OpenThread; stope; throughput; Wi-Fi6

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1. Introduction

A high-bandwidth wireless solution would be of significant value in modern mining operations to enhance efficiency, safety, and productivity. They enable the real-time transmission of critical data, ensuring that information from various sensors and monitoring devices is swiftly communicated to control centres and decision-makers. This immediacy supports advanced automation technologies, allowing for the precise remote control of machinery and vehicles, and the seamless operation of automated processes. Furthermore, a high-bandwidth infrastructure ensures rapid and reliable safety communications, which is vital for protecting workers in the hazardous stope environment. It allows for instant alerts and emergency responses, enhancing the overall safety of mining operations. Additionally, a high-bandwidth infrastructure supports comprehensive data analysis, where the data can be analysed to optimize operations and inform strategic decisions. By leveraging a high-bandwidth wireless infrastructure, mining companies can significantly improve their operational effectiveness, reduce risks associated with equipment failures and environmental hazards, and achieve better overall performance, ultimately leading to increased productivity, profitability, and safety for stope activities. An example of an application could be the transmission of LiDAR data from robots to facilitate automation, mapping terrain, detecting potential obstacles, and determining safe pathways in real-time. These automated robots could be used to calculate the ideal locations to place dynamite in a stope, as well as facilitating the installation of the dynamite instead of using people, thus reducing risk to human lives. Another example could be the transmission of thermal and acoustic data to a processing node to identify loose rocks and trigger alarms if the area is unsafe. The transmission and analysis of geophone or accelerometer data could also be used to detect seismic activity and trigger appropriate alarms. Other applications include maintaining communication infrastructure; environmental monitoring using gas, temperature, and humidity sensors; and equipment monitoring to ensure high efficiency and safety. Due to the critical nature of these applications, the communication infrastructure would need to have excellent levels of jitter and latency; and if high-bandwidth applications such as LiDAR signal transmissions or geophone analysis are required then the infrastructure would need to support excellent levels of jitter and latency whilst transmitting at very high bandwidths.

The number of studies on wireless communication in stopes is extremely limited. While various technologies have been proposed for tunnels and soft rock mines such as coal mines [1,2], none have emerged as a mainstream solution for hard rock stopes such as the underground gold and platinum stope environment. Underground gold and platinum mine stopes are seen as much harsher environments due to their small size (approximately 1.5 m in height and 20 m in width), rough surfaces, as well as their irregular shape due to the requirement of blasting for hard rock mines, and frequent path blockages due to support pillars as well as large metallic mining equipment. Gold and platinum mines are also several kilometres underground; thus, it is vital to have an energy efficient system to prevent unnecessary battery replacements as it is not feasible to store large numbers of batteries underground due to health and safety reasons. To develop the best possible wireless solution for underground mine stopes, the technology would need to support high data rates for productivity-enhancement applications, low-power consumption to reduce battery replacements, and robustness to cope with the harsh stope environment.

Underground mines are dynamic, with each having peculiar conditions. They continue to involve extreme occupations in very hazardous environments, such as vehicle accidents, roof falls, fire, explosions, the release of toxic gases, and floods. Hard rock mines, particularly gold and platinum mine stopes, are very harsh environments. Mineral excavation in hard rock stopes is characterized by the usage of explosives. Due to the narrow and short nature of stopes and their rough, rocky surfaces, the wireless signals undergo excessive amounts of signal reflections and scatterings. For home usage, Wi-Fi signals can pass through layers of brick or blocks; however, in underground mines, wireless signals cannot pass through the thick layers of dense rock; thus, the signals are contained within a stope, which significantly increases the possibility of destructive interference alongside excessive multipath propagation. Wireless transmissions in confined areas tend to experience more multipath propagation as compared to spacious areas. In confined areas, the reflected signals have a much greater potential to interact with each other, and there is also the increased possibility of causing distortions, such as fading, ghosting, or signal dropout. For these reasons, stopes are seen as a difficult environment for wireless communications. Stopes are very small in size, and it is not feasible to install excess amounts of cabling in this environment as it would pose many health and safety risks. Cabling should be limited to high-powered equipment that are critical to the operation of the mine. A wireless solution is considered the most viable option for such an environment.

Coded Orthogonal Frequency Division Multiplexing (COFDM) has been identified as a promising technology for addressing the harsh conditions of underground hard rock stopes. This technology is well known for its role in the transformation of the terrestrial broadcasting domain [3,4]. However, the prohibitive cost associated with COFDM equipment limits its widespread adoption in the mining industry. In [5], Wi-Fi6 was shown to offer similar signal robustness as COFDM, However, the experiments were performed in a non-ideal office corridor. This work expands on [5] by performing the Wi-Fi6 experiments in a test stope. Additional experiments were also performed to give a more comprehensive analysis of Wi-Fi6 signal performance in a stope. The signal quality evaluations were performed on an Asus RT-AX53U using the open-source OpenWrt OS with open-source mesh routing protocols, namely B.A.T.M.A.N.-adv [6] and HWMP [7]. The industry standard for low-powered wireless communications was identified as IEEE 802.15.4 [8]. OpenThread was selected as the IEEE 802.15.4 variant. Wi-Fi6 was identified as the potential candidate for stope communications due to its potential for reliable high-bandwidth communications and power efficiency. This work compared the power consumption of Wi-Fi6 vs. OpenThread by using an identical setup. The nRF7002dk was used alongside Zephyr OS, since it supported both Wi-Fi6 and OpenThread. By using the same boards, same OS, same transmission frequencies, and same input voltage, we were able to achieve the accurate power consumption comparisons of the protocols.

2. Related Work

Due to the importance of communication in mining environments, wireless communication solutions have been developed and performance experiments have been conducted for different mining areas and categories in real mining environments [9]. Due to the costs of testing equipment, the unavailability of mining test sites, and the difficulty in experimental applications, practical mine test experimental results are wide and few, and this is especially true for underground gold and platinum mine stopes. In [10], an experimental study of the Line-of-Sight Millimetre-Wave Underground Mine Channel was conducted. In [11], experimental results for Zigbee in an underground mine are presented. The authors of [12] study Multiple-Input and Multiple-Output (MIMO) antenna configurations for underground mine communication and present measurements for a gold mine. Ref. [13] presents experimental results obtained from narrowband and wideband radio-channel measurements in an underground mine at 2.4 GHz. Ref. [14] explores and tests a smart phone network for communicating sensor data from the underground production environment to the surface, in a tunnel, stope, and shaft.

Power consumption is one of the major considerations for underground mine applications. The major drawbacks of high bandwidth wireless communications are that of high-power consumption as well as the inability to cope with excessive multipath propagation [15]. Low-power Wi-Fi6 systems have emerged as a potential candidate for the underground mine stope. Ref. [16] presented an empirical study of Wi-Fi performance where aerial-ground robots could be used to map, navigate, and search in an unknown underground environment in the experimental mine of the Colorado School of Mines. Laptops were used to represent the robots. The results show that the signal throughput drops significantly over large distances within line of sight and is non-existent around a corner. Ref. [17] performed measurements for mining Wi-Fi vehicle-to-vehicle (V2V) communication to be utilized in a tunnel to increase the safety and productivity of the transportation of mining goods. Furthermore, a signal performance analysis between COFDM [18] vs. Wi-Fi6 (IEEE 802.11ax) [19] demonstrated the potential performance of Wi-Fi6 for the underground mine stope [5]. In [5], the Asus RT-AX53U Wi-Fi6 device was compared with the SOL8SDR COFDM device. In this paper, Wi-Fi6 was shown to be more power efficient than the current industry standard of low power communications, IEEE 802.15.4 [8]. Even though Wi-Fi6 uses more peak power to transmit data, the total power consumed for sending data is much less due to the shorter transmission durations. The idle power consumption for both Wi-Fi6 and IEEE 802.15.4 (OpenThread [20]) were roughly the same.

It is also important to incorporate a mesh topology for stope communications due to its ability to enable multiple pathways between nodes and ease of network extensions and strategic node placement. Furthermore, a critical component of mesh topologies is its mesh routing protocol. These protocols are generally summarized into reactive and proactive protocols. For proactive routing protocols, every node keeps a current list of routes, and examples include the Optimized Link State Routing (OLSR) [21] and Destination-Sequenced Distance Vector (DSDV) [22]. For reactive routing protocols, the routes are only set up when necessary, and examples include Ad Hoc On-Demand Distance Vector (AODV) [23] and Dynamic Source Routing (DSR) [24]. In [25], the throughput of proactive routing was better than reactive routing with multipath fading. This research extends this by practically experimenting the performance of a decentralized proactive mesh routing protocol (B.A.T.M.A.N. advanced) vs. the hybrid approach of using both proactive and reactive routing (e.g., HWMP). For the highly regulated mining environment, where mining equipment is notably costly and typically vendor-controlled, there exists a compelling need for cost-effective alternatives to proprietary solutions. One such alternative is the adoption of a mesh system employing an open-source mesh routing protocol, such as the Hybrid Wireless Mesh Protocol (HWMP) or the Better Approach To Mobile Ad Hoc Networking—advanced (B.A.T.M.A.N.-adv) protocol. Renowned for their versatility and widespread adoption, these protocols offer the advantage of extended system lifespans, as a result of their continual development within the open-source community. This strategic shift not only mitigates cost concerns but also enhances adaptability and long-term viability within the mining infrastructure. To our knowledge, an experimental investigation of these two protocols has not been conducted in terms of multi-hop performance for the harsh underground gold and platinum stope environments. The performance of these protocols needs to be investigated for this type of stope environment; this is undertaken in this work.

3. Aim

The aim of this work is to demonstrate that Wi-Fi6 can offer reliable high-bandwidth performance in an underground hard rock stope using open-source mesh routing protocols, namely B.A.T.M.A.N.-adv and HWMP. This will be achieved by obtaining the fundamental characteristics of wireless performance, namely throughput, jitter, and latency results, in a stope and comparing them with the results from a more spacious tunnel which is considered a friendlier environment for wireless communications. The aim of this work is also to demonstrate that the Wi-Fi6 power efficiency rivals that of the industry standard for low-powered wireless communications, namely IEEE 802.15.4.

4. Scope of Work

This work develops experimental measurement results for the following:

- Performance of Wi-Fi6 in a test simulation mine developed with the intention of providing an easily accessible environment which closely resembled the conditions of a real mine with a stope. The experiments were conducted in a high multipath stope environment as well as a low multipath spacious tunnel environment within the mine to evaluate the impact of excessive multipath propagation on Wi-Fi6.
- The performance parameters of throughput, jitter, power consumption, and latency were considered. Different criteria such as the effects of channel bandwidths, transmission frequencies, mesh routing protocols, transport layer protocols, and multi-hop impact on the signal performance were investigated.
- The performance comparison of Wi-Fi6 and IEEE 802.15.4 (OpenThread) in terms of power consumption was performed. The experiment setup features the nRF7002dk alongside the Zephyr operating system transmitting at a frequency of 2.4 GHz. The results indicated that even though Wi-F6 has a greater instantaneous power consumption, its overall power consumption is much lower than that of OpenThread due to the shorter transmission times. The idle power consumption of both protocols was noted as being very similar.
- The performance comparison of HWMP and B.A.T.M.A.N.-adv routing protocols in terms of reactive and proactive routing for stope environments. The experimental test bed featured the open-source OpenWrt OS installed in the Wi-Fi6 nodes which were configured using the IEEE 802.11s mesh standard. The results indicate that even with the increased overhead of HWMP, it still outperforms B.A.T.M.A.N.-adv for stope environments.
- The throughput, latency, and jitter performance of the protocols was surprisingly found to be better in a stope than a spacious tunnel. This was attributed to the Wi-Fi6

technology taking advantage of the waveguide nature of a stope and its ability to efficiently handle the multipath signals.

5. Characteristics of the Applied Communication Technologies for the Underground Mine Stope

5.1. Wi-Fi6

Wi-Fi has evolved drastically over the years. Wi-Fi1 initially introduced Direct Sequence Spread Spectrum (DSSS) modulation [26], which spread a signal over a wider bandwidth as compared to its original size. This approach of spreading data reduced the effects of interference from other signals or noise, making the communication more robust. Wi-Fi2 uses Orthogonal Frequency Division Multiplexing (OFDM) [27], which enabled multi-user capabilities by allocating subcarriers to individual clients. For OFDM, the entire subcarrier could only be allocated to a single client. Wi-Fi3 uses the concept of channel bonding [28], which allows adjacent 20 MHz channels to be combined to create wider 40 MHz channels. This can effectively double the data throughput under optimal conditions. Wi-Fi4 applies Multiple-Input Multiple-Output (MIMO) technology [27], which allows for multiple streams of data to be transmitted simultaneously via multiple antennas. This improved spectral efficiency and greatly improved throughput. Wi-Fi5 introduced Multi-User MIMO (MU-MIMO) [29] for simultaneous data transmission to multiple clients. For MIMO, each antenna pair served a single client, whilst MU-MIMO serves multiple clients concurrently by spatially multiplexing the data streams. Whilst MIMO focused primarily on improving the performance of a single client, MU-MIMO enables simultaneous communication with multiple clients, thereby increasing overall network performance. Wi-Fi6 uses Orthogonal Frequency Division Multiple Access (OFDMA) [30] for improved efficiency in high-density environments. Wi-Fi6 also introduced BSS colouring [31], which is used to address co-channel interference. This helps devices make better decisions regarding channel access, hence reducing collisions and improving overall network efficiency in high-density environments. Due to the low-powered nature of Wi-Fi6, the devices can be installed in certain allocated points in stopes without being a burden to the miners. All these properties make Wi-Fi6 a good candidate for stopes.

Wi-Fi6 implements several technologies to address the concerns of multipath interference. Wi-Fi6 uses OFDMA, which allows for a single channel to be divided into smaller sub-channels known as Resource Units (RUs) [32]. These RUs can be transmitted to different users simultaneously, thus allowing for the increased utilization of the available spectrum, hence reducing the impact of multipath interference. Wi-Fi6 also introduced techniques such as BSS colouring with spatial frequency reuse [33] which enables multiple devices within close proximity to communicate simultaneously whilst limiting interference. This spatial reuse capability helps mitigate the effects of multipath interference by allowing the more efficient use of the available spectrum. Although MU-MIMO was introduced in Wi-Fi5; Wi-Fi6 expanded its capabilities by supporting MU-MIMO in both uplink and downlink transmissions. This functionality enables multiple devices to simultaneously receive and transmit data, even in environments with excessive multipath interference, by using multiple antennas to spatially separate the signals [34]. Wi-Fi6 also utilizes an improved beamforming technique, which enhances the reliability and efficiency of transmissions by directing signals towards the intended recipients [35]. For these reasons, Wi-Fi6 has become the perfect low-cost candidate for mine stope communications.

Previous research [5] has shown that COFDM offers slightly better signal robustness as compared to Wi-Fi6, which would have made COFDM the ideal choice for a stope. However, the cost of a COFDM device is much greater than that of a Wi-Fi6 device. Wi-Fi6 devices are substantially cheaper than COFDM devices whilst offering similar signal robustness. Wi-Fi6 devices also had substantially greater throughput than COFDM devices. The reason why Wi-Fi6 is so desirable for stopes is because the technology is mainstream, which prevents overly inflated prices. COFDM devices are expensive due to their niche market and limited consumer demand for the technology, i.e., a situation where a few vendors can dictate the price of the COFDM devices. Stopes are very harsh environments, where devices frequently become damaged. Due to the low cost of Wi-Fi6 devices, they are considered expendable whilst giving more emphasis to productivity. Whereas previous Wi-Fi generations focused mainly on speed improvements, Wi-Fi6 mainly focused on improved spectral efficiency, making it a good contender for a mine stope. Due to its characteristics, it is capable of dealing with harsh environments such as the underground gold and platinum mine stopes. Therefore, the practical performance of Wi-Fi6 needs to be investigated.

5.2. OpenThread

IEEE 802.15.4, alongside its variants, is well known for its place as the industry standard for low-powered wireless communications [8]. Its low power consumption makes it ideal for battery-operated devices and sensors, ensuring prolonged operation without frequent maintenance or battery replacements. OpenThread [36], an open-source implementation of the thread networking protocol, is an IEEE 802.15.4 variant that was engineered specifically for low-rate wireless personal area networks (LR-WPANs) [37]. OpenThread incorporates highly efficient modulation schemes optimized for long-range communication and minimal power consumption. Leveraging Offset Quadrature Phase Shift Keying (O-QPSK) [38], OpenThread achieves lower data rates tailored to the demands of Internet of Things (IoT) applications, distinguishing itself from the Quadrature Amplitude Modulation (QAM) utilized by Wi-Fi [39] within the same 2.4 GHz spectrum, albeit with reduced throughput. O-QPSK was primarily designed to reduce the peak-to-average power ratio (PAPR) in the transmitted signal [40]. By staggering the phase changes of the in-phase and quadrature components, O-QPSK ensures that the phase changes are more gradual compared to traditional QPSK. This results in a more constant envelope signal, which is easier for power amplifiers to handle efficiently without significant distortion. The authors of [41] demonstrate the low-powered nature of O-QPSK through the simulation of 180 nm, 90 nm, and 45 nm CMOS technologies and attempt to improve the power efficiency through reframing using a booth multiplier. This modulation scheme, combined with OpenThread's mesh networking capabilities, provides reliable and resilient communication by allowing devices to connect through multiple pathways, which is particularly advantageous in harsh and obstructed environments; however, its low throughput is a significant limitation. An experimental performance comparison of OpenThread and Wi-Fi6 is necessary to determine the feasibility of deployment of the two for the underground gold and platinum stope environments.

5.3. Mesh Routing Protocols

The Hybrid Wireless Mesh Protocol (HWMP) is the default mesh routing protocol for IEEE 802.11s. HWMP offers a combination of proactive routing (where nodes maintain routing tables with precalculated paths) and reactive routing (where routes are discovered on-demand) [7]. HWMP is an adaptation of the reactive Ad Hoc On-demand Distance Vector (AODV) routing protocol [42] called Radio-Metric AODV (RM-AODV) [43]. AODV operates in the IP layer and uses the hop count as its routing metric, whilst RM-AODV operates in the MAC layer and uses the radio-aware routing metric for its path selection.

The Better Approach To Mobile Ad Hoc Networking (B.A.T.M.A.N.) [6] protocol is a proactive mesh routing protocol. The main contribution of the B.A.T.M.A.N. mesh protocol was the decentralization of knowledge regarding the complete route of a message chain, from start to finish. A node in the network will not attempt to determine the complete path of the message it is passing, but rather it will only determine its best next hop towards the destination. The version known as B.A.T.M.A.N.-adv was used for this research. This version of B.A.T.M.A.N. operates in the MAC layer.

An experimental performance comparison of HWMP and B.A.T.M.A.N is necessary to determine the deployment of the two in different stope environments. Unfortunately, the short length of stopes limits the number of hops deployed to a minimum of three, considering the range of the deployed Wi-Fi6 systems.

6. Mine Layout

The layout of an underground platinum mine where room and pillar mining is being used, as shown in Figure 1. The tunnel is used to facilitate movement of machinery, personnel, and equipment, as well as ventilation and the removal of ore. A stope is the area where excavation and expansion occur. Stopes are within a room, a previously mined area, and the room is within a panel. Support structures are installed to stabilize the room whilst the stope is expanded. The entrance to the room is through a small tunnel called gully.

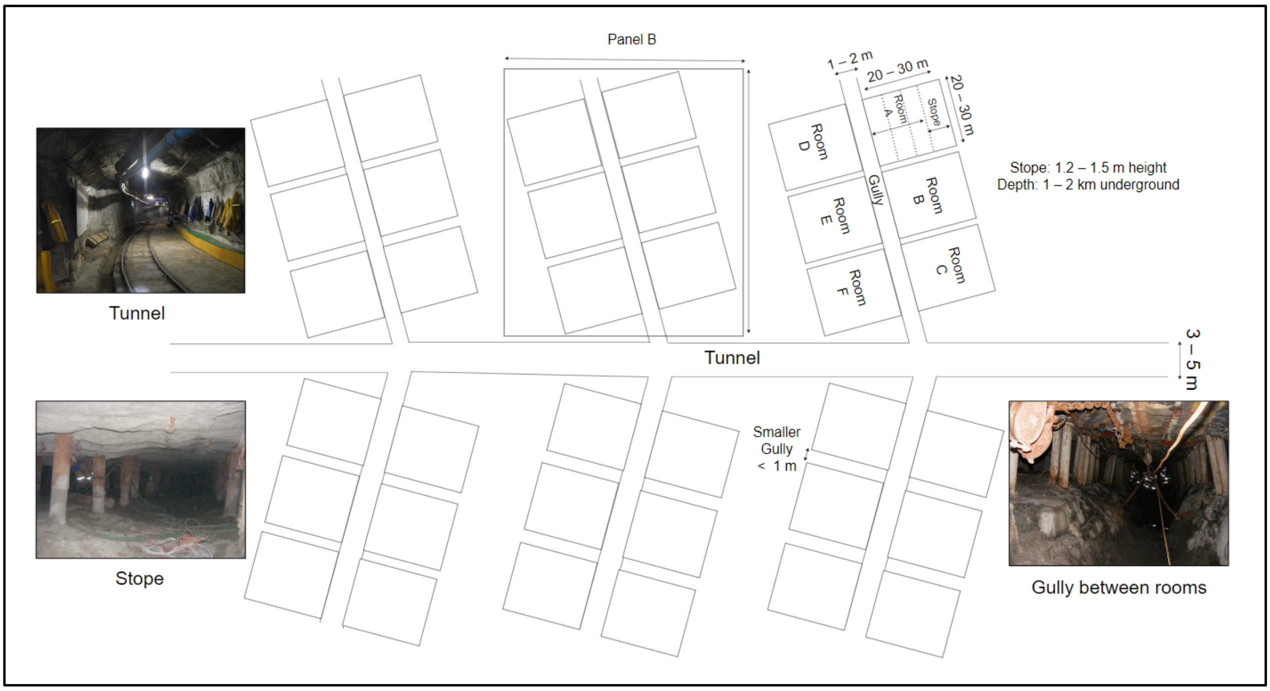

Figure 1. Mine layout.

7. Stope Characteristics

A stope in an underground hard rock mine is an area where blasting occurs; thus, it is the area of mine expansion and where the extraction of ore takes place. Figure 2 shows the stope, where support structures were installed to support the stope and prevent the collapsing of the stope. The stope is around 1.5 m in height and 20 m in width. The depth varies as the stope expands. The rooms, gulleys, etc., feature heavy machinery, ventilation pipes, and many other obstacles. All these obstacles present communication challenges.

The depth of a stope continually expands, necessitating the need for a dynamic mesh network. This area is very harsh for wireless communications as signals experience excessive contained reflections, resulting in great deal of signal attenuation due to the destructive interference that occurs as a result of the thick, layered walls and the large machinery deployed for mining. A wireless mesh system is suitable for ease of adaptability, route redundancy, and extensions required for such a system. The environment in a stope features high seismic activities, temperature, and humidity levels. This results in frequent breakdowns in communication system equipment, requiring a flexible ad hoc network communication system. A stope is also continuously expanded to areas rich in ore. As node distances increase, so does the path loss. A robust, low-powered, small-sized, self-healing wireless mesh system with ad hoc capabilities is required for a stope.

Figure 2. The stope.

8. Mine Wireless Communication Topology

Figure 3 shows the proposed mesh network topology for the mine stope. This architecture is universal by nature and should be adapted according to the specifications of the intended stope. The distance between nodes should be varied according to a stope's dimensions and characteristics. For short tunnels, the use of intermediate nodes is not encouraged, and they are only used as backup in the event of blocked nodes. A maximum of two to three hops is usually utilized. Research has shown that it is more efficient to transmit data via Wi-Fi6 over a long distance between two nodes directly rather than having additional repeater nodes installed with shorter wireless hops [5]. The nodes should be used for forwarding data packets to/from the client devices and the gateway node. The gateway node acts as a sink node which is used for processing the data. The gateway node is connected to the first node via a wired connection and is installed in an area a considerable distance away from the harsh stope environment. The wired cable should be installed in the gully. The whole system forms a mesh communication wireless network for a stope.

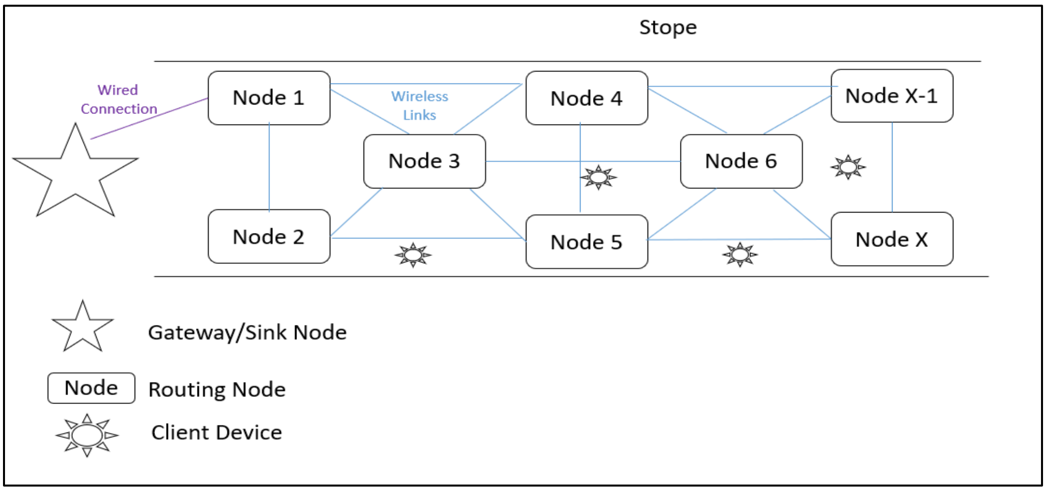

Figure 3. Wi-Fi6 intended deployment for a stope.

9. Materials and Methods

9.1. The Node Hardware

The nodes consisted of Wi-Fi6 routers for our signal quality experiments. The Asus RT-AX53U router was chosen for its ease of accessibility, low-cost, and support of the open-source OpenWrt [44] operating system. The Asus RT-AX53U is a 2 × 2 dual-band Wi-Fi6 router that provides 80 MHz channel bandwidth and 1024 QAM for fast wireless transmissions. The device was limited to an 80 MHz channel bandwidth due to an OpenWrt limitation. It supports OFDMA, BSS Colouring, and two spatial streams, which allows it to cope well with multi-hop performance in a stope environment. The throughput and jitter results were recorded using the iperf3 utility within OpenWrt, whilst the latency was obtained using the ping utility within OpenWrt. The utilized topology for signal quality evaluation is shown in Figure 4.

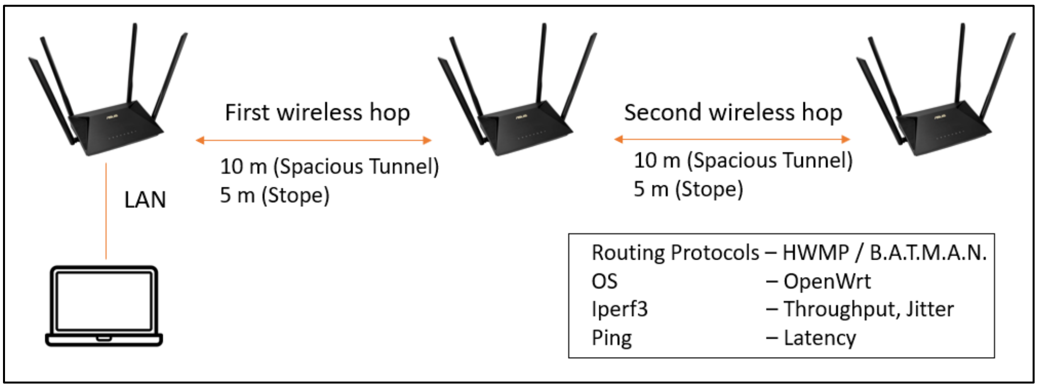

Figure 4. Asus RT-AX53U Wi-Fi6 router.

To achieve an accurate power consumption comparison, the nRF7002dk [45] device was used to evaluate both Wi-Fi6 and OpenThread protocols. The nRF7002dk is shown in Figure 5. The nRF7002dk was flashed with an open-source operating system known as Zephyr OS [46]. The boards were configured to transmit data via the 2.4 GHz channel for both protocols. By using the same OS, same transmission frequency, same input voltage, and same development kits, accurate power consumption comparison was achieved. The power evaluation setup is shown in Figure 5.

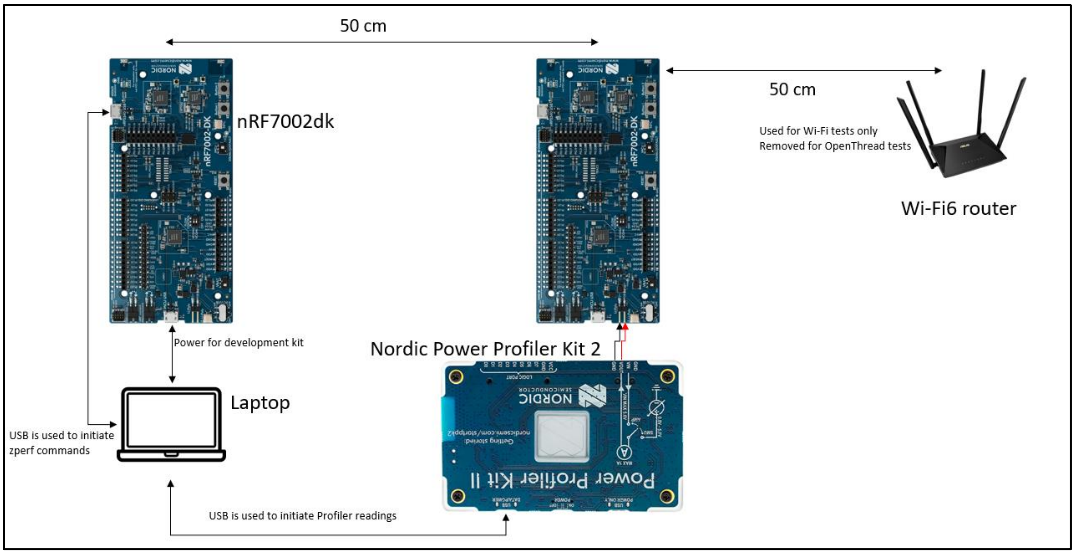

Figure 5. Power evaluation setup.

The Nordic Power Profiler Kit 2 (PPK2) was used to analyse the power consumption of the nRF7002dk. The PPK2 provides measurement with a resolution of 0.2 µA and allows for sampling at 100 KHz. Zephyr's zperf utility was used to transmit data at specific throughput values. The PPK2 was then used to record the power consumption for the different transmission rates. Nordic Power Profiler software [47] was used to analyse power consumption. The PPK2 powered the nRF7002dk with 3.3V for both of the Wi-Fi6 and OpenThread tests. The PPK2 only recorded the power consumption of the nRF7002dk that it was connected to during each test. At the time of performing the experiments, Zephyr OS did not support Wi-Fi directly, so an additional Wi-Fi6 router was used for the Wi-Fi6 test, but the results are still accurate since the receive power was obtained directly from the nRF7002dk and the transmit power was also obtained directly from the nRF7002dk during transmissions. The two nRF7002dk boards alternated between being transmitters and receivers. The PPK2 recorded the power consumption that the development kits used to send/receive 10 MB of data at different transmission rates. Each test case was performed several times, and the average results were recorded.

9.2. Test Environment

The performance comparison experiments to determine the effects of multipath fading were performed in a spacious tunnel (Figure 6), where there is less multipath, as well as a test stope (Figure 7), where there is severe multipath.

Figure 6. Test mine tunnel.

Figure 7. Stope.

The general experimentation parameters are shown in Table 1.

Table 1. General experimental parameters.

Hardware	Asus RT-AX53U, nRF7002dk, Nordic Power Profiler Kit 2
Software	OpenWrt, Zephyr OS, iperf3, zperf, ping, Nordic Power Profiler software
Frequency	2.4 GHz and 5 GHz
Node distance	5 m (stope) 10 m (spacious tunnel) 0.5 m (nRF power evaluations)
Routing protocols	HWMP (hybrid of reactive and proactive) B.A.T.M.A.N.-adv (proactive)
Packet size	Default iperf3 OpenWrt values (128 KB TCP, 1460 B UDP) 1 KB (nRF power evaluations)
Sample Rate	100 KHz (nRF power evaluations)

10. Results

10.1. Mesh Throughput Results

The average TCP and UDP throughput results for the tunnel as well as the stope are shown in Figure 8. Transmissions were automatically recorded at 1 s intervals, and a total of 120 samples were recorded for each test case. Each test was performed three times, after which the average throughput was calculated. The 2.4 GHz experiments in the tunnel proved ineffective in a multi-hop scenario due to the limitation of a 40 MHz channel bandwidth; hence, only the 5 GHz experiments were performed in the stope.

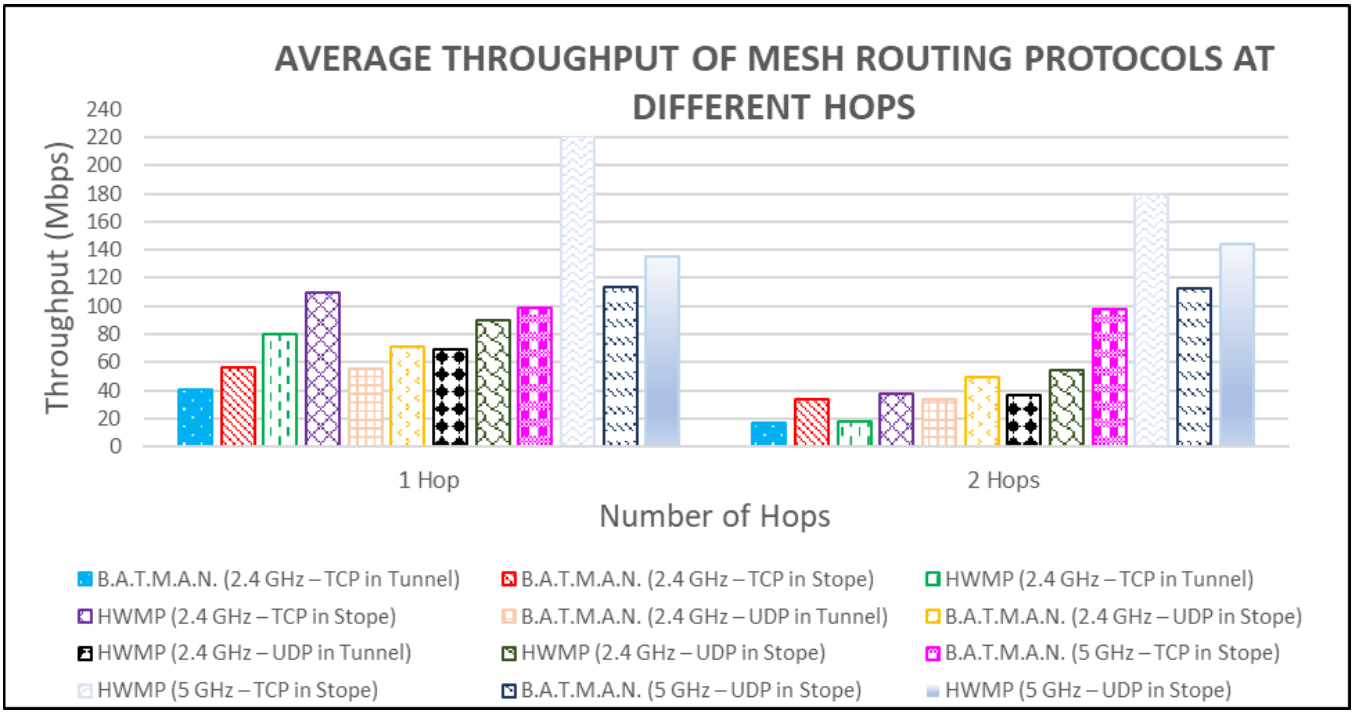

Figure 8. Average Wi-Fi6 throughputs for tunnel and stope.

Figure 9 shows the samples used to calculate the average results that were utilized in Figure 8. Each of the 120 samples from Figure 9 were averages calculated from three separate test cases.

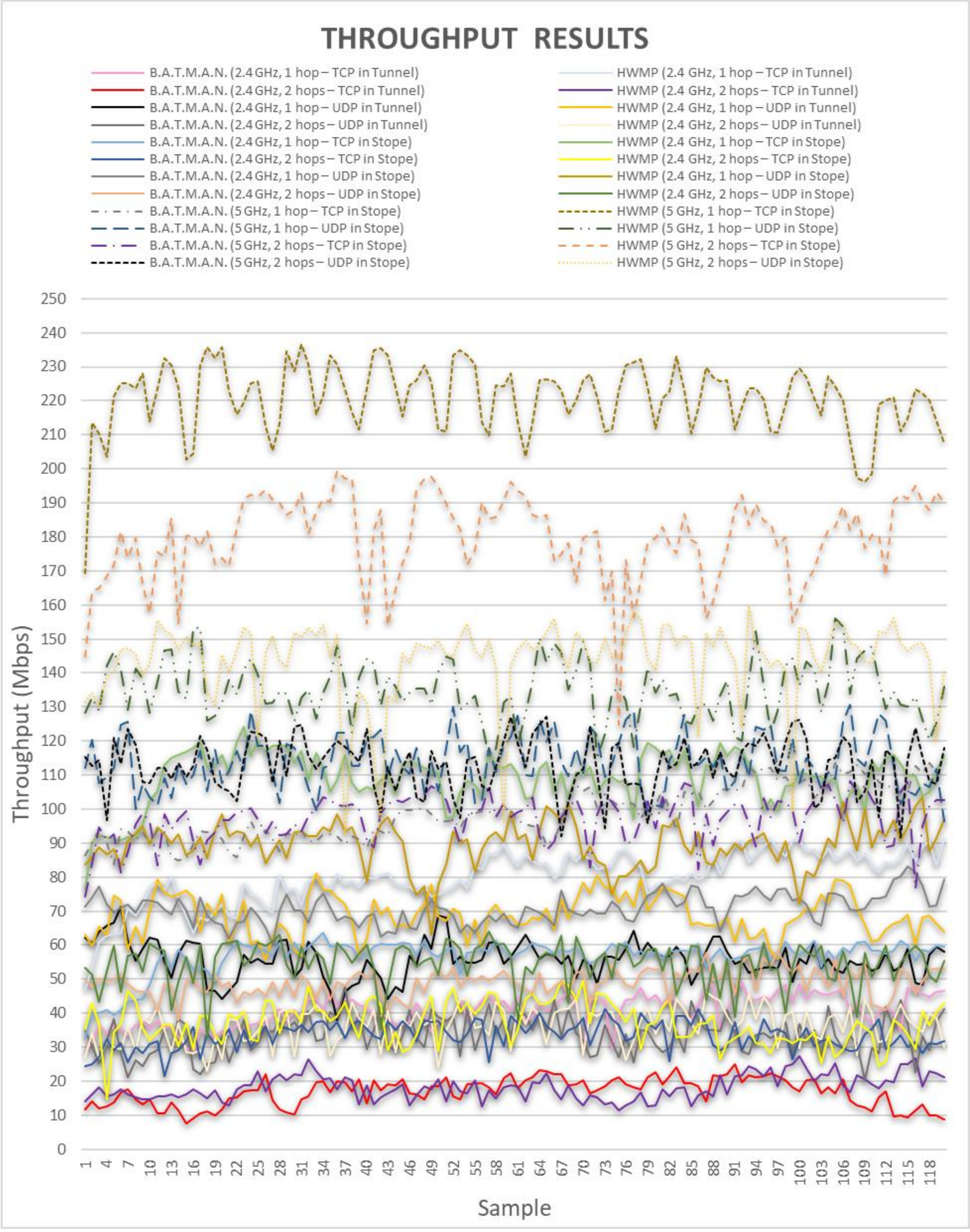

Figure 9. Wi-Fi6 sample throughput.

10.1.1. Frequency and Channel Bandwidth

At 2.4 GHz, the single hop throughput was significantly better than the double hop throughput. However, at 5 GHz, the single hop throughput was marginally better than the double hop throughput with the exception of HWMP UDP throughput in a stope, which was greater with a double hop. Static hops were assigned to ensure that a wireless hop did occur to ensure accurate results. To confirm the root cause behind the vast difference in multi-hop performance between the 2.4 GHz and 5 GHz experiments, an additional experiment was conducted. Multi-hop performance was recorded at different channel bandwidths, and the results are given in Table 2. The 5 GHz multi-hop experiments performed well due to it utilizing an 80 MHz channel bandwidth, whilst the 2.4 GHz experiments performed poorly due to its utilization of a 40 MHz channel bandwidth. For HWMP transmitting at 5 GHz, at a 20 MHz channel bandwidth, there was 50% loss of throughput across a wireless hop; at a 40 MHz channel bandwidth, there was 43% loss of throughput across a wireless hop; and at an 80 MHz channel bandwidth, there was 14% loss of throughput across a wireless hop. The higher channel bandwidth, alongside BSS Colouring, OFDMA, and beamforming, allowed for the efficient use of the spectrum, which enabled Wi-Fi6 to utilize the waveguide effect provided by the stope to enhance the signal quality rather than attenuating the signal.

Table 2. HWMP multi-hop performance using various channel bandwidths at 5 GHz.

CONFIGURATION	20 MHz	40 MHz	80 MHz
1 hop TCP	120 Mbps	210 Mbps	220 Mbps
2 hops TCP	60 Mbps	120 Mbps	190 Mbps
1 hop UDP	140 Mbps	140 Mbps	140 Mbps
2 hops UDP	80 Mbps	130 Mbps	130 Mbps

Table 2 shows the multi-hop performance which was recorded at different channel bandwidths.

10.1.2. Stope vs. Tunnel

The results also indicate that the throughput performance of both mesh routing protocols in the stope was better than in the tunnel. This is contrary to the previous belief that wireless communications suffer from degradation due to the nature of stopes. With Wi-Fi6's introduction of OFDMA, BSS Colouring, and MU-MIMO in both uplink and downlink, as well as improved beamforming technologies, it has become much smarter, with the ability to cope in high-density environments. This capability has resulted in Wi-Fi6 being able to make much more efficient use of the spectrum, which allows it to utilize the benefits of the waveguide affect provided by a stope. Wi-Fi6 recognizes and uses the waveguide properties of a stope to its advantage, improving signal quality and the resulting throughput results compared to the open tunnel.

10.1.3. UDP vs. TCP

The results also indicate that for both mesh routing protocols, a double hop resulted in better UDP performance as compared to TCP. This can be attributed to TCP's handshake acknowledgement packets being lost across wireless hops, which would result in retransmissions leading to a decrease in throughput. For single hop throughput performance, HWMP performed better with TCP, since there was a low risk of acknowledgement packets being lost due to no extra hops being required. B.A.T.M.A.N.-adv performed better with UDP for both single and double hops. This can be attributed to the B.A.T.M.A.N.-adv protocol's decentralized proactive nature.

10.1.4. HWMP vs. B.A.T.M.A.N.-Adv

The throughput performance of HWMP was better than B.A.T.M.A.N.-adv for all tests. This can be attributed to HWMP's utilization of a hybrid approach which uses both reactive and proactive mesh routing whilst B.A.T.M.A.N. only uses proactive mesh routing. The reactive component proved to be worth the expense of the additional overhead.

10.2. Mesh Jitter Results

The average jitter results for the tunnel as well the stope are shown in Figure 10. The jitter values were obtained from the iperf3 UDP throughput results, and the average values was calculated and plotted accordingly. The results show that the 5 GHz experiments performed the best for both B.A.T.M.A.N. and HWMP. The results were also better in the stope for both mesh routing protocols. The stope provided better results due to the waveguide effect that it offered. The jitter values increased across the double hop; however, this was expected due to the variation of latency caused by the additional signal processing across each wireless hop. Generally, the system exhibited good jitter performance results for all conducted experiments, enhancing the suitability of applying the system in mines.

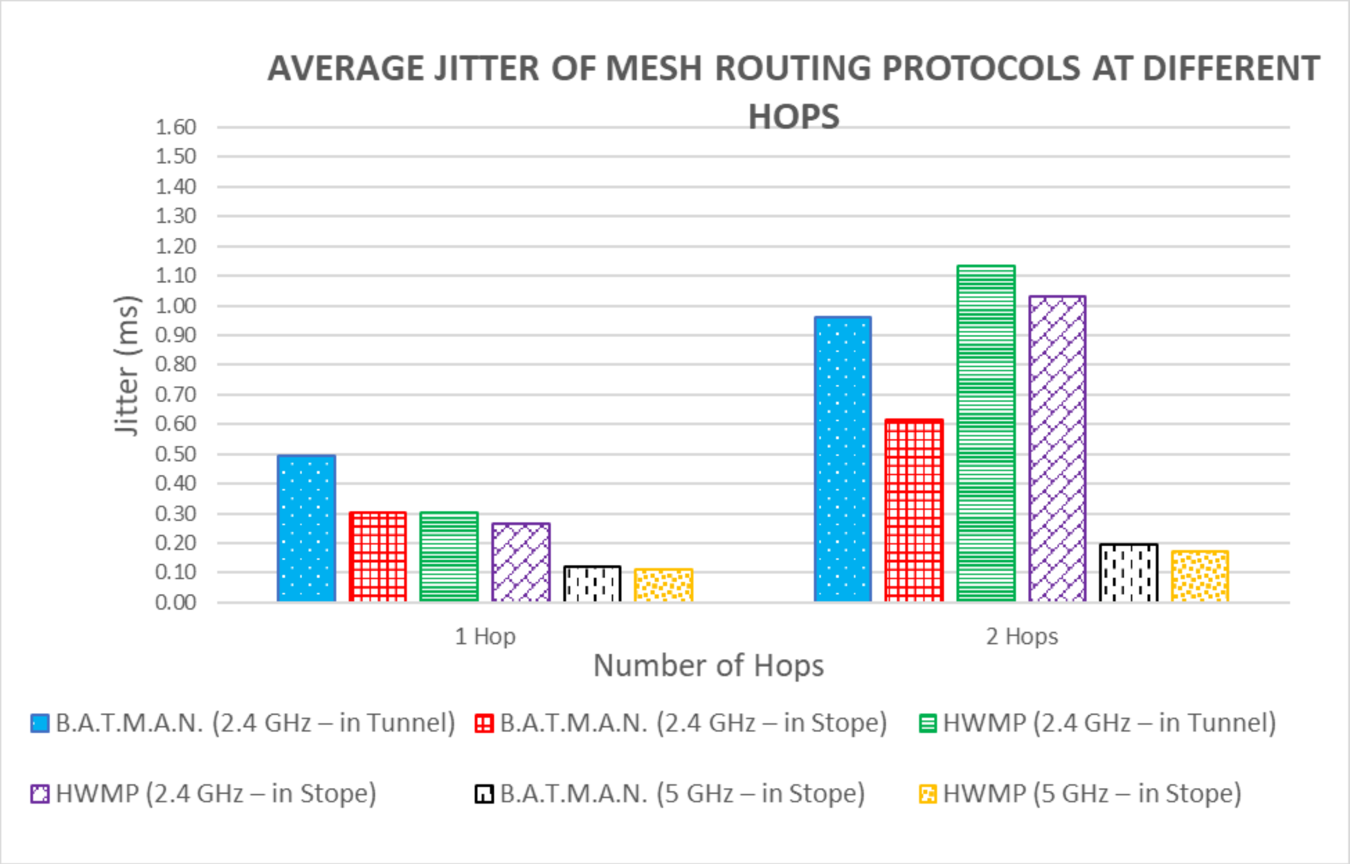

Figure 10. Average jitter.

Figure 11 shows the samples used to calculate the average results used in Figure 10. Each sample from Figure 11 were averages calculated from three separate test cases.

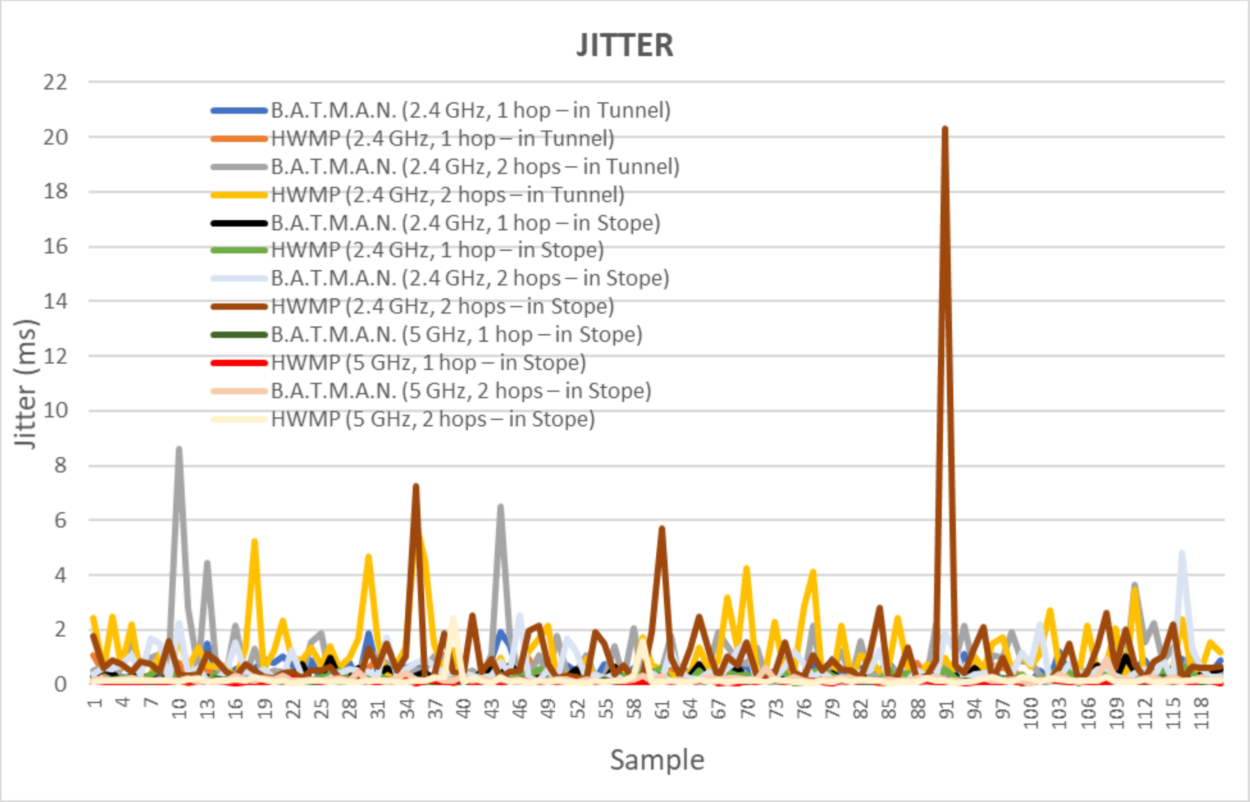

Figure 11. Wi-Fi6 jitter samples.

10.3. Mesh Latency Results

The average latency results for the tunnel as well as the stope are shown in Figure 12. The latency values were obtained using the OpenWrt ping utility. A total of 2000 samples were recorded for each latency test case. Each test case was also performed three times, after which the average latency was calculated. The results show that the double hop experiments had higher latency values as compared to a single hop; however, this was expected due to the additional signal processing that occurs across each wireless hop. The results also show that the best performance for both protocols were in the stope. This can be attributed to the waveguide effect provided by the stope. The 5 GHz experiments also gave the best results, and this is expected due to its higher transmission frequency. The difference in latency results for B.A.T.M.A.N.-adv and HWMP were found to be negligible (approximately 1 ms difference). Overall, the latency values were good for all conducted experiments, enhancing the applicability of technology in mining.

Figure 13 shows the samples used to calculate the average results used in Figure 12. Each sample from Figure 13 were averages calculated from three separate test cases.

10.4. Wi-Fi6 vs. OpenThread Power Results

The performance of Wi-Fi6 is evaluated against IEEE 802.15.4 (OpenThread), the industry standard for low-powered communications. The nRF7002dk was used since it supported both OpenThread and Wi-Fi6. An open-source operating system known as Zephyr OS was flashed onto the boards, and both protocols transmitted at 2.4 GHz. By using the same boards, same OS, and same input voltage, we were able to obtain an accurate power consumption comparison between the two protocols.

Figure 14 shows the total power for both protocols consumed to download 10 MB of data. Due to the modulation limitations inherent in OpenThread's O-QPSK scheme, its data rates remain notably low and lack competitiveness when compared to the QAM technique employed by Wi-Fi6. The OpenThread power evaluations were recorded from

20/40/80 Kbps data transmission rates, whilst the Wi-Fi6 power evaluations were recorded at 1/3 Mbps as well as 80 Kbps data transmission rates.

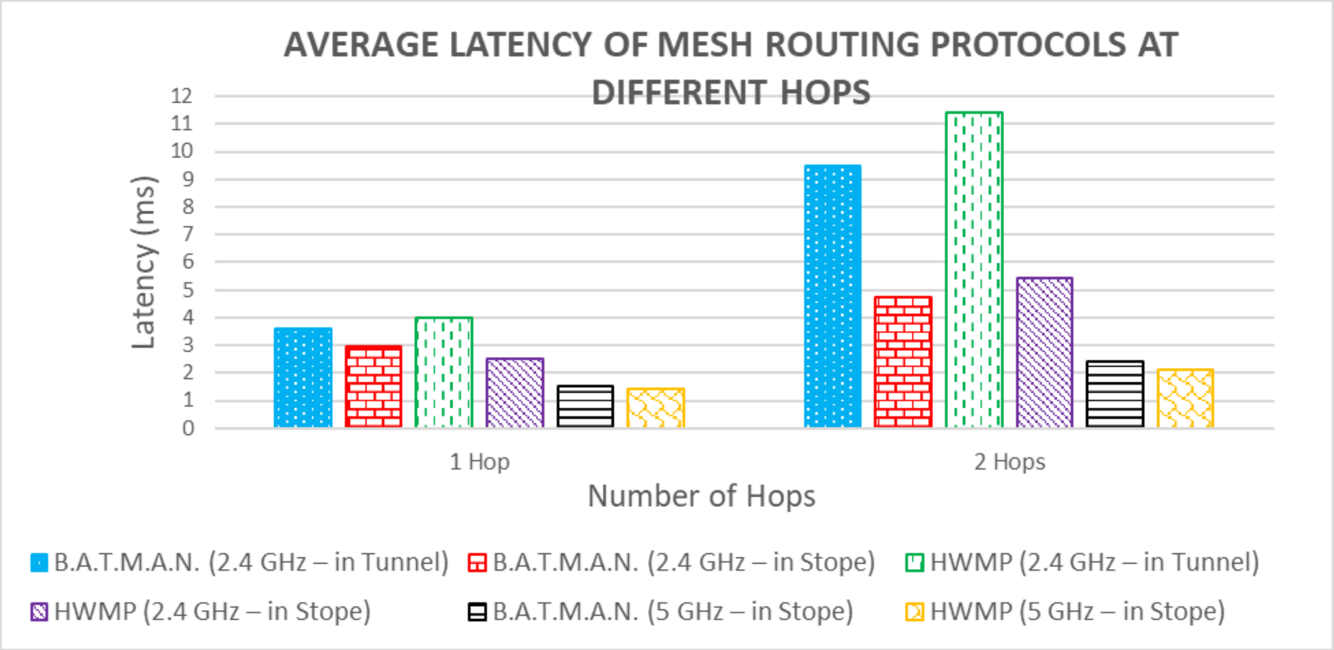

Figure 12. Average latency.

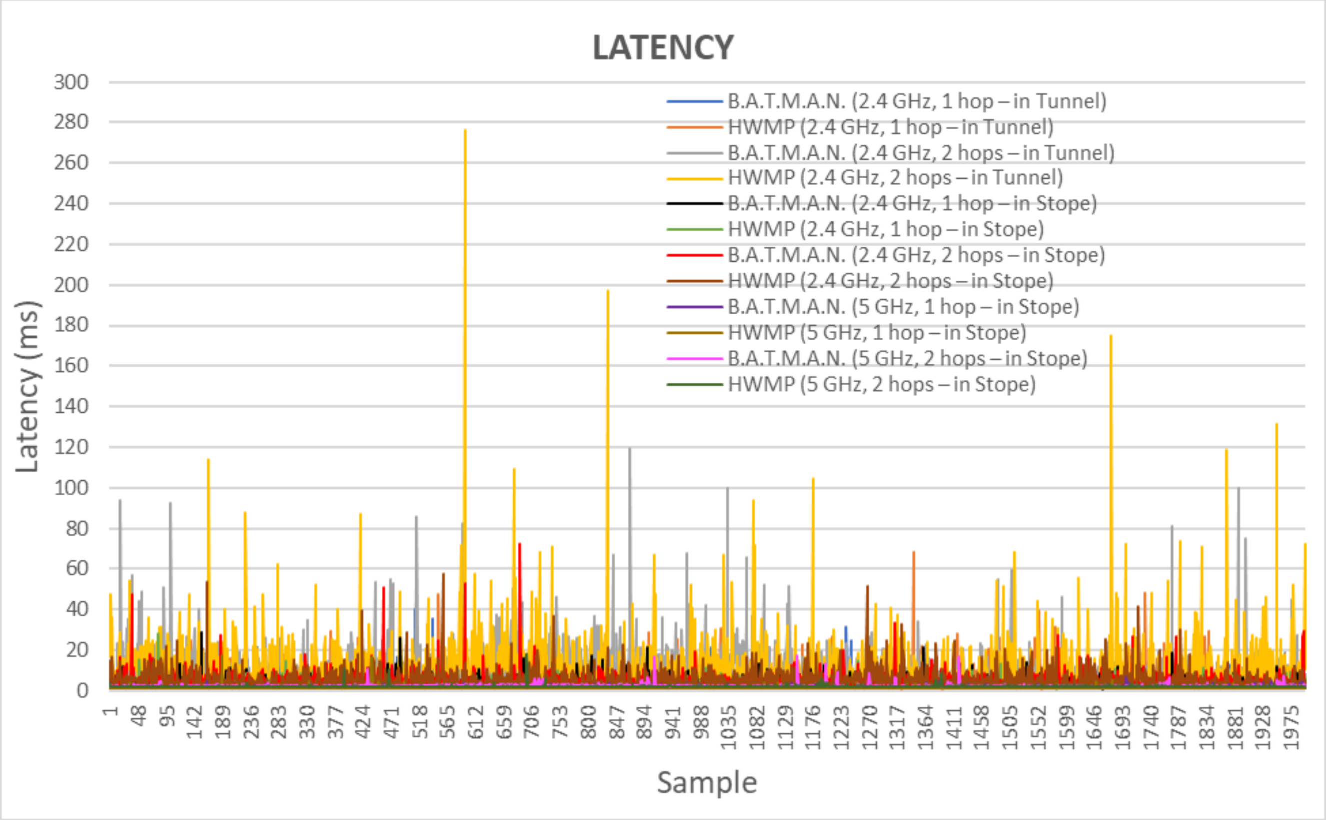

Figure 13. Wi-Fi6 latency samples.

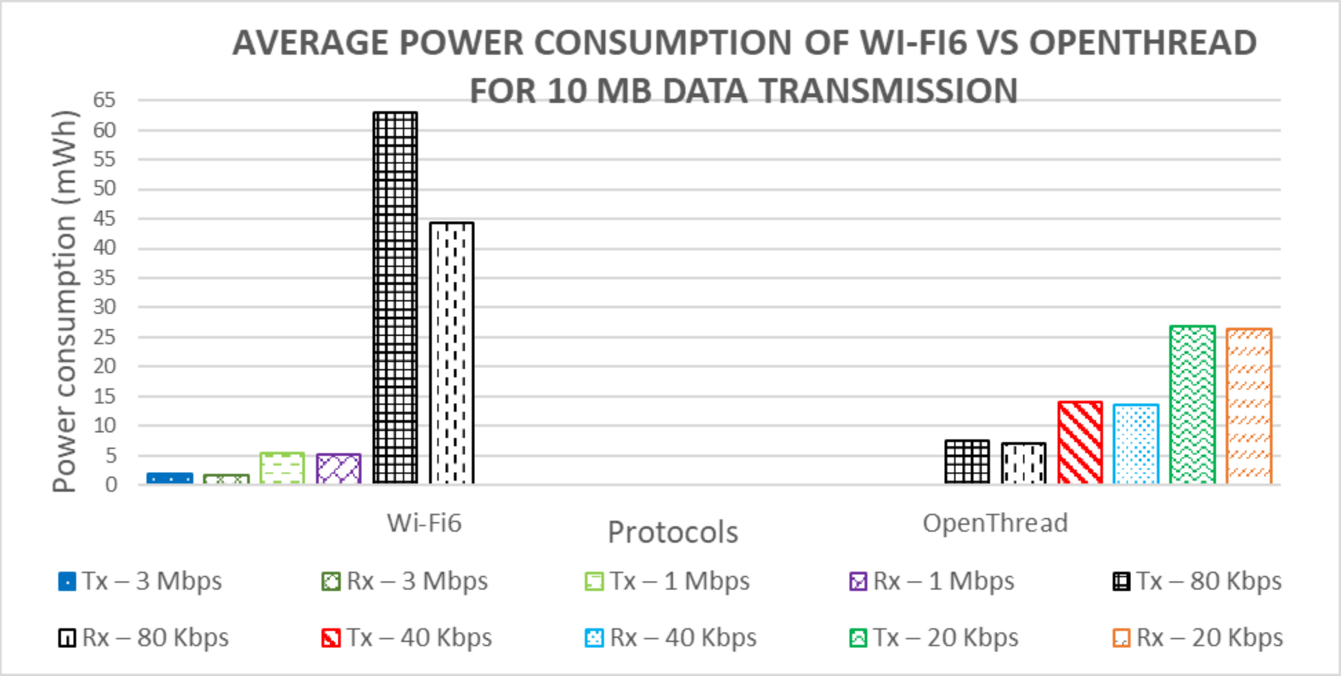

Figure 14. Power consumption for transmitting 10 MB of data.

The results show that both protocols performed best whilst transmitting at close to their peak transmission rates with no packets loss. When trying to send at rates faster than their peak transmission, they suffered from packet loss. The Wi-Fi6 device demonstrated a maximum transmission rate of 3.6 Mbps, whereas the OpenThread device peaked at 86 Kbps. From the results, it can be seen that Wi-Fi6 was the most power-efficient protocol with best transmission power consumption of 3.7 times less than that of OpenThread for the transmitter and 3.9 for the receiver. Despite Wi-Fi6 exhibiting higher instantaneous transmission power compared to OpenThread, its overall power consumption is significantly lower due to its shorter transmission times. For the idle power consumption evaluation, both OpenThread and Wi-Fi6 nodes operated as zperf servers; Wi-Fi6 exhibited an idle power consumption of 26.62 mW, whilst OpenThread recorded 22.61 mW, exhibiting a similar performance. Additionally, the results illustrate that at low transmission rates, specifically when both protocols transmit the same data amount at 80 Kbps, OpenThread consumed 8.3 times less power than Wi-Fi6. This can be attributed to the increased overhead requirements of Wi-Fi6. However, the viability of Wi-Fi6 is still better for mine applications.

11. Discussion

There is a significant research gap regarding high-bandwidth wireless communications for hard rock stope environments. Solutions have been proposed for tunnels and soft rock mines such as coal mines, but there is currently no mainstream high-bandwidth wireless solution for underground hard rock mine stopes, such as underground gold and platinum mines stopes, and little research has been conducted in these areas. This work provides real-world practical performance metrics of Wi-Fi6 in a tunnel and stope, and it was found that the Wi-Fi6 performance is greater in the stope as compared to the tunnel. This can be attributed to Wi-Fi6's newly introduced features which mainly focus on spectral efficiency which allowed it to utilize the waveguide nature of the stope to its advantage. This work also emphasizes the minimal feasible requirements for a mesh system in the stope, and it was found that the 5 GHz channel with 80 MHz channel bandwidth and two spatial streams provided good results even with a multi-hop scenario in the stope. This work also outlines the expected performances of using two of the most widely used open-source mesh routing protocols, namely B.A.T.M.A.N.-adv and HWMP alongside the IEEE 802.11s mesh standard.

This work emphasizes a wireless mesh solution for stopes. A wired connection should be used to interconnect the first node of the mesh to a gateway/sink node, which would be installed at a safe distance away from the stope. This work does not specify the routing method to the surface above the mine. In terms of high-bandwidth solutions, IEEE 802.15.4 and its variants cannot be used due to its modulation scheme throughput limitations. COFDM is a great solution for harsh environments, and [5] showcases its signal robustness. For critical mine safety applications, COFDM is still desirable; however, the technology is not available to the mainstream public as most vendors are of the broadcasting and military nature. Due to COFDM not being mainstream, there are wide fluctuations in price, and the technology is expensive. Wi-Fi6 is mainstream, and Wi-Fi has matured enough to be a good solution for stopes.

12. Conclusions

This research has provided experimental results for the viability of the application of Wi-Fi6 in underground gold and platinum mine stopes. This is due to its strong abilities, namely resilience to excessive multipath propagation alongside multiple wireless hops the ability to take advantage of the waveguide effect of stopes and its efficient spectrum usage due to BSS Colouring, OFDMA, uplink and downlink MU-MIMO, and enhanced beamforming techniques. Compared to other technologies like IEEE 802.15.4 (OpenThread), it was proven to be more energy-efficient and provides better throughput in a stope. For routing Wi-Fi6, the use of HWMP over B.A.T.M.A.N. is recommended due to HWMP's reactive nature, which establishes routes only when needed; this is crucial for stopes, as signals undergo excessive amounts of contained reflections which increases the risk of destructive interference. As for the Wi-Fi6 transport protocol, it is recommended that TCP as opposed to UDP is used due to stopes' waveguiding effect and Wi-Fi6's ability to make efficient use of its spectrum, which limit packet losses, ensuring that the robust performance of TCP is maintained in a multi-hop setup. This recommendation is based on a wide 80 MHz channel bandwidth. If a lower channel bandwidth must be used, then UDP should be the preferred choice due to the increased contention, resulting in dropped acknowledgement packets.

From the 5 GHz experimental results, it can be seen that the latency and jitter values were exceptional in the stope, even across multiple wireless hops. This informs us that real-time applications in a stope will work quite reliably. Furthermore, the exceptional jitter results were obtained at very high throughputs; thus, this indicates that the system will easily be able to handle real-time video processing. A low-spec Wi-Fi6 mesh system with two spatial streams utilizing an 80 MHz channel bandwidth should easily handle the processing of real-time LiDAR feedback, which is generally considered very bandwidth-intensive (e.g., 100 Mbps).

This work opens frontiers to the practical applications of high-bandwidth wireless communications in underground hard rock mine stopes. The world is rapidly advancing towards automation and integrated networks, yet stopes has been largely overlooked in this progress. It is crucial to demonstrate that incorporating automation and technology in stopes is not only financially feasible but also sustainable, aligning it with the advancements seen in other industries.

Wi-Fi7 has recently been released; however, there are currently very few development kits available, and none are currently supported by the open-source Wi-Fi operating system known as OpenWrt. This will be crucial for testing the open-source mesh standard, IEEE 802.11s, alongside mesh-routing protocols such as HWMP and B.A.T.M.A.N.-adv. When this technology is better established, it would be a good initiative to replicate these experiments with Wi-Fi7, as each iteration of Wi-Fi differs greatly.

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References

1. Dohare, Y.S.; Maity, T.; Das, P.S.; Paul, P.S. Wireless Communication and Environment Monitoring in Underground Coal Mines—Review. *IETE Tech. Rev.* **2015**, *32*, 140–150. [CrossRef]
2. Misra, P.; Kanhere, S.; Ostry, D.; Jha, S. Safety assurance and rescue communication systems in high-stress environments: A mining case study. *IEEE Commun. Mag.* **2010**, *48*, 66–73. [CrossRef]
3. Wu, Y.; Pliszka, E.; Caron, B.; Bouchard, P.; Chouinard, G. Comparison of terrestrial DTV transmission systems: The ATSC 8-VSB, the DVB-T COFDM, and the ISDB-T BST-OFDM. *IEEE Trans. Broadcast.* **2000**, *46*, 101–113. [CrossRef]
4. Joshi, A.; Saini, D.S. Coded-OFDM in various multipath fading environments. In Proceedings of the 2010 the 2nd International Conference on Computer and Automation Engineering (ICCAE), Singapore, 26–28 February 2010; pp. 127–131.
5. Chetty, B.L.; Isaac, S.J.; Walingo, T. An Experimental Investigation into High Bandwidth Wireless Communication Standards for the Underground Mine Stope. In Proceedings of the 2023 IEEE AFRICON, Nairobi, Kenya, 20–22 September 2023; pp. 1–6.
6. Sanchez-Iborra, R.; Cano, M.-D.; Garcia-Haro, J. Performance Evaluation of BATMAN Routing Protocol for VoIP Services: A QoE Perspective. *IEEE Trans. Wirel. Commun.* **2014**, *13*, 4947–4958. [CrossRef]
7. Mozumder, A.H.; Acharjee, T.; Roy, S. Scalability performance analysis of BATMAN and HWMP protocols in wireless mesh networks using NS-3. In Proceedings of the 2014 International Conference on Green Computing Communication and Electrical Engineering (ICGCCEE), Coimbatore, India, 6–8 March 2014; pp. 1–5.
8. Singh, K.; Prabhakar, T.V.; Kuri, J. Improving Access to Network Resources in IoT Networks. In Proceedings of the 2020 International Conference on COMmunication Systems & NETworkS (COMSNETS), Bangalore, India, 7–11 January 2020; pp. 259–266.
9. Yarkan, S.; Guzelgoz, S.; Arslan, H.; Murphy, R.R. Underground Mine Communications: A Survey. *IEEE Commun. Surv. Tutor.* **2009**, *11*, 125–142. [CrossRef]
10. El Khaled, M.; Fortier, P.; Ammari, M.L. A Performance Study of Line-of-Sight Millimeter-Wave Underground Mine Channel. *IEEE Antennas Wirel. Propag. Lett.* **2014**, *13*, 1148–1151. [CrossRef]
11. Kawamura, Y.; Moridi, M.A.; Sharifzadeh, M.; Jang, H. Development of Underground Mine Communication and Monitoring Systems by Using ZigBee Technology. In Proceedings of the ISRM International Symposium—8th Asian Rock Mechanics Symposium, Sapporo, Japan, 14–16 October 2014; p. ISRM-166.
12. Ben Mabrouk, I.; Talbi, L.; Nedil, M. Performance Evaluation of a MIMO System in Underground Mine Gallery. *IEEE Antennas Wirel. Propag. Lett.* **2012**, *11*, 830–833. [CrossRef]
13. Nerguizian, C.; Despins, C.L.; Affes, S.; Djadel, M. Radio-Channel characterization of an underground mine at 2.4 GHz. *IEEE Trans. Wirel. Commun.* **2005**, *4*, 2441–2453. [CrossRef]
14. Ikeda, H.; Kolade, O.; Mahboob, M.A.; Cawood, F.T.; Kawamura, Y. Communication of Sensor Data in Underground Mining Environments: An Evaluation of Wireless Signal Quality over Distance. *Mining* **2021**, *1*, 211–223. [CrossRef]
15. Elazhari, M.E.; Talbi, L.; Nedil, M. Comparative study of Four Path Loss Models for UWB off-body Propagation Channel Inside a Mine. In Proceedings of the 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Atlanta, GA, USA, 7–12 July 2019; pp. 2103–2104.

16. Zhu, L.; Wen, X.; Han, Q.; Fryer, A.; Suttora, N.; Petruska, A.J. Performance evaluation of wi-fi for underground robots. In *MobiQuitous '19: Proceedings of the 16th EAI International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services, Proceedings of the 16th EAI International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services, Houston, TX, USA, 12–14 November 2019*; Association for Computing Machinery: New York, NY, USA, 2020; pp. 498–503.
17. Viittala, H.; Soderi, S.; Saloranta, J.; Hamalainen, M.; Iinatti, J. An Experimental Evaluation of WiFi-Based Vehicle-to-Vehicle (V2V) Communication in a Tunnel. In Proceedings of the 2013 IEEE 77th Vehicular Technology Conference (VTC Spring), Dresden, Germany, 2–5 June 2013; pp. 1–5.
18. Sandoval, F.; Poitau, G.; Gagnon, F. Optimizing Forward Error Correction Codes for COFDM With Reduced PAPR. *IEEE Trans. Commun.* **2019**, *67*, 4605–4619. [CrossRef]
19. Magrin, D.; Avallone, S.; Roy, S.; Zorzi, M. Performance Evaluation of 802.11ax OFDMA through Theoretical Analysis and Simulations. *IEEE Trans. Wirel. Commun.* **2023**, *22*, 5070–5083. [CrossRef]
20. Biradar, A.G.; Johari, S.; Kulkarni, S.S.; Maheshwari, A.; Venkatesh, K. OpenThread Based Mesh Enabled IoT Smart Device Cluster for Health Monitoring of the Elderly in Old Age Homes. In Proceedings of the 2020 4th International Conference on Electronics, Materials Engineering & Nano-Technology (IEMENTech), Kolkata, India, 2–4 October 2020; pp. 1–6.
21. Gangopadhyay, S.; Jain, V.K. A Position-Based Modified OLSR Routing Protocol for Flying Ad Hoc Networks. *IEEE Trans. Veh. Technol.* **2023**, *72*, 12087–12098. [CrossRef]
22. Al-Zahrani, F.A. On Modeling Optimizations and Enhancing Routing Protocols for Wireless Multihop Networks. *IEEE Access* **2020**, *8*, 68953–68973. [CrossRef]
23. Santana, C.; Macedo, M.; Alves, E.; Guerreiro, M.T.; Valadares Siqueira, H.; Gokhale, A.; Bastos-Filho, C.J.A. Bio-Inspired Multi-Objective Algorithms Applied on the Optimization of the AODV's Routing Recovery Mechanism. *IEEE Access* **2023**, *11*, 116480–116496. [CrossRef]
24. Tan, X.; Zuo, Z.; Su, S.; Guo, X.; Sun, X.; Jiang, D. Performance Analysis of Routing Protocols for UAV Communication Networks. *IEEE Access* **2020**, *8*, 92212–92224. [CrossRef]
25. Istikmal; Subekti, A.; Perdana, D.; Ridha Muldina, N.; ArifIndra, I. Sussi Dynamic Source Routing and optimized Link State Routing Performance in Multipath Fading Environment with Dynamic Network Topology. In Proceedings of the 2019 4th International Conference on Information Technology, Information Systems and Electrical Engineering (ICITISEE), Yogyakarta, Indonesia, 20–21 November 2019; pp. 373–378.
26. Zhao, Y.-F.; Yin, S.-J.; Tao, W.; Li, X.-Y.; Meng, J. Gesture Recognition System Resilient to Interdevice Interference Based on Direct Sequence Spread Spectrum. *IEEE Sens. Lett.* **2023**, *7*, 1–4. [CrossRef]
27. He, Y.; Chen, Y.; Hu, Y.; Zeng, B. WiFi Vision: Sensing, Recognition, and Detection With Commodity MIMO-OFDM WiFi. *IEEE Internet Things J.* **2020**, *7*, 8296–8317. [CrossRef]
28. Barrachina-Muñoz, S.; Bellalta, B.; Knightly, E.W. Wi-Fi Channel Bonding: An All-Channel System and Experimental Study From Urban Hotspots to a Sold-Out Stadium. *IEEE/ACM Trans. Netw.* **2021**, *29*, 2101–2114. [CrossRef]
29. Piracha, A.Z.; Farid, H.; Shahzad, K.; Zeeshan, M. A Low Complexity Signal-to-Total Variance Precoding Scheme for Downlink Multi-Stream MU-MIMO Systems. In Proceedings of the 2022 3rd International Conference on Electrical Engineering and Informatics (ICon EEI), Virtual Conference, 19–20 October 2022; pp. 53–58.
30. Lee, K.-H. Using OFDMA for MU-MIMO User Selection in 802.11ax-Based Wi-Fi Networks. *IEEE Access* **2019**, *7*, 186041–186055. [CrossRef]
31. Behara, A.; Venkatesh, T.G. Performance Study of High-Efficiency IEEE 802.11ax WLAN Standard Using NS-3 Simulator. In Proceedings of the 2022 IEEE 27th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), Paris, France, 2–3 November 2022; pp. 226–231.
32. Chen, Q.; Ding, Z. Accommodating LAA within IEEE 802.11ax WiFi Networks for Enhanced Coexistence. *IEEE Trans. Wirel. Commun.* **2020**, *19*, 7621–7636. [CrossRef]
33. Šepić, N.; Kočan, E.; Pejanović-Djurišić, M. Evaluating spatial reuse in 802.11ax networks with interference threshold adjustment. In Proceedings of the 2020 24th International Conference on Information Technology (IT), Zabljak, Montenegro, 18–22 February 2020; pp. 1–4.
34. Yildirim, H.C.; Storrer, L.; Louveaux, J.; De Doncker, P.; Horlin, F. Impact of MU-MIMO on Passive Wi-Fi Sensing: Threat or Opportunity? In Proceedings of the 2022 2nd IEEE International Symposium on Joint Communications & Sensing (JC&S), Seefeld, Austria, 9–10 March 2022; pp. 1–6.
35. Tran, V.H.; Misra, A.; Xiong, J.; Balan, R.K. WiWear: Wearable Sensing via Directional WiFi Energy Harvesting. In Proceedings of the 2019 IEEE International Conference on Pervasive Computing and Communications (PerCom Workshops), Kyoto, Japan, 11–15 March 2019; pp. 1–10.
36. Kim, H.-S.; Kumar, S.; Culler, D.E. Thread/OpenThread: A Compromise in Low-Power Wireless Multihop Network Architecture for the Internet of Things. *IEEE Commun. Mag.* **2019**, *57*, 55–61. [CrossRef]
37. *IEEE Std 802.15.4-2020 (Revision of IEEE Std 802.15.4-2015)*; IEEE Standard for Low-Rate Wireless Networks. IEEE: Piscataway, NJ, USA, 2020.
38. Zhang, G.; Shi, C.; Han, C.; Li, X.; Wang, D.; Rabie, K.; Kharel, R. Implementation-Friendly and Energy-Efficient Symbol-by-Symbol Detection Scheme for IEEE 802.15.4 O-QPSK Receivers. *IEEE Access* **2020**, *8*, 158402–158415. [CrossRef]

39. Zhong, L.; Zou, Y.; Zhang, S.; Dai, X.; Zhang, J.; Cheng, M.; Deng, L.; Yang, Q.; Liu, D. An SNR-Improved Transmitter of Delta-sigma Modulation Supported Ultra-High-Order QAM Signal for Fronthaul/WiFi Applications. *J. Light. Technol.* **2022**, *40*, 2780–2790. [CrossRef]
40. Makarov, S.B.; Liu, M.; Ovsyannikova, A.S.; Zavjalov, S.V.; Lavrenyuk, I.L.; Xue, W.; Xu, Y. A Reduction of Peak-to-Average Power Ratio Based Faster-Than-Nyquist Quadrature Signals for Satellite Communication. *Symmetry* **2021**, *13*, 346. [CrossRef]
41. Usha, S.M.; Mahesh, H.B. Mahesh Low Power and Area Optimized Architecture for OQPSK Modulator. In Proceedings of the 2019 International Conference on Wireless Communications Signal Processing and Networking (WiSPNET), Chennai, India, 21–23 March 2019; pp. 123–126.
42. Atto, M.; Mstafa, R.J.; Alkhayyat, A. Improving AODV Routing Protocol for Image Transmission over Mobile Video Sensor Networks. *IEEE Access* **2020**, *8*, 169396–169407. [CrossRef]
43. Katila, C.J.; Di Gianni, A.; Buratti, C.; Verdone, R. Routing protocols for video surveillance drones in IEEE 802.11s Wireless Mesh Networks. In Proceedings of the 2017 European Conference on Networks and Communications (EuCNC), Oulu, Finland, 12–15 June 2017; pp. 1–5.
44. OpenWrt. Welcome to the OpenWrt Project. Available online: https://openwrt.org/ (accessed on 16 April 2024).
45. Nordic Semiconductor. nRF7002 DK. Available online: https://www.nordicsemi.com/Products/Development-hardware/nRF7002-DK (accessed on 16 April 2024).
46. Zephyr Project. About the Zephyr Project. Available online: https://www.zephyrproject.org/learn-about/ (accessed on 16 April 2024).
47. Nordic Semiconductor. nRF Connect for Desktop. Available online: https://www.nordicsemi.com/Products/Development-tools/nRF-Connect-for-Desktop (accessed on 16 April 2024).