Bibliography

[1] ETSI, “Electromagnetic compatibility and Radio spectrum Matters (ERM); Digital Mobile Radio (DMR) Systems; Part 1: DMR Air Interface (AI) protocol,” ETSI, ETSI Technical Specification TS 102 361-1 V2.6.1, May 2023, https://www.etsi.org/deliver/etsi$_{t}s/102300_{1}02399/10236101/02.06.01_{6}0/ts_{1}0236101v020601p.pdf$.

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Radio Mobile Project

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Chapter 1

Introduction

This report presents a detailed design of a Private Mobile Radio (PMR) placed in Cedar City, Utah, United States of America (USA). The aim of the designed network is to provide reliable communications for digital voice and data communication over 100 km $\times$ 100 km (a square region centered around the city). The project addresses the need for a robust and reliable communication infrastructure for a limited number of professional users and security services. Unlike public cellular networks, PMR systems are designed for dedicated communication, emphasizing reliability and specialized functionalities.

The proposed network ensures that all authorized users and the central Operations Center can simultaneously receive communications across the entire service area. The design process involved the use of Radio Mobile software for network planning and analysis. The subsequent sections of this report will detail the PMR network structure, including the design of the microwave interconnection network, and the coverage analyses.

1.1 Problem Statement

The fundamental problem addressed by this project is the requirement to design an efficient and comprehensive PMR Network centered around Cedar City shown in figure 1.1.

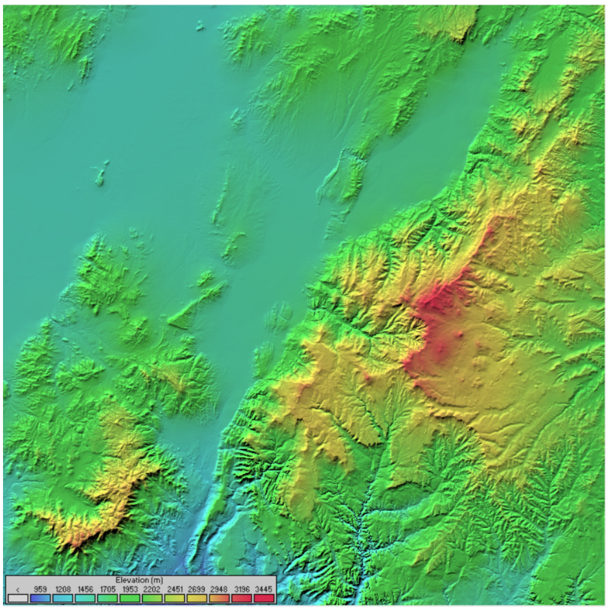


Figure 1.1: Area to be served

The design must specifically incorporate a SIMULCAST conceptual topology, wherein a user's signal, once received by the closest repeater, is distributed across all other repeaters via microwave links, allowing all other network users and the Operations Center to listen to the communication simultaneously. It is explicitly stated that radio coverage over sea, if present within the designated area, is not a requirement. The design is constrained by the following specifications and objectives:

- Network Optimization and Coverage:
  - The network design must minimize the number of repeaters (Base Stations (BSs)) utilized for the specified 100 km x 100 km area coverage. It is anticipated that between 5 and 15 repeaters will typically be sufficient, depending on the local orography.
  - Repeaters are to be strategically located on mountain tops or high-rise buildings to maximize their coverage, as individual repeaters can achieve a radius of coverage spanning tens of kilometers.
- Radio Network Specifications:
  - The frequency of operation for the radio network is 173 MHz.
  - The employed modulation type is European Telecommunications Standards Institute (ETSI) Digital Mobile Radio (Digital Mobile Radio (DMR)), the standard defines 4 Frequency Shift Keying (FSK) as modulation scheme [1].
  - Motorola SLR5500 repeater stations (DMR).
  - Motorola DM4000e vehicular terminals (DMR).
  - The gain for the vehicular antennas is assumed as 0 dBi.
- Repeater Interconnection Network (Microwave Links):
  - All repeaters must be interconnected using point-to-point microwave links.
  - To ensure reliable routing, repeaters must “see" each other, with a minimum of two other repeaters required to be visible to any given repeater.
  - The operational frequency for each microwave link must be chosen based on its length, based on the following criteria:
    * For urban links (less than 5 km), frequencies of 32 or 38 GHz are to be used, with parabolic antennas of 0.3 to 0.6 meters diameter.
    * For short haul links (0 – 10 km), frequencies of 18 or 23 GHz are to be used, with parabolic antennas of 0.6 to 1.2 meters diameter.
    * For mid haul links (10 – 25 km), frequencies of 13 or 15 GHz are to be used, with parabolic antennas of 0.9 to 1.2 meters diameter.
    * For long haul links (25 – 70 km), frequencies of 7 or 10 GHz are to be used, with parabolic antennas of 1.8 meters diameter and above.
  - The link margin for all microwave connections must be at least 10 dB above the modulation threshold. A higher margin is generally desired for frequencies exceeding 10 GHz to counteract potential rain attenuation.

Chapter 2

Network Design

The PMR network operates as a SIMULCAST system, all other users across the entire coverage area can hear the communication simultaneously. This seamless wide-area coverage is achieved through the coordinated operation of two network layers working together.

The first layer is the User Access Network (Very High Frequency (VHF) Network), which operates at 173 MHz. Mobile users such as police officers in handheld or vehicle mounted radios transmit at this frequency and automatically connect to the nearest repeater (see figure 2.2). Each repeater uses omnidirectional antennas to cover a circular area with a radius of several tens of kilometers.

The second layer is the Backbone Network (Microwave Network), which connects all the repeaters through than the VHF network (see figure 2.1) working at 10 GHz. These links use highly directional parabolic antennas, similar to satellite dishes, pointing directly between repeaters to form a robust mesh network. This topology ensures that each repeater connects to multiple others, providing redundancy and reliability.

The basic communication sequence works as follows: when a mobile user presses the talk button, their radio transmits on 173 MHz and the nearest repeater receives the signal via its VHF antenna. The repeater then immediately forwards this signal through the microwave network to all other repeater sites. All repeaters simultaneously retransmit the same signal on 173 MHz, allowing every mobile user and the Operations Center across the entire coverage area to receive the transmission at the same time. This simultaneous retransmission is the core of the SIMULCAST approach, enabling synchronized communication across a wide geographic area.

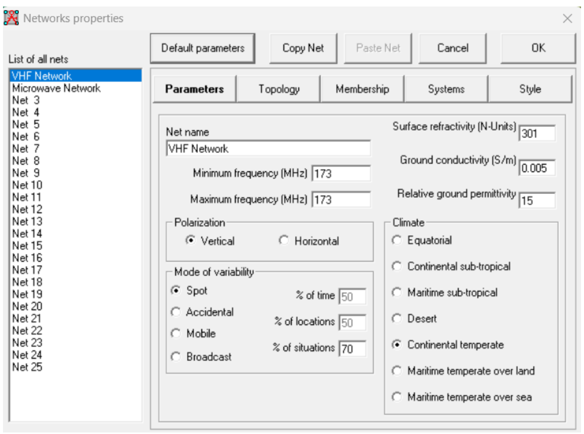


Figure 2.1: VHF Network

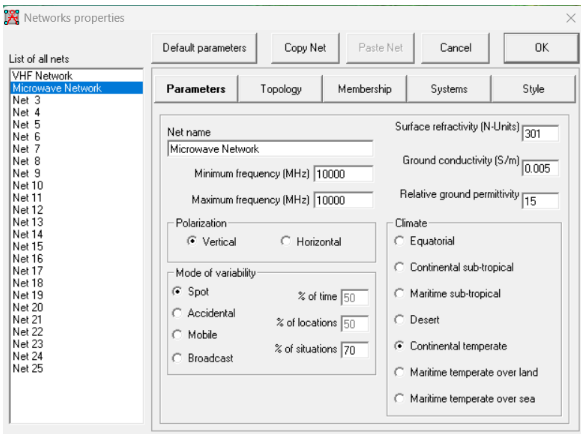


Figure 2.2: Microwave Network

Using two distinct frequency bands, VHF for user access and microwave frequencies for repeater interconnection, combined with the mesh network design, the system ensures reliable, wide reaching, and redundant communication for all users within the coverage area.

2.1 VHF Network

Based on the characteristics of the Cedar City mountainous area and the specifications of the mobile radios and repeaters available. The primary goal was to ensure reliable, full coverage for all mobile users throughout the region. To achieve this, selected devices and configured the network to maximize coverage while maintaining clear and consistent communication. The use of omnidirectional antennas on repeaters and strategically placed sites allows each mobile user to connect seamlessly to the closest repeater, providing uninterrupted service across the terrain.

Mobile unit

The Motorola DM4000e mobile radio was specified by the project requirements. Even though it was provided as the required mobile radio, its specifications proved advantageous for the mountain environment:

- Better Sensitivity: The mobile radio has 0.16 μV digital sensitivity, which is better than the repeater sensitivity (0.2 μV). This means mobile radios can hear repeaters even when repeaters might not hear the mobile radios back, providing better coverage for mobile users.
- Flexible Power: The radio can transmit between 1-25 W, allowing operators to adjust power based on battery life needs and coverage requirements.
- Frequency Compatibility: It works perfectly at the required 173 MHz frequency since its working frequency range is 136-174 MHz.
- Integration with Network Design: The mobile units where configurated to operate at 173 MHz using DMR digital technology with 4-FSK modulation to match the repeater system. The mobile radios automatically connect to the strongest repeater signal in the area, providing seamless communication as vehicles move around.
- Project Specification: The project required assuming 0 dBi antenna gain for mobile units. This realistic assumption accounts for the fact that mobile antennas are often not installed in perfect conditions and may have reduced performance compared to base station antennas.

All of these properties were configurated as it is shown in figure 2.3.

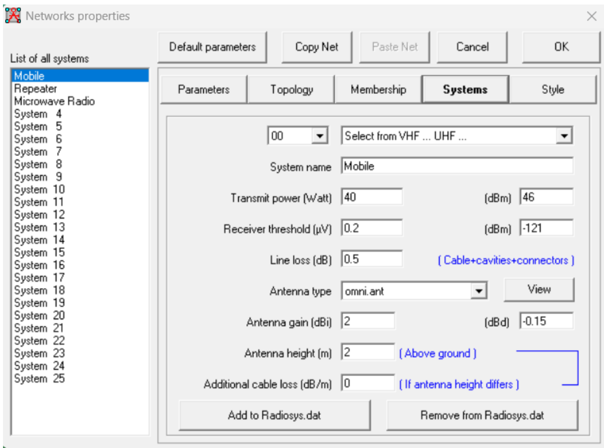


Figure 2.3: Mobile Unit Properties

Repeater

The Motorola SLR5500 repeater was given in the project requirements. The analysis of its specifications showed it was well-suited for the challenging mountain environment, and its specifications proved appropriate for the application:

- Power Output: The repeater outputs 45W of power (slightly less than its 50W maximum capacity), providing strong coverage while maintaining equipment reliability in harsh mountain conditions.
- Good Sensitivity: The 0.2 μV sensitivity means it can receive weak signals from mobile radios even in difficult terrain.
- Robust Design: Built for continuous operation in challenging environments.

VHF Antenna

In order to select an appropriate antenna type that would work well with the Motorola SLR5500 and provides good coverage in the mountain environment. BAN034R omnidirectional collinear antenna was chosen as repeater antenna after analyzing several options. Its characteristics are:

- Signal Gain: The 5 dBi gain provides much better coverage than basic antennas while still broadcasting in all directions, which is essential for mobile communications.
- Frequency Compatibility: The antenna works perfectly at 173 MHz (designed for 156-174 MHz range).
- Weather Resistance: It can an survive 180 km/h winds and is made of galvanized steel, which is necessary for Utah mountain installations.
- Power Compatibility: It can handle 50W, providing plenty of safety margin above the 45W from the Motorola SLR5500 repeater (See figure 2.4.

Coaxial cable

With the Motorola SLR5500 repeaters and BAN034R antennas selected, it is needed a coaxial cable system to connect them properly while maintaining signal quality, especially for long cable runs needed in mountain-top installations.

A low-loss coaxial cable designed for 173 MHz operation is the key feature for selection. Since cable losses increase with frequency, so selecting the right type is important for system performance. RT 50/20 low-loss coaxial cable was used for VHF applications, due to its attenuation characteristics around 173 MHz and its mechanical robustness for outdoor environments.

According to the manufacturer's datasheet, the attenuation at 200 MHz (the closest available frequency to 173 MHz) is 6.0 dB per 100 meters. For the 10-meter cable length used in each installation, this corresponds to a total loss of approximately 0.6 dB. This value was used directly in the Radio Mobile simulation for each repeater site line loss, as it is shown in figure 2.4.

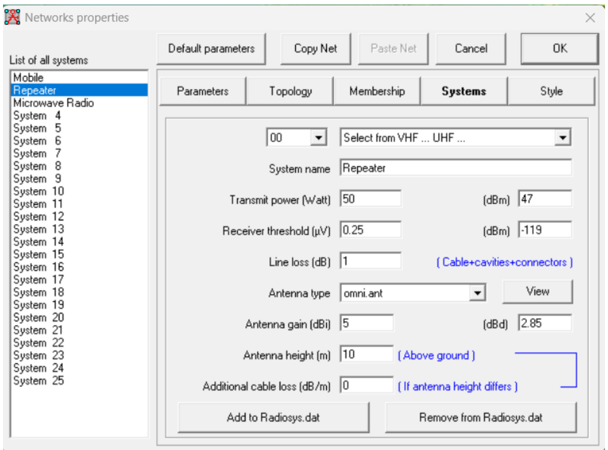


Figure 2.4: VHF antenna and line loss configuration

2.2 Microwave Network

Considering the geographic challenges and the need for efficient. High-capacity connections between repeater sites were used. The designed backbone network uses point-to-point microwave links operating at a high frequency than the VHF network. These links use highly directional antennas that enable long-distance, line-of-sight communication with minimal interference. The purpose is to interconnect all repeater sites reliably to facilitate the simulcast system, ensuring that signals are distributed quickly and simultaneously across the entire coverage area. Thereby supporting seamless communication between users regardless of their location.

The VHF network design was established using the specified equipment as its shown in figure 2.2. The project specifications required operation in the 10 GHz frequency band for the microwave backbone based on the distance between the repeater sites. Moreover, this frequency offers a good balance between bandwidth capacity, antenna size, and reliable propagation in the mountainous terrain of the coverage area. Operating at 10 GHz allows the use of directional antennas with manageable sizes that provide high gain and narrow beamwidth. Additionally, the 10 GHz band is commonly used and well supported by available commercial microwave equipment, ensuring compatibility and ease of deployment

Microwave radio unit

After analyzing various options, the team selected the PTP 820S microwave radio based on its suitability for the 10 GHz requirement and link distances:

- Frequency Support: Works from 6-38 GHz, which includes the required 10 GHz frequency.
- At 10 GHz, it transmits 26 dBm of power and can receive signals as weak as -85.0 dBm, which is suitable for the measured link distances.
- Advanced Features: Uses smart modulation (QPSK to 2048 QAM with automatic adjustment) to get the best performance and fade protection.
- Reliability: it has backup systems (1+1 HSB protection) to ensure the network stays working for emergency communications.
- Integration Capability: Has Ethernet connections that work well with the DMR repeater systems.

Antenna Microwave Link

With the PTP 820S microwave radios selected and the 10 GHz frequency requirement, there is the needed of choosing appropriate antenna for the point-to-point microwave links between repeater sites. The requiered diameter is 1.8m for a parabolic antennas for all microwave links based on the technical recommendations. The main characteristics of the chosen antenna are:

- Name: Antenna THP 18-100 DI WB.
- Frequency Range: 10-11.7 GHz.
- Size: 1.8m diameter with 1880mm height, 1880mm width, and 1284mm depth.
- Gain, low band: 42.1 dBi.
- Installation: It includes pole mount for towers up to 89mm diameter.
- Construction: Its industrial-grade materials makes it suitable for mountain installations.
- Wind Resistance: It is built to survive high winds common in mountain environments.
- Distance Requirements: The measured link distances, ranging from 26 to 56 km, required the use of high-gain antennas to achieve the necessary 10 dB safety margin.
- Focused Signal: Parabolic antennas focus the signal in one direction, reducing interference with other microwave services and providing precise point-to-point communication.

Waveguide

With the PTP 820S microwave radios and antenna THP 18-100 DI WB selected, it is needed to choose the appropriate transmission line to connect them. The decision between waveguide and coaxial cable was critical for 10 GHz operation in the harsh mountain environment. After comparing options, a waveguide is selected over coaxial cable for the 10 GHz connections because of several important technical and practical advantages:

- Much Lower Signal Loss: Waveguides have much lower loss in comparison to coaxial cables for example WR-90 waveguide only loses 0.1 dB per foot (0.33 dB per meter) at 10 GHz. Even the best coaxial cables designed for microwave frequencies lose much more signal. For example, RG402 semi-rigid coaxial cable (a high-quality microwave cable with PTFE dielectric) shows 43.4 dB per 100 feet (142.39 dB per 100 meters) at 10 GHz. Over 4 times higher loss than waveguide, making it completely impractical for the required cable runs.

- Antenna Interface Compatibility: The selected 1.8m parabolic antennas come with waveguide inputs and not a coaxial cable connection. Even if a coaxial cable was chosen to save money, if would be needed a waveguide-to-coax adapter, which would introduce additional costs, connection points, and signal losses, making the overall system more expensive and less reliable.
- Better Power Handling: Waveguides can handle much higher power levels than coaxial cables without overheating or breaking down. This is important for the 26 dBm (400mW) power from the PTP 820S radios.
- Weather Resistance: WR-90 waveguide made from copper alloy provides better protection and mechanical strength compared to flexible coaxial cables in harsh mountain conditions.
- Temperature Stability: Waveguide performance stays the same across the wide temperature range (-33°C to +55°C) found in Utah mountains.
- Long-term Reliability: No plastic materials that can break down over time, unlike coaxial cables which use foam plastic that can absorb water.

Based on all of below criteria, the chosen waveguide is WR-90 waveguide system (PE-W90S001-12) with the following specifications:

- Frequency Range: 8.2 to 12.4 GHz, which perfectly covers the 10 GHz operating frequency.
- Voltage Standing Wave Ratio: 1.03:1 maximum, ensuring good signal transfer.
- Signal Loss: 0.1 dB/ft or 0.33 dB/m, minimizing signal loss over the required distances
- Section Length: 12 in or 304.8 mm.
- Connections: Standard UG-39/U flanges for reliable connections.
- Material: High-quality copper alloy construction for durability and performance.

Installation Strategy:

Since the PTP 820S is designed as an outdoor unit compatible with harsh weather conditions,the microwave radios were placed directly on the towers near the antennas. This approach allowed the use of short 12-inch WR-90 waveguide sections to connect the radio to the antenna, minimizing signal losses and installation complexity. The outdoor-rated PTP 820S can operate in the temperature range from -33°C to +55°C, making it perfect for Utah mountain installations.

The low signal loss characteristics of the selected WR-90 waveguide were incorporated into the Radio Mobile simulation by including the waveguide attenuation in the total loss budget of the backbone microwave network. This ensured accurate modeling of signal degradation over the point-to-point microwave links connecting the repeater sites.

Chapter 3

Results

3.1 Site Selection Strategy:

With the repeater model specified, the repeaters were strategically placed on mountain tops to ensure optimal coverage, as higher elevations enhance radio signal propagation at VHF frequencies. The Cedar City area is characterized by a mix of mountains and valleys. The first repeater was placed at the highest point in the entire region. Once its coverage was established (see Figure 3.2a), the second repeater was positioned to serve a valley in the southwest part of the area (see Figure 3.2b).

However, a section on the backside of a hill in the southwest remained uncovered. To address this, a third repeater was placed at the upper part of that valley (see Figure 3.2c). The decision to install repeater 4 was based on the need to cover both a large and a small valley in the southeast corner of the region; its coverage is shown in Figure 3.2d.

In the northeast corner, a small area lacked coverage. This issue was resolved by placing repeater 5 at the highest point of a subregion, as shown in Figure 3.2e. Finally, repeater 6 was installed to ensure complete coverage of the northwest area (see Figure 3.2f).

The proposed network design minimizes the number of repeaters, as required by the project guidelines. Additionally, each repeater can communicate with at least two others via microwave links, creating redundant signal paths. This redundancy ensures that the network remains operational even in the event of a repeater failure.

Figure 3.1 presents the results [1] of the established radio links within the microwave network. For each link, the table shows the signal quality. These values provide insight into the signal propagation characteristics and performance of each link in the network, which are essential for evaluating coverage, reliability, and overall link quality.

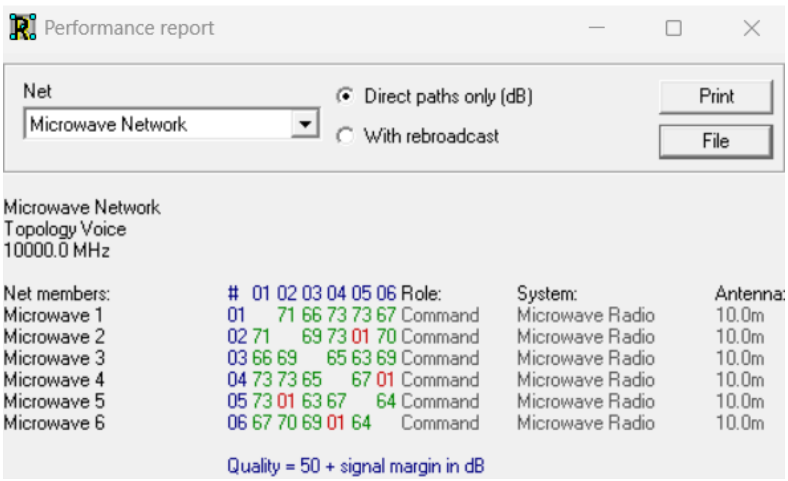
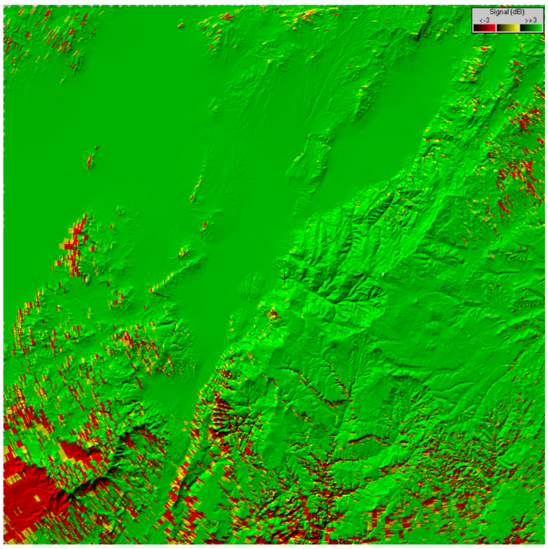
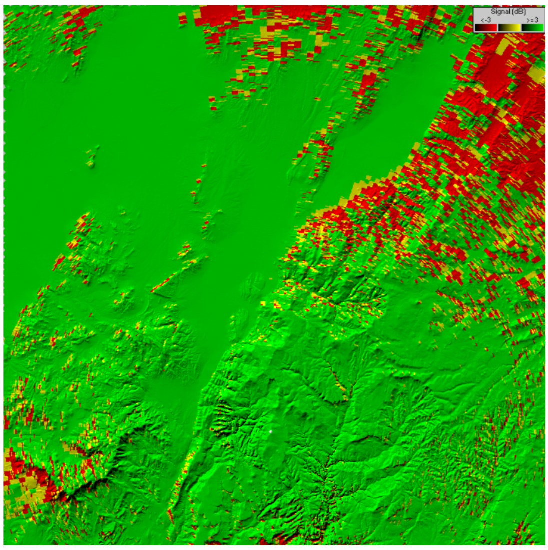


Figure 3.1: Microwave network performance

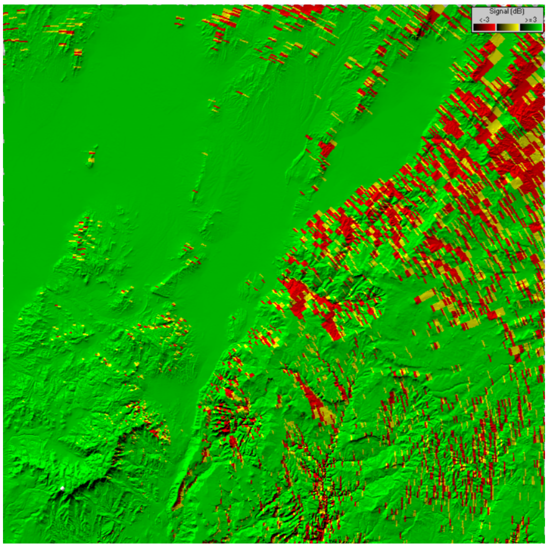
[1] All the radio links results and the network report are attached in the Appendix A



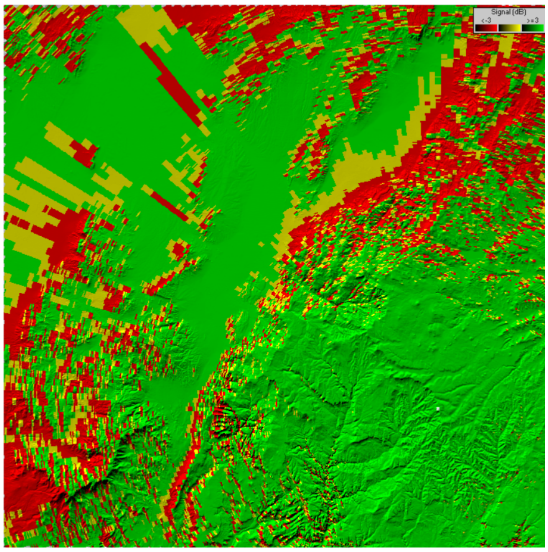
(a) Coverage repeater 1



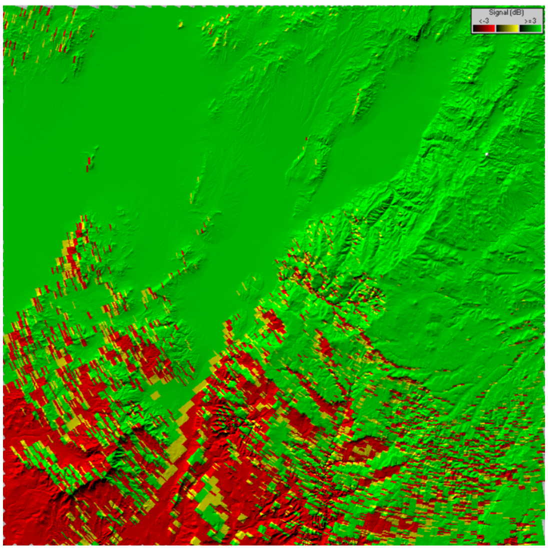
(b) Coverage repeater 2



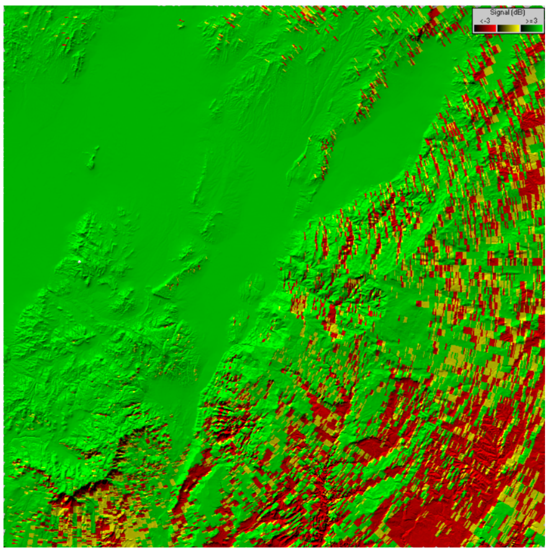
(c) Coverage repeater 3



(d) Coverage repeater 4



(e) Coverage repeater 5



(f) Coverage repeater 6

Figure 3.2: Individual coverage areas of the repeaters deployed to guarantee the radio network performance.

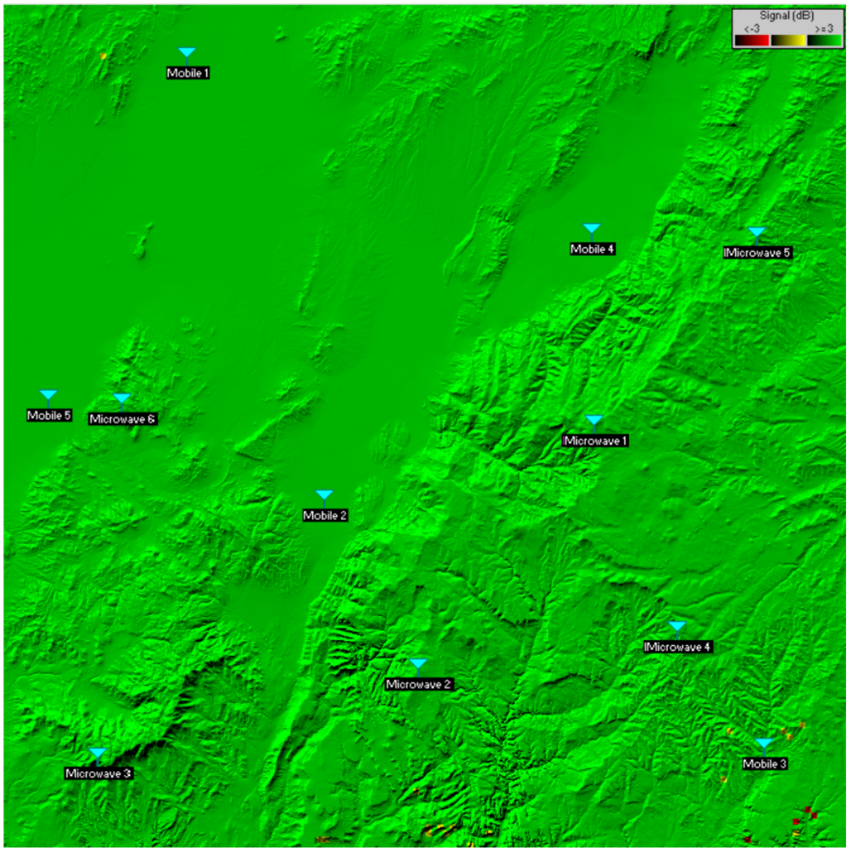


Figure 3.3: Coverage of the assigned area

Each link was designed to have at least 10 dB of safety margin above the minimum signal level. The measured performance shows received signal levels from -44.3 dBm to -38.0 dBm (see table **??**), which provides good margins above the -85.0 dBm minimum that the PTP 820S needs at 10 GHz. This ensures reliable operation even during bad weather in Utah. The figure 3.3 illustrates the complete coverage achieved by the network configuration. It provides a visual representation of the areas reached by the transmitted signals, highlighting the effective range of each transmitter and the overall distribution of coverage across the region.

Chapter 4

Conclusions

This project successfully designed and implemented a comprehensive PMR network for Cedar City, Utah. The final network topology was designed to maximize coverage and minimize obstructions by placing repeaters at elevated positions. The SIMULCAST topology ensures that all authorized users and the Operations Center can simultaneously receive communications across the entire service area, fulfilling the primary objective of reliable professional communication. These strategic placements, combined with microwave links, ensure robust connectivity and provide routing redundancy to enhance network reliability.

The proposed PMR network relies on a constellation of six repeaters strategically placed atop mountain peaks to guarantee uninterrupted radio coverage across the entire 100 $\times$100 km service area. By distributing the repeater sites at high elevations, we maximize line-of-sight propagation and minimize shadowing effects caused by rugged terrain, ensuring that every corner of the region falls within reliable service contours.

These repeaters are interconnected via a robust 10 GHz microwave mesh backbone, employing 1.8 m parabolic dish antennas. Each site maintains dual point-to-point links to at least two neighboring stations, creating a fault tolerant ring topology that preserves network integrity in the event of individual link failures. This redundant interlinking not only enhances resilience but also balances traffic loads dynamically, optimizing throughput and latency across the mesh.

On the user-facing side, mobile units operate on a 173 MHz DMR channel. When a handheld radio transmits, the closest repeater captures the signal and injects it into the microwave network, which then propagates the traffic in real time to all other repeater sites. Each repeater simultaneously rebroadcasts the transmission, yielding seamless simulcast coverage so that end users experience uninterrupted communications regardless of their movement within the service zone.

Through precise link-budget planning and antenna optimization, we have guaranteed that each microwave hop maintains a receive level at least 10 dB above the –85 dBm sensitivity threshold, ensuring robust, high quality communications even in challenging environmental conditions. Combined with the VHF repeaters' high-gain antennas and elevated placements, this margin ensures clear voice quality, low error rates, and robust performance even under adverse weather conditions. The result is an economical, scalable, and resilient PMR system with minimal physical infrastructure, built in redundancy, and straightforward pathways for future site additions or capacity upgrades.

Overall, the project successfully delivers a PMR network that meets the defined specifications. The design ensures reliable communication for professional users across the designated area, demonstrating the effectiveness of careful planning and technical decisions for the professional users within the defined geographical area.

References

[1] ETSI, "Electromagnetic compatibility and Radio spectrum Matters (ERM); Digital Mobile Radio (DMR) Systems; Part 1: DMR Air Interface (AI) protocol," ETSI, ETSI Technical Specification TS 102 361-1 V2.6.1, May 2023, https://www.etsi.org/deliver/etsi_ts/102300_102399/10236101/02.06.01_60/ts_10236101v020601p.pdf.

Appendix A

Extra Information

A.1 Results

The complete set of results for the radio link simulations and network report are available at the following links: Network Report and Microwave link results

A.2 Datasheets

- Antenna Microwave links: Antenna THP18-100 DI WB
- Antenna Repeaters: BAN034 Omnidirectional collinear Antenna
- Mobile unit: MOTOTRBO DM4000e
- Repeater: MOTOTRBO SLR 5500
- Waveguide: PE-W90S001-12
- Radio unit microwave links PTP 820S Licensed Microwave Radio
- Coaxial Cable: Coaxial Cable RT 50/20